D

APPLICATION OF THE 3G PCS TECHNOLOGIES TO THE MOBILE SUBSYSTEM OF THE NEXT GENERATION TACTICAL COMMUNICATIONS SYSTEMS

by

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ABSTRACT

The advances in high-speed computations, multimedia and wireless communications promise new opportunities to develop more robust and agile battlefield communications systems. However, there are some major distinctions between the military and commercial communications. We can enumerate the most basic two of them as the hostile environment in battlefield, and the rapid deployment requirement. In our study, we discuss how to employ emerged and evolving civilian commercial technologies, namely the third generation (3G) Personal Communications Services (PCS) techniques for military communications in spite of the existence of such distinctions. We propose an approach called Virtual Cell Layout (VCL) in which the communications area is tessellated with regularly shaped fixed virtual cells starting from a geographic reference location. The radio resources are managed in a multitier hybrid network by employing both cellular and ad hoc techniques and using VCL.

We also propose a simulation approach for the performance evaluation of the tactical communications systems. In this approach, the commands entered during the military computer aided exercises are replayed by running a constructive (combat) model which generates mobility, posture and status data for a number of units, then these data are enhanced and drive a simulation which produces the data related to the performance metrics. The evaluated performance of the system shows that the VCL based architecture satisfies the rapid deployment requirement and gives an acceptable grade of service.

ÖZET

İşlem gücü ile çoğul ortam ve telsiz iletişimlerinde sivil alanda gerçekleştirilen ilerlemeler, daha sağlam ve etkin muharebe iletişim sistemlerinin geliştirilmesi için yeni olanaklar yaratmaktadır. Bununla beraber, askeri ve sivil iletişim arasında bazı temel farklılıklar bulunmaktadır. Bu farklılıklardan en önemli iki tanesini, muharebe sahasındaki düşmanca ortam ve acil konuşlandırılma gereksinimi olarak sıralayabiliriz. Çalışmamızda, bu temel farklılıklara rağmen, üçüncü nesil PCS sistemleri olarak adlandırılan, kullanıma sunulmuş ve geliştirilmeye devam edilen sivil iletişim teknolojilerinin askeri ortama nasıl uyarlanabileceğini inceliyoruz. İletişim yapılacak alanı, bir referans noktasından başlayarak düzgün şekilli ve sabit boyutlu sanal hücrelerle kapladığımız, Sanal Hücre Kalıbı (SHK) yaklaşımını bu amaca hizmet edecek bir çözüm olarak öneriyoruz. Hem hücresel hem de "ad hoc" teknikleri kullandığımız karışık çok katmanlı bir ağda, sanal hücre kalıbını kullanarak telsiz kaynakları yönetiyoruz.

Taktik iletişim sistemlerinin başarımlarının değerlendirilmesi amacıyla bir benzetim yöntemi de öneriyoruz. Bu yöntemde, önceden gerçekleştirilen bilgisayar destekli askeri tatbikatlarda girilen emirleri, çok sayıdaki birliğe ait hareket, görev ve durum gibi verileri toplayan bir yapıcı (muharebe) model kullanarak tekrar işletmekteyiz. Daha sonra toplanan bu veriler daha da detaylandırılarak, başarı ölçütlerimize ait değerleri üreten benzetimi sürmekte kullanılmaktadır. Sistemi değerlendiren başarım ölçümleri, SHK'dan yararlanılarak geliştirilen mimarinin, acil konuşlandırılma ihtiyacını karşıladığını ve kabul edilebilir bir hizmet derecesine sahip olduğunu göstermektedir.

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LIST OF SYMBOLS

a_n	n^{th} member of a sequence
B	Bandwidth
B_{ss}	Spread spectrum bandwidth
C_k	Correlation between a sequence and *k* phase shifted version of it
d_o	The distance between the interfering mobile and the interfered base
d_m	The distance between the interfering mobile and its base
E_b/N_o	Bit energy to noise density ratio
E_p	Topology view produced by the chooser processor *p*
F	Having traffic in forward link
F_p	Topology view produced by the foreseer processor *p*
f	The boundry between two interfering cells
f_o	Carrier *0*
G(t)	Spreading code at time *t*
I	The interference
k	The multiplication factor to convert VCL cell radius to real cell radius
M	The number of channels carrying the traffic other than voice
N	The number of voice channels
p	Random variable for the channel activity in forward direction
Pb_o	Original position of the RAP
Pb_d	Destination position of the RAP
Pm_o	Original position of the MPR
Pm_d	Destination position of the MPR
PG	Processing gain
P_t	Voice transmission probability
P_r	Data retransmission probability
q	Random variable for the channel activity in reverse direction
R	Having traffic in reverse link
R_b	Bit rate
R_k	Correlation between *a* sequence and *k* phase shifted version of *b* sequence
R_p	Chip rate
R_t	The range of a transciever equipments

r	VCL cell radius
r_v	Transmission range of node *v*
S	The signal power at the receiver
SF	Spreading factor
S_r	Reservation or auction slot
$S_t(t)$	Spread spectrum signal transferred at time *t*
S_v	Voice slot
t	The distance between the interfered base and the base of the interfering cell
T	The cell residency time
T_d	Propagation delay
T_s	Bit transmission time
V_b	The velocity of the RAP
V_m	The velocity of the MPR
V_c	Changed topology view
V_p	Topology view of processor *p*
x(t)	Data transmitted at time *t*
α	Voice activity factor
α_b	The movement direction of the RAP according to the reference line
α_m	The movement direction of the MPR according to the reference line
β	The angle between the reference line and the line that connects two original position
ε	Gausian random variables
ϕ	Random variable for the channel activity
γ	The slope value for the propagation model
η	Background noise
σ	Standard deviation
τ_k	The variable that indicates the existence of an interfering access point in the k^{th} interfering cell
ψ	The probability of having an interfering channel at a point

LIST OF ACRONYMS

AC	Authentication Center
ACI	Adjacent Channel Interference
ACUS	Area Common User Systems
ADC	American Digital Cellular
AMPS	Advance Mobile Phone System
ATM	Asynchronous Transfer Mode
ATTCS	Army Tactical Command and Control System
BCCH	Broadcast Control Channel
BDCL	Borrowing with Directional Channel Locking
BFA	Battlefield Functional Area
B-ISDN	Broadband Integrated Services Digital Network
BTS	Base Transceiver Station
BSS	Base Station System
C4I	Command, Control, Communications, Computer and Intelligence
CAX	Computer Aided Exercise
CCF	Call Control Function
CCAF	Call Control Agent Function
CDMA	Code Division Multiple Access
CNR	Combat Net Radio
CSMA	Carrier Sense Multiple Access
CSS	Communications Simulation System
DARPA	Defense Advanced Research Projects Agency
DBS	Direct Broadcast Satellite
DCA	Dynamic Channel Assignment
DCH	Dedicated Channel
DECT	Digital Enhanced Cordless Telephone
DISN	Defense Information System
DPCCH	Dedicated Physical Control Channel
DPDCH	Dedicated Physical Data Channel
DS-CDMA	Direct Sequence Code Division Multiple Access

D-TDMA	Dynamic Time Division Multiple Access
DTG	Digital Transmission Group
ECCM	Electronic Counter Counter Measures
ECM	Electronic Counter Measures
EIR	Equipment Identity Register
ETSI	European Telecommunications Standards Institute
ESM	Electronic Support Measures
FACH	Forward Access Channel
FCA	Fixed Channel Assignment
FDD	Frequency Division Duplexing
FDR	Future Digital Radio
FDMA	Frequency Division Multiple Access
FH-CDMA	Frequency Hopping Code Division Multiple Access
GEO	Geo-stationary Earth Orbit
GIU	Gateway Interface Unit
GloMo	Global Mobile
GMF	Ground Mobile Force
GPS	Global Positioning System
GPU	General Purpose User
GSM	Global System for Mobile Communications
HCA	Hybrid Channel Assignment
HCTR	High Capacity Trunk Radio
HLR	Home Location Register
IFF	Intelligence of Friendly or Foe
IN	Intelligent Network
IS	Interim Standard
ISDN	Integrated Services Digital Network
IP	Intelligent Peripheral
JTLS	Joint Theater Level Simulation
LA	Locational Area
LAN	Local Area Network
LAS	Local Area Subsystem
LEO	Low Earth Orbit

LOS	Line of Sight
MA	Multiple Access
MAC	Medium Access Control
MAHO	Mobile Assisted Handoff
MBMMR	Multi Band Multi Mode Radio
MCF	Military Computer Family
MCHO	Mobile Controlled Handoff
MCS	Maneuver Control System
MNS	Material Need Statement
MPR	Man Packed Radio
MPRT	MPR Tier
MRR	Multi Role Radio
MS	Mobile Subsystem
MSC	Mobile Switching Center
MSE	Mobile Subscriber Equipment
MT	Mobile Terminal
MTBF	Mean Time Between Failure
NAP	Network Access Point
NCHO	Network Controlled Handoff
NMT	Nordic Mobile Telephones
NTDR	Near Term Digital Radio
NTT	Nippon Telephone and Telegraph
OTM	On The Move
PACS	Personal Access Communication Services
PBX	Private Branch Exchange
PCH	Paging Channel
PCS	Personal Communications Services
PDC	Personal Digital Cellular
PHS	Personal Handy-phone System
PN	Pseudo Noise
PR	Packet Radio
PRMA	Packet Reservation Multiple Access
QI	Quality Indicator

RA	Registration Area
RACH	Random Access Channel
RAMA	Resource Auction Multiple Access
RAP	Radio Access Point
RAPT	RAP Tier
RP	Radio Port
RPCU	Radio Port Control Unit
RSSI	Received Signal Strength Indication
SATT	Satellite Tier
SBB	Switched Backbone
SCF	Service Control Function
SCP	Service Control Point
SDF	Service Data Function
SDP	Service Data Point
SF	Spreading Factor
SINCGARS	Single Channel Group and Airborne Radio System
SN	Service Node
SNR	Signal to Noise Ratio
SR	Software Radio
SRF	Service Resource Function
SS7	Signaling System No. 7
SSF	Service Switching Function
SSM	Surface to Surface Missile
SSP	Service Switching Point
SYNC	Synchronization
TACOMS	Tactical Communications
TACS	Total Access Communications System
TAFICS	Turkish Armed Forces Integrated Communications System
TASMUS	Tactical Communications System
TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
TF	Transport Format
TIU	Trunk Interface Unit

TPN	Tactical Packet Network
TrCh	Transport Channel
TRI-TAC	Triservice Tactical
UAV	Unmanned Aerial Vehicle
UAVT	UAV Tier
UMTS	Universal Mobile Telecommunications System
UTRA	UMTS Terrestrial Radio Access
VCL	Virtual Cell Layout
VLR	Visitor Location Register
WAS	Wide Area Subsystem
WCDMA	Wideband Code Division Multiple Access
WEI	Word Error Indicator

1. INTRODUCTION

The next generation tactical communications systems leverage evolving and emerged technologies, continuing initiatives and interim solutions to improve the way that the war fighters communicate. The goal is an efficient, robust, flexible and tailorable network that can convey multimedia traffic among the components of a battle force. They have four subsystems in common, namely the wide area subsystem, the local area subsystem, the mobile subsystem and the system management and control subsystem. Among these subsystems, the mobile subsystem is the one that will provide the ultimate for the communications of the war fighters in a hostile and unpredictable environment.

Personal Communications Services (PCS) technologies which are generally based on cellular network and Intelligent Network (IN) techniques evolve towards the goals of personal, terminal and service mobility. PCS technologies promise an immense improvement in the way war fighters communicate in a mobile environment. However, the current PCS technologies have some major adaptability problems with the tactical communications systems. Cellular networks are fixed base-station oriented. Since they require a large immobile infrastructure, it is not an easy task to employ them as a technology for a system that requires rapid deployment capability. Such an immobile infrastructure also weakens the survivability of a communications system in a hostile environment.

Survivability and rapid deployment capability are the key benchmarks for anything military. We propose and discuss the approaches that adapt the current PCS technologies without violating these key features required for the battlefield systems.

PCS technologies are categorized into three generations. The first generation PCS systems are the analog systems with some limited capacity. The capacity is improved in the second generation systems like Global System for Mobile Communications (GSM) which are digital cellular systems that can transfer voice traffic together with low speed data. A mass market has been achieved through the second generation networks. Third generation PCS networks which will convey multimedia traffic through mobile and wireless environments are planned to be deployed starting from the year 2002 (Samukic, 1998). The standards are still being developed for the third generation.

European Telecommunications Standards Institute (ETSI) is developing Universal Mobile Telecommunications System (UMTS) which will replace GSM gradually. In January 1998, UMTS Terrestrial Radio Access (UTRA) is selected as the radio access technology for the third generation UMTS. UTRA uses Wideband Code Division Multiple Access (WCDMA) (Dahlman, 1998).

1.1. Contribution of the Thesis

In our thesis, we investigate the approaches that can employ UTRA as the radio access technique for the mobile subsystem of the next generation tactical communications systems. We propose an approach named Virtual Cell Layout (VCL) which enables the management of scarce resources efficiently in a mobile environment with a mobile infrastructure.

In VCL, the area of communications is tessellated with regularly shaped, fixed size hexagons. Each hexagon represents a VCL cell to which the available spectrum is assigned according to the $N=3$ frequency reuse plan. The short codes that define the access points in UTRA, and the preamble codes used for random access are distributed among the fixed VCL cells, as well. Hence, the mobile access points can determine the most appropriate set of carriers and codes without a need for a central topology database or a central resource manager, if they can pinpoint their current geographic location.

Based on this approach, we propose some algorithms and schemes which enable us to employ UTRA as the radio access technique used by a mobile infrastructure. In order to make the proposed system compatible with UMTS, we design these schemes in a way that a UTRA terminal can access the proposed system, or a terminal of the system can access a UMTS network.

We also work on an ad hoc approach that make the mobile terminals of the proposed system be self organized in the absence of an access point in the vicinity. VCL is used to devise some distributed ad hoc techniques that organize the unconnected mobile terminals into clusters and relay these clusters to an access point. Moreover, we propose some handoff and routing techniques that can run on the proposed architecture.

We also propose an approach to evaluate the performance of the tactical communications systems by using the current combat simulation systems which are generally referred as constructive or combat models (Çayırcı, 1997a). In this approach, the commands entered during a Computer Aided Exercise (CAX) are recorded. These recorded commands are replayed, and the results of these commands are translated into a database which stores some mobility and posture information about a number of units. The translated database is used to drive a simulation software which enhances the resolution of the information produced by the constructive models, generates the calls and events, and collects the data related to the predetermined performance metrics for the proposed communications system. A final module analyzes the data collected for the performance metrics.

With the aid of the described simulation system, the performance of the VCL based system was evaluated. The evaluated performance of the system shows that the VCL based architecture satisfies the rapid deployment requirement and gives an acceptable grade of service.

1.2. Structure of the Thesis

In Chapter 2, the current technologies related to wireless communications are discussed. We examine PCS and the technologies which can transfer multimedia data between untethered nodes (nomadic or mobile) through terrestrial networks in this chapter.

In Chapter 3, we discuss the challenges of the battlefield communications systems and the ongoing efforts to apply the evolving wireless communications network technologies into a battlefield. The ongoing development efforts and emerged technologies for the tactical communications components are elaborated in this chapter, too. We base our assumptions for the future components to these discussions.

We define the proposed system architecture in Chapter 4. This definition includes VCL approach, the algorithms and schemes used by the access points of the system, and an ad hoc approach for the mobile terminals.

We developed a simulation software that can interact with a constructive combat model, namely Joint Theater Level Simulation (JTLS), to evaluate the performance of the proposed system. The architecture of the developed simulation software and the results of the simulation studies are given and analyzed in Chapter 5.

Finally, in the last chapter, we conclude our study.

2. WIRELESS NETWORKING

Wireless networking is the way to provide the mobile users and the mobile networks with an access to a communications network. One can distinguish two basic wireless networking paradigms, namely ad hoc networking and cellular networking (Bambos, 1998). The existence of a fixed infrastructure is the main difference between these two paradigms.

In ad hoc networking paradigm, mobile terminals establish links among themselves. Hence, they build a network topology in which multihop connectivity is generally allowed. In cellular networking paradigm, mobile terminals access to a fixed infrastructure through a single hop wireless link which is to an access point. The cellular networking paradigm is a special case (single hop) of the more general ad hoc networking one (wireless multihop). The most basic characteristics of these paradigms are compared in Table 2.1.

TABLE 2.1. Ad hoc and cellular networking paradigms (Bambos, 1998).

Ad hoc networking	Cellular Networking
There is no fixed infrastructure.	A fixed infrastructure is required.
There is wireless multihop communication, dynamically set up and reconfigurable as nodes move around.	There are access points where the mobiles connect via single hop links.

In both of these paradigms and in the hybrid approaches, some of the communication links are established through wireless medium. The wireless medium is differentiated from the other media by the followings:

- The wireless medium is more error prone.
- The errors which occur in wireless medium are more bursty.
- The capacity of wireless medium is limited.

In this chapter, we examine the wireless medium and the wireless networking issues related to the approach proposed in our thesis.

2.1. Multiple Access Schemes

One problem associated with the wireless feature is that the system bandwidth is limited. To satisfy the huge service demand and to fulfill the multimedia requirement with limited bandwidth, an efficient Multiple Access (MA) scheme is required. The used MA scheme will have a significant impact on the user performance, the system capacity, and the hardware complexity. A successful MA scheme needs to take full advantage of the characteristics of different kinds of traffic to achieve high multiplexing efficiency. Some of these characteristics are well known. For instance, in packetized voice communication, the user's speech consists of a sequence of talkspurts and silence gaps. In the silence gaps, nothing is transmitted, and the channel can be released for other users. Compared to short data communication, which generates only one or two delay insensitive packets during one connection, the talkspurt, including a sequence of packets generated periodically, can be considered as continuous and delay sensitive. For this kind of continuous and delay sensitive traffic, the connection oriented transmission mode is better than the connectionless one, which is preferred in short data transmission. On the other hand, video traffic can also be considered as a sequence of delay sensitive packets generated continuously. Contrary to conventional voice traffic, it requires much higher data rate and has more stringent performance requirements. When video traffic is integrated in the system, the major problem is how to support the mixed traffic with varying data rates efficiently.

In the literature, it is possible to find numerous MA protocols. In our study, we classify the MA schemes and examine only the ones which are more important for the system that we work on. Our classification which is adopted from (Rom, 1990) is illustrated in Figure 2.1.

At the highest level of the classification we distinguish between conflict free and contention protocols. Conflict-free protocols are those ensuring that a transmission, whenever made is a successful one, that is, will not be interfered by another transmission. Conflict free transmission can be achieved by allocating the channel to the users either statically or dynamically. The channel resources can be viewed, for this purpose, from a time, frequency, mixed time-frequency or code standpoint. Hence, the multiple access channel can be shared by a large number of users either on a frequency basis using Frequency Division Multiple Access (FDMA), on a time basis using Time Division Multiple Access (TDMA), on a both time and frequency basis using Frequency Hopping Code Division Multiple Access (FH-CDMA) or on a code basis by using Direct Sequence Code Division Multiple Access (DS-CDMA) (Abramson, 1994) (Pahlavan, 1995).

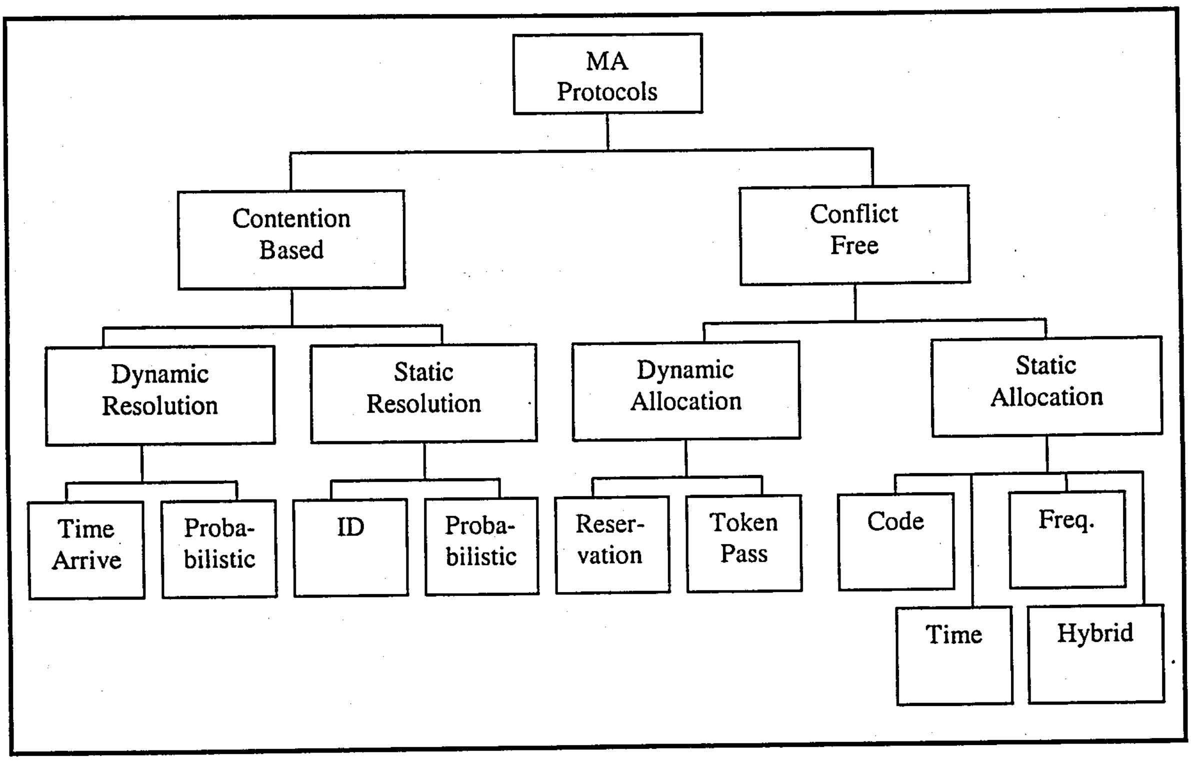


FIGURE 2.1. Classification of Multiple Access Protocols (Rom, 1990).

Contrary to the static allocation, the dynamic one allocates channels based on demand so that a user who happens to be idle uses only a little, if at all, of the channel resources, leaving the majority of its share to the other, more active users. Such an allocation can be done by various reservation schemes in which the users first announce their intent to transmit and all those who have so announced will transmit before new users have a chance to announce their intent to transmit. Packet Reservation Multiple Access

(PRMA), Dynamic TDMA (D-TDMA), Resource Auction Multiple Access (RAMA) (Qiu, 1998) are example of reservation based dynamic allocation protocols. Another common dynamic allocation scheme is referred to as token passing in which a single (logical or physical) token is passed among the users permitting only the token holder to transmit, thereby guaranteeing noninterference. Token-ring and token-bus are examples of this class.

Contention based schemes differ in principle from conflict-free schemes since a transmitting user is not guaranteed to be successful. The protocol must prescribe a way to resolve conflicts once they occur so all messages are eventually transmitted successfully. The resolution process does consume resources and is one of the major differences among the various contention protocols. As in the conflict free case, here too, both static and dynamic resolution exist. Static resolution means that the actual behavior is not influenced by the dynamics of the system. A static resolution can be based, for example, on user ID's or any other fixed priority assignment, meaning that whenever a conflict arises the first user to finally transmit a message will be the one with, say, the smallest ID (this is done in some tree-resolution protocols). A static resolution can also be probabilistic, meaning that the transmission schedule for the interfering users is chosen from a fixed distribution that is independent of the actual number of interfering users as is done in Aloha-type protocols and the various versions of Carrier Sense Multiple Access (CSMA) protocols.

Dynamic resolution, namely taking advantage and tracking system changes is also possible in contention based protocols. For example, resolution can be based on time of arrival, giving highest (or lowest) priority to the oldest message in the system. Alternatively, resolution can be probabilistic but such that the statistics change dynamically according to the extent of the interference. Estimating the multiplicity of the interfering packets, and the exponential back off scheme of the Ethernet standard fall into this category.

In cellular paradigm where there are two types of wireless multiple access channels, namely uplink (the link from the mobiles to the access point) and downlink (the link from the access point to the mobiles). Not only the multiple access to a common media, but also dublexing that media is a critical issue. The common media air is shared between these two links according to one of the dublexing techniques. The mostly used two examples for the dublexing techniques can be enumerated as follows:

- Frequency Division Duplexing (FDD),
- Time Division Duplexing (TDD),

In this section we examine static allocation and reservation based dynamic allocation schemes in detail, since they are mostly implemented schemes for the current mobile communications systems.

2.1.1. Static Allocation Schemes

In FDMA (Frullone, 1994) (Jung, 1993) (Li, 1995), the spectrum is divided into equal frequency channels and channels are appropriately spaced. Then each of these channels is assigned to a single active mobile terminal. TDMA make use of the digital technology. In TDMA (Falconer, 1995) (Frullone, 1994) (Jung, 1993), the usage of each radio channel is partitioned into multiple timeslots, and each active mobile terminal is assigned a specific frequency/time slot combination. With CDMA (Akyildiz, 1999) (Belcore, 1996) (Bottomley, 1993) (Chan, 1994) (Frullone, 1994) (Fukasawa, 1996) (Gihousen,1991) (Hminy, 1996) (Hong, 1996) (Jansen, 1995) (Jung, 1993) (Kohno, 1995) (Lee, 1991a) (Liu, 1996) (Lu, 1996) (Moshavi, 1996) (Muammar, 1992) (Pickholtz, 1991) (Trabelsi, 1994) (Tsai, 1994) (Yang, 1996), the whole spectrum is used simultaneously by multiple mobile terminals in a given cell, and the signals are distinguished by spreading them with different codes.

The use of spread spectrum techniques for military communications has become quite common over the 80s. However there has been even greater interest in understanding both the capabilities and the limitations of spread spectrum techniques for commercial applications in recent years. CDMA (Faruque, 1996) is a well known spread spectrum technique. CDMA capacity is only interference limited unlike FDMA and TDMA capacities which are primarily bandwidth limited. We can list the advantages of CDMA over FDMA and TDMA as follows:

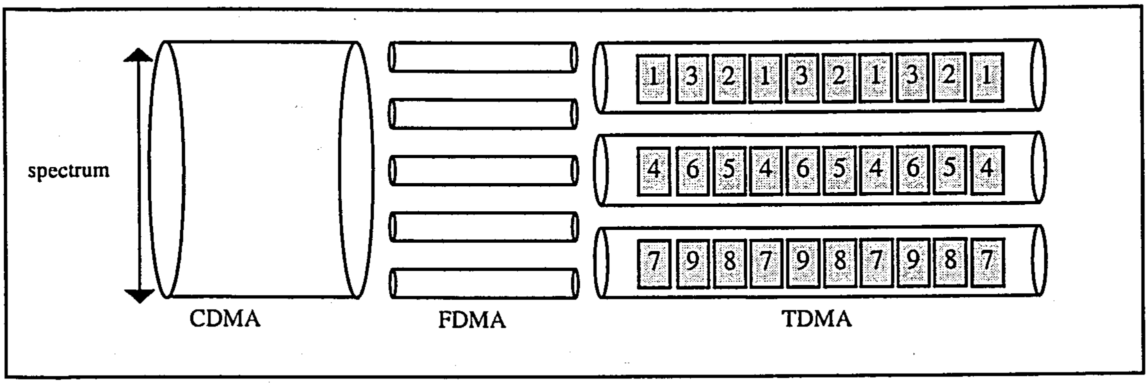


FIGURE 2.2. Multiple access schemes.

- CDMA capacity is only interference limited while FDMA and TDMA capacities are primarily bandwidth limited. Any reduction in interference converts directly and linearly into an increase in capacity (Gihousen,1991).
- Since voice and data links are idle generally with a duty factor of approximately 3/8, capacity can be increased by an amount inversely proportional to this factor by suppressing transmission during the quiet periods. This is natural in CDMA, and no extra effort is needed since it is only interference limited. However, care should be taken for the same result in FDMA and TDMA.
- Extra capacity enhancement is possible through decreasing interference by spatial isolation which can be achieved by multibeamed and multisectored antennas.
- Channel separations by FDMA or TDMA yield suboptimal system capacity since there is wasted spectrum between frequency channels, and some time slots are wasted. Handoffs requires switching of channels in the case of FDMA and TDMA which increases operational complexities and decrease system capacity. On the other hand, a CDMA system maximizes capacity because each user uses the entire frequency band and retains his unique code permanently, and there is no wasted space between codes (Fukasawa, 1996).
- CDMA can reuse the same (entire) spectrum for all cells, thereby increasing capacity by a large percentage of the normal frequency reuse factor. FDMA and

TDMA rely on attenuation for frequency reuse which requires certain spacing among the channels that uses the same spectrum.

- CDMA is the most secure MA most notably in hostile environments.

There are two CDMA techniques, Direct Sequence (DS) and Frequency Hopping (FH). An FH receiver equips *N* frequency channels for an active call to hop over those *N* frequencies with a determined hopping pattern. If the information channel width is 10 kHz and there are 100 channels to hop, $N=100$, the FH bandwidth $B_{ss}=1$ MHz. The spectrum is spread from 10 kHz (no hopping) to 1 MHz (frequency hopping). The spectrum spreading in FH is measured by the *Processing Gain* (PG) as

$$PG = 10\log N \text{ (in dB)} \qquad (2.1)$$

Then the PG of the above example is 20 dB.

The total hopping frequency channels are called *chips*. There are two basic hopping patterns; one is called fast hopping which makes two or more hops for each symbol. The other is called slow hopping which makes two or more symbol for each hop. In general, the transmission data rate is the symbol rate. The symbol rate is equal to bit rate at a binary transmission.

DS-CDMA is a multiple access technique where several independent users simultaneously access a multipoint-to-point channel by modulating preassigned signature waveforms, known as Pseudo Noise (PN) sequences or spread spectrum codes. The incoming signal at the receiver is, therefore, a superposition of such signals. Upon observation of this composite signal and equipped with a knowledge of the spreading code, the receiver demodulates and decodes the information. Because the spreading and despreading are accomplished by direct application of PN sequences, the overall process is described as Direct Sequence-CDMA. Since the data traffic from the large population of users is considered to be bursty, then DS-CDMA is used in a random access mode of operation (Trabelsi, 1994).

In direct sequence, each information bit is symbolized by a large number of coded bits called *chips*. For example, if an information bit rate $R=10\ kb/s$ is used, and it needs an information bandwidth $B=10\ kHz$, and if each bit of 10 kb/s is coded by 100 chips, then the chip rate is 1 Mb/s which needs a DS bandwidth, $B_{ss}=1\ Mhz$. The bandwidth is thus spreading from 10 kHz to 1 Mhz. The spectrum spreading in DS is measured by the *processing gain* in decibels.

$$PG = 10 \log (B_{ss}/B) \text{ (in dB)} \tag{2.2}$$

Then the PG of the above example is 20 dB or we can say this spread spectrum system has 20 dB processing gain.

The basic DS technique is illustrated in Figure 2.3. The data $x(t)$ transmitted with data rate R_b is modulated by a carrier f_o first, then by a spreading code $G(t)$ to form a DS signal $S_t(t)$ with a chip rate R_p which takes a DS bandwidth B_{ss}. The DS signal $S_t(t-T_d)$ after a propagation delay T_d is received and goes through a correlator using the same spreading code $G(t)$ prestored in the receiver to despread the DS signal. Then the despread signal $S(t-T_d)$ is obtained. After demodulating it by f_o, $x(t)$ is recovered.

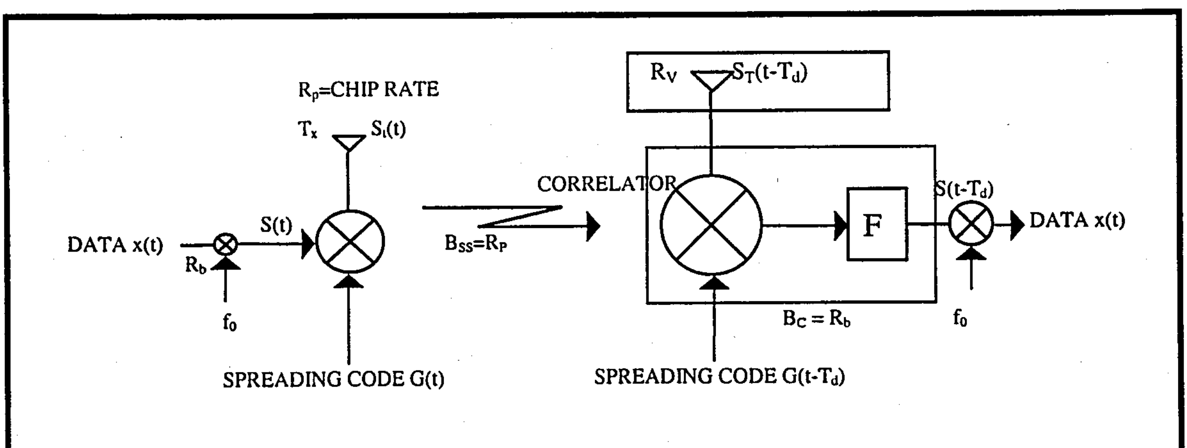


FIGURE 2.3. Basic spread spectrum technique (Lee, 1991).

The spreading code in DS-CDMA is a bit sequence. CDMA sequences can be classified into two groups, namely *Pseudo Noise* (PN) sequences and orthogonal sequences. The desirable properties of sequences are listed below:

- Good auto correlation for synchronization and synchronous CDMA,
- Low cross correlation for low Multiple Access Interference (MAI),
- Availability of large number of codes.

Auto correlation is the degree of correspondence between a sequence and a phase-shifted replica of itself.

$$C_k = \sum_{n=1}^{N} a_n a_{n+k} \tag{2.3}$$

In Equation 2.3, C_k is the correlation between a sequence and k phase shifted version of it, N is the length of the sequence, and a_n is the n^{th} member of the sequence.

Cross correlation is the degree of agreement between two different sequences.

$$R_k = \sum_{n=1}^{N} a_n b_{n+k} \tag{2.4}$$

In Equation 2.4, R_k is the correlation between the sequence a and k phase shifted version of the sequence b, and N is the length of the sequences.

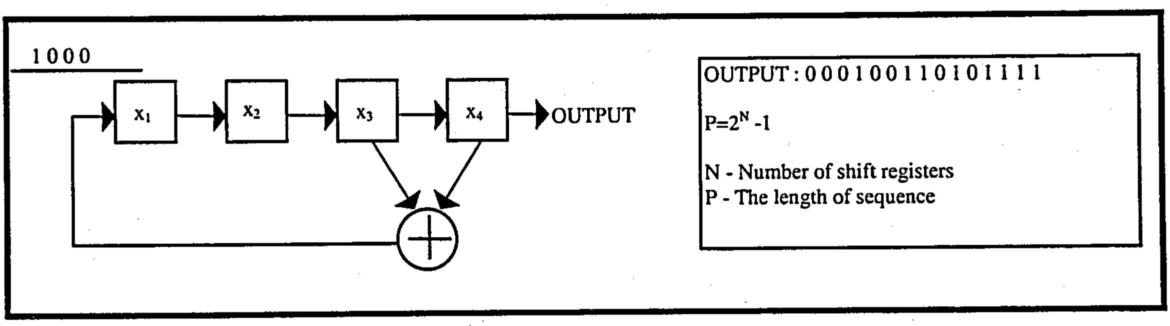


FIGURE 2.4 The linear maximal length sequence (PN Code) generator (Lee, 1991).

PN sequences contains three properties.

- *Balance Property* : The numbers of zeros and ones of a PN code are different only by one.
- *Run Property* : Half of the runs is 1 runs and the other half is 0 runs, and $1/2^n$ proportion of the runs are of length n in a PN code. For instance, in the example

given in Figure 2.4, there are 4 zero runs and 4 one runs, and 1/2 of the runs are of length 1, 1/4 of the runs are of length 2, and 1/8 of the runs are of length 3.

- Good Auto Correlation Property : If the sequence is shifted by any number of elements, the resulting sequence will have equal number of agreements and disagreements with the original sequence.

An important class of sequences called maximal length linear feedback shift register sequences are well known to exhibit above properties (Gihousen,1991). Gold and Kasami are the other well known sequences (Dinan, 1998).

Length of a PN sequence can be calculated by applying the Equation 2.5 in which *n* is the number of shift registers, and *N* is the length of the PN sequence.

$$N = 2^n - 1 \qquad (2.5)$$

$$H_1 = [0] \qquad H_2 = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$$

$$H_4 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix} \qquad H_{2n} = \begin{bmatrix} H_n & H_n \\ H_n & H_n \end{bmatrix}$$

FIGURE 2.5. Walsh-Hadamard codes.

PN sequences are generally classified into two groups, namely short and long codes. The length of short codes in IS-95 is $2^{15}-1$ and can be transferred within *26.67* seconds with *1.2888* Mcps chip rate. On the other hand, the length of IS-95 long codes is $2^{42}-1$ and can be transferred within *44.5* days. Short codes are generally used to identify cells and sectors. Long codes are used to identify the subscribers.

Orthogonal sequences are used for channelization in forward links. Auto correlation of orthogonal sequences usually are not good, but their cross correlation with the sequences orthogonal to them is zero. When two orthogonal sequences are multiplied and then integrated, the result is zero. Therefore if they are used for channelization, theoretically there is no MAI. Walsh-Hadamard Codes are the orthogonal sequences used in IS-95.

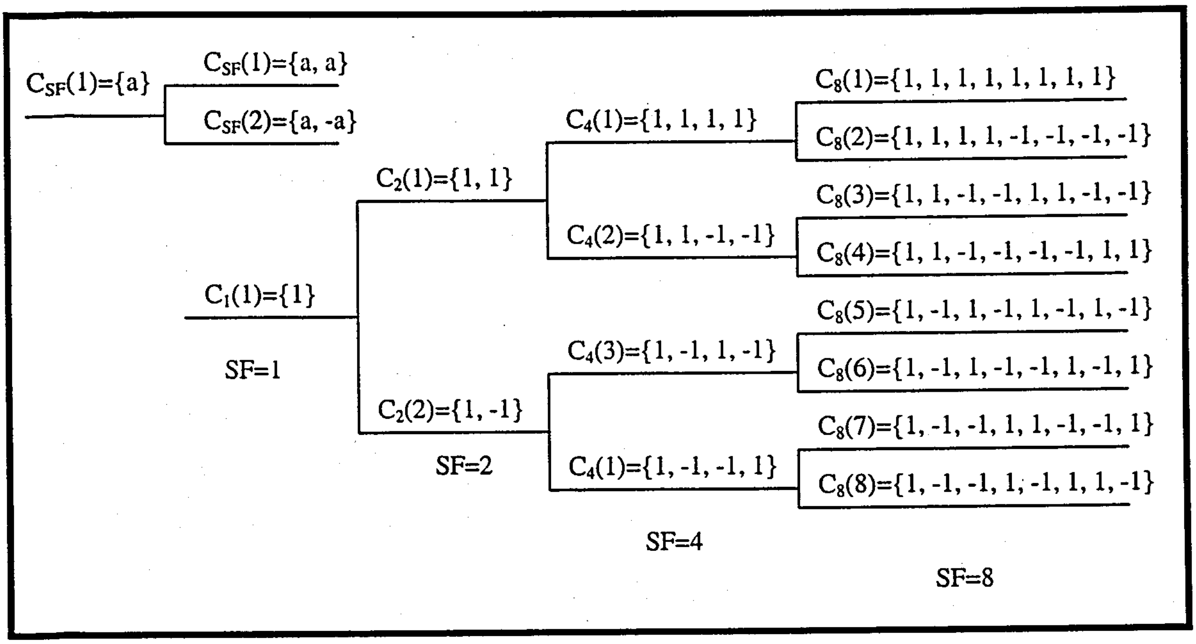


FIGURE 2.6. Code tree generation of variable length orthogonal codes.

In WCDMA described with 3rd Generation PCS, Variable Length Orthogonal Codes are used, since WCDMA is designed to support a variety of data services from low to very high bit rates. In this approach, the length of orthogonal codes depends on the Spreading Factor (SF). The ratio of PN sequence bit rate to data bit rate is called the spreading factor. Code tree for generation of variable length orthogonal codes is illustrated in FIGURE 2.6.

Spreading process of the signals is illustrated in Figure 2.7. If the signal spread by applying a sequence is despread with the same sequence the original signal is achieved.

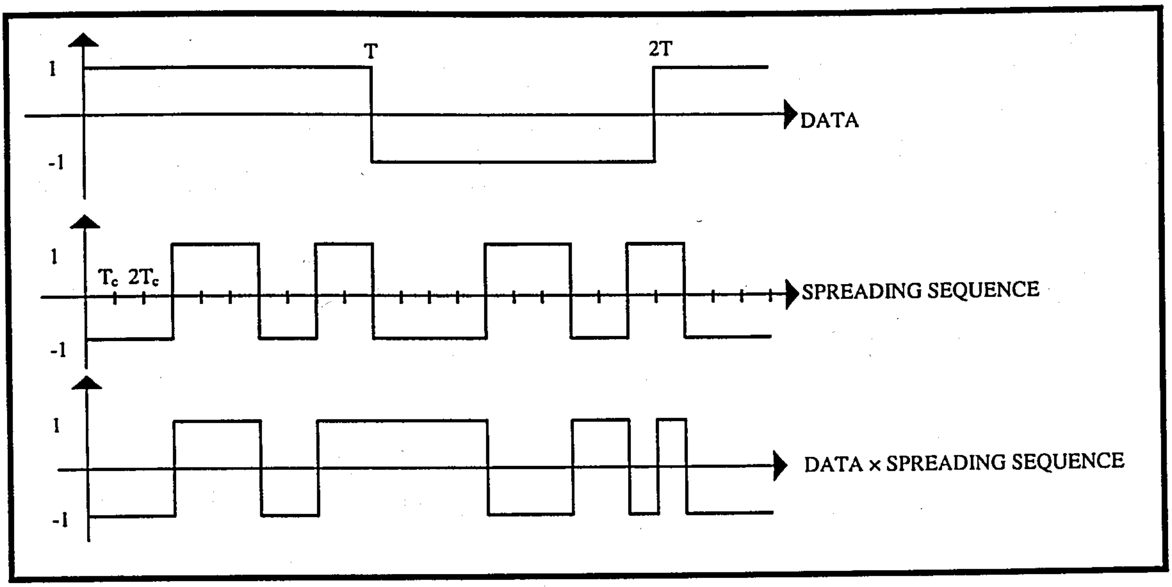


FIGURE 2.7 Time waveforms involved in generating a direct sequence signal

2.1.2. Reservation Based Dynamic Allocation Schemes

In this section, we will briefly describe three representative protocols of the reservation family: PRMA, D-TDMA, and RAMA. All of them have the frame structure and the contention-based reservation mechanism. The following are defined in (Qiu, 1998).

In PRMA, time is divided into slots which are grouped into frames. The frame length is determined by the voice-packet-generation rate. One voice packet is generated in a frame. The frame structure is shown in Figure 2.8(a). A slot in a frame is either available or reserved by the voice user. Both voice and data users can contend for the available slots, based on the voice-transmission-permission probability p_t and the data-retransmission probability p_r, respectively. Here, "voice users" refers to those who have a newly generated talkspurt, but have not obtained reservation yet. If a voice user succeeds, this slot will be labelled as reserved and this voice user can use the corresponding slot in subsequent frames until the end of the current talkspurt. If a data user succeeds in the contention, this slot is still labelled as available, and the data user can only use this slot in the current frame and no reservation is allowed. Contrary to other reservation protocols, no dedicated reservation packet is needed in PRMA. The information packet is used for channel access.

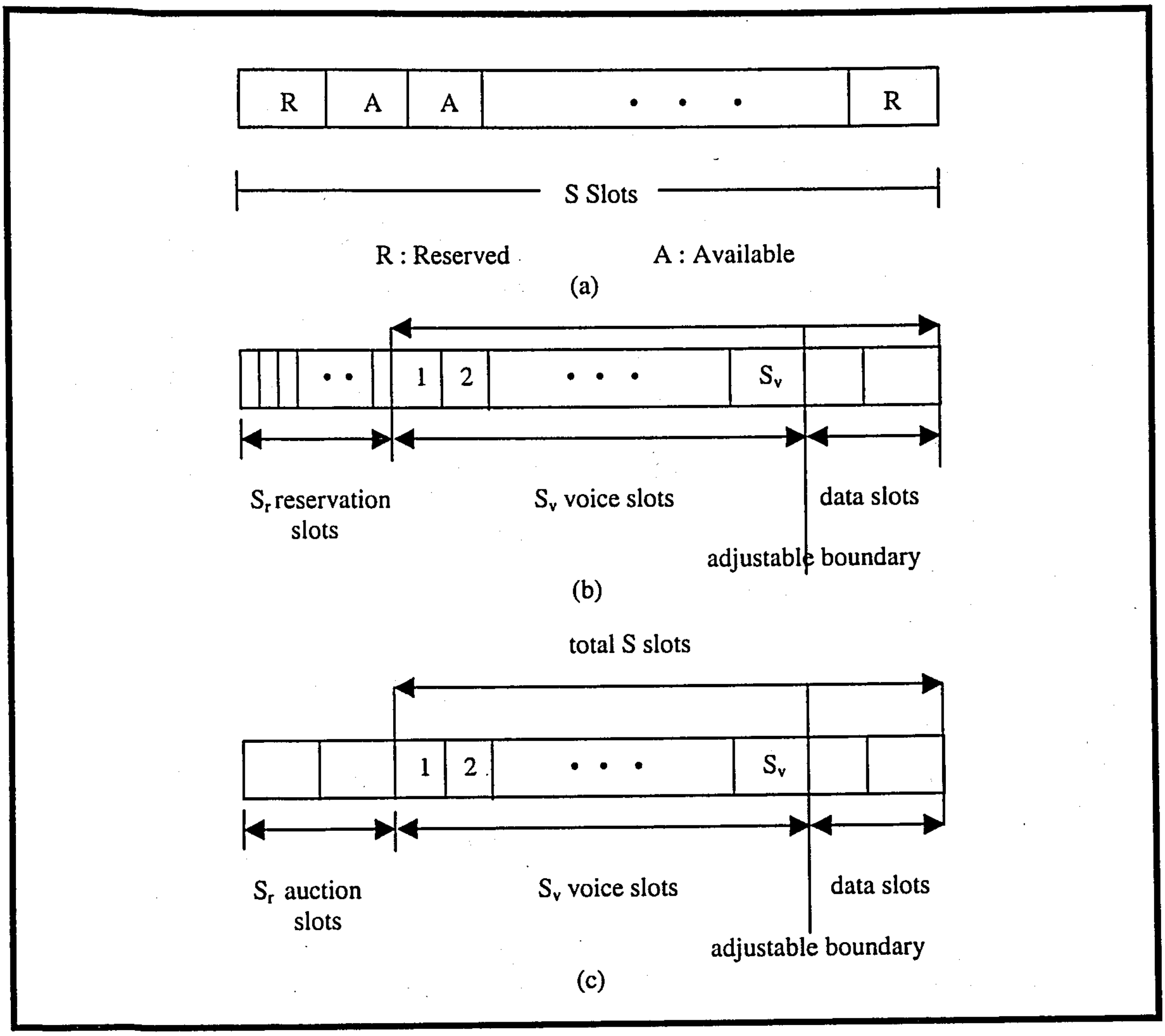


FIGURE 2.8. Frame structure of PRMA, D-TDMA, and RAMA (Qiu, 1998).

D-TDMA was first introduced in satellite communications and has recently been proposed as a candidate multiple access scheme for the third-generation wireless communication systems. Time on the channel is also divided into a contiguous slots, voice slots, and data slots. The frame structure is shown in Figure 2.8(b), where there are S_r reservation slots, S_v voice slots, and the remaining slots are exclusively assigned to data. The base station keeps track of the information slots, which are either reserved or available. There are two types of packets being transmitted in the channel: the reservation packet and information packet. The reservation packet is used for the reservation of information slot (either voice or data slots). It often includes the original and destination addresses for data or the calling and called users' ID's for voice. It is usually much shorter than the information packet.

A terminal generating a new voice talkspurt or a new data packet transmits the appropriate reservation packet in the reservation slots of the next frame, based on the voice-transmission-permission probability p_t or the data-retransmission probability p_r. If there is more than one packet transmitted in the same reservation slot, collision occurs. All the packets are destroyed. At the end of each reservation slot, the successful or unsuccessful reservation will be identified and broadcasted by the base station. The unsuccessful user can retry in the next reservation slot with probability p_t or p_r. This reservation procedure is quite similar to that used in PRMA.

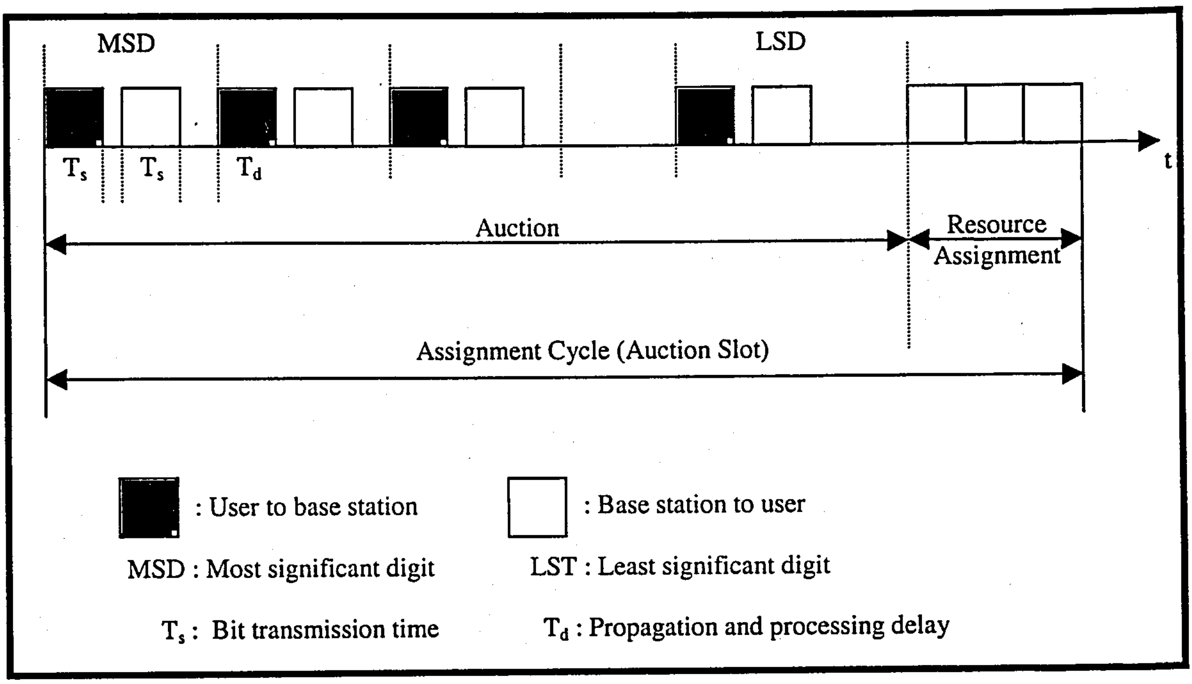


FIGURE 2.9. Illustration of the resource auction procedure in RAMA (Qiu, 1998).

The voice user successfully transmitted in the reservation slot will be assigned one of the available voice slots and will keep using it in subsequent frames until the end of the talkspurt. If there is no voice slot available, the voice user has to recontend in the next frame. After the assignment of voice traffic, data users who transmitted successfully in reservation slots can use all the remaining slots, but cannot reserve them. If there is no slot available, the data user has to recontend in the next frame. No reservation queue is maintained in the base station

The frame structure of RAMA is quite similar to that of D-TDMA except that the reservation slots are replaced by the auction slots, as shown in Figure 2.8(c). The assignment of voice slots is subject to a limit S_v. The data user can use the remaining capacity. The base station maintains a list of available and reserved slots. In each auction slot, the available resource will be auctioned to requesting users and assigned to the winner. The auction procedure is based on the user's needs to contend. For instance, the user's ID can be an eight-digit binary number with two additional digits for priority assignment. The number of digits in the ID depends on the number of users in the system. A sufficient number of digits should be used to keep the probability of two independent users generating the same number small. It is assumed here that voice users always have higher priority than data users. The priority digits of voice are "10," and those of data are "00." (Note that a third kind of traffic with priority higher than voice can have priority digits "11.") At the beginning of the auction, the requesting user will transmit its ID in the auction slot, one digit at a time. Following each transmitted digit, the base station will announce the highest value among received digits on the downlink channel. Any user with digit value less than the announced one will drop out from further participation in this auction. Note that multiple users with identical digit value do "collide," but do not cause an erasure or failure. When all the digits have been transmitted, there will be a final winner. The base station will assign this user an available slot, subject to certain constraints (e.g. whether it is voice or data). This auction and assignment procedure is illustrated in Figure 2.9. It is clear that if there is a voice user transmitting in an auction slot, data users will always drop out. The users dropping out in the current auction slot can enter the next one. An available information slot will always be assigned to one of the requesting users in the auction, irrespective of the traffic load. This kind of deterministic assignment procedure compares very well to PRMA or D-TDMA, especially when the traffic is high. Under heavy traffic, the contention success probability of PRMA or D-TDMA will degrade very quickly due to frequent collisions.

2.2. Ad Hoc Paradigm

For ad hoc paradigm, there are three major research areas apart from the other common ones related to wireless environment, namely topology maintenance for connectivity, scheduling for interference minimisation, and routing.

In ad hoc networks, topology maintenance is a demanding and required task, since topology change is very common in such a dynamic environment. Informally a topology change in a network of computers is a change of the status of a link or a processor. Topology maintenance is the problem of keeping at each computer a correct graph of the currently operational portion of the network, when the network is subject to topology changes. A correct graph of the network is important for route computation, congestion control, and fault tolerance (Abu-Amana, 1993)

Topology maintenance (network awareness), the property of having knowledge about the current status of underlying network resources, is especially necessary in mobile networks and hostile environments such as military applications. Distributed network aware applications, executing in volatile network environments have the ability to react in response to changes in the status of the network, with the ultimate goal of minimizing the impact of these changes on the application's performance.

Hybrid networks (a combination of reliable terrestrial links, wireless links and both fixed and volatile mobile nodes) present a major knowledge for any distributed application: network topology can change constantly, bandwidth can be limited, latency can be high and communication links can be down. Existing network aware systems monitor such parameters as latency, available bandwidth, packet loss rate, and CPU load for different computers in the network. The topology maintenance process can be classified according to the following criteria:

- Traffic generated for monitoring purposes: active or passive.
- Monitoring frequency: on demand (event driven) or continuous (time driven).
- Replication of information: centralized or distributed.

In an event driven algorithm, a computer broadcasts its topology information only when the computer detects a topology change. In a time driven topology maintenance algorithm, the computers periodically broadcast their topology information regardless of whether any topology change actually occurs. The followings are the example protocols for these two classes of algorithms (Abu-Amana, 1996) (Abu-Amana, 1993):

- Time driven doubling protocol: Each node periodically broadcasts its local view by using a breadth-first broadcast protocol. Upon receiving such messages, the processor uses them to update its global view of the network.
- Event driven optimistic-with-backup-protocol: There are two layers in each of which a different protocol operates. The bottom layer is a slow self-stabilizing topology maintenance protocol that uses traditional point-to-point communication. Following a topology change the topology view of the bottom layer is inaccurate for some period of time. During this period the top layer tries to foresee the resulting topology view of the bottom layer. At any processor *P*, the output of the bottom layer is a topology view V_p. The top layer contains two components, a foreseer and a chooser. The topology view produced by the foreseer is F_p, and the view produced by the chooser is E_p. The chooser computes its output view to be equal to F_p if the foreseer has recently indicated a topology change by sending a V_c message; otherwise the chooser computes its output view to be equal to V_p.

As a distributed topology maintenance scheme, the usage of mobile agents for network awareness has been proposed in several papers (Caripe, 1998). Mobile agents are software systems designed precisely to handle volatile network environments, moving from machine to machine while preserving their state information. Agents are accepted as software entities that can act autonomously or with some guidance on the user or software system's behalf. Agents are active computational entities that are persistent, can perceive, reason, and act in their environments, and can communicate with other agents.

Unconstrained transmission in broadcast media may lead to the time overlap of two or more packet receptions, called collision or interference. There are two types of collisions as stated in (Bertossi, 1995):

- Primary interference,
- Secondary interference.

Primary interference is said to occur when a transceiver is expected to perform more than one operation at the same time, such as receiving from two different transmitters at the same time or transmitting and receiving at the same time. Secondary interference occurs when a transmission from a neighbouring transmitter unwillingly interferes at the receiving end of a communication between a transmitter and receiver (Sen, 1996). Primary interference can be of two types. In Figure 2.10 (a), the transceivers *a* and *b* are within the transmission range of one another. In this case if *a* and *b* start transmission at the same time, then both transceivers will be expected to transmit and receive simultaneously. In Figure 2.10 (b) the transceivers *a* and *b* are not within the transmission range of one another, but there is a third transciever *c* which is within the transmission range of both *a* and *b*. In this case if *a* and *b* start simultaneous transmissions, then *c* will be expected to receive from both *a* and *b* at the same time. In Figure 2.10 (c), *a* and *b* are not within the transmission range of one another, and they communicate with *c* and *d* respectively. Since *c* is within the transmission range of both *a* and *b*, the transmission of *a* interfered with the transmission of *b*, although *a* does not intend to transmit any packet to *c*.

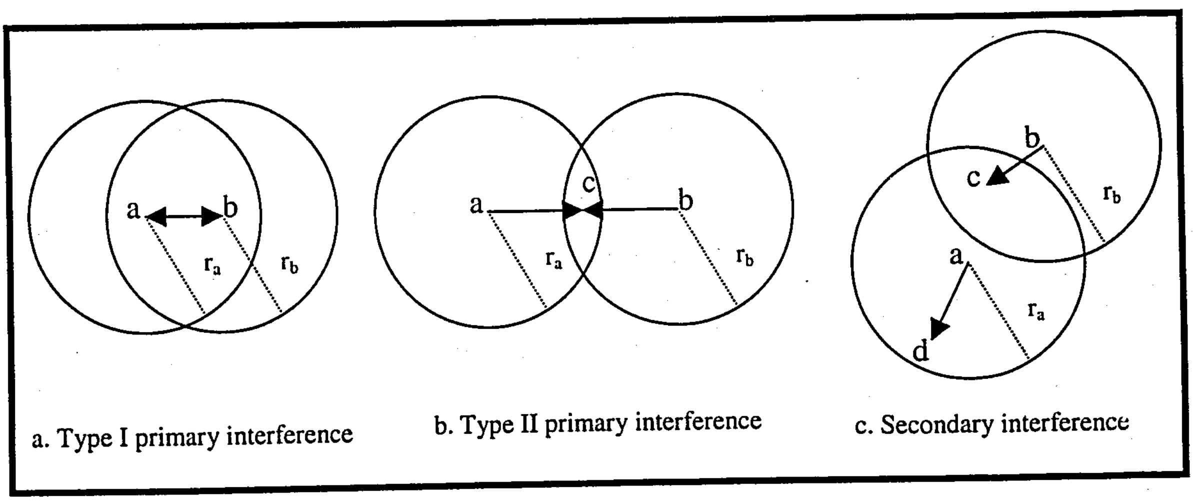


FIGURE 2.10 Types of interference.

A schedule is a sequence of fixed length time slots where a slot is assigned to a set of noninterfering transceivers for transmission of messages. Schedule length is measured by the number of time slots in a schedule. A schedule is said to be optimal if it uses the minimum number of slots.

There are two different types of schedule:

- Broadcast schedule : Each transceiver is scheduled to ensure collision-free transmission of messages to all transceivers within its range.
- Link schedule : The transmission of a station is intended for only one specific transceiver within its range and the schedule needs to ensure that there are no collisions.

For the purpose of constructing an optimal schedule, the research found in literature modelled a packet radio network as a graph, where a node in the graph represents a transceiver, and there is a directed edge between two nodes if the ending node of the directed edge is within the transmission range of the starting node (Sen, 1996). Many scheduling problems were shown by the researchers to be NP-complete using this model. Most of the scheduling problems are formulated as graph colouring problems. Broadcast scheduling problems are generally set up as the node colouring problem.

An optimal broadcast schedule construction can be defined formally as follows if we store the positions of nodes as a set of points P as stated in (Sen, 1996):

Is there a partition $P= P_1 \cup P_2 \cup ..... \cup P_n$ such that if u and v are distinct points in some set P_i of the partition, than

- $d(u,v) > max(r_u, r_v)$ where $d(u,v)$ represents the Euclidean distance between the points u and v, and r_u represents the transmission range of u, and
- there is no point w in the set of P such that $d(u, w) \leq r_u$ and $d(v, w) \leq r_v$.

Various schemes are proposed for topology maintenance and scheduling in the literature (Baker, 1981) (Bertossi, 1995) (Corson, 1999) (Hu, 1993) (Huang, 1994) (Manthar, 1995) (Pei, 1999) (Ramanathan, 1993) (Sen, 1996) (Shor, 1993) (Stern, 1995) (Wang, 1993).

In ad hoc networks, another major task is routing. In the ad hoc networking paradigm, the network supports multihop wireless connections on source-destination paths, comprising many links of certain QoS distributed over various channels. Given a set of required source destination connections of specified QoS, the global minimum routing problem to choose the links and the channels in which to establish each one, to either minimize the total power needed to support the connections on the network or minimize the maximum power spent at any node. This is an intractable combinatorial optimization problem for any sizeable network; hence, one has to search for justifiable heuristic to obtain good practical solutions. The more tractable and practical case is the minimum-power routing problem in which the objective is to chose the links to route a newly arrived connection request, minimizing the total power spent on its links without reshuffling already established links of previously arrived connections. This is quite similar to shortest path problem. However, military applications generally prefer to minimize the maximum power because of some military considerations such as Electronic Support Measures (ESM).

Routing schemes used in ad hoc paradigm can be classified into two broad categories (Haas, 1999) (Royer, 1999):

- Table driven routing protocols
    - Destination-sequenced distance vector routing
    - Clusterhead gateway switch routing
    - Wireless routing
- Source initiated on demand routing protocols
    - Ad Hoc on demand distance vector routing
    - Dynamic source routing
    - Temporarily ordered routing
    - Associativity based routing
    - Signal stability routing

Table driven routing protocols attempt to maintain consistent, up-to-date routing information from each node to every other node in the network. These protocols require each node to maintain one or more tables to store routing information, and they respond to changes in the network topology by propagating updates throughout the network in order to maintain a consistent network view. The areas in which they differ are the number of necessary routing tables and the methods by which changes in the network structure are broadcast.

A different approach from table driven routing is source initiated on demand routing. This type of routing creates routes only when desired by the source node. When a node requires a route to a destination, it initiates a route discovery process within the network. This process is completed once a route is found or all possible route permutations have been examined. Once a route has been established, it is maintained by a route maintenance procedure until either the destination becomes inaccessible along every path from the source or until the route is no longer desired.

2.3. Cellular Networks

In this section, we examine the cellular networks and enabling concepts. In cellular networks, the region of communications is tessellated with macro, micro or pico cells (Everitt, 1994) (Husain, 1996) (Li, 1995) (Noerpel, 1996) as shown in Figure 2.11 in which a Radio Port (RP)(named as Base Transceiver Station (BTS) in GSM) can provide a wireless communication path with every point within the cell, and the communication path from the RP to any point on the cell boundary is not longer than the range of the RF equipment used by the Mobile Terminals (MTs) and the RPs. These RF equipment is named as transceiver equipment in the rest of the thesis.

The cellular network technology brings up a number of advantages to the wireless communications systems. These advantages can be summarized as follows:

- Since the region of communication is divided into smaller cells and the distances between the RPs and the MTs within the cells are small, the use of small battery powered portable handsets with lower RF transmit power than the large vehicular mobile units used in earlier systems is possible.

- This brings up another advantage, namely frequency reuse. The same frequencies can be repeated in the other cells , because the lower powered MTs can interfere the communication in a couple of following neighboring cells at most. This makes possible a much higher subscriber density per MHz of spectrum than the previous systems (Cimini, 1994b) (Çayırcı, 1997b) (Çayırcı, 1998b) (Lee, 1991b) (Li, 1995) (Padgett, 1995) (Pahlavan, 1995) (Pandya, 1995).

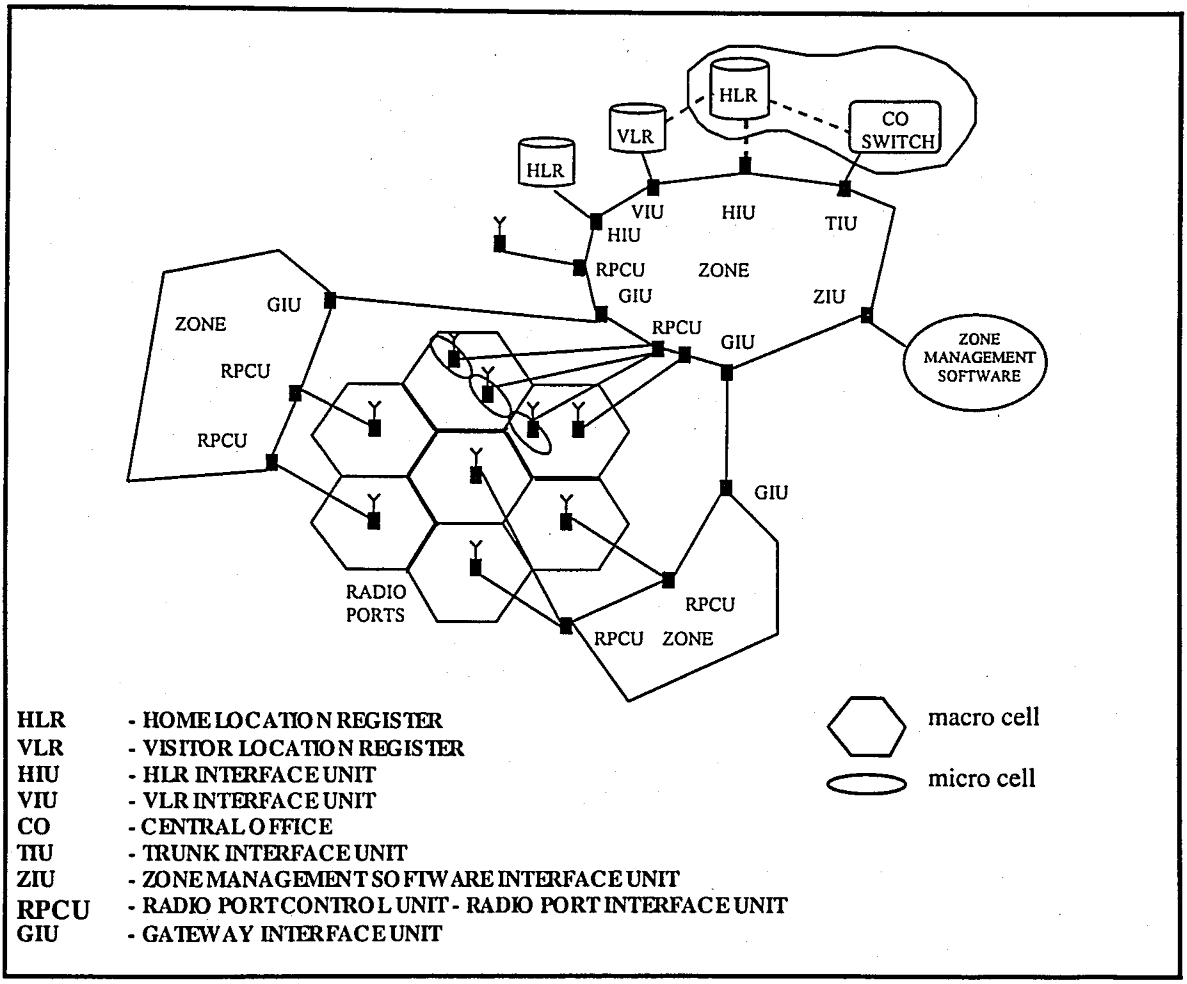


FIGURE 2.11 The components of a cellular network.

Other components of cellular systems are illustrated in Figure 2.11. Base Station Systems (BSSs) which are responsible to provide the access for the MTs to the core network are generally composed of Radio Port Control Units (RPCU) (named as Base Station Controller (BSC) in GSM) and RPs (named as Base Transceiver Station (BTS) in

GSM). RPs are only responsible for transmitting and receiving the radio signals, while RPCUs are responsible for the management of radio resources, too. A different terminology may be used for the same components in other systems.

Since the subscribers of cellular networks may roam while communicating, this cellular architecture brings up a number of challenging tasks for the cellular networks. These tasks are listed below:

- Mobility management : Since the subscribers are mobile, tracking their locations (registration strategies, etc.), locating and paging them when they are called (paging strategies, etc.), and providing seamless communication lines for them when roaming among cells (handoff strategies, etc.) are essential.
- Resource management : Capacity allocation to the cells and to the mobiles in a very dynamic environment requires carefully designed strategies for the efficient utilization of the scarce wireless resources.
- Call management : Call establishment, termination and other call related issues also require some carefully designed strategies in mobile environments.

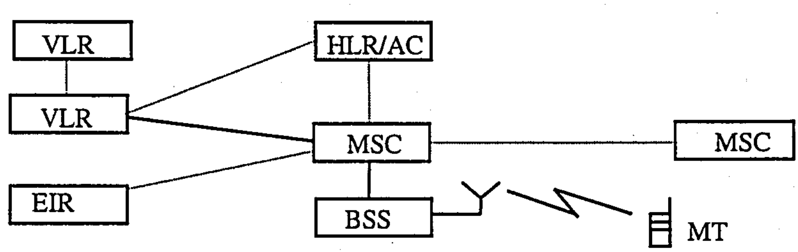
2.3.1. Mobility Management

Mobility management is the process of keeping track of and locating users so that calls arriving for them can be directed to their current location (Akyildiz, 1996b) (Akyildiz, 1996c) (Brown, 1997) (I, 1997) (Lin, 1994) (Lin, 1996b) (Lin, 1997b) (Lin, 1998b) (Madhow, 1995). In our study, we name this task as location management which is generally used as synonymous of mobility management. We also examine one of the key phanemonens of the cellular systems, namely handoffs, in this section.

2.3.1.1. Location Management. Location Management consists of two parts: users notifying the system of their current location (updating, triggered at certain events); and the system notifying the user that a call has arrived for them (paging) (Brown, 1997).

In Figure 2.12, the components generally used for location management are illustrated. In the illustrated architecture, Home Location Registers (HLRs) which are responsible for maintaining a series of records for a group of MT (Cellular Subscribers Station (CSS) is another common term to name the MTs in Cellular Networks) are used to support automatic roaming. The HLR records for each MT generally include at least the following fields:

- A Mobile Identification Number (MIN) to which the MT will respond.
- The Electronic Serial Number (ESN) burned into the MT during its manufacture.
- The service profile of the MT.
- The state of the MT.
- A pointer to the VLR to which the MT is registered last time.



Visitor Location Register Home Location Register Equipment Identity Register
Authentication Center
Mobile Switching Center Base Station System Mobile Terminal

FIGURE 2.12. ITU-T Recommendation Q.1001.

Every MT is assigned to a HLR when it is placed in service and given a MIN. An MT may have multiple MINs, and as such, may be serviced by multiple HLRs. However for a given MIN/ESN pair, there is one and only one HLR supporting it (La Porta, 1995).

VLRs are used in conjunction with HLRs to support automatic roaming. VLRs perform two functions: they assist in locating an MT for call delivery, and they act as local, temporary repositories for subscriber information, most of which is obtained from HLRs via profile transfer during MT registration.

The network tracks the whereabouts of MTs via a multistep registration process. MTs are forced to register upon some events according to the preferred method. There are four principal types of location update methods known to us (Akyildiz, 1996b) (I, 1997) (Lin, 1996b):

- Geographic (movement based): A user updates the system when it enters a new Locational Area (LA). LA is sometimes named as Registration Area (RA). LAs are made up of one or more radio port coverage areas. Every LA is associated with a VLR. A VLR may serve one or more LAs. This is the method used in most of the second generation cellular systems.
- Timer (time based): The user updates the location periodically with a given average time.
- Stimulus (request based): The user performs a location update only when requested.
- ON/OFF: A location update occurs only after a mobile powers on and before a mobile powers down.

In registration, the user profile and location information of the MT is stored into the VLR related with the registered MSC and the VLR pointer in the HLR of the MT is changed with the pointer to the current VLR. When an MT initiates a call, the VLR in the calling MT's LA is checked first. If the record for the called MT is not found in this VLR, then the HLR of the called MT is searched. The MIN of the called MT indicates the HLR of it. This query returns the VLR of LA to which the called MT registered last. Then the cells in this LA is paged for the called MT either sequentially or simultaneously (Tonguz, 1998). When the called MT answers, the last procedures for the connection establishment initiated.

When an MT is registered to a new LA, it should be removed from the former one, so the resources allocated for the MT in the former LA can be deallocated. This process is called deregistration. There are three well known deregistration strategies (Lin, 1998a):

- Explicit deregistration : When a mobile is registered to a new LA, it is deregistered from the old LA.

- Timeout deregistration : After a time from the last registration, the MT is deregistered. In this scheme, MT reregistered periodically.
- Implicit deregistration : When the database is full and a new registration is required, one of the older registration records is removed.

The size of LA (how many cells in a LA) is an important parameter. When it is too small, too many registrations are required which means higher signaling traffic in the core network. When it is too large, too many cells should be paged for call establishments, which means longer call establishment times and paging traffic.

Location tracking algorithms in cellular networks are expensive. Various algorithms have been proposed to reduce the location update costs. One of these algorithms is pointer forwarding in which unnecessary registrations are avoided by setting up a forwarding pointer from the previous VLR when a new LA is accessed (Lin, 1998b).

The other components implemented in the most of the mobile networks and illustrated in Figure 2.12 are Authentication Center (AC) and Equipment Identity Register (EIR). EIR maintains records associated with the identity of mobile equipment. The International Mobile Equipment Identity (IMEI) of a mobile station can be checked, for example by an MSC, against the available records to determine whether it is an authorized equipment for service. The AC checks to verify the authorization for the requested service. Subscriber authentication may be initiated by the VLR to protect the network from access by non-registered or fraudulent MTs.

Mobile networks are the networks that Intelligent Network (IN) concepts (Duran, 1992) (Garrahan, 1993) (Homa, 1992) (Hussain 1996) (Jabbari, 1992) can be implemented. One of the possible mappings of IN concepts into mobile networks is illustrated in Figure 2.13.

Various combinations of Service Control Points (SCPs) and adjuncts may provide the functionality of EIR, AC, VLR and HLR databases. However, from the point of view of IN concept the implementation of HLR functions is more appropriately suited for SCP. The EIR can also be integrated in the same SCP. The AC can be integrated into the same

SCP or may be separate SCP, depending on the system security. The VLR can be either a SCP or an adjunct. The adjunct performs functions similar to the SCP, but it is used in a dedicated fashion. In some cases an adjunct may be more suitable for VLR function due to high speed transaction processing needed. The intelligent peripheral (IP)/ Service Node (SN) will provide functionality such as announcements, mid-call digit collection or interactive voice response which may typically not be available in the switching system. In GSM, the VLR and MSC functions are collocated whereas the SCP incorporates the HLR and AC functions (Homa, 1992) (Jabbari, 1992).

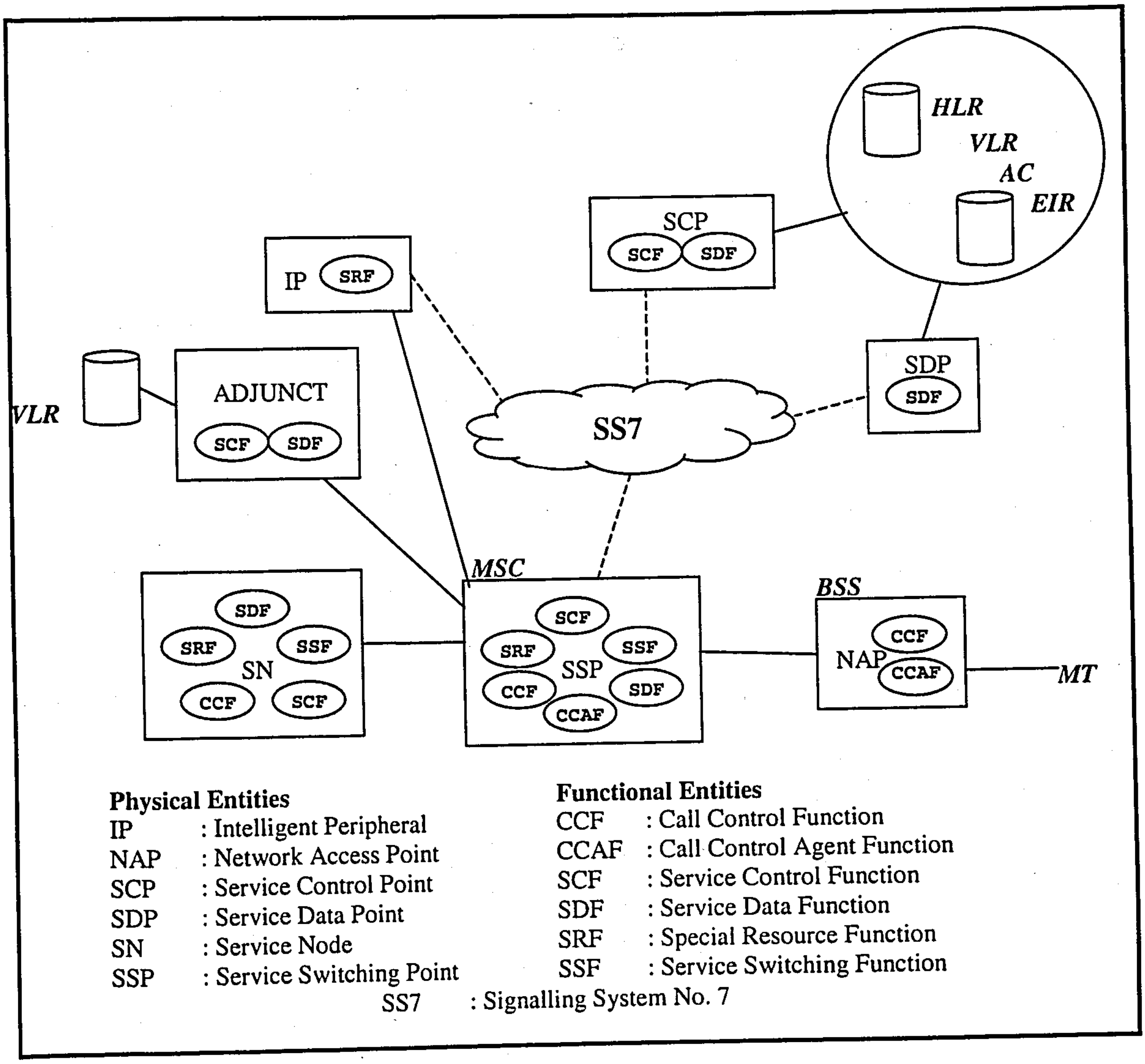


FIGURE 2.13 A possible mapping of IN concepts into mobile networks (Jabbari, 1991).

SS7 illustrated in Figure 2.13 is the set of protocol standards used in mobile networks to convey the signalling traffic among MSCs, VLRs, HLRs and other components. This standards has been originally developed for ISDN network signalling (Kearns, 1990) (Modarressi, 1990) (Pollini, 1996).

2.3.1.2. Handoffs. Handoffs (Hong, 1986) (Nanda, 1993) are one of the most critical and unique features of the cellular networks. Intercell movements of MTs require complex frequency and source usage rearrangements according to the used multiple access scheme, and updates in the databases related to the MT. During a handoff, a cell hand over the responsibility of the MT to a new cell. The cost of handoffs differs according to the cellular network topology and the cell pair involved in the operation. Handoffs may require:

- the change of the communication channel only,
- the change of RP,
- the change of RPCU,
- the change of zone (LA).

The handoff may occur even upper levels of network. The cost of handoff gets higher in the upper levels. In order to avoid extensive signaling, the handoff control should be performed on a lowest possible level in the network. Otherwise the cost of handoff becomes almost the same regardless the level that handoff occurs.

The performance of handoff schemes can be defined basically by the following three criteria:

- the processing delay due to the execution of the functional entities,
- the number of physical links included,
- the handoff signaling traffic volume.

Handoffs are generally conducted in three stages: decision stage, planning stage and execution stage. In decision stage, the system detects a new RP for an MT which can serve better than the current one and then decide to handoff the responsibility of the MT from the current RP to the new one.

Handoff detection is based on the link measurement process. The measurement process determines the need for handover and the target or new channel for transfer. Three measurements are used to determine the quality of a channel (Noerpel, 1997):

- Word Error Indicator (WEI) is an indication of whether the current burst was demodulated properly in the portable.
- Received Signal Strength Indication (RSSI) is a measure of co-channel interference power and noise. The RSSI metric has a large useful dynamic range (typically between 80 to 100 dB).
- Quality Indicator (QI) is the estimate of the eye opening of a radio signal, which relates to the signal-to-interference (S/I) plus noise ratio, including the effects of dispersion. QI has a narrow range (relating to the range of S/I from 5 dB to perhaps 25 dB).

The fundamental differences among the different handoff techniques are based on techniques used to determine the quality of a channel and the time to handover. In this respect, the handoff techniques can be classified into three groups (Noerpel, 1997):

- Mobile Controlled HandOff (MCHO) : In this technique, the MTs monitor the quality of the channel and determine the time to handoff. The second generation low tier PCS networks such as DECT and PACS (Çayırcı E, 1998a) use this technique.
- Network Controlled HandOff (NCHO) : In this technique, fixed equipment of the network located with base station systems terminals monitor the quality of the channel and determine the time to handoff. Advance Mobile Phone System (AMPS) uses this technique. Every base station system has an equipment called location receiver which measures the strength of the signals received from the MTs in AMPS. According to these measurements, the network decides on handoff (Faruque S., 1994).

- Mobile Assisted HandOff (MAHO) : In this technique, the MTs monitor the quality of channels and send their measurement results to the network. The network decides on handoffs according to these measurements. This is the technique used in GSM.

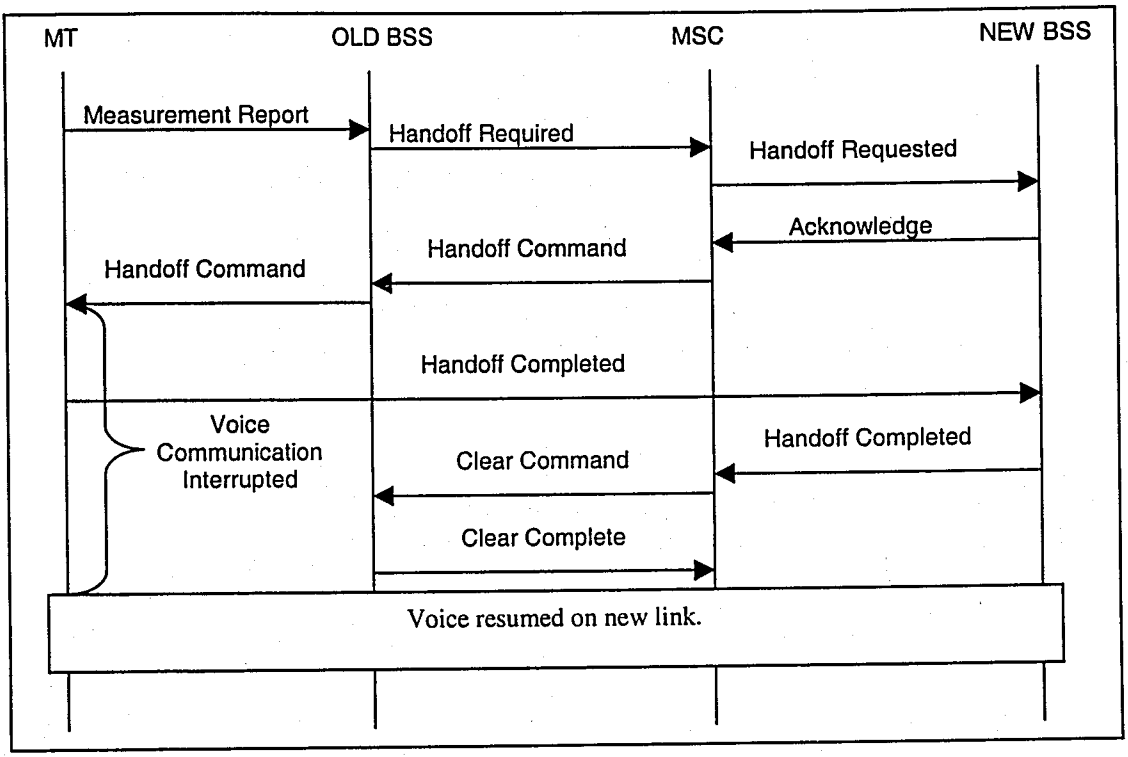


FIGURE 2.14. Handoff procedures in GSM.

In all of these techniques, ping-pong effect or hysterisis should be avoided. Ping-pong occurs when an MT moves just on the border of two cells and changes cell from one to other continuously. Some measures to stop ping-pong can be taken which are explained in the reference (Faruque, 1994). Besides, the methods to avoid from the higher level ping-pong, namely loops, is discussed later in this section.

In the planning stage, the new resources are allocated in the new cell, and the required arrangements for routing is finished. When it is necessary the tasks such as authentication and database updates can be carried or started in this stage.

The procedures used in this stage is protocol dependent. The GSM handoff procedures is illustrated in Figure 2.14.

The time required for handoff in GSM is around one second. The most critical part of this one second is the time spent for the execution stage in which the communication is actually interrupted. For instance, the execution stage lasts 200 ms in AMPS which cause a "click" sound.

Loops are another important issue which influence the strategies applied to planning stage. If a mobile comes back to the cell which it left before, it completes a loop. Loops may involve two cells or more than two cells. If the loop is completed within two cells (if mobile returns back to the same cell after visiting only a single cell), it is called mini loop. If loop involves more than two cells, it is called macro loop. When a mobile moves on the border of two cells, it causes many mini loops at a high frequency. This is named as ping-pong as stated before.

One of the most common ways of resolving mini and macro loops is connecting the zones with gateways as shown in Figure 2.15. Instead of changing the path between two ends of communication completely during handoffs, the path is reserved, but the packets received by the changed zone are routed to the new zone via these gateways in this technique. When a loop is detected, the rerouting through the gateway is canceled. An optimizer runs in the background, and optimizes the paths. When the optimizer detects a path which is inefficient beyond the threshold taught to it, it orders a change of path to the system (Akyildiz, 1996a) (Çayırcı, 1997b) (Pollini, 1995)(Toh, 1996).

Handoff schemes can be classified according to the above discussion as full, incremental and multicast re-establishment based schemes (Toh, 1996). The full re-establishment based scheme requires a completely new path to be set up during a handover and this is slow, inefficient and not transparent. The incremental re-establishment scheme requires only a new partial path to be set up and allows circuits to be reused, meaning it is fast and efficient. This scheme is often referred as crossover switch or anchor based handover schemes. Lastly, the multicast-based re-establishment scheme is fast but not efficient as problems of cell duplicates, excessive buffering requirements and abundant pre-reservation of bandwidth exist during handoff. Examples of this scheme are footprint and group multicast (Acampora, 1996).

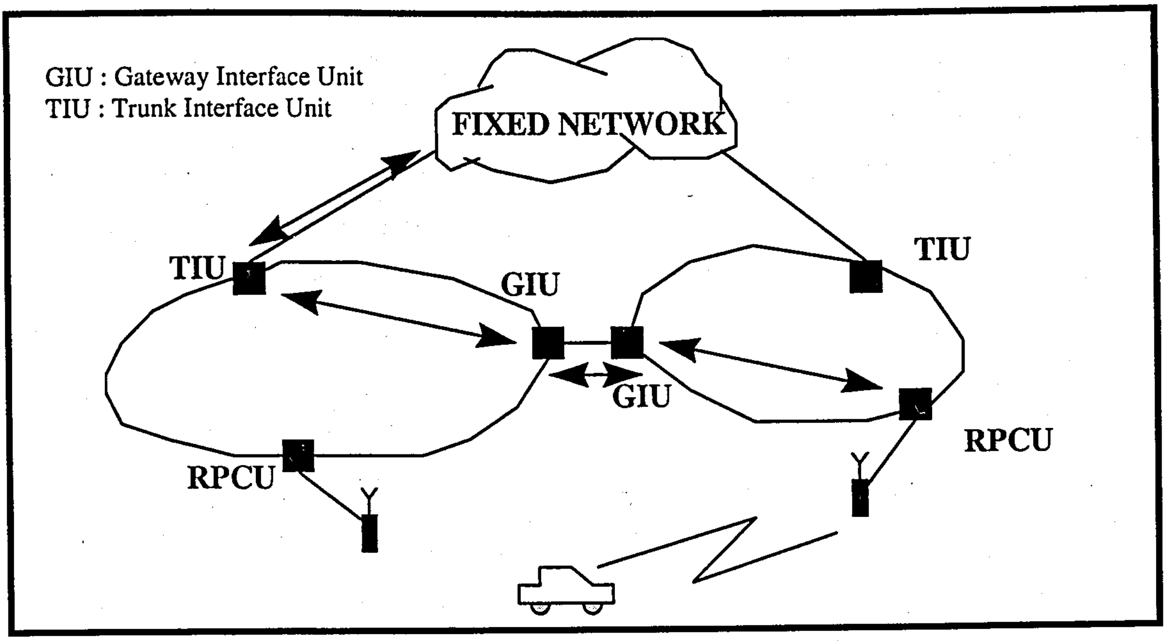


FIGURE 2.15 The usage of gateways between zones (Acampora, 1996).

In the execution stage, MT starts communicating through the new RP and release the resources in the old one. This stage can be conducted as soft handoff or hard handoff (Fukasawa, 1996) (Kim, 1999) (Pahlavan, 1995) (Wong , 1997). The hard handoff method switches the traffic channel served to the MT from the former cell to the new one in a way that there can be traffic only either in the former channel or in the new channel at a time. On the other hand, in the soft handoff, firstly a new channel is established in the new cell, and then the former channel is broken. The process of transferring of information flow between the old and new paths are subject to very stringent maximum allowable delay limits. Protocols may also need to insure the following:

- Sequenced delivery of information, that is , the receiver must receive packets in sequential order. Sequenced delivery does not exclude receiving multiple copies of a packet (one on the old and one on the new path).
- Assurance that only a single copy of each packet arrives.

The main goal of this stage is to identify the first packet sent on the new path and make the other hand aware of this. There are three possible techniques known to us (Pollini, 1995):

- Marking : The last packet sent on the old path is marked prior to being transmitted.
- Last sent : An independent message on the new path indicates the last packet sent on the old path.
- Last received : An independent message on the new path contains the sequence number of the last packet received on the old path.

2.3.2. Resource Management

In this section, we discuss resource management which is one of the key arguments in Cellular Mobile Systems. Firstly, we discuss some physical layer issues which is related to resource management. For further information, (Faraque, 1996) (Lee, 1986), (Pahlavan, 1995) and (Yue, 1996) are refered.

2.3.2.1. Frequency Reuse, Cochannel Interference, Adjacent Channel Interference and Power Control. The available spectrum should be shared among various tasks in cellular networks. Firstly, the spectrum is to be divided into two portions: one for downlink (forward link) and the other for uplink (reverse link). Secondly, the uplink and downlink should be allocated to different tasks. For instance, in down link we need at list two different channels: one is for traffic and the other is for control, and uplink should be shared by the random access and traffic channels. And of course some of these channels are multiple access channels which are shared among multiple users at a time. The most important advantage of the cellular networks comes up at this point. It is possible to use a carrier in a short distance from a site which uses the same carrier in a cellular network which means higher subscriber densities for the available spectrum. This is known as frequency reuse, and cells using the same carriers are termed cochannel cells (Sarkar, 1998).

Because of some factors such as cochannel interference, it is generally not viable to use the same carriers in neighbor cells when TDMA or FDMA is used. To avoid the usage of the same carriers in the neighboring cells, the cells are grouped into cell clusters and the available spectrum are divided into carriers. Then the carriers are evenly distributed among cells in the cluster, so each cell in the cluster has a unique set of carriers. This procedure is accomplished by applying some well known channel reuse plans (Faruque, S., 1996) which are named by the number of cells in the clusters, i.e. N=7 channel reuse plan which is shown in Figure 2.16.

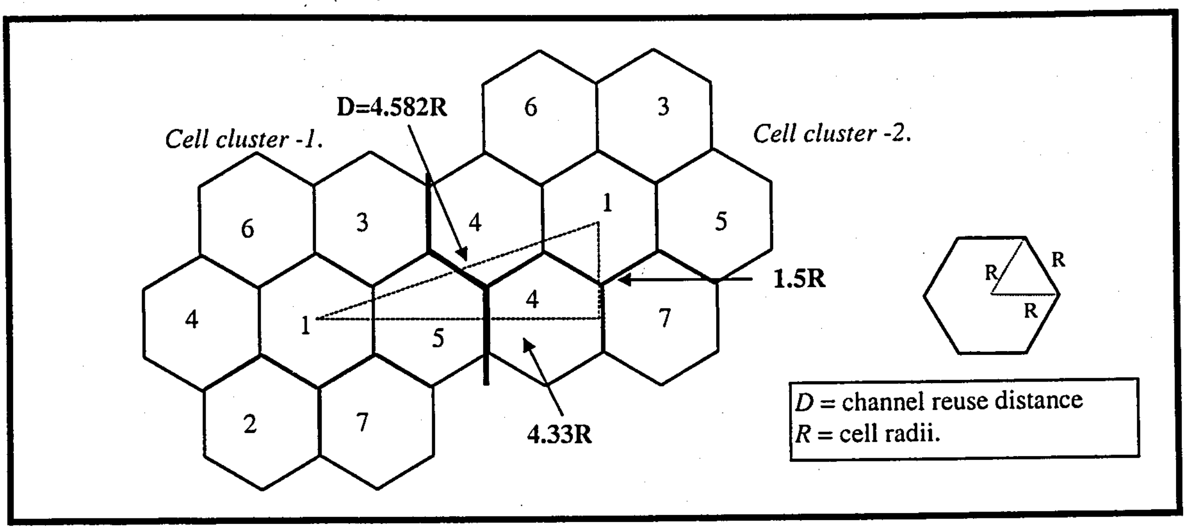


FIGURE 2.16 Channel reuse distance in the N=7 reuse plan.

Adjacent Channel Interference (ACI) arises from energy slipover between two adjacent channels. ACI can be minimized or removed by removing adjacent channels and reassigning them elsewhere (Faruque, 1996).

In the reverse link a problem called *near-far* is faced most notably in CDMA. The signal of an undesired MT closer to the BS can mask the received signal of a desired MT. A near-far problem which is less severe than the reverse-link near-far problem is also possible in forward-link.

Power control schemes are used to reduce especially the interference caused by the near-far problem. In a reverse-link power control scheme, the transmitted power from all mobile terminals are adjusted such that all signals are received with equal power at the base station (Chan, 1991) (Grandhi, 1994) (Lee, 1996) (Lee, 1998a) (Lee, 1998b) (Sim, 1999). The power control takes a role of controlling the interference caused by cochannel reuse. The transmitter power at a cell, on one hand, must be reduced to minimize the interference at other cochannel cells, and, on the other hand, it must be sufficient for communication. Thus, the capacity of the cellular system can be maximized with an efficient way of power control. In CDMA cellular systems, power control is the most important issue since the capacity of CDMA is only interference limited (Lee, 1998). The power control is important not only for reducing interference but also for power saving mechanisms (Bambos, 1998).

2.3.2.2. Capacity Assignment. Capacity assignment (Baiocchi, 1995) (Chang, 1994) (Cheng, 1996) (Cimini, 1994a) (Cimini, 1994b) (Del Re, 1995) (Duque-Anton, 1993) (Duque-Anton, 1997) (Frodigh, 1994) (Haas, 1997) (Jaimes-Romero, 1997) (Katzela, 1996) (Kim, 1994) (Lai, 1996) (Rappaport, 1996) (Wang, 1996) (Woo, 1997) (Yeung, 1995) (Zhang, 1989) (Zhang, 1991) appears as a combinatorial optimization problem closely related to graph coloring, and is as such known to be NP-complete, an exact search for the best solution is practically impossible due to an exponentially growing calculation time (Duque-Anton, 1993).

When channel assignment algorithms are compared based on the manner in which cochannels are separated, they can be categorized into three classes:

- Fixed Channel Assignment (FCA),
- Dynamic Channel Assignment (DCA),
- Hybrid Channel Assignment (HCA).

In FCA schemes, the area is partitioned into a number of cells, and a number of channels are assigned to each cell according to some reuse pattern, depending on the desired signal quality. FCA schemes are very simple, however they do not adopt to changing traffic conditions and user distribution.

In DCA, all channels are placed in a pool and are assigned to new calls as needed such that $(\text{Carrier/Interference})_{min}$ criterion is satisfied. At the cost of higher complexity, DCA schemes provide flexibility and traffic adaptability. However, DCA strategies are less efficient than FCA under heavy traffic conditions.

HCA schemes combines the features of FCA and DCA to create a channel allocation scheme which is both adaptive and efficient. In HCA a portion of the total frequency channels use FCA and the rest use DCA.

When channel assignment strategies are compared based on the way they are implemented, there are two groups of channel assignment strategies, namely centralized and distributed. FCA is a centralized channel assignment technique. On the other hand DCA can be implemented distributed. HCA is a scheme in which both centralized and distributed algorithms can be used.

In the simple FCA strategy, the same number of nominal channels is allocated to each cell. This could result in poor channel utilization due to nonuniform traffic. It is appropriate to tailor the number of channels in a cell to match the load in it by nonuniform channel allocation or static borrowing. Nonuniform channel allocation technique is the one explained in the example above. Borrowing can be done in a scheduled manner in which the number of channels assigned to a cell change in time as it is scheduled. This technique is also named as Flexible Channel Allocation (FLCA). In FLCA schemes, the set of available channels is divided into fixed and flexible sets. Each cell is assigned a set of fixed channels that typically suffices under a light traffic load. The flexible channels are assigned to those cells whose channels have become inadequate under increasing loads. The assignment of these emergency channels among the cells is done in either a scheduled or predictive manner. FLCA can also be considered as a HCA technique.

In contrast to FCA, there is no fixed relationship between channels and cells in DCA. All channels are kept in a central pool and are assigned dynamically to the cells as new calls arrive in the system. The main idea of all DCA schemes is to evaluate the cost of using each candidate channel and select the one with the minimum cost provided that certain interference constraints are satisfied. The selection of the cost function is what differentiates DCA schemes.

The selected cost function might depend on

- the future blocking probability in the vicinity of the cell,

- the reuse distance,
- the channel occupancy distribution under current traffic conditions,
- the channel measurements of individual mobile users,
- the average blocking probability of the system.

Based on information used by channel assignment, DCA strategies could be classified either as call-by-call DCA or adaptive DCA schemes. In the call-by-call DCA, the channel assignment is based only on current channel usage conditions in the service area, while in adaptive DCA, the channel assignment is adaptively carried out using information on the previous as well as present channel usage conditions.

The DCA schemes can also be divided into centralized and distributed schemes with respect to the type of control they employ. The distributed control entails that decisions are made by the mobile stations or by base stations rather than by a centralized network control station. In distributed DCA, each base station keeps information about the current available channels in its vicinity. This reduces control information exchanges and increases system robustness. A list of some known distributed and centralized DCA schemes is given below (Katzela, 1996):

- Centralized DCA
    - First available,
    - Selection with maximum usage on the reuse ring,
    - Mean square,
    - Nearest neighbor,
    - Nearest neighbor + 1,
    - 1-clique
- Distributed DCA
    - Locally Packing Distributed DCA (LP-DDCA),
    - LP-DDCA with ACI constraint,
    - Moving direction.

Another classification of DCA algorithms can be made as timid and aggressive algorithms. In timid algorithms, an MT takes a channel only if there are no nearby interferes on that channel. In aggressive algorithms MTs may take a channel even if there is interference present. The aggressive algorithms perform better, but they are less stable and require reconfiguration efforts. The Maximum Packing policy which is a timid scheme specifies that a new call attempt is to be allowed if and only if there is some way of rearranging channel assignments, possibly involving the whole network, to accommodate the new request. Since global information is required, this obviously a policy which is centrally administered.

Finally two different classes of DCA schemes can be identified: traffic adaptive and C/I adaptive (Argyropoulos, 1999) (Frodigh, 1994). Traffic adaptive DCA algorithms adapt the channel assignment to the number of active terminals in each cell in the system, but the quality is still guaranteed by the reuse distance. Traffic adaptive DCA strategies are named as the interference-free, timid, not conditioned class. By interference-free we mean that no interference is allowed at any time beyond a given threshold (Baiocchi, 1995) (Shin, 1999). C/I adaptive DCA schemes base their choice of channels on information of the resulting C/I in the intended receivers.

In a DCA scheme, each cell selects a channel at random to sense whether or not the channel is used in another cell. If it is not used, the cell uses it, otherwise another channel is tried. This method yields a low spectrum efficiency because of the random use of channels. Channel segregation was proposed to improve the spectrum efficiency of such a DCA scheme. In this method, each cell acquires its favorite channels through learning from experience how each channel was used between it and the other cells. As the result of learning, the optimum channel reuse is self-organized resulting in improvement of the spectrum efficiency (Akaiwa, 1993).

Channel borrowing strategies, which are classified as FCA techniques in the literature, deal with short term allocation of borrowed channels to cells; once a call is completed, the borrowed channel is returned to its nominal cell. The channel borrowing schemes can be divided into simple and hybrid. In simple channel borrowing schemes, any nominal channel in a cell can be borrowed by a neighboring cell for temporary use. In hybrid channel borrowing strategies, the set of channels assigned to each cell is divided into two subsets, local channels and borrowable channels.

We can list some well-known borrowing schemes as follows (Katzela, 1996):

- Simple channel borrowing
  - Simple borrowing,
  - Borrow from the richest,
  - Basic algorithm,
  - Basic algorithm with reassignment,
  - Borrow first available,
- Hybrid channel borrowing
  - Simple hybrid borrowing scheme,
  - Borrowing with channel ordering,
  - Borrowing with directional locking,
  - Sharing with bias,
  - Channel assignment with borrowing and reassignment,
  - Ordering dynamic channel assignment with rearrangement.

In the Borrowing with Directional Channel Locking (BDCL), the channel locking in the co-channel cells is restricted to those directions affected by borrowing. In BDCL, when a call request arrives and finds all nominal channels busy, a channel is borrowed from a neighbouring cell, providing that the borrowing will not violate the cochannel interference constraints (Yum, 1997). The BDCL strategy only needs local cells information, and it gives lowest blocking probability among all strategies proposed in the literature that do not require system wide information (Chang, 1998) (Yeung, 1998). It's four distinct features are:

- channel ordering,
- immediate channel reallocation,
- directional channel locking,
- analytical tractability.

Lastly Fixed and Dynamic Channel Allocation (FDCA) is a combination of FCA and DCA which tries to realize the lower of each technique's blocking rate depending on traffic intensity. In low traffic intensity the DCA scheme is used; in heavy traffic situations the FCA is used.

In systems with prioritized channel assignment, another important issue is to decide the minimum number of guard channels required in each cell so that a desired level of quality of service (in terms of a limit on forced termination probability) for handoff calls is met.

The new calls are less delay sensitive than the handoff calls, so they may be queued and delayed until a channel becomes available in the cell.

2.3.3. Multitier Cellular Networks

The cellular systems for the next generation of wireless multimedia networks will rely on cells that are smaller than those used today. In particular, in the proposed microcellular systems, the cell radius can shrink down to as small as 400 m. Smaller cell radii are also possible for systems with smaller coverage, such as pico and nanocells in local area environment. The size of the cells is closely related to the expected speed of the mobiles that the system is to support. Furthermore, the cell size is also dependent expected system load. Finally, the cell size also depends on the required quality of service level (Ganz, 1997) (Lagrange, 1997).

Size is not the only difference between the pico, micro and macro cells. Base Transceiver Systems (BTS), their locations and output power differ, too. The antenna of a macrocell BTS is generally mounted several meters high on a tower to cover a large area. On the other hand, the antenna of a microcell BTS is mounted at lampost level (approximately 5 m. Above ground) and transmits lower output power. This also change the topological design and coverage characteristics of the microcells. For instance, microcells encounter a propagation phenomenon called the corner effect. The corner effect is characterized by a sudden large drop (e.g., 20-30 dB) in signal strength (e.g., at 10-20 m distance) when a mobile turns around a corner. The corner effect is due to the loss of the

Line Of Sight (LOS) component from the serving BTS. Because of this, in a microcellular system there may be two types of handoff scenarios: a LOS handoff and a non-LOS handoff. A LOS handoff is a handoff from a LOS BTS to another LOS BTS. A non-LOS handoff is a handoff from a non-LOS BTS to a LOS BTS. In a non-LOS handoff, handoff must be done as fast as possible (Tripathi, 1998).

Microcells can be classified as one-, two-, or three-dimensional, depending on whether they are along a road or a highway, covering an area such as a number of adjacent roads, or located in multilevel buildings, respectively (Tripathi, 1998). Microcells can be classified as hot spots (service areas with a higher traffic density or areas that are covered poorly), downtown clustered microcells (contiguous areas serving pedestrians and mobiles), and in-building 3-D cells (serving office buildings and pedestrians).

Since the microcell BTSs are located among the buildings lower then their roofs, the cell layouts have some distinctions from the regular macrocellular cell layouts. The best known cell layouts for microcells can be enumerated as: half-square cell plan, full-square cell plan and rectangular cell plan. These cell plans which are illustrated in Figure 2.17 have some major distinctions such as the corner effect does not naturally exist in half square cell plan unless an obstacle such as a truck eliminate the LOS path between the BTS and the mobile. However, in the full square and rectangular cell plans, corner effect naturally exists.

The current cellular networks are broadly categorized into two classes, namely high tier, and low tier cellular networks. High tier networks can accommodate faster MTs (faster than 180 km/h). Low tier networks can handle mobility class with lower speeds.

When there are multiple mobility classes that a cellular network should handle, it is useful to consider cell splitting, which results in a multitier system. For example, in a two-tier system, one tier consists of smaller cells (called microcells or tier-2 cells), which are used by low mobility users, and the other of larger cells (called macrocells or tier-1 cells), used by high mobility users (Lee, 1991b).

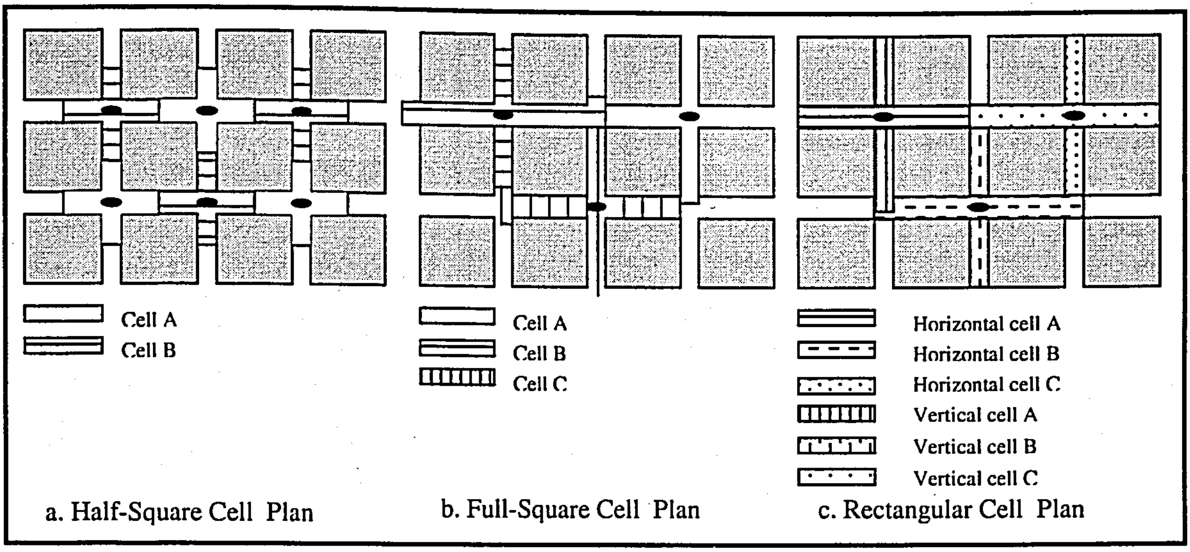


Figure 2.17. Microcellular cell layouts (Lee, 1991b).

TABLE 2.2. Cell sizes.

Cell Type	Size
Macro	2-20 Km.
Micro	0.4 - 2 Km.
Pico	20 – 400 m.

Multitier networks are useful when there are a multitude of traffic types with drastically different parameters and/or different requirements, such as different mobility parameters or quality of service requirements. In such situations, it may be cost-effective to build a multitude of cellular infrastructures, each serving a particular traffic type. The network resources (e.g., the radio channels) are then partitioned among the multitude of tiers (Ganz, 1997). In general, the micro-macro cellular two tier systems are accepted as a viable approach to increase the capacity and the efficiency of the cellular networks. In these systems, the microcells provide strategic radio coverage to areas with high traffic capacity using low elevation antennas with low transmit power. The macrocells provide umbrella radio coverage to a wider area (I, 1993) (Lin, 1996a) (Yeung, 1996). This system is sometimes named as Underlay/Overlay systems in the literature (Tripathi, 1998).

Resource management and mobility management within and among the tiers are the most demanding tasks in multitier cellular networks (Park, 1997) (Sarnecki, 1993). The existence of multiple tiers makes these tasks more complex. Since there are multiple tiers cross-tier interference together with co-channel interference should also be considered in multitier networks.

It is possible to use different multiple access schemes in different tiers such as: TDMA for microcell and CDMA for macrocell. We can use the same access technique for both overlay and underlay cells such as: TDMA for both microcells and macrocells.

The classification of multitier systems can also be based on the determination of appropriate tier in the registration phase and the schemes for the intertier handoffs.

2.4. Personal Communications Services

The underlying vision for the emerging PCS is to enable communication with a person at any time, at any place and in any form. The enabling concepts for providing universal personal communications include: terminal mobility provided by wireless access, personal mobility based on personal numbers and service mobility or portability through management of user service profiles (Grillo, 1996) (Husain, 1996) (Lam, 1997) (Pandya, 1995).

The definition of PCS has evolved over time. Some of the earlier definitions have been as follows (Husain, 1996):

- An extension and integration of current and emerging wired and wireless telecommunication network capability allowing, ultimately, communication with persons.
- A wide array of personal communications services: cellular, cordless phones, paging, wireless private exchanges (PBXs), wireless local area networks (LANS), and so on.

The most current definition of PCS can be found in the American National Standards Institute (ANSI) approved standard, "Personal Communications Terminology" (ANSI T1.702-1995): "A set of capabilities that allows some combination of terminal mobility, personal mobility, and service profile management." We can make the definitions of terminal, personal and service mobility as follows:

The end users of the PCS networks will access to the system at any point, from any terminal, and system will identify the user. This is called personal mobility and based on the use of a unique personal identity.

The second capability is enabling the mobile terminals to communicate with the system while they are in motion. Terminal mobility needs wireless access to the system. It differs from the personal mobility, since the end users do not need to carry a portable terminal for personal mobility, but they do for the terminal mobility.

Lastly, the end users are enabled to use the subscribed services (voice, data, video, image) in the terminals designated by themselves by the service portability or mobility. This concept is related to the effective management and availability of service profiles of each subscriber. Service portability concept also imply that future PCS networks will be integrated services networks.

We can categorize PCS networks into three classes according to their evolution (Prasad, 1997):

The first generation was introduced in 1980 in analog form to provide local mobile speech services. Various standard system of this generation were developed worldwide: AMPS (Advanced Mobile Phone Service) in the United States, NTT (Nippon Telephone and Telegraph) in Japan, TACS (Total Access Communications System) in the United Kingdom, NMT (Nordic Mobile Telephones) in European Countries, and so on.

Fast user growth was observed, penetrating up to 10 percent of the calls in North America, Western Europe, and Japan. The access technique used was FDMA. Capacity and quality were the major problems in the first generation systems, as well as incompatible systems.

Advancements in digital technology gave birth to the second generation systems like digital cellular and cordless telecommunication systems. The best known three examples of digital cellular systems represent three major economical regions in the world, namely GSM (formerly Groupe Special Mobile, now Global System for Mobile Communications) in Europe (Gardiner, 1995), PDC (Personal Digital Cellular) in Japan, and IS 54/136 (Interim Standard 54) or ADC (American Digital Cellular) and IS 95 in North America (Li, 1995) (Padgett, 1995). IS 54 is a system very similiar to GSM in many respects. It's a TDMA system. IS 136 is a developed version of IS 54 which is also TDMA. IS 95 is CDMA second generation PCS system. The technical specifications of these systems are compared in Table 2.3. In these system, TDMA is used as an access technique, except for IS-95 which is based on CDMA (Pandya, 1995). All of these digital cellular systems are high tier systems.

The development of new digital cordless technologies gave birth to cordless communication systems which can be accepted as the supplementary second generation systems. Cordless telecommunication systems are low tier systems and the best known examples for these systems can be listed as PHS (Personal Handyphone System) in Japan, DECT (Digital Enhanced Cordless Telephone) in Europe, and PACS (Personal Access Communication Services) in North America.

TABLE 2.3. Radio characteristics for some digital cellular systems.

	GSM	ADC (IS-54)	PDC
Frequency Band	890-960 MHz	880-960 MHz	810-956 MHz
Access Method	TDMA/FDD	TDMA/FDD	TDMA/FDD
Carrier Spacing	200 kHz.	30 kHz	25 kHz
Modulation	GMSK	pl/4 DQPSK	PI/4 DQPSK
Channel Bit Rate	270.8 kb/s	48.6 kb/s	42 kb/s
Channel Codding	13 kb/s	1.2 kb/s	11.2 kb/s
Frame Duration	4.6 ms	20 ms.	20 ms
Channels/Carrier	8 (full rate) 16 (half rate)	3 (full rate) 6 (half rate)	3 (full rate) 6 (half rate)
MT power levels	0.8, 2, 5, 8	0.8, 1, 2, 3	0.3, 0.8, 2

A mass market has been achieved through the second generation networks. GSM specifically have been well introduced to the global market. At the end of June 1998, there were 293 members of Memorandum of Understanding Association (MoU) GSM from 120 countries worldwide committed to the GSM system. In 1998, there were 278 GSM networks in operation serving 95 million subscribers. It is expected 235 millions subscribers should be served by GSM networks at the end of the year 2000.

The mass market development may be further strengthened through the multiband terminals (i.e. GSM/DCS 1800/PCS 1900) or multimode multiband terminals covering various combinations of the second generation terminals (e.g., DECT/GSM, PHS/GSM, and GSM/satellite). The expected penetration for mobile communication in the developed countries is expected to rise to 50%-80% within the time frame for the introduction of third generation PCS.

2.4.1. The Third Generation PCS

The third generation is expected to be deployed in the year 2002 via Universal Mobile Telecommunications System (UMTS) (Cheung, 1994) (Dasilva, 1996) (Fleming, 1998) (Kreller, 1998) (Markoulidakis, 1997) (Munro, 1998) (Nijhof, 1994) (Norp, 1994) (Ojanpera, 1998a) (Ojanpera, 1998b) (Samukic, 1998) in Europe, which will provide multimedia services to mobile subscribers. The third generation PCSs are in the process of development worldwide by ITU within the framework of the IMT-2000 (International Mobile Telecommunications-2000) (Buchanan, 1997) (Carsello, 1997a) (Jabbari, 1996) (Leite, 1997) (Pandya, 1997) activities. IMT-2000 used to be known as FPLMTS (Future Public Land Mobile Telecommunications Systems). In Europe this is supported by UMTS (Universal Mobile Telecommunication System) program within the European Community.

The main features of the third generation PCS networks can be enumerated as follows (Li, 1995) (Samukic, 1998):

- Multiple environments,
- Multimedia services with high quality,
- Multiple user types,

- Global Roaming Capability,
- Single personal telecommunication number,
- Very high capacity,
- Universal handset,
- Service security.

TABLE 2.4. UMTS phase 1 standards (Samukic, 1998).

Services	• Multimedia services phase 1: - at least 2 Mbps with maximal speed of 10 kmph - at least 384 Kbps in suburban outdoor with maximal speed of 120 kmph - At least 144 kbps in rural with maximal speed of 500 kmph • High quality speech (like fixed networks) using low bit rates • Packet and circuit switched services for the different bit rates and the different radio environments • Service creation and measurement toolkit • Services portability when roaming into other networks • Advanced addressing mechanisms, e.g. personal, Internet style • New charging mechanisms (e.g. volume) • Dual band/mode operation UMTS/GSM incl. Roaming between UMTS islands • Roaming between UMTS and GSM networks • Operate in any suitable band that becomes available, e.g. GSM, DCS 1800, PCS 1900
Terminals	• Mobiles and Subscriber Identity Modules (SIM) with downloading capabilities over the air for e.g. data and applications (feasibility in phase 1 needs further study) • Multimedia terminals • Dual mode/band GSM/UMTS terminals • Adaptive terminals
Access network	• New UMTS BSS - Flexible bearer - Rates ≤ 2Mbps - fast, self adapting interface • high capacity • support of variable bit rates and mixed traffic types • high spectrum efficiency for multimedia and low bit rate speech
Core transport network	• evolution of the GSM NSS (Network Switching Subsystem) and ISDN/IN (Intelligent Network) • new charging and accounting mechanisms • support of service mobility across networks – VHE (Virtual Home Network) • support of variable bit rates and mixed traffic types • mobile fixed convergence elements • support of packet data by Internet protocols
Security	• protection of network use • provision of security services to the user • control of misuse and/or Abuse of the network
Operation & Maintenance	• automatic establishment of roaming relations • support of multivendor networks

The third generation systems differ from the second generation systems most notably with multimedia communications (Schwartz, 1996) (Steinmetz, 1996) and global roaming capabilities. The content of UMTS Phase 1 which will be in operation in the year 2002 is illustrated in Table 2.4.

TABLE 2.5. Teleservices for the Third Generation PCS (Cheung, 1994).

Teleservice	Throughput (Kbps)	Target BER
Telephony	8-32	10^{-3}
Teleconference	32	10^{-3}
Voice mail	32	10^{-3}
Program sound	128	10^{-6}
Video telephony	64	10^{-7}
Video conference	384-768	10^{-7}
Remote terminal	1.2-9.6	10^{-6}
User profile editing	1.2-9.6	10^{-6}
Telefax	64	10^{-6}
Voiceband data	64	10^{-6}
Database access	2.4-768	10^{-6}
Message broadcast	2.4	10^{-6}
Unrestricted digital information	64-1920	10^{-6}
Navigation	2.4-64	10^{-6}
Location	2.4-64	10^{-6}

A subset of proposed teleservices for UMTS is illustrated in Table 2.5 (Cheung, 1994):

The third generation systems are expected to evolve from the existing systems. For instance, UMTS evolves from GSM, and it is intended to use GSM core network for both GSM and UMTS when UMTS is operable. Therefore there may be several third generation systems in the future. European Telecommunications Standardization Institute (ETSI) Special Mobile Group (SMG) proposed that all third generation systems including UMTS should be seen as an IMT-2000 family member. The IMT-2000 family concept offers needed flexibility and at the same time opens considerable commonality. This concept is recognized by ITU as a suitable approach to accommodate the need for evolution/migration toward IMT/2000 in the wireless communications industry. That will enable roaming between IMT-2000 family members which is important for global roaming concept.

ETSI selected new radio interface for UMTS Terrestrial Radio Access (UTRA) in the January of 1998 and proposed UTRA (Adachi, 1998) (Berutto E., 1998) (Dahlman,

1998) (Latva-aho, 1998) (Nikula, 1998) (Ojanpera, 1998b) as standard radio interface to ITU for all IMT-2000 members. Some of the decided key characteristics can be listed as follows:

- For the paired bands (1920-1980 and 2110-2170) Wideband CDMA (WCDMA) will be used in FDD operation (UTRA/FDD Mode).
- For the unpaired bands of total 35 MHz time division CDMA (TD-CDMA) will be used in TDD operation (UTRA/TDD Mode).
- UTRA/FDD is based on 5 MHz WCDMA with a basic chip rate of 4.096 Mchips/s, corresponding to a bandwidth of approximately 5 MHz. Higher chip rates are intended for the future evolution of the W-CDMA air interface toward even higher data rates (>2 Mbps).
- WCDMA carriers are located on a 200 kHz carrier grid with typical carrier spacing in the range 4.4-5.0 MHz. The carriers in GSM are 200 kHz (Goodman, 1997). This choice makes UMTS more compatible with GSM.
- WCDMA physical layer Transport Channels (TrCh) which are very similar to GSM transport channels (Goodman, 1997), namely Broadcast Control Channel (BCCH), Forward Access Channel (FACH), Paging Channel (PCH), Random Access Channel (RACH), Dedicated Channel (DCH). There are two different types of DCH, namely Dedicated Physical Control Channel (DPCCH), and Dedicated Physical Data Channel (DPDCH). Each TrCh has a Transport Format (TF) set from which Medium Access Control Layer (MAC) can choose one for each connection. TFs are simply transfer rates.

3. TACTICAL COMMUNICATIONS SYSTEMS

Since timely, accurate and secure transfer of information is the key requirement for the success of a military operation, current concept for military operations is stated as Command, Control, Communications, Computer and Intelligence (C4I) (Maxwell, 1996). We use the term C4I to describe the systems and functions used by decision makers and war-fighters to gather, process, transmit, display, and use information. It also includes the systems and functions used by decision makers to store, retrieve and analyze information, and to communicate with all levels of command before, during and after decision making process of information management and information usage (Allen, 1995).

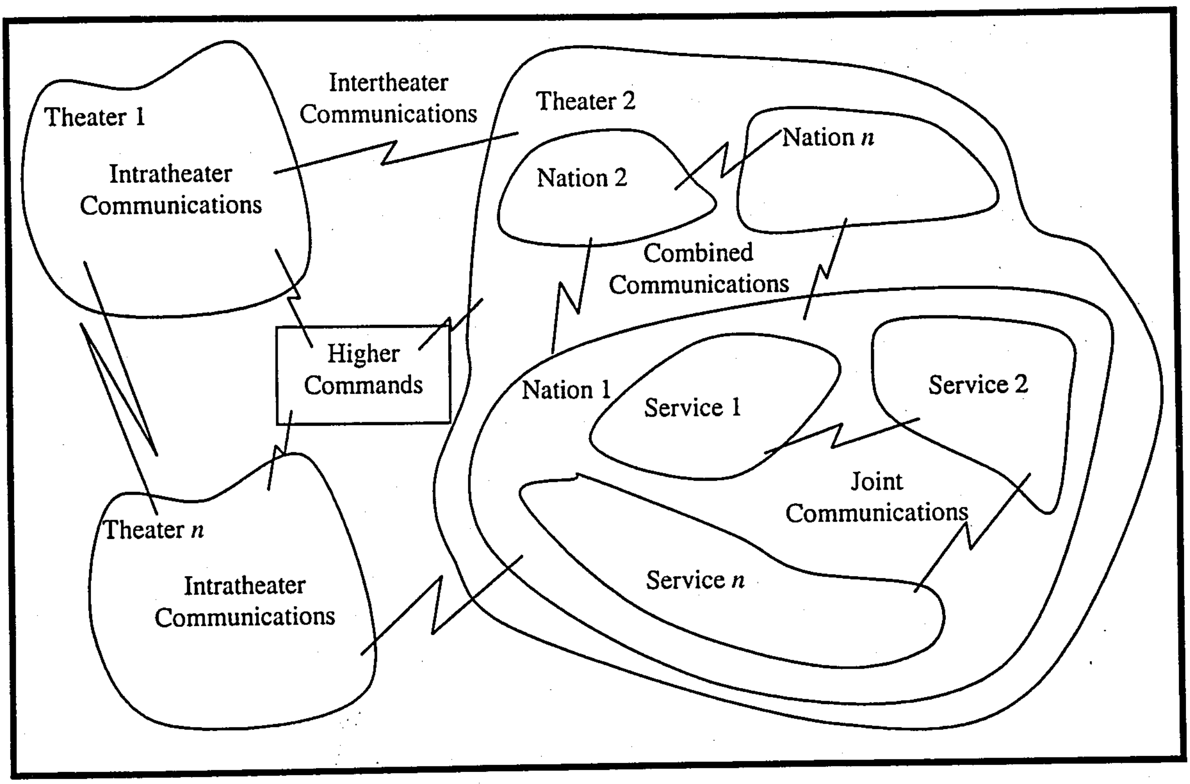


FIGURE 3.1. The military communications hierarchy.

The most basic need of C4I is the integrated communications system which can be defined as the ability to convey reports, orders, data, information, knowledge in any form (video, image, voice, text, graphics or a combination of them) among the leaders, the headquarters and the other components of the battle forces in a secure and timely manner. It has always been a major challenge to provide effective communications in the battlefields and in the theaters. However the evolution of various technologies makes communications more crucial, since they push the leaders to gather information, to decide and to disseminate the orders together with available information faster and faster.

In Figure 3.1, the military communications challenges are illustrated. These challenges can be enriched further.

A war may be carried in multiple theaters as was the case in the First and the Second World Wars. The communications among these theaters which may be spread all over the World, and among the theaters and the higher level of commands such as the National Commands is the first priority communications to be established. Apart from this, there may be the armed forces of different nations which are in the same combined force, and the armed forces of each nation may have forces from different services which are in the same joint force. The combined and joint communications is another important characteristics of contemporary military communications. Based on this discussion, we can categorize the military communications systems according to three levels of operations : global, theater, and tactical.

The subscribers of the same military communication system may be all or some of the following:

- Infantry men,
- Tanks, armored vehicles or other vehicles such as trucks,
- Aircrafts or helicopters,
- Ships,
- Sensors such as radars,
- Jammers,
- Other weapon systems such as Surface to Surface Missiles (SSMs), etc.

These subscribers which have different characteristics, communicate with each other. For instance, the data gathered by sensors in satellites and conveyed through this communication system may guide an SSM.

Historically, military command and control (C2) communications have followed the chain of command. At the lower echelons, status reports provided to the leaders are consolidated, edited, and then relayed up to the leaders in the higher echelons. From higher echelons, battle plans and operational orders are relayed downward, being expanded in detail and tightened in focus at each echelon. "This approach has been proven effective throughout the history of modern warfare, particularly for voice communications. But out of Operation Desert Storm came a new realization – the necessity to exchange information outside of this echelon oriented flow pattern. The need for horizontal information dissemination became clear (Sass, 1995)."

We can enumerate the characteristics of military communications as follows:

- Different mobility patterns : While some of the subscribers move in supersonic speeds, some others may move very slowly or may even be fixed.
- Wide range of terminal types : Different sort of equipment such as sensors (video camera, radar, sonar, thermal camera, etc.), single channel radios, computers can be attached to military communications networks.
- Variable communications distances: Communications can be carried in three levels of operations, namely global, theater, tactical. The communications distances vary from a couple of meters up to thousands of kilometers in military communications according to the level of operation.
- Variable communications medium characteristics: The communications may be carried via tethered or untethered nodes through wires, optical fibers, air or even through sea.
- Rapidly changing communication locations: The regions covered with extensive communications networks may be deserted and the same networks may be installed in different regions within days in military operations.
- Hostile and noisy environments: The communication lines of the enemy side is a high priority target in the battlefield. Also thousands of exploding bombs, vehicles and intentional jamming cause noise on the communication lines.
- Bursty traffic: Generally everybody tries to communicate at the same time.
- Different types of application: Military communication networks host some real time applications together with batch applications. Some of applications may

require to satisfy very stringent transfer delay constraints. On the other hand some does not apply any time constraint.

- Different security constraints: Some unclassified data together with top secret data flow through the same lines.

The key system requirements for military communications system include the following:

- Multimedia communications,
- Multi-tier networking,
- Mobile networking,
- Mobile and rapidly deployable infrastructure,
- Survivable infrastructure,
- Tailorable infrastructure,
- Multi-functional infrastructure,
- Modular infrastructure,
- Flexible infrastructure,
- Nonterrestrial networking,
- Horizontal and vertical communications ability,
- High circuit quality and wide bandwidth,
- Secure networking,
- Real-time and batch networking,
- Ability to operate in every weather and terrain conditions.

In this chapter, we examine military communications technology in two sections, namely the communications technology employed in Desert Shield/Desert Storm Operations, and the ongoing development efforts in military communications.

3.1. The Communications Technology Employed in the Gulf War

The most sophisticated and developed communications equipment ever provided is employed during the Gulf War (Brendler, 1992) (Frakes, 1992) (Gibson, 1992) (McKenzie, 1992) (O'Neil, 1992) (Salerno, 1992) (Slupik, 1992) (Toma, 1992) (Tuttle, 1992) (Wallace, 1992). "At the height of the operation, the system supported 700,000 telephone calls and 152,000 messages per day. More than 30,000 radio frequencies were managed to provide the necessary connectivity and to ensure the minimum interference. Not only the communications carried by the Desert Shield/Desert Storm communications architecture, but also the time required to build it up is impressive. In less than five months, the Desert Storm architecture, not only rivaled but surpassed the mature, 40 year old European network. Within 90 days, what had been single-thread, point-to-point systems in the region prior to the crisis grew into a true force multiplier – a network of sophisticated, integrated, information systems fully capable of supporting a high technology battlefield (Toma, 1992)."

Although, commercial applications are the driving force behind the technology in general, the emerged components and techniques supported the Desert Shield/Desert Storm operations are still the most developed and available technologies in the year 1999. However the current development efforts indicate that this will not last long.

"In the late 1980s, the fielding of Triservice-Tactical (TRI-TAC) switchboard equipment initiated the transition from the old analog backbone instruments to digital system. TRI-TAC features hybrid (analog and digital) capabilities and sophisticated automatic circuit switching. TRI-TAC also includes store and forward message switching.

During Desert Shield/Desert Storm operations, TRI-TAC switched communication networks were used to provide steadfast and reliable communications. One of the TRI-TAC developments, the Ground Mobile Force (GMF) satellite digital multi-channel radio, was used extensively to provide the primary transmission links for its Switched BackBone (SBB). The GMF multi-channel radios use the Super High Frequency

(SHF) wideband satellites as a retransmission platform enabling them to be operated theater-wide with no limit on the transmission link distance.

Two of the TRI-TAC equipment have the major role: AN/TSC-85B, AN/TSC-93B. The AN/TSC-85B serves as the center, or "hub" of a digital multi-channel network. Capable of multiplexing up to eight Digital Transmission Groups (DTGs) into one digital supergroup, it then modulates this supergroup onto one carrier frequency, which is then transmitted to a satellite for frequency translation and subsequent retransmission back down to other AN/TSC-85B or AN/TSC-93B terminals. The AN/TSC-93B is a smaller terminal, known as a "spoke", which can break out two DTGs of the supergroup that has broadcast from the hub. Each hub is capable of handling four spokes, and these spokes can be either an AN/TSC-93B, a special Defense Communications System (DCS) Gateway for connection into the Defense Switched Network, or even another AN/TSC-85B. Also, two AN/TSC-93B terminals may connect together in a point to point mode, passing two DTGs between each other.

Each of the DTGs passed over a GMF network has a 576 kbps transmission rate, giving anyone hub a capacity limit of 4.608 Mbps. This is roughly equivalent in size to three commercial T1 carriers with one main exception. While T1 uses individual DS0 channels of 64 kbps each, TRI-TAC networks use smaller 16 kbps or 32 kbps voice channels. At a voice channel or circuit switch rate of 16 kbps, each hub network is capable of handling 288 voice channels.

The eight DTGs that come together at the hub are combined in a group multiplexer called the Tactical Satellite Signal Processor (TSSP), or TD-1337(v)1. The spoke terminals have a similar group multiplexer, which combines only two DTGs and is a smaller version of the TSSP, called the TD-1337(v)2. The wide-bandwidth supergroup of eight DTGs is transmitted from the hub to all spoke terminals; however, each spoke only decombines, or breaks out its own two groups from the transmitted signal (O'Neil, 1992)."

An alternative to satellite communications during Desert Storm was HF radio (Wallace, 1992). HF radio communications are carried out in the frequency band of 2 MHz to 30 MHz. Essentially there are two primary modes of propagation: surfacewave (groundwave and line-of-sight, or LOS) and skywave.

Groundwave communications relies upon the earth's surface as the path for the radio signal's propagation. For successful groundwave communications, higher powered radios often are necessary and vertical antennas are required. Skywave communications relies upon the ionosphere for reflection of the propagated radio signal (Wallace, 1992).

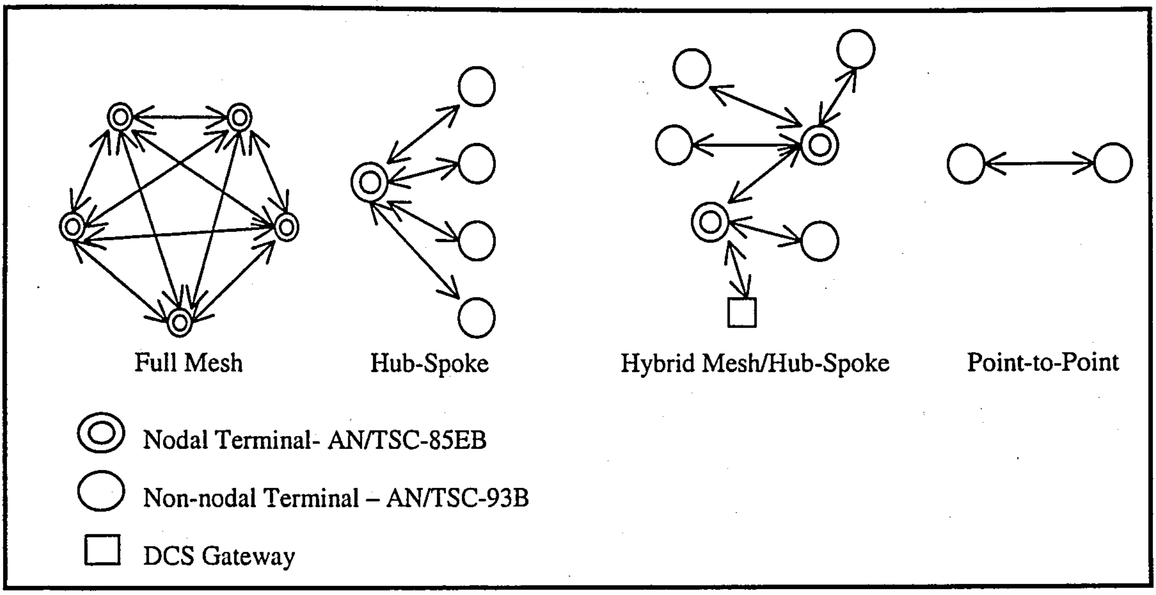


FIGURE 3.2. Backbone network configurations (O'Neil, 1992).

In the late 1980s, the U.S. Armed Forces started to replace its older communications systems with Mobile Subscriber Equipment (MSE) at echelons corps and below, with Digital Group Multiplexing at echelons above corps. Both fully digital systems are classified as Area Common User Systems (ACUS).

With MSE came several new ideas in U.S. tactical communications. First, subscribers now own their own terminal instruments (e.g., phone, fax, message terminal). Second it includes a cellular radio-telephone system, and third, it employs flood search routing (Kershenbaum, 1993) instead of deterministic routing for call establishment.

Flood searching is a technique whereby a switchboard initiating a call sends a call request to all of its neighbors. The neighbors do likewise. The first switch that can connect the call does so and the others are released. This makes MSE a much more survivable area communications system. The idea of user-owned and operated equipment is termed the General Purpose User (GPU) concept. It saves on personnel costs.

"As previously stated, MSE is an all-digital system and correspondingly extends digital cellular telephone service to mobile subscribers. It is the first tactical system to do so, and because it is digital, it puts the U.S. Army one step ahead of the general public. MSE retains the TRI-TAC message switch, but it replaces the TRI-TAC circuit switch at Corps and the analog extension switch in Divisions.

The SINgle Channel Ground and AirBorne Radio System (SINCGARS) radio is also a frequency hoping radio, provides increased survivability of communications in a jamming environment. MSE telephones and the new generation of Combat Net Radios (SINCGARS) both have ports for the connection of data devices. This allows computers or facsimiles to use the system. Additionally, it has a Mean Time Between Failure (MTBF) that is orders of magnitude better than the combat net radio it replaces.

The Army's Signal leadership recognized early on in the 1970s the potential utility of automation. The Military Computer Family (MCF) program was started and special data networks in the communications architecture such as the Army Distribution System (ADDS) were taking shape. Sixteen kbps data capability on SINCGARS in ECCM (Electronic Counter Counter Measures) mode, fully encrypted, was planned at that time.

The Army's plan for the automation, which had been underway since 1978, called for the development of interactive tactical computer systems. Thus emerged a battlefield requirement for networking computers. Analog modems abounded and it became apparent that data users soon would contend with voice users for the network's limited bandwidth. As the Army developed data ports for its digital telephones, it began planning for a tactical packet network. This has since been contracted for, but was not to begin fielding until late 1991.

The Army Tactical Command and Control System (ATCCS) includes one more communications system: the Army Data Distribution System. ATCCS also includes five Battlefield Functional Areas (BFAs), each of which sponsors a Battlefield Automated System (BAS) and several subordinate automated systems. These will utilize tactical computers. The Maneuver Control System (MCS) is the BAS which has been fielded. It is built on a common hardware computer platform using the Unix operating system and, among other capabilities, provides electronic mapping and Command Control (C2) reporting. Terminals generate a significant data traffic load which must be carried by circuit switching or combat net radio until the Tactical Packet Network (TPN) is fielded. This further exemplifies the need for ADDS, SINCGARS data transport capabilities, and the TPN, and the integration of each into a seamless network (Gibson, 1992)."

3.2. The Ongoing Development Efforts in Military Communications

The evolving broadband networks, digital cellular systems, wireless computer networks, computer systems, global positioning and other technologies cause a new breakthrough in the military communications systems in the late 1990s (Allen, 1995) (Evanowsky, 1995) (Lackey, 1995) (Leiner, 1996) (Quan, 1995) (Sass, 1995). Electronic mail, cellular telephone for voice and data, vehicle position reporting/tracking systems, and many other products have appeared and become commonplace in civilian market. These commercially available technologies attract the military.

Based on the previously defined requirements and the evolving technologies numerous researches are carried both in the U.S. and in NATO, such as Defense Information System (DISN) (Sass, 1995), Post-2000 Tactical Communications (TACOMS) (Quan, 1995), Global Mobile Communications (Leiner, 1996). Figure 3.3 illustrates the architecture of the next generation tactical communications systems which is derived from DISN and TACOMS efforts.

The architecture has four subsystems: the Local Area Subsystem (LAS), the Wide Area Subsystem (WAS), the Mobile Subsystem (MS), and the System Management and

Control Subsystem (SMCS). An integrated security architecture also provides the security services associated with the communication.

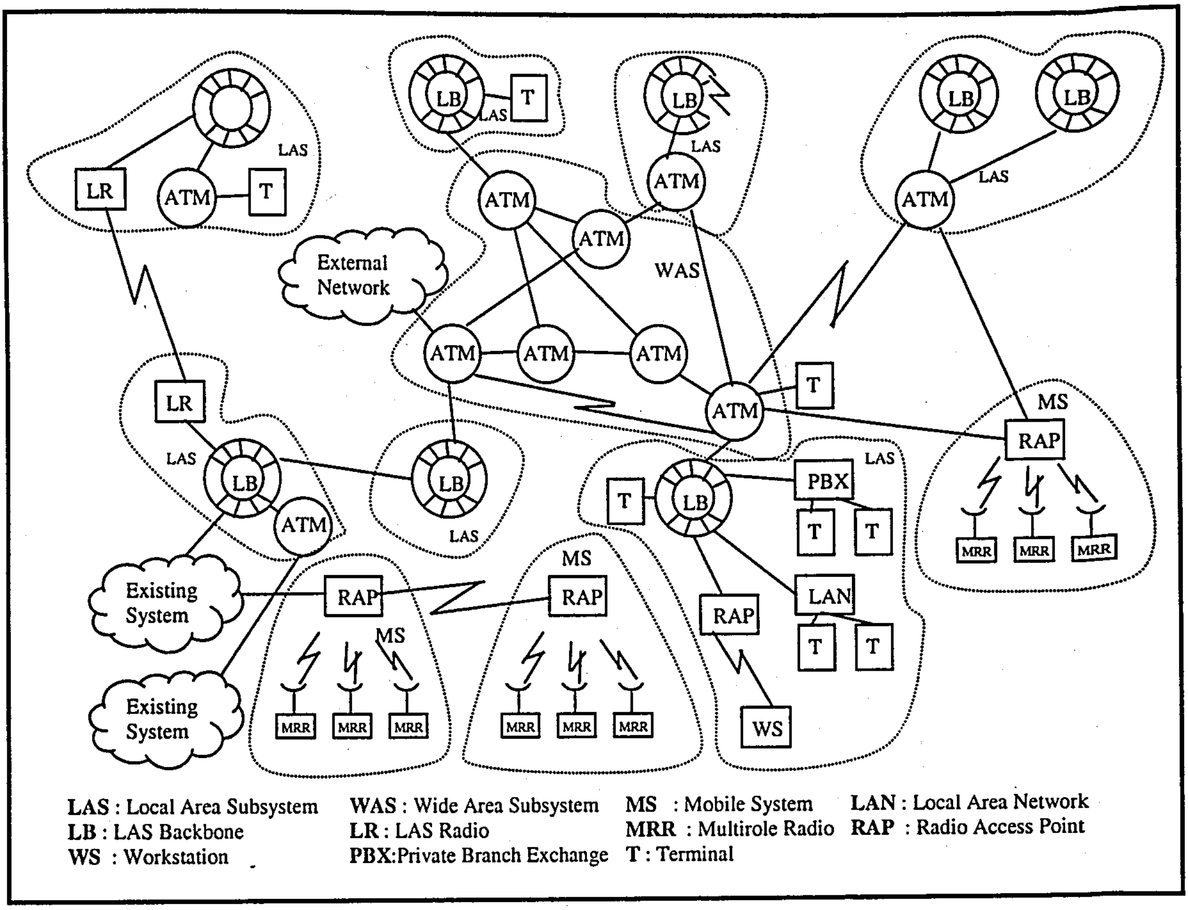


FIGURE 3.3. The next generation tactical communications systems.

The WAS provides a transit function to LAS and MS users over the long-haul tactical transport system. It also provides the switching services at the network level for the tactical users crossing LAS or MS boundaries. The WAS is designed to allow modular connection of multiple LASs and MSs into a single larger network. ATM is selected as the multiplexing and switching architecture of this subsystem.

The LAS (Nazlibilek, 1997) is designed to support local and internal communications of a self-sustained community in a geographically restricted area (e.g., headquarters). The LAS is also the subsystem that provides users with access to WAS, interface to the strategic networks, and connection to commercial networks. The LAS is modular in design and can be configured for various network topologies (meshed, bus, tree or rings). The centerpiece in the LAS is the LAS backbone which transports standard ATM cells. At the lower echelons, the requirement for mobility may dictate a wireless LAS with limited throughput and system facilities confined to transportable equipment such as vehicles. Where mobility is not paramount, the LAS will be configured via cabling using fiber optic cables where throughput can be measured in the gigabit per second range.

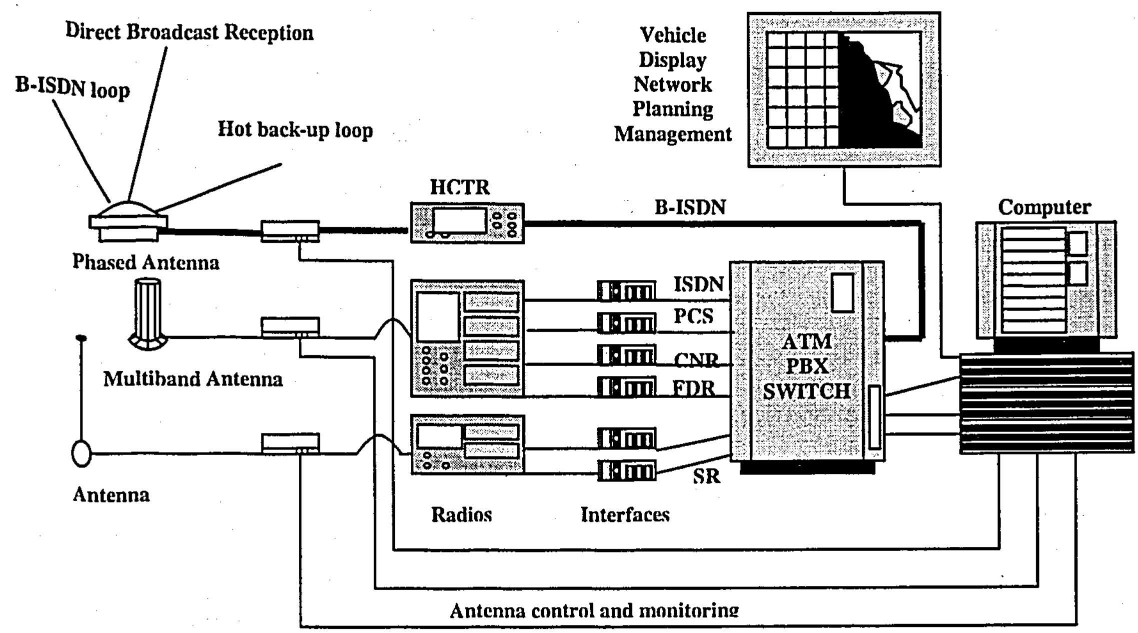
The MS is designed for mobile operations. The MS characteristics allow it to be operated as an independent network or as a part of the overall tactical system. The MS supports three modes of operation: combat net radio (CNR), mobile telephone (MT), and packet radio (PR). The two major components in the MS are the multi-role radio (MRR), or Multiband Multimode Radio (MBMMR), and the radio access point (RAP). The MRR will integrate user services (voice, data, imagery) including position, navigation and Intelligence of Friendly or Foe (IFF) into the three communications modes (CNR, MT, and PR).

The SMCS is not a separate subsystem but is integral to the architecture. System management functions conform to ITU standards and incorporated as application layer functions in designated authorized network management terminals. The five network management functions – fault management, performance management, accounting management, configuration management, and security management – as well as network planning functions will use artificial intelligence techniques and be fully automated in the system.

The technology components of this architecture and its subsystems are defined as follows in (Sass, 1995):

- ATM : The ATM (Le Boudec, 1992) (Prycker, 1995) is one of the target technologies chosen as the multiplexing and switching architecture of the next generation military communications systems.

- Radio Access Point (RAP): RAP will integrate several component technologies into a prototype fieldable combat system. The RAP will support, on the subscriber side, a variety of subscriber devices that individually support the separate voice, data, or video requirements of the legacy system. Equipped with a multiband multimode radio, the RAP will serve multiple mobile subscriber populations over wide coverage areas, adjusting networks dynamically as the battle unfolds. As the technology enables truly integrated services to be extended to mobile subscribers, the RAP will naturally evolve to this as well.



HCTR	: High Capacity Trunk Radio	**B-ISDN**	: Broadband Integrated Services Digital Network
FDR	: Future Digital Radio	**ISDN**	: Narrowband Integrated Services Digital Network
PCS	: Personal Communication Services	**SR**	: Software Radio
CNR	:Combat Net Radio		

FIGURE 3.4. The block diagram of the objective RAP (Sass, 1995).

A block diagram of the objective RAP is provided in Figure 3.4. The RAP will include a number of radios. The High Capacity Trunk Radio (HCTR), a digital trunk capable of supporting ATM bandwidths, will provide the trunk connectivity to the fixed ATM infrastructure. A variety of subscriber radios, each supporting lower bandwidth, often single media services, will be supported by a collection of "legacy radios" or preferably, by an MBMMR from the Tri-Service Speakesy program. In addition, the Army's Near Term Digital Radio (NTDR) will be integrated into the RAP to support its existing subscriber population.

- Speakeasy (MBMMR) : Conceived in the early 1990s, the Speakeasy program was initiated as a joint service research and development program with Advanced Research Projects Agency (ARPA) to develop the architecture and standard building block technology for a software programmable (Hentschel, 1999) (Mitola, 1999) (Reichart, 1999) (Salkintzis, 1999) (Seskar, 1999) (Tuttlebee, 1999), joint-service MBMMR for the 21st century. Phase II Speakeasy will develop the final open system and demonstrate simultaneous four channel operation over a frequency band 2-2,000 MHz, network and internetwork (IP) protocols, voice and data, and programmable INFOSEC.

- Future Digital Radio (FDR) :In 1994, the Army Signal Center, Director of Combat Developments, prepared a draft Materiel Needs Statement (MNS) for a programmable multimode multiband radio known as the Future Digital Radio (FDR). The FDR was envisioned as a manpacked radio, capable of multiple simultaneous transmission and receptions over a variety of bands from HF through upper UHF, and supporting voice and data waveform interoperability with numerous legacy systems among the services. Acquisition of an FDR is projected for post 2000, scheduled to replace the Army's current generation of separate Combat Net Radios (HF, SINCGARS, TACSAT, HAVE-QUICK).

- Near-Term Digital Radio (NTDR) :The goal of NTDR program is to establish an open architecture to permit growth to the FDR in the year 2000. The NTDR have the data distribution capability, and is capable of internetworking with SINCGARS and MSE using Tactical Multinet Gateway (TMG) and internet Controller (INC) IP based technology. The NTDR is being acquired as a "turn key" system, including all radio hardware and software, and installation kits to support all platforms. No waveform or frequency band is being specified in an attempt to optimally capitalize on commercial developments.

- High Capacity Trunk Radio : In order to support the extended reach required by mobile forces supported by a RAP, a high-bandwidth trunk radio system is required. The RAP will rely on the HCTR, relayed through wideband (45-155 Mbps) aerial relays, to terrestrial ATM switching sites. The RAP system include the HCTRs, wideband aerial relays, a family of sophisticated interfaces as well as a family of subscribers, lower bandwidth radio equipment to support mobile subscribers with legacy and emerging communications systems.

The HCTR is a next generation Line Of Sight (LOS) trunk radio evolving from the narrowband radios available today. The radios will be engineered to achieve 99.9 per cent path reliability through improvements in bit error rate, use of spectrum efficient high order modulations, adaptive waveform management, and adaptive dynamic equalization. The HCTR is a critical component for extending B-ISDN services from fixed-site surface locations to mobile ATM access points such as the RAP.

- On The Move (OTM) Antennas : A key requirement for the RAP will be OTM communications, at high bandwidths through airborne relays or terrestrial HCTR trunks. Developing, acquiring and testing a high performance phased array antenna system is, therefore fundamental to the success of the Army's RAP program. The army's development in this area will exploit phased array developments already underway.

- Personal Communications Systems : Digital cellular services, including Personal Communications Services (PCS), will be exploited in terrestrial and satellite forms. The biggest limitation is that these systems require a terrestrial infrastructure supporting the mobile subscriber population. One solution that appears attractive to the military is the concept of a space based, or UAV based, cellular infrastructure that eliminates the requirement for a terrestrial network of cell sites. A number of commercial satellite based Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO) PCS systems are expected to become commercially available. These PCS developments are currently being monitored through vendor interviews, technical journals, and marketing literature. UAV base-station concepts will also be evaluated. In addition, the Army will investigate surrogate satellite constellations, launched by manned or unmanned aircraft, that could be used in military crises until commercial satellites are operational worldwide.

- Direct Broadcast Satellite : Direct Broadcast Satellite (DBS) video broadcast, now available at low cost in the United States for commercial subscribers, represents a powerful technology for military exploitation. These systems use commercial satellites and a standard commercial MPEG video format. This has enabled the development of a huge market for low cost home video broadcast receivers with small (18 inch) dishes. Commercial equipment designed for this service will be exploited for use in intelligence dissemination (e.g., still and full-motion color imagery); unidirectional, highbit-rate, wide area data transmission, and for providing one-half of non-symmetrical, point-to-multipoint duplex circuits.

To satisfy defense requirements for rapidly deployable and robust information systems it is critical that the technologies be available to support operation in mobile environment. GloMo program (Leiner, 1996) which was initiated by Defense Advanced Research Projects Agency (DARPA) of the United States (US) in 1994 is aimed at the development and demonstration of technologies to support this requirement. The generic objective of the efforts is to progress toward secure, seamless, theatre-wide, multimedia communications for all tactical users.

There are multiple technology focus areas that are worked on by the three services of the US Armed Forces, including such diverse areas as satellite based PCS, Direct Broadcast Systems (DBSs), unmanned airborne vehicle relays, high capacity trunk radios, programmable multiband multimode radios, terrestrial PCS, conformal antennas, and high speed Local Area Networks (LANs).

As an example of the drivers behind the GloMo program, the US Army has launched a major initiative to digitize the battlefield. In digitizing the battlefield (Çayırcı, 1996) the US Army is seeking to harness the power of the computer to help the commander and his forces better understand their situation, improve force synchronization, and enhance combat effectiveness.

The GloMo program covers a range of technologies:

- Design techniques, tools, languages, and environments previously developed under DARPA Microsystems program and related activities are being extended to support design and prototyping of wireless computing systems.
- The program is developing and demonstrating scalable adaptable untethered systems exploiting low-power commercial technology. Architectures for modular untethered nodes that allow leveraging commercial advances in wireless technologies through the use of advanced design methodologies will be developed and demonstrated.
- New networking techniques that support rapid deployment and robust networking service in a hostile and dynamic environment are being developed and demonstrated. Robust self-configuring networking technology supporting military and civilian crisis management will be developed.
- Advances in end-to-end networking technologies developed in the Internet research community are being leveraged to provide highly capable communications services that can operate over a heterogeneous mix of networks, including a variety of wireless networks. Enriched network service procedures supporting dynamically changing bandwidth and connectivity will be developed.
- New distributed computing techniques supporting mobile operation (file systems, migratable computing, locality awareness) are being developed to provide an underlying infrastructure supporting applications operation in an environment characterized by sporadic connectivity and varying QoS.

3.3. High Quality Networking Efforts in the Turkish Armed Forces

The Turkish Army has initiated some major development efforts on communications infrastructure, hardware and software. There are two major efforts which are integrated to each other, namely the Turkish Armed Forces Integrated Communication System (TAFICS) and Tactical Communications System (TASMUS). The goal of TAFICS is to cover Turkey with high quality lines which are mainly fiber optic. It is going to be a fault tolerant system with eleven nodes, and will be monitored in a central node in Ankara. TASMUS will be the mobile communications system for the echelons lower than corps.

4. APPLICATION OF THE 3G PCS TECHNOLOGIES TO THE MOBILE SUBSYSTEM OF THE NEXT GENERATION TACTICAL COMMUNICATIONS SYSTEMS

The final point reached in wireless communications technologies, namely cellular and intelligent networks, make multimedia services amenable to be deployed for mobile communications. PCS systems based on these technologies have been emerging since 1980s, and evolving towards their final goals. It is believed that PCS will be the next breakthrough in communications when the third generation technologies will be deployed in the beginning of 2000s.

The services that have become available with PCS, cellular network and intelligent network concepts can also change the nature of the battlefield command and control systems. The motivation of our study is to investigate an approach to employ PCS and cellular network concepts for the Mobile Subsystem (MS) of the next generation tactical communications systems, and to eliminate some of the common weak features of the current tactical communications systems. These weak features of the current tactical communications systems are enumerated below:

- The current tactical communications systems can convey voice (generally analog) and low rate data traffic among the warriors. However, high rate data and multimedia communications is very important to create complete, accurate and timely tactical view before the decision makers. The range and effectiveness of the current and evolving fire power technologies make the quick detection of the enemy units the most important activity. The detection is based on gathering and disseminating the information collected by various sensors and units and requires multimedia communications.
- Since the users of the battle force are mobile, they need mobile communications through the wireless media. The wireless media have limited spectrum which should be utilized carefully. However, the current military technologies use a frequency channel only for one component in a large area, and utilize the spectrum in a poor manner.

- It is possible to collect very important intelligence by eavesdropping the enemy communications, or locating the enemy communication components which are high priority targets by sensing their emissions. Since this activity which is named as Electronic Support Measures (ESM), requires that the enemy signals reach the friendly sensors, it is important to use the lowest possible power to communicate. The current military technologies generally cover the distance between two ends of a communication with a single wireless line which means higher power emissions and also higher power consumption.
- The important portion of the current mobile tactical communications systems are the collections of small wireless voice networks. These small networks are generally analog single hop broadcast networks. For instance, in a battalion, each company commander and the battalion commander has a radio that can broadcast in a frequency channel which is common for that battalion. This makes it possible that company commanders can transfer their combat reports to the battalion commander, and the battalion commander can disseminate the information gathered to his company commanders through this battalion network. This is named as vertical or hierarchical communications. There are some other networks such as company and brigade networks in higher and lower echelons. This system does not allow direct communications horizontally or out of hierarchy. For instance, a company commander cannot reach to his neighbor company commander which belongs to another battalion or a brigade commander cannot reach a platoon commander directly. However, the speed and the dynamics of the current battlefield makes it necessary to communicate horizontally or out of hierarchy.

Cellular networks and PCS offer some approaches that can eliminate these weak points of the current systems. However, cellular networks stipulate that a well designed large immobile infrastructure should be deployed. The need for fixed infrastructure brings up some major adaptability problems listed below for cellular networks to be employed as the MS of the tactical communications systems:

- The infrastructure for MS should be mobile, because the area of communications in the battlefield changes continuously.

- The infrastructure should be robust and survivable, because the communications systems are high priority targets to be attacked in the battlefield. What we mean by unreliable is that the nodes of the network do not rely on the other nodes to communicate. In this kind of networks, a failed node does not stop the other nodes or at least the nodes outside of its branch.

In our study, we investigate the approaches that can employ cellular concepts for MS of the next generation tactical communication systems in spite of the existence of these major adaptability problems. We work on a multitier, self configuring system illustrated in Figure 4.1. In our study, we assume the availability of the following equipment. Our assumptions are based on ongoing development efforts which are explained in Chapter 3 (Sass, 1995) (Leiner, 1996).

- The availability of Man Packed Radios (MPR): The MPRs will be capable to communicate with *n* other radios, and even concentrate the traffic of *n* other radios into a single higher capacity channel which can be established with other MPRs, Radio Access Points (RAPs), Unmanned Aerial Vehicles (UAVs) and satellites. It is also essential that a man packed radio can communicate in two carriers simultaneously. Man packed radios are the radios that have the abilities of the Future Digital Radios explained in Chapter 3.2. They are not essentially man packed. They may be mounted on the vehicles of different types.
- The availability of RAPs: RAPs will be capable of communicating with *m* MPRs simultaneously and concentrate their traffic into a single trunk that can be established with UAVs, satellites, Wide Area Subsystem (WAS) gateways or even with other RAPs.
- The availability of UAVs.
- The availability of satellites.
- The availability of WAS gateways.
- The availability of location tracking systems: We assume that every MPR, RAP and UAV is capable to find out its geographic location. This can be accomplished either with Global Positioning Systems (GPSs) which are ubiquitous or with some other location finding systems (Hellebrandt, 1997). In the case that none of these systems

are available or not functioning properly, we assume that the geographic locations can be entered into the communications devices manually by the operators.

We envision four tiers in the Mobile Subsystem (MS) that we propose:

- MPR Tier (MPRT) (microcell): This will be the low tier microcellular part of the MS. One of the man packed radios act as a cell head, and the cell head or one of the other man packed radios act as a gateway to other tiers, other cells or directly to a WAS access point.
- RAP Tier (RAPT) (macrocell): This will be the high tier macrocellular part of the MS. RAPs act as mobile base stations. RAPT cells may also construct underlay clusters, since we perceive RAPT and MPRT cells as underlay cells and a RAPT may include a number of MPRT cells.
- UAV Tier (UAVT): This is the first level overlay tier of the MS. UAVT cells cover the areas which are hidden for the lower tiers, and also help the lower tier cells to access the WAS and communicate with each other.
- Sattellite Tier (SATT): This is the topmost overlay tier over the UAVT.

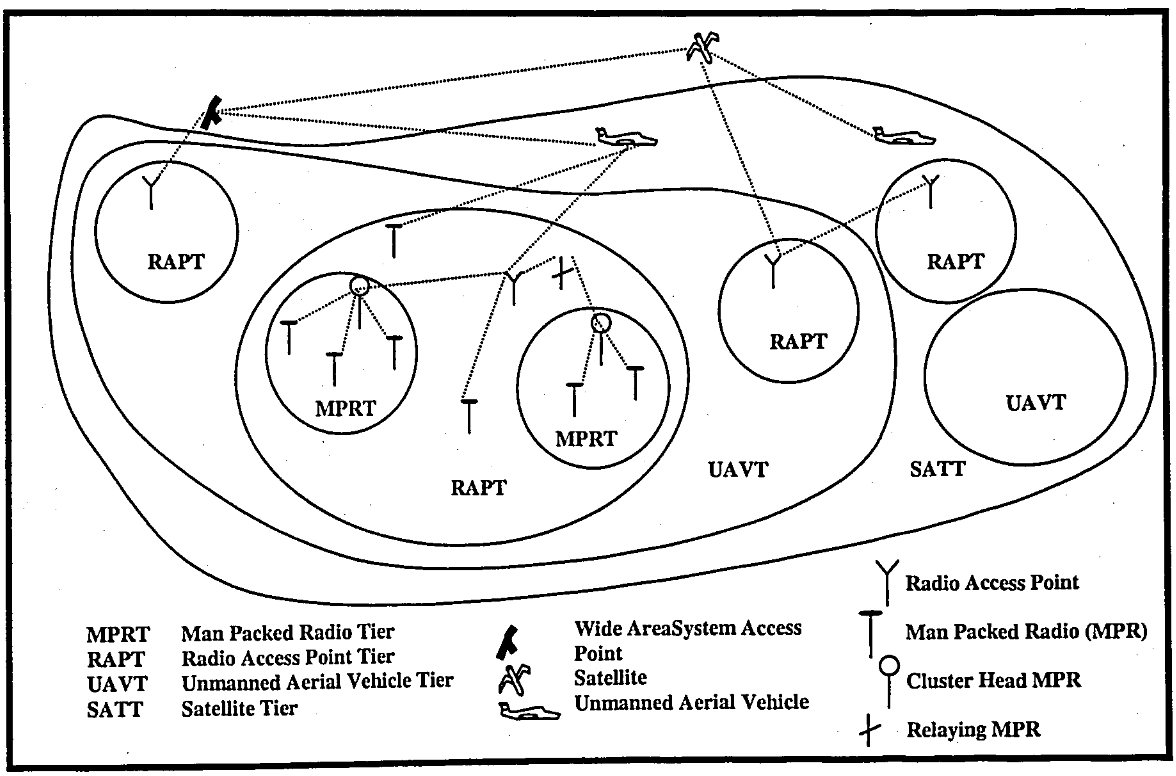


FIGURE 4.1. Multitier mobile subsystem.

The system should be self configuring, since it is a very dynamic one. We intend to use procedures similar to the mobility management functions employed in ordinary cellular networks with the following basic concepts to make the system self-configuring:

- MPRs are registered to RAPT cells whenever possible, if the tier to be registered is not set explicitly by the operators. If there is not a RAPT cell to be registered, MPRs try to register to an MPRT cell.
- If the MPRs cannot find an MPRT or a RAPT cell to be registered, they create a new MPRT cell and connect this new cell to the lowest possible overlay cell.
- MPRs handoff between the cells as they move and if it is required. If it is required and there are enough resources, they can handoff to the upper or the lower tiers.
- MPRs may reach to one of the tiers by multihop which indicates that we utilize ad hoc approaches especially in MPRT.
- All concepts, schemes and strategies are distributed.
- In the case of scarce resources or if needed, the network sometimes may be divided into smaller subnetworks that cannot communicate with each other. These smaller subnetworks can be as small as an MPRT cell.

In the proposed approach, we consider sudden changes and outages in the system. In commercial nets, mobility may cause the links fade gradually. However in military networks, any of the links can fail suddenly due to enemy fire or Electronic Counter Measures (ECM).

Engineering decisions such as the code length, the chip rate, the channel spacing related to the physical layer are not considered in this study. WCDMA and UTRA values (Dahlman, 1998) are used when such parameters are needed to analyze the performance of our proposal.

4.1. The System Description

In the devised approach, the communications area is tessellated with virtual cells which are regularly shaped and sized hexagons that are placed starting from a reference geographic location. This Virtual Cell Layout (VCL) is used for resource planning tasks, such as code, preamble code or carrier assignment. By the help of VCL, these tasks can be carried in a distributed way and without relying on the existence of a central system or an accurate and timely topology database. If an access point knows its geographic location, this location information can be mapped into a VCL cell index which can be mapped into radio resources which are a carrier set, a spreading code, and a preamble code index for a UTRA based application.

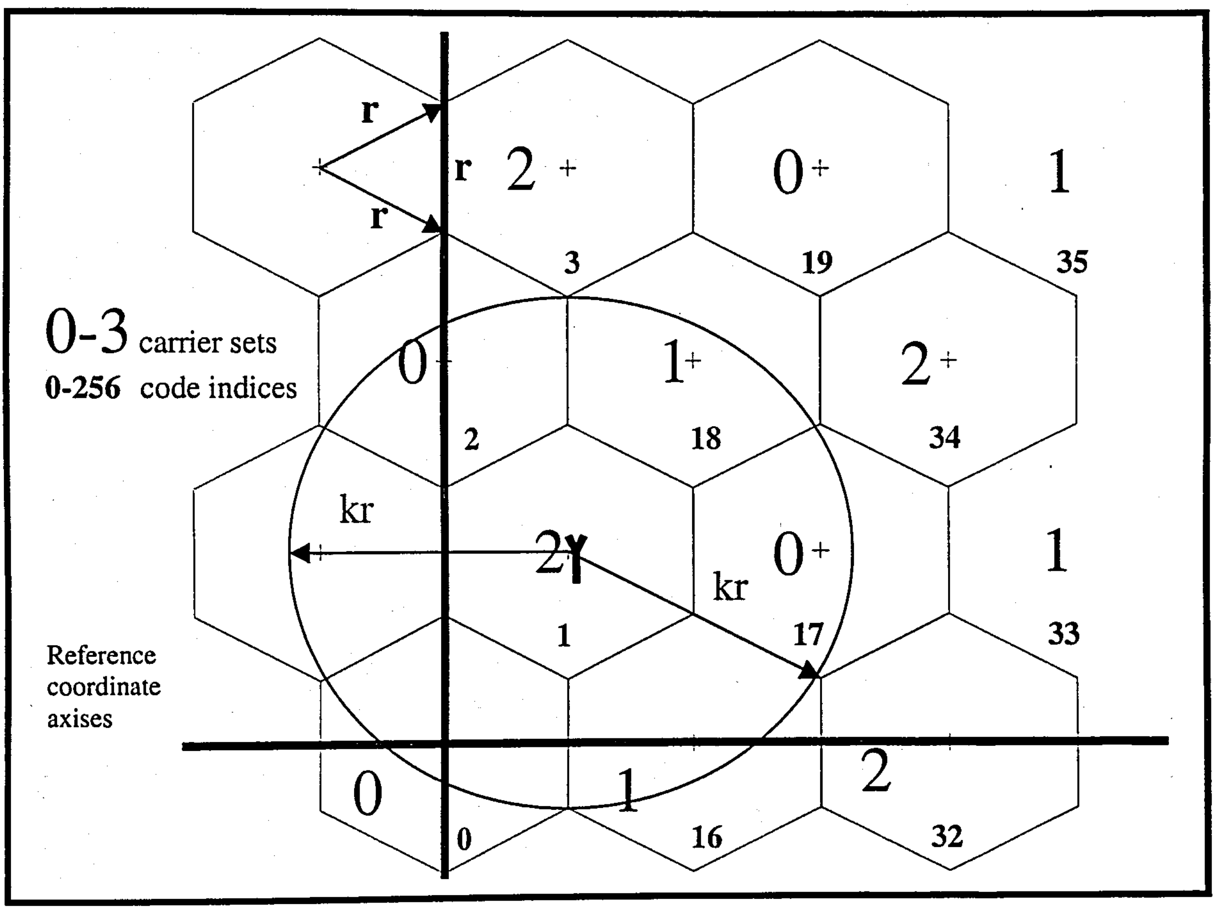


FIGURE 4.2. Virtual cell layout.

The real cells are mobile and created by either RAPs or MPRs acting as cluster heads. The size of real cells may be different than the size of VCL cells. If we say the side length of a VCL cell is r, then the real cell radius becomes kr in which k is a multiplication factor to figure out the real cell radius from the VCL cell radius. When the multiplication factor is one, the real cell usually can not cover all of the virtual cell, because the access points are mobile.

We assume that the frequency band allocated for this system is divided into carriers which have bandwidths between 4.4 and 5 MHz and 200 KHz rasters as in UTRA. These carriers are divided into three carrier sets, and each VCL cell is assigned a carrier set according to the N=3 fixed frequency reuse plan as illustrated in Figure 4.2. The $N=3$ frequency reuse plan is used in the proposed approach, because it is the one with the highest frequency reuse that ensures none of the VCL cells has a neighbor VCL cell using the same carrier set.

Five hundred twelve short codes (scrambling) available for base stations in UTRA are divided into two groups of 256 codes in the proposed approach. The first 256 codes are used by RAPs, and the last 256 codes are used by MPRs acting as cluster heads for MPRT cells. We assign two codes to each VCL cell as illustrated in Figure 4.2; one for RAPs and one for MPR cluster heads. This implies that we distribute 256 code sets among the VCL cells.

We use a nine bit code indicator to represent codes in our implementation. The most significant bit defines the group of the code (whether MPR or RAP) and named as the Major Code. The bits following the Major Code Bit in the code indicator is divided into two groups of four bits. The more significant group is named as the Minor High Code, and the other one is named as the Minor Low Code. The Minor High Code gives the column number for a code sector, and the Minor Low Code gives the row number. In the Secondary Synchronization (SYNC) Channel which is the modulated synchronization channel, the access point broadcasts the most significant four bits of the code indicator. These four bits are ample to indicate whether the broadcasting base is an MPR or RAP and which one of the 32 code sets (two columns of codes) is used by the base. Similarly, UTRA broadcasts one of the 16 codes which indicates a code set including 32 scrambling codes in the secondary SYNC channel. In our implementation, each code is also related with one preamble code used to access the Random Access Channel (RACH) in UTRA.

Finally, we can say that every component can learn the spreading code, the preamble code, and the carrier set without a need for a central system or a database, if it can find out its location and uses the VCL approach. One of the following approaches can be used to find out the location: the use of Global Positioning Systems, the use of other location finding approaches (Hellebrandt, 1997), and manual entry of the location information if the previous approaches are not applicable.

In our thesis, we only work on RAP and MPR tiers. Effect of higher tiers such as UAVT and SATT, is left as the future work. In RAP and MPR tiers we have two basic types of nodes, namely RAPs and MPRs. In the following sections we define the algorithms and approaches used by these components.

4.2. Radio Access Points

We assume that each RAP has a connection to the WAS through one of the access points in the higher tiers such as WAS edge nodes, satellites or UAVs. Since the number of these sort of components are relatively limited, we can use some more complex algorithms in these tiers (Evans, 1999) or we can implement VCL approach also for these tiers.

RAPs act similar to the base stations of UTRA. However, they do not rely on any other node to work. They utilize a VLR in which it records the nodes registered to it and the other nodes registered to its children and grandchildren nodes in the hierarchy. If it can be registered to a node higher in the hierarchy, the nodes registered to it are also registered to this higher node. When a call request arrives, firstly the local VLRs are looked up, and if the destination for the call is not found in the VLR, the call is routed to the higher node in the hierarchy. Since in most of the cases, the subscribers try to communicate with the nodes close to them, the probability to find the destination for a call in the earlier VLR lookups is high.

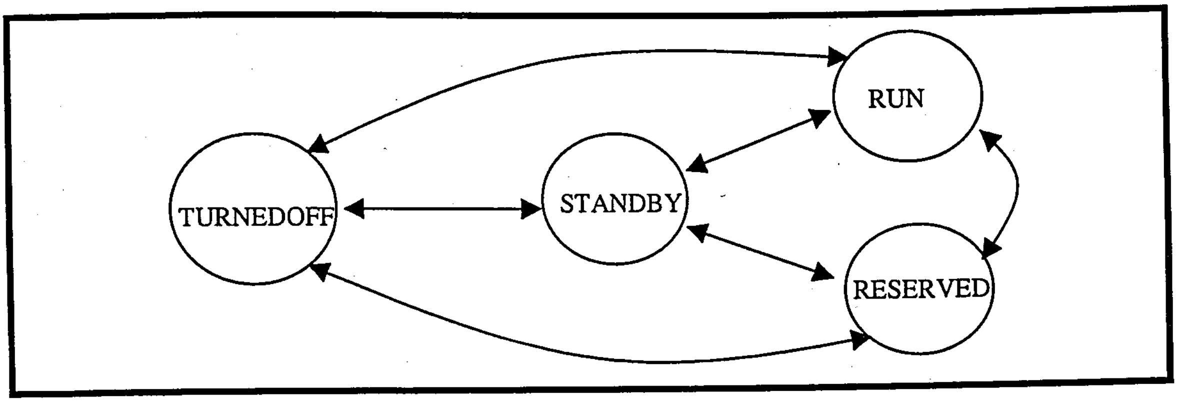


FIGURE 4.3. States and state transitions for RAPs.

A RAP can be in one of the four states illustrated in Figure 4.3. It runs the procedure of its current state and collects the data for the required parameters by sensing the environment.

The RAP power on algorithm consists of a sequence of procedures run by RAPs when they are turned on. So it is the first and the only procedure that can be run in *TURNEDOFF* state. Pseudo-code of the algorithm is given in Figure 4.5.

When a RAP is turned on, it firstly tries to find out its location by GPS or asks for the manual entry of the current location if GPS is not available. It then calculates the time for the next location check. This is the calculation of the time required to reach to the closest edge of the current VCL cell according to the current location and speed. This time cannot be longer than a network defined value. Initially, the next location check time is calculated basing on the maximum speed entered to the system.

When the location is determined, this information is mapped to the VCL cell index which is mapped to the resource information. Each VCL cell means a scrambling code, a random access preamble code and a set of frequency carriers. When this information is found out, each of the carriers is listened in a random order to understand if they are used by some other RAPs. If one unused carrier is found, the BCCHs, and SYNCs in that carrier with the known scrambling code are activated, and the RAP completes its transition to *RUN* state. The search for an unused carrier is proceeded randomly, otherwise it is quite possible to use the same carriers from the carrier sets in every cell and increase the remote cell interference which means less capacity.

In RUN state, the RAP broadcasts an unmodulated signal which is not scrambled in the Primary SYNC channel, and another unscrambled signal which is modulated to carry the "major code" with the most significant three bits of the "minor high code" in secondary SYNC channel. MPRs reaches the slot synchronization by using the primary SYNC channel, and understands whether the broadcasting node is a RAP or MPR and which scrambling code group (32 scrambling codes) it uses by demodulating the secondary SYNC channel. Although, an MPR can find out the scrambling and preamble codes by interpreting the location information, we keep this scheme for initial cell search which is the same as in UTRA. Hence, the proposed system is fully compatible with UTRA.

1. *Find out the current location and calculate the next location check time.*
2. *Map location information into carrier set and codes information.*
3. *Listen to the carriers in the carrier set.*
4. *If an unused carrier is found*
    - *Start to broadcast in Sync and Broadcast Control Channels.*
    - *Change status to RUN.*
    - *Update the topology databases in the hierarchy.*

   End.
5. *If an unused carrier is not found*
    - *Access to the RAPs using the carriers one by one and ask if they are replicated.*
    - *If there is a RAP which is not replicated*
        - *Replicate that RAP.*
        - *Change status to RESERVED.*
    - *Else*
        - *Change status to STANDBY.*
    - *End.*

   End.

FIGURE 4.4. Power on algorithm for RAPs.

If all of the carriers in the carrier set are detected as being used, RAPs in these carriers are asked whether they are replicated or not. If one of them is found not replicated, it is replicated and the RAP is put in *RESERVED* state. If a RAP to replicate is not found, the state of the RAP becomes *STANDBY*.

```
1. If the time is up for the next location check,
       Check the location.
       If a new VCL cell is entered,
               If the status is RUN,
                       Make an interfrequency handoff.
               Else if the status is RESERVED,
                       Notify the replicated RAP.
                       Change status to STANDBY.
               End.
       End.
       Calculate the time for the next location check.
   End.

2. If the RAP is in STANDBY status
     Listen to the carriers in the carrier set.
     If an unused carrier is found
       Start to broadcast in Sync and Broadcast Control Channels (BCCH).
       Change status to RUN.
       Update the topology databases (VLRs and HLRs) of the higher levels in the
        hierarchy.
     Else
        Access to the RAPs using the carriers one by one and ask if they are replicated.
        If there is a RAP which is not replicated
               Replicate that RAP.
               Change status to RESERVED.
        Else
               Stay in STANDBY
        End.
     End.
   End.

3. If the RAP is in RESERVED status
     If a service outage is detected,
        Handover to the replicated node.
     Else
       Listen to the carriers in the carrier set.
       If an unused carrier is found
         Start to broadcast in Sync and Broadcast Control Channels (BCCH).
         Change status to RUN.
         Update the topology databases (VLRs and HLRs) of the higher levels in hierarchy.
       Else
         Stay in RESERVED state.
       End.
     End.
   End.
```

FIGURE 4.5. Periodic tasks of a RAP.

A RAP in *RESERVED* state replicate another RAP which means the information about the registered MPRs and relayed calls of the replicated RAP are copied, and updated simultaneously. Whenever a service outage is detected in the services of the replicated RAP, the replicating RAP hand over the tasks of the replicated RAP. When a replicated RAP carries an interfrequency handoff, the replicating RAP starts to use the left carrier. We leave the procedures to detect a service outage and the procedures to hand over the replicated RAP as further works. There are numerous studies on similar topics for ATM in the literature (Anderson, 1994) (Ayanoglu, 1993) (Ayanoglu, 1994) (Daneshmand, 1993) (Doverspike, 1994) (Dun, 1994) (Hasegawa, 1994) (Herzberg, 1995) (Kajiyama, 1994) (Katzela, 1995) (Kawamura, 1994) (Kawamura, 1995) (Landegem, 1994) (Liew, 1994) (May, 1995) (Medhi, 1994) (Mederlof, 1995) (Shi, 1995) (Taka, 1994) (Wang, 1993a) (Wasem, 1994) (Wu, 1994) (Zachary, 1993) (Zolfaghari, 1994) (Zorzi, 1998).

RAPs periodically run the procedure given in Figure 4.5. In our implementation, the period is one second. At each period, RAPs first check if the next time for the location check is reached. The RAPs make a location check, when the next location check time is reached. If it is detected that a new VCL cell is entered in these location checks, an interfrequency handoff is conducted.

Interfrequency handoff starts with mapping the current VCL cell info to the new resource and code indexes. If the RAP is in RUN state, it tries to find an unused carrier in the new carrier set. If it finds one, it changes the carriers and codes of the registered nodes and routes for the ongoing calls, and then update the databases of the higher levels in the hierarchy and starts to serve with the new carrier and the code set. In this procedure, timing and rerouting schemes related to the handoff shall change the required signaling traffic and time. We keep the more detailed studies on these schemes as future work.

If an unused carrier is not found in the new carrier set, the registered MPRs are forced to make interRAP handoffs. This is possible, because the absence of an unused carrier indicates the presence of a number of serving RAPs in the new VCL cell. As a result, the MPRs enforced to handoff can find a new RAP in the vicinity.

1. Determine the resources for the current hexagon.

2. If the RAP is in RUN state,
Listen to the carriers in the new carrier set.
If an unused carrier is found
Start to broadcast in Sync and Broadcast Control Channels (BCCH).
Update the topology databases (VLRs and HLRs) of the higher levels in the hierarchy.
Carry the tasks required to change the carrier and code set for each MPR and routes for each ongoing call.
If this is a replicated RAP,
Notify the replicating RAP to make it conduct a state transition to RUN state.
End.
Else
If this is a replicated RAP,
Handover the current tasks to replicating RAP.
Else
Enforce the registered MPRs to handoff.
End.
Stop broadcasting in SYNC and BCCHs.
Update the topology databases (VLRs and HLRs) of the higher levels in hierarchy.
Change status to STANDBY.
End.
End.

3. Else if the RAP is in RESERVED state,
Inform the replicated node that it is not replicated anymore.
Change status to STANDBY.
End.

FIGURE 4.6. Interfrequency handoffs for RAPs.

If the RAP is replicated before handoff, the replicating RAP is informed so that it can start to use the left resources. If the RAP is in STANDBY state prior to the handoff, the next periodic check is waited for a promotion in status.

If a RAP is in *RUN* state, it continuously broadcasts in SYNC and BCCHs, and listens to the RACH. It also carries the registration, call setup and call management functions. A RAP in *STANDBY* status tries to find a carrier, or at least another RAP to replicate every period. A RAP in *RESERVED* state checks if there is a service outage every period, and handover the tasks of the replicated RAP, if it detects an outage. Otherwise, it tries to promote *RUN* state by checking the carriers in the current carrier set.

4.3. Man Packed Radios

MPRs communicate with each other through the RAPs as they are subscribers of a digital cellular system. Actually, they are the terminal equipments which are the equivalent of the mobile radios in UTRA with some additional abilities. First of these additional abilities is that they have the intelligence of knowing the possible codes and carriers that can be used in their current location, or the possible codes and the carriers to handoff. They do not need to retrieve this information from a base that they are registered. This is the result of VCL approach. Secondly, we assume that they can act as a base station with some limited capabilities when required. This means that they can relay the communications of other MPRs to the higher levels in the hierarchy. This is essential for the ad hoc approaches we devised in this level.

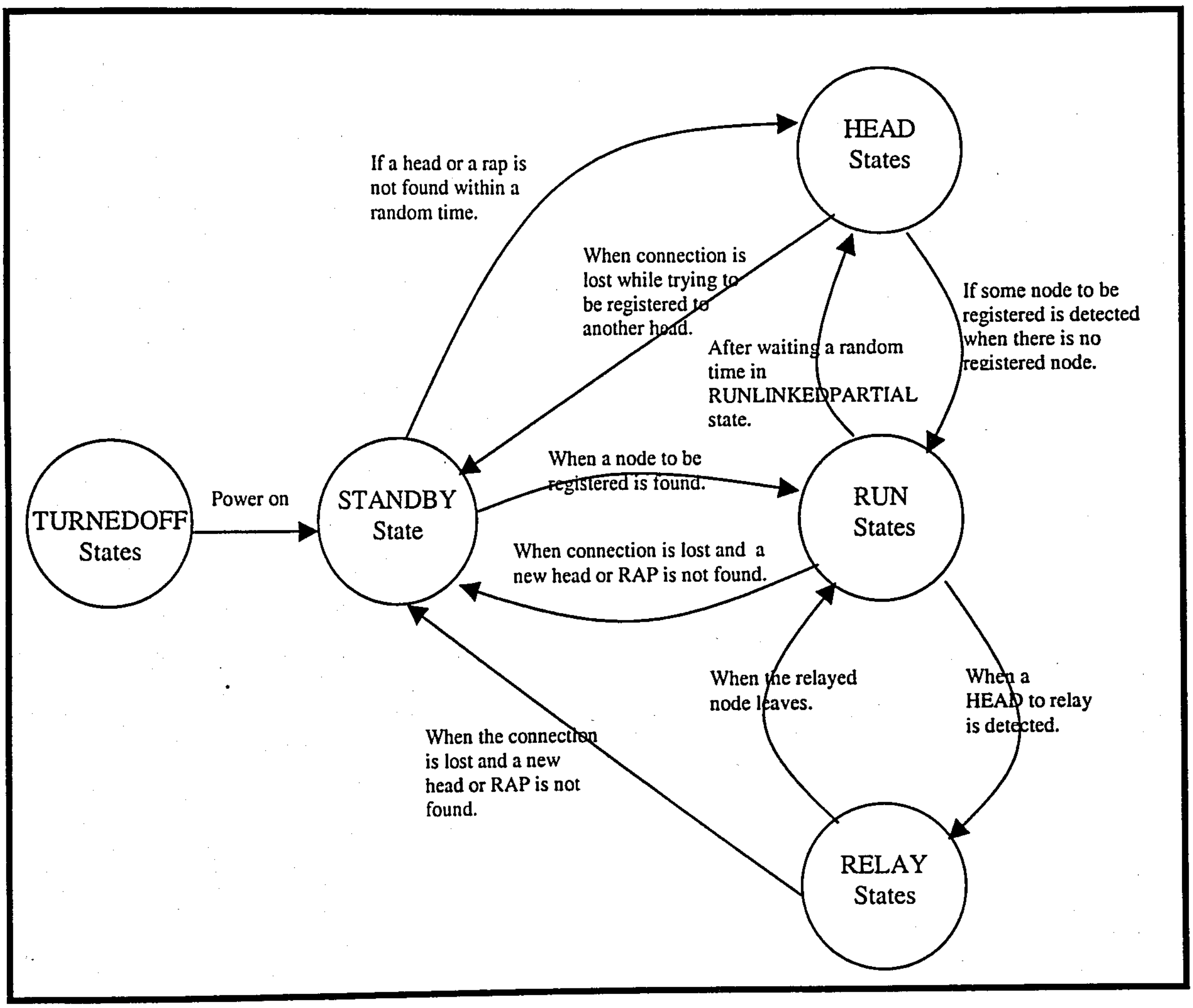


Figure 4.7. The state transitions for MPRs.

By ad hoc approach, what we mean is not an approach which ensures that each component has a communications path with each other component in the network. Our approach is a fully distributed one which is devised to make the components communicate terrestrially even if they do not have an access to a RAP. As we stated before, we envisioned a multitier system in which UAVs and satellites provide umbrella cells. However, we prefer to communicate terrestrially by using multihop approaches compared to communicating through UAVT and SATT cells. Hence, we lower the emissions and power consumption, and our design becomes more robust by avoiding from the usage of more vulnerable components, namely satellites and UAVs..

MPRs use the procedures related to their current status and gather the required data by sensing the environment as RAPs do. Though, they can work distributed without a need for a central topology database. The basic design principle is having a system in which two MPRs can communicate with each other even if they cannot communicate with anybody else.

The state transition diagram of an MPR is illustrated in Figure 4.7. It is more complex than the one for the RAPs, because they sometimes act as limited RAPs or relaying stations. When an MPR can communicate with an access point, it behaves like a terminal equipment in a cellular network. The MPRs that cannot access the network organizes themselves into cell clusters and try to find an MPR that can relay the cluster to the higher levels.

In Figure 4.7, possible transitions from other states to *TURNEDOFF* state are not illustrated. The states in Figure 4.7 are aggregated states except for *STANDBY* and *TURNEDOFF* states. When the aggregated states are poped up, the complex state diagram illustrated in Figure 4.8. is obtained.

We use Figure 4.7. to express the overall concept for MPRT, and the figures prepared separately for each state to explain the details about the state transitions. When we power on an MPR, it tries to put itself into the most appropriate state by sensing the environment. It prefers being in one of the run states. There are three types of run states, namely *RUN*, *RUNLINKED*, *RUNLINKEDPARTIAL*. In *RUN* state which is the most preferred one, the MPR is registered directly to a RAP. If a RAP to be registered is not found, but there is an MPR acting as a cluster head, the MPR is registered by this head. If the registered *HEAD* is relayed to a RAP or WAS, the state entered is named as *RUNLINKED*. Otherwise, the state entered is called *RUNLINKEDPARTIAL*. *RUNLINKED* state is preferred compared to *RUNLINKEDPARTIAL* state.

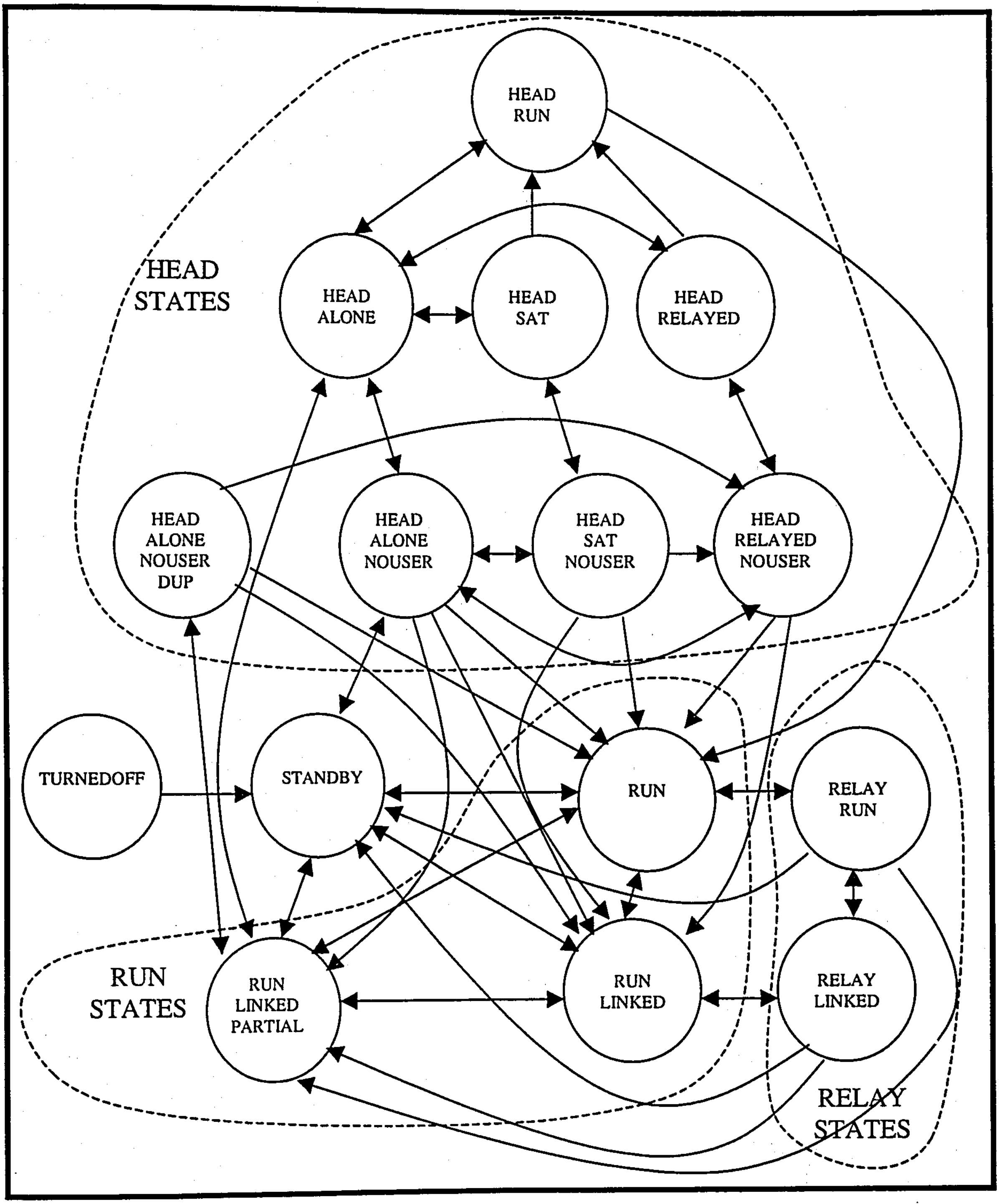


FIGURE 4.8. States and state transitions for

The MPRs in *RUN* and *RUNLINKED* states sense the environment to find a cluster head which is not relayed to upper layers. If they find one, they make a state transition to one of the *RELAY* states, namely *RELAYRUN* and *RELAYLINKED*.

If MPRs cannot find any node to be registered during a time period which is determined randomly after the transition to *STANDBY* state, they enter to *HEADALONENOUSER* state. The MPRs in *HEAD* states act as cluster heads.

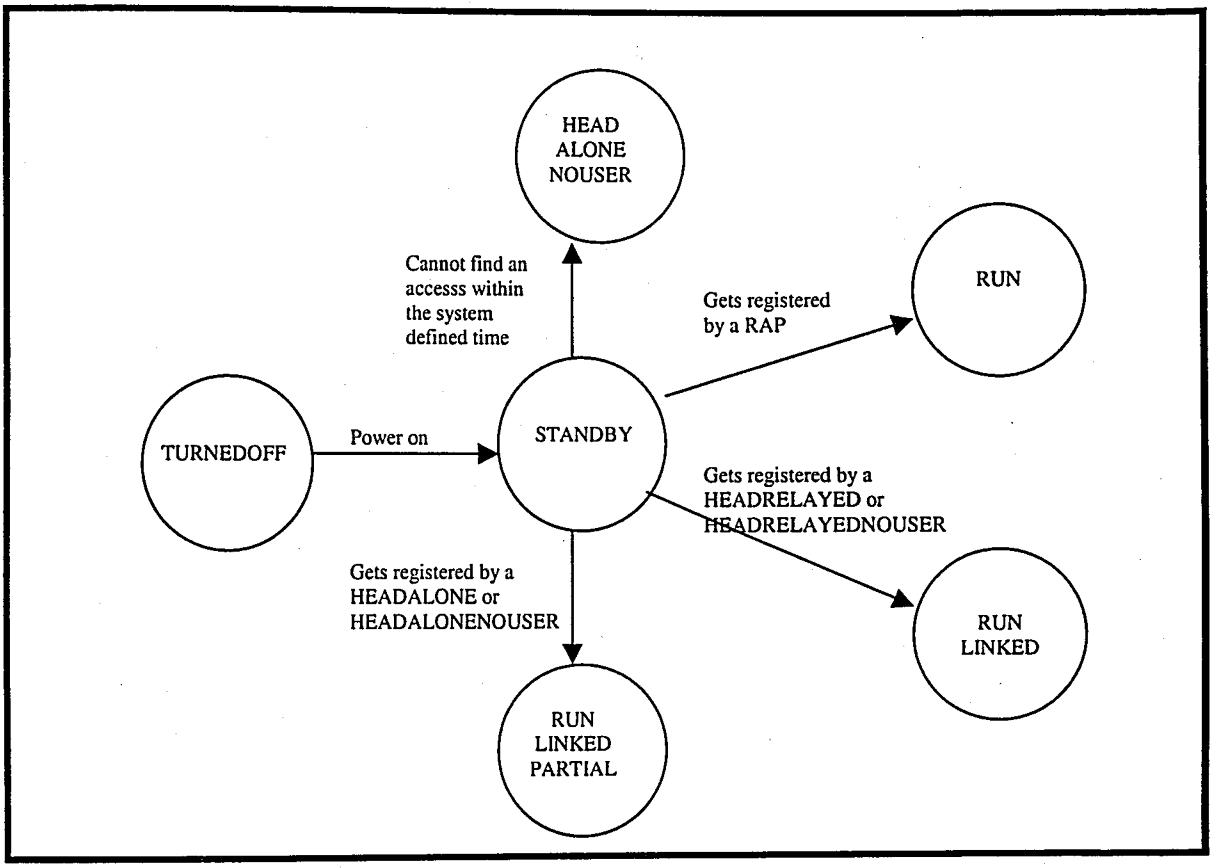


FIGURE 4.9. State transitions from *STANDBY*

Each state in this diagram has a different degree of priority. The MPRs try to make transitions to the states higher in priority when the conditions for that state is detected. We can enumerate the states according to the priorities from the highest to the lowest as follows:

- *RELAYRUN*,

- *RUN,*
- *RELAYLINKED,*
- *RUNLINKED,*
- *HEADRUN,*
- *HEADRELAYED or HEADRELAYEDNOUSER,*
- *HEADSAT or HEADSATNOUSER,*
- *HEADALONE, HEADALONENOUSER, HEADALONENOUSERDUP or RUNLINKEDPARTIAL,*
- *STANDBY.*

If a primary SYNC channel is detected
Accomplish slot syncronization with the strongest primary SYNC channel.
Demodulate the secondary SYNC channel to learn the code group.
Carry an exhaustive search on the code group to learn which code is used as the scrambling code by the synchronized RAP.
Initiate process for the registration by the synchronized RAP.
Else
Determine the length of the time period to wait and search for a SYNC channel before the declaration of being a cluster head.
End.

FIGURE 4.10. Initial cell search algorithms for MPRs.

The states to which an MPR can be transferred from *STANDBY* state are illustrated in Figure 4.9. An MPR in *STANDBY* state tries to be in one of *RUN*, *RUNLINKED* or *RUNLINKEDPARTIAL* states in the same order if an appropriate RAP or cluster head is found. MPRs search for a RAP or cluster head by using the procedure of the initial cell search in UTRA. As stated before, every cluster head or RAP in our design, broadcast primary and secondary SYNC channels together with BCCH as specified in UTRA. Actually, MPRs of our design has an advantage comparing to the terminals of UTRA. If they know their geographic location, they can find out the possible codes and carriers used in that location. Hence, they can order the carriers and codes, and scan them according to this order in the initial cell search procedure. The initial cell search algorithm which is also power on algorithm for MPRs is illustrated in Figure 4.10.

If a cluster head or RAP is not found for a random period of time, then MPR maps its location information to the code and carrier set information for the VCL cell in which the MPR is located. The first carrier from the carrier set and the code whose major code bit is set are used. This combination of code and carrier indicates an MPR which is acting as a cluster head and not relayed to higher layers, namely the states of *HEADALONE* or *HEADALONENOUSER*. The procedure used by an MPR to declare itself as a cluster head is illustrated in Figure 4.11.

An MPR in *RUN* state searches for an MPR which is in *HEADALONE* or *HEADALONENOUSER* state with some time intervals. If it can finds one, it starts to relay the found MPR. In this case, the MPR being relayed makes a state transition to *HEADRELAYED* or *HEADRELAYEDNOUSER* state.

1. *Find out the current location and calculate the next location check time.*
2. *Map location information into carrier set and codes information.*
3. *Start to broadcast in Sync and Broadcast Control Channels of the first carrier in the carrier set.*
4. *Change status to HEADALONENOUSER.*

FIGURE 4.11. Cluster head declaration algorithm.

When an MPR is relaying the traffic of another MPR which is a cluster head, the cluster head assigns the required number of forward and reverse channels with the required Transfer Format (TF) to the relaying MPR for each connection that it should convey to the higher levels in the hierarchy. Then the relaying MPR tries to establish a connection with the RAP as if the relayed calls are its own calls. Hence, relaying MPRs can be handled without many changes in the UTRA design.

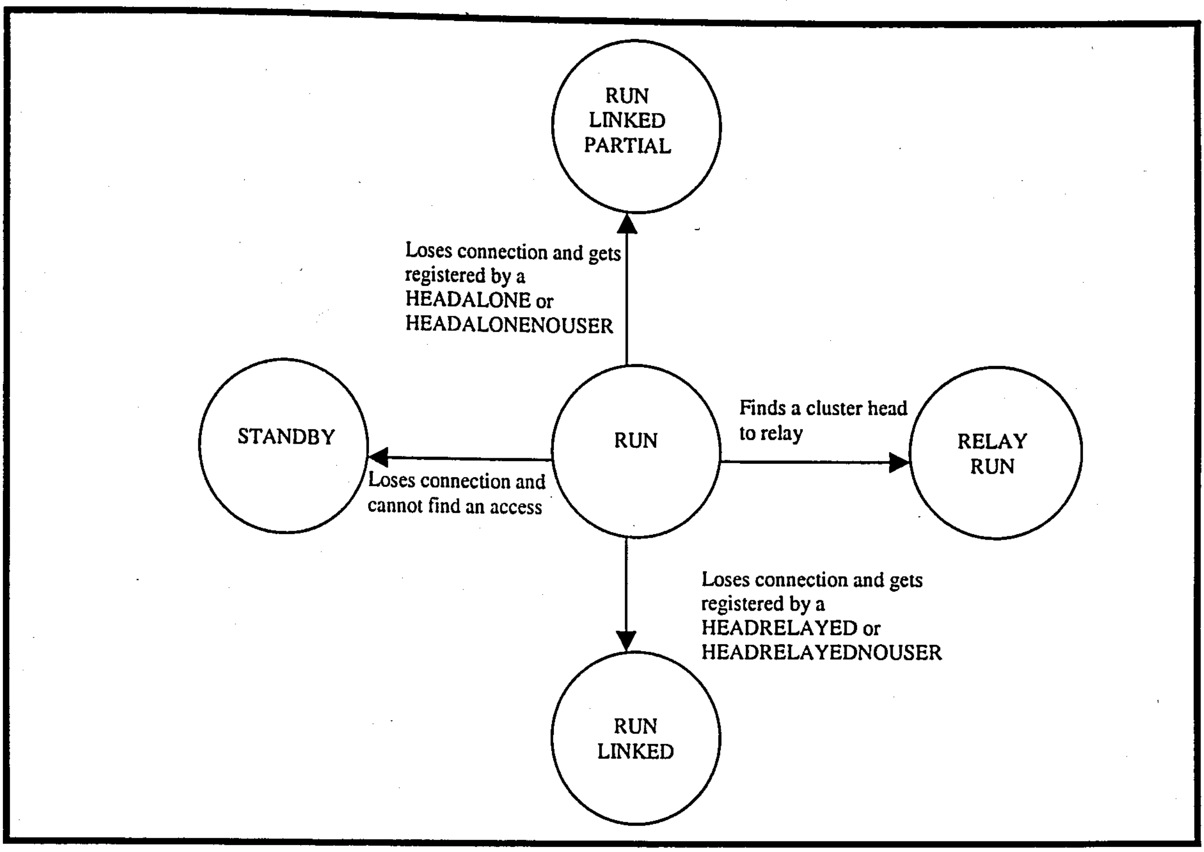


FIGURE 4.12. State transitions from *RUN* state.

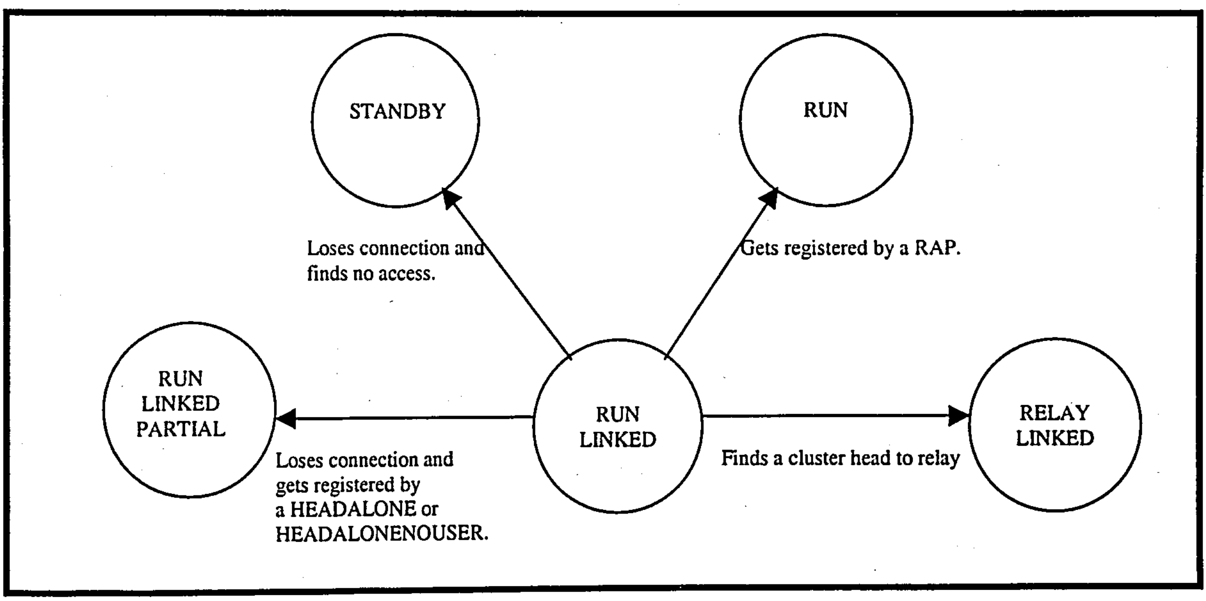


FIGURE 4.13. State transitions from *RUNLINKED*

Another issue for the relayed components is routing related. When an MPR relays a cluster head, it appends its VLR to the VLR of the registered RAP by changing the id of registering node with its own id, and incrementing the hop number. Though the registered RAP can route the traffic of the relayed components to the relaying MPR. The details about the location management is given in Section 4.5.

When an MPR in *RUN* state needs to make a handoff or the registered RAP is destroyed, it starts a cell search, and if it can find a RAP, it makes a handoff without changing its state. However, it may not find another RAP, and need to make a state transition to *RUNLINKED, RUNLINKEDPARTIAL* or *STANDBY* states.

An MPR in *RUNLINKED* state behaves almost the same as it is in *RUN* state. There is only one difference. Since *RUN* state is a more preferred state, an MPR in *RUNLINKED* state searches for a RAP that it can be registered to, and if it finds one, it makes a transition to *RUN* state.

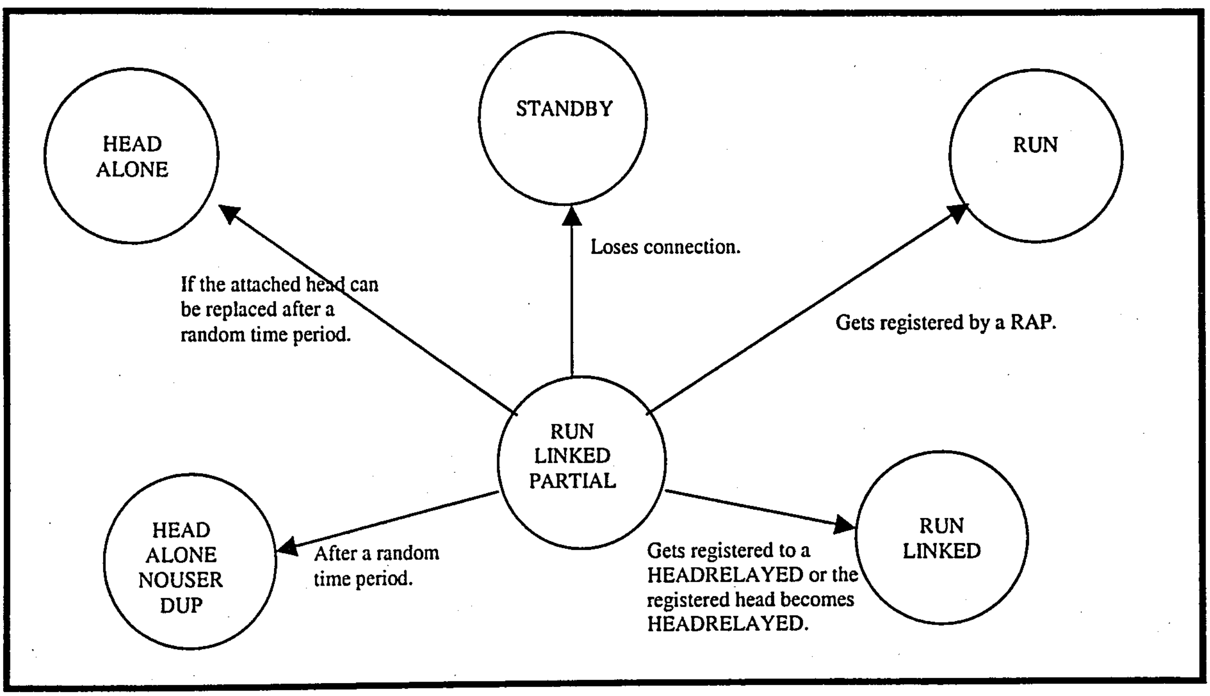


FIGURE 4.14. State transitions from *RUNLINKEDPARTIAL* state.

RUNLINKEDPARTIAL state is the least desirable state after *STANDBY* state. In this state, an MPR can communicate with the cluster head that it is registered to and the other MPRs registered to the same cluster head. Since the destination in call requests are generally in the vicinity in military communications, the most of the call requests can be fulfilled even in this case.

An MPR in *RUNLINKEDPARTIAL* state continues to search for a RAP or a relayed cluster head with some time intervals. If it finds one, it makes a handoff to the found head or RAP and a state transition to *RUN* or *RUNLINKED* state.

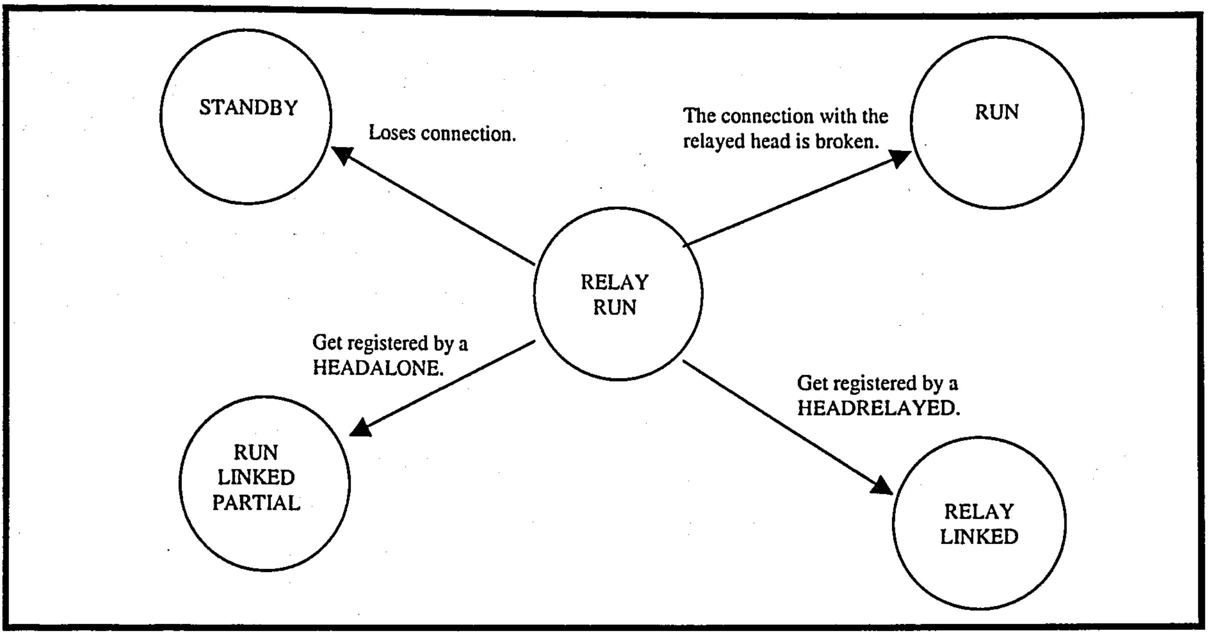


FIGURE 4.15. State transitions from *RELAYRUN* state.

When an MPR makes a state transition to *RUNLINKEDPARTIAL* state, it determines a time period randomly. If it is still in *RUNLINKEDPARTIAL* state after this time period, it checks if the cluster can be relayed when it becomes a head. Firstly, it checks if there is any communications conveyed or initiated by the current cluster head. If there is none, it becomes the new cluster head using the resources according to its current location, and registers the former cluster head. The MPRs registered to the former cluster head are forced to deregister. This means a state transition to *HEADALONE* state for the MPR becoming the cluster head. If the former cluster head has some ongoing communications, a state transition to *HEADALONENOUSERDUP* state is made. Before making the state transition to *HEADALONENOUSERDUP* state, it determines the code and carrier set of its current location. If there is another MPR using the same code and the carrier set which is in *HEADALONENOUSERDUP* state, it quits the state transition procedure and waits for another random period. If the MPR using the resource set is in *HEADALONE* or *HEADALONENOUSER* states, it shifts the code of its current VCL cell to the code of the furthest VCL cell by using a function, and starts to broadcast by using this shifted code and the first carrier of the carrier set. The MPRs searching for the cluster heads to relay, checks these shifted codes, too.

If an MPR in *RELAYRUN* state has to handoff, it tries to find a new RAP to handoff. If it can find a RAP, no state transition is needed. On the other hand, if there is a relayed MPR that can be handoffed, this requires a state transition to *RELAYLINKED* state. If there is only an MPR which is not relayed or no RAP or cluster head to be registered, the relayed cluster head is deregistered and forced to a state transition to *HEADALONE* or *HEADALONENOUSER* states, and than a state transition to *RUNLINKEDPARTIAL* or *STANDBY* state is initiated. If the relayed cluster head leaves the region or deregistered, the relaying MPR makes a state transition to *RUN* state.

An MPR in *RELAYLINKED* state behaves similar to an MPR in *RELAYRUN* state with an exception. Since being registered by a RAP is preferred compared to being registered by a cluster head, if a RAP to be registered is found when the state is *RELAYLINKED*, a state transition to *RELAYRUN* state is initiated.

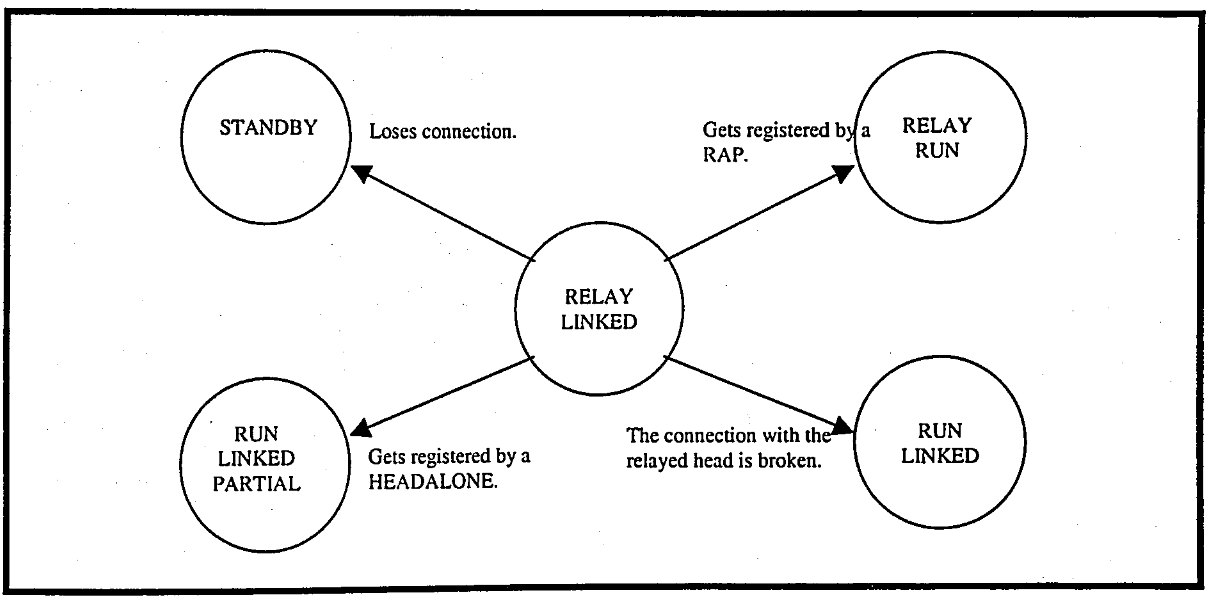


FIGURE 4.16. State transitions from *RELAYLINKED*

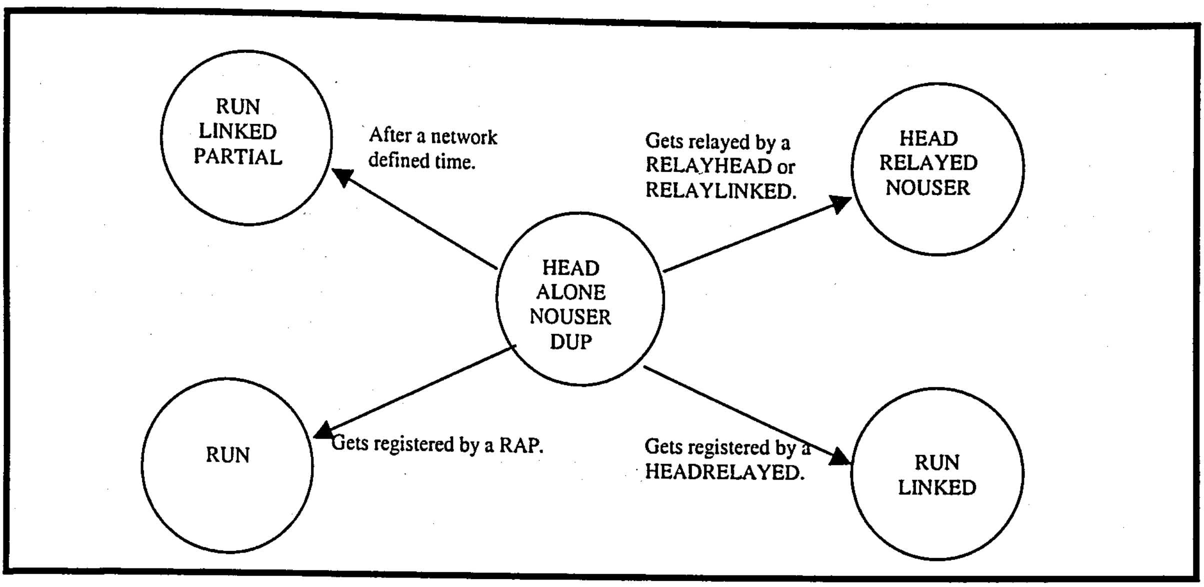


FIGURE 4.17. State transitions from *HEADALONENOUSERDUP* state.

In *HEADALONENOUSERDUP* state, an MPR does not register any MPR. This is the state in which an MPR tries to be detected by an MPR which is in *RUN* or *RUNLINKED* state. If there is an MPR that can relay it, it changes its state to *HEADRELAYEDNOUSER* state. If a RAP or a relayed cluster head is detected before a relaying MPR detects it, it makes a state transition to *RUN* or *RUNLINKED* state. When an MPR is put in *HEADALONENOUSERDUP* state, it is assigned a network defined time. During this time period it tries to find an MPR that can relay it, or a relayed MPR or a RAP. If it cannot find one until the end of this time period, it returns to *RUNLINKEDPARTIAL* state.

In *HEADALONENOUSER* state, the MPR tries to promote to *RUN*, *RUNLINKED*, *RUNLINKEDPARTIAL* or *HEADRELAYEDNOUSER* states in the same order. If a RAP or a cluster head is detected, it is registered. If a relaying MPR detects this node, it starts to relay which means a state transition to *HEADRELAYEDNOUSER* state. When an MPR is registered to this node, the current state becomes *HEADALONE*. If there is a satellite cover in the current region and a RAP, cluster head or a relaying MPR is not detected for a certain period of time, the cluster head is relayed through the satellite. If the MPR detects to much interference that indicates another MPR in the same VCL cell when it is in *HEADALONE* or *HEADALONENOUSER* state, it makes a state transition to *STANDBY* state.

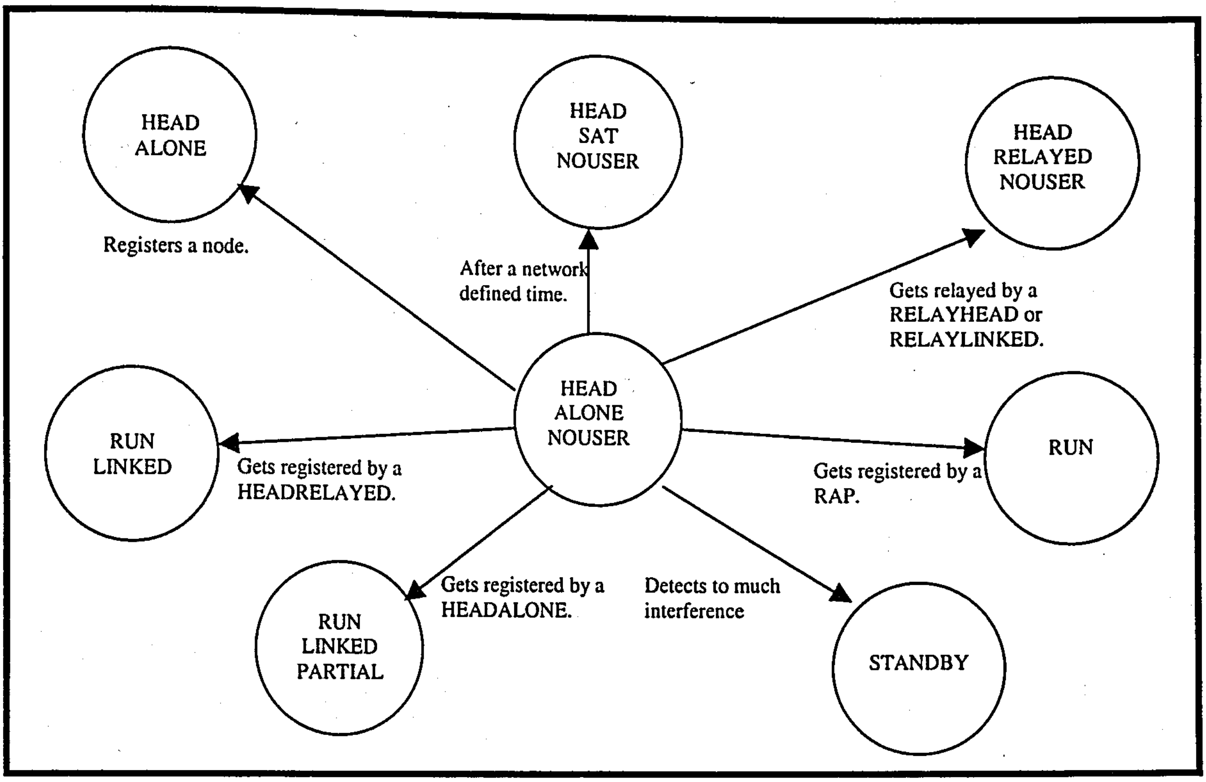


FIGURE 4.18. State transitions from *HEADALONENOUSER* state.

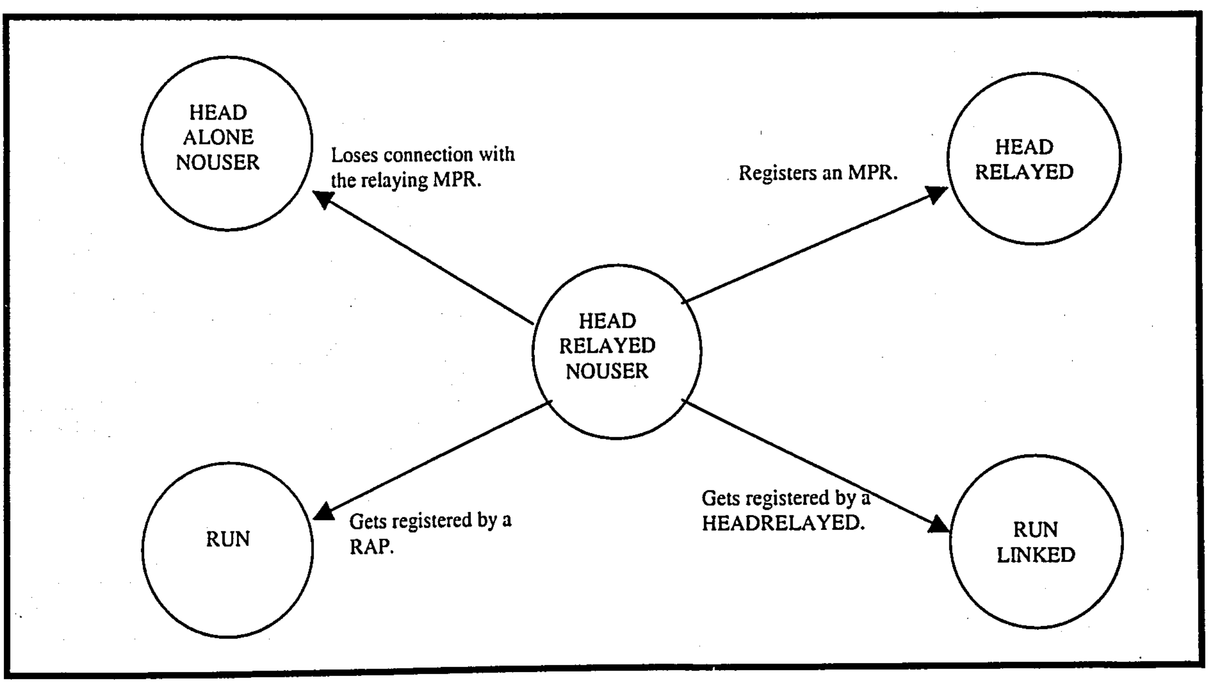


FIGURE 4.19. State transitions from *HEADRELAYEDNOUSER* state.

An MPR in *HEADRELAYEDNOUSER* state tries to find a RAP or *HEADRELAYED* to be registered. If it finds one, it is registered by the found access point and makes the appropriate state transition. If it registers an MPR, the current state becomes *HEADRELAYED*. When the relaying MPR loses its connection to the registered component, or the relaying MPR is lost, a state transition to *HEADALONENOUSER* state is done.

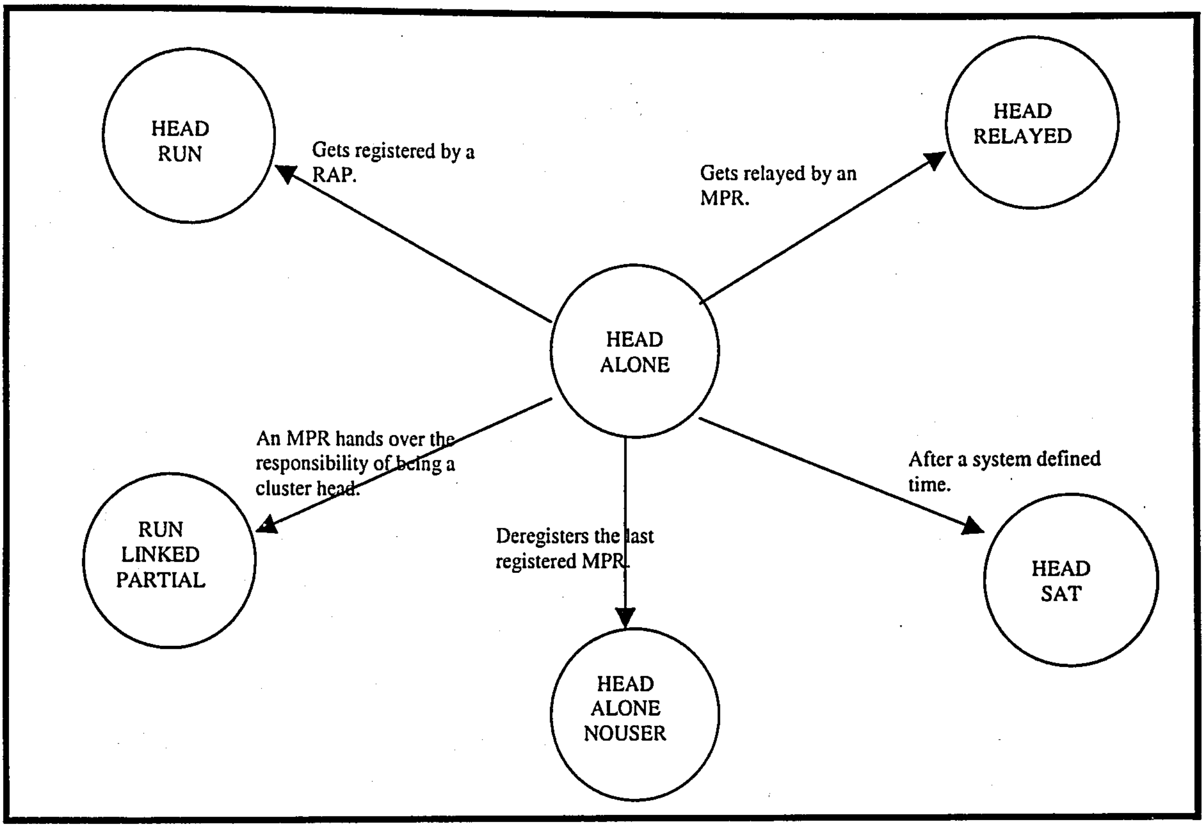


FIGURE 4.20. State transitions from *HEADALONE* state.

When an MPR in *HEADALONE* state detects a RAP, or a linked MPR detects it, it makes the appropriate state transition to *HEADRUN* or *HEADRELAYED* states. If it is still in *HEADALONE* state after a certain period of time, and there is satellite cover, it can change its state to *HEADSAT* state. When the last MPR is deregistered, it returns to *HEADALONENOUSER* state. If there is not an active call relayed or initiated by it when one of the registered MPRs tries to make a state transition to *HEADALONENOUSERDUP* state, it is forced to make a state transition to *RUNLINKEDPARTIAL* state and be registered to the MPR making the state transition to *HEADALONENOUSERDUP* state.

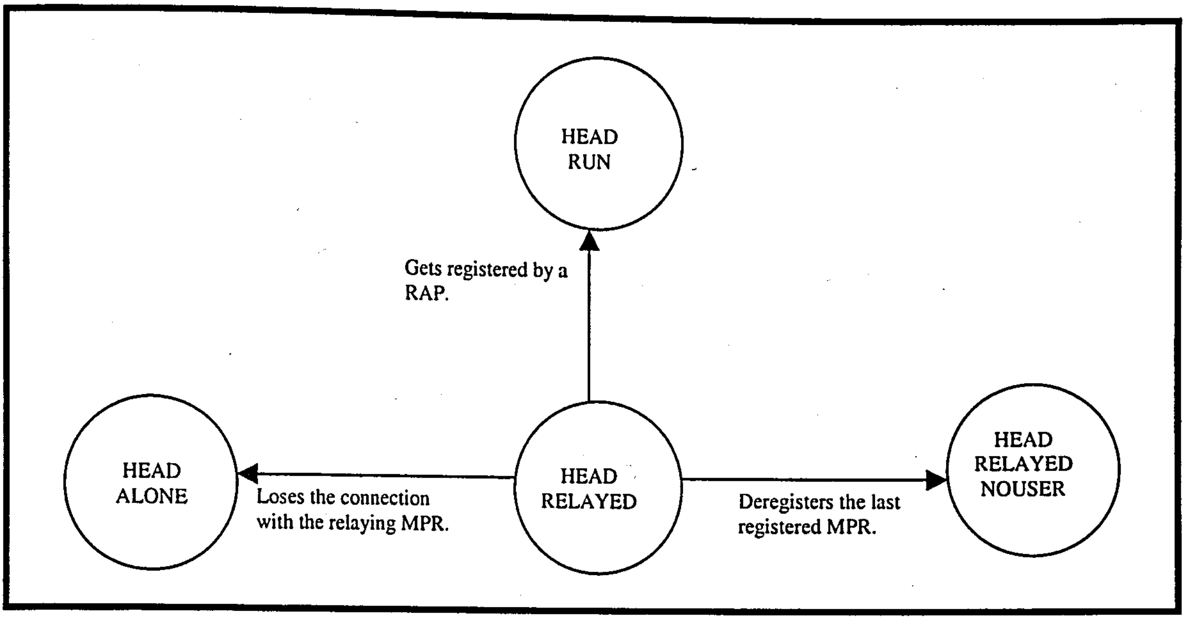


FIGURE 4.21. State transitions from *HEADRELAYED* state.

An MPR in *HEADRELAYED* state makes a state transition to *HEADRUN* state, if it finds a RAP to be registered. If the last MPR is deregistered, the current state becomes *HEADRELAYEDNOUSER*. When the connection to the relaying MPR is lost or the relaying MPR loses its connection to the registering component, a transition to *HEADALONE* state is made.

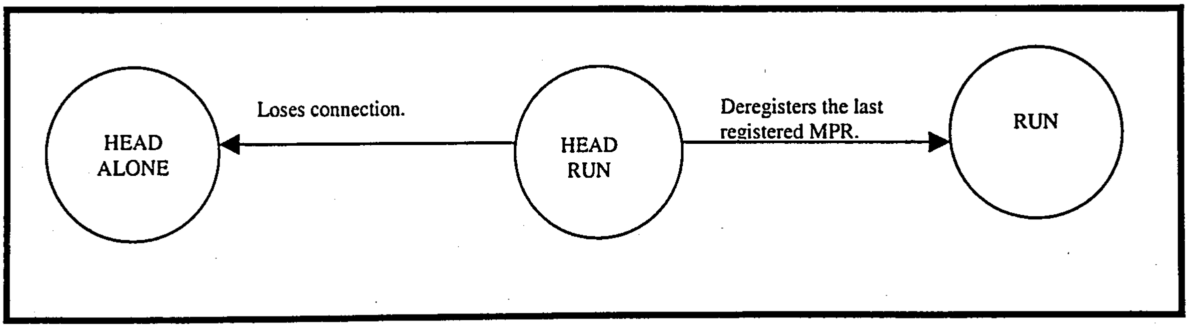


FIGURE 4.22. State transitions from *HEADRUN* state.

When an MPR in *HEADRUN* state deregisters the last registered MPR, its state becomes *RUN* which means that it stops to act as a cluster head. If the MPR in *HEADRUN* state loses its connection with the RAP which has registered it, this MPR makes a state transition to *HEADALONE* state.

The MPRs in any state can make handoffs to the better states or better serving bases. The basic principles related to MPR level handoffs can be summarized as follows:

We use MCHO (See Section 2.3.1.2.), since we prefer distributed techniques. Testing other techniques such as MAHO and NCHO for our system is left as future work. We do not work on choosing techniques such as last sent, last received and marking methods used in execution stage and left these issues as physical layer related issues which will be worked on later. The algorithm used by MPRs to decide to make handoff is illustrated in Figure 4.23.

If an access point which can serve better than the current one in the current carrier is found
If the difference in quality is more than a predetermined threshold
Initiate a soft handoff procedure for the new access point.
End.
Else if the quality indicator of the current access point is below the predetermined limit
Initiate initial cell search procedure.
If a new access point is found
Initiate a hard handoff procedure for the new access point.
End.
End.

FIGURE 4.23. Handoff decision algorithm.

The geographic location information can help MPRs to find out the preamble codes and candidate carriers to handoff. RAPs also determine the candidate carriers which should be monitored for candidate cells to handoff, and preambles for the MPRs registered to them, and broadcast them for the sake of being compatible with UTRA. In UTRA, each BTS has a BCCH which is a code in a frequency channel. BTSs broadcast in these channels, and mobiles decides which BTSs they should communicate with according to the quality of signals received in these channels. The search of mobiles should be limited to a list of neighboring cells broadcast from the network, otherwise mobiles should check too many channels to decide for a handoff (Dahlman, 1998).

Although, *N=3* frequency reuse plan is used, MPRs do not monitor other candidate carriers to handoff continuously. Instead, they monitor their link quality and the carrier they use currently. If they find a stronger base in the same carrier with them, they handoff to the new base. If their current link quality is not acceptable, and there is not a base that can serve in the current carrier, they search for a new carrier. This brings up two major advantages:

- Since the RAPs move with a group of MPRs, it is better to stay with the current RAP when passing nearby a different RAP, if a handoff is not essential.
- With this scheme soft handoff will be given a priority.

In Figure 4.24, we illustrate how the proposed algorithms and schemes work. In our scenario, we have six MPRs and a RAP. MPRs *a* and *b* are in the range of the RAP, so they are immediately put on *RUN* state when they are turned on. However, the other MPRs are out of range, so they are in *STANDBY* state after being turned on.

The MPRs determine a random period, when they make a state transition to *STANDBY* state. These random periods are shown at the upper right side of the MPR symbols in Figure 4.24. They try to find an MPR in *HEAD* states or a RAP during this period. If they cannot find one until the end of the period, they make a state transition to *HEADALONENOUSER* state. This transition is illustrated in Figure 4.24(b). The MPR *e* makes a state transition to *HEADALONENOUSER* state. Then the MPR *c* detects MPR *e*, is registered by it, and make a state transition to *RUNLINKEDPARTIAL* state which also indicates a state transition to *HEADALONE* state for the MPR *e*. The MPR *c* determines a time period that it will wait in *RUNLINKEDPARTIAL* state when enters to that state.

In Figure 4.24(c), the MPR *d* makes some similar transitions. However, the ultimate state of *d* is *HEADRELAYED*, since it is in the range of the MPR *b* which can relay it to a RAP.

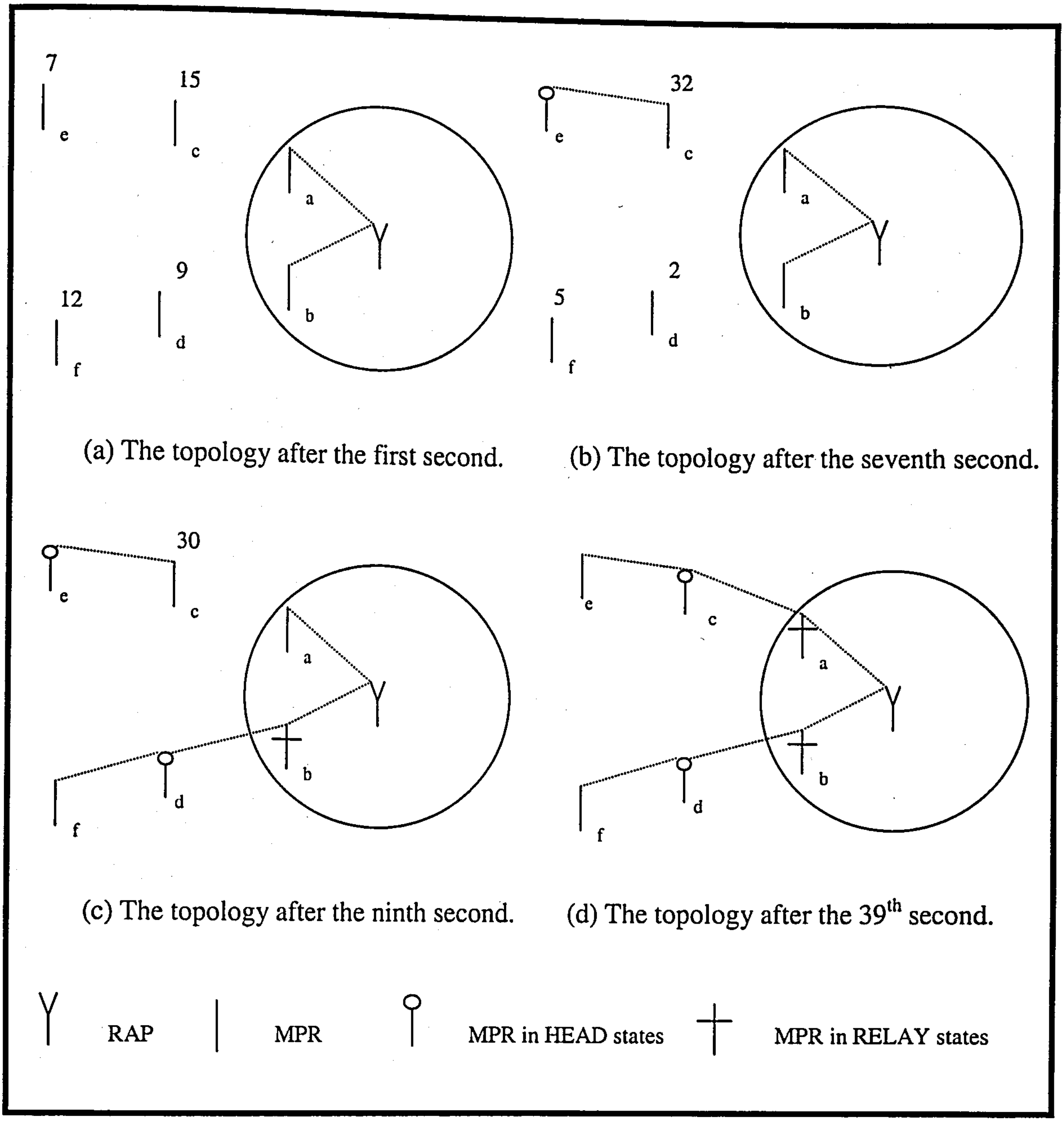


FIGURE 4.24. An example scenario.

Lastly, the MPR *c* handover the MPR *e*, because it is still in *RUNLINKEDPARTIAL* state after the determined period of time. Since the MPR *c* is in the range of the MPR *a* which can relay it, its ultimate state becomes HEADRELAYED. At the end of these stages, all components of the network is connected to each other.

In this example, the components are fixed to illustrate the procedures more clearly. When they move, the same procedures are applied.

4.4. Call Management

Our call model is based on the known call models. However, we enriched the states which a call can be in for our implementation. Though, we can trace the details about the call. In our implementation, the call is in *CONNECTING* mode after the call is generated. During the connection phase, the called party is found and paged. If the resources are ample, and the called party accepts the call, the call is served until it is completed or terminated. If the network resources or the resources of the called party is not enough to handle this call, the call is blocked by the network or the destination. If the destination is not in the network, then the call is unreachable.

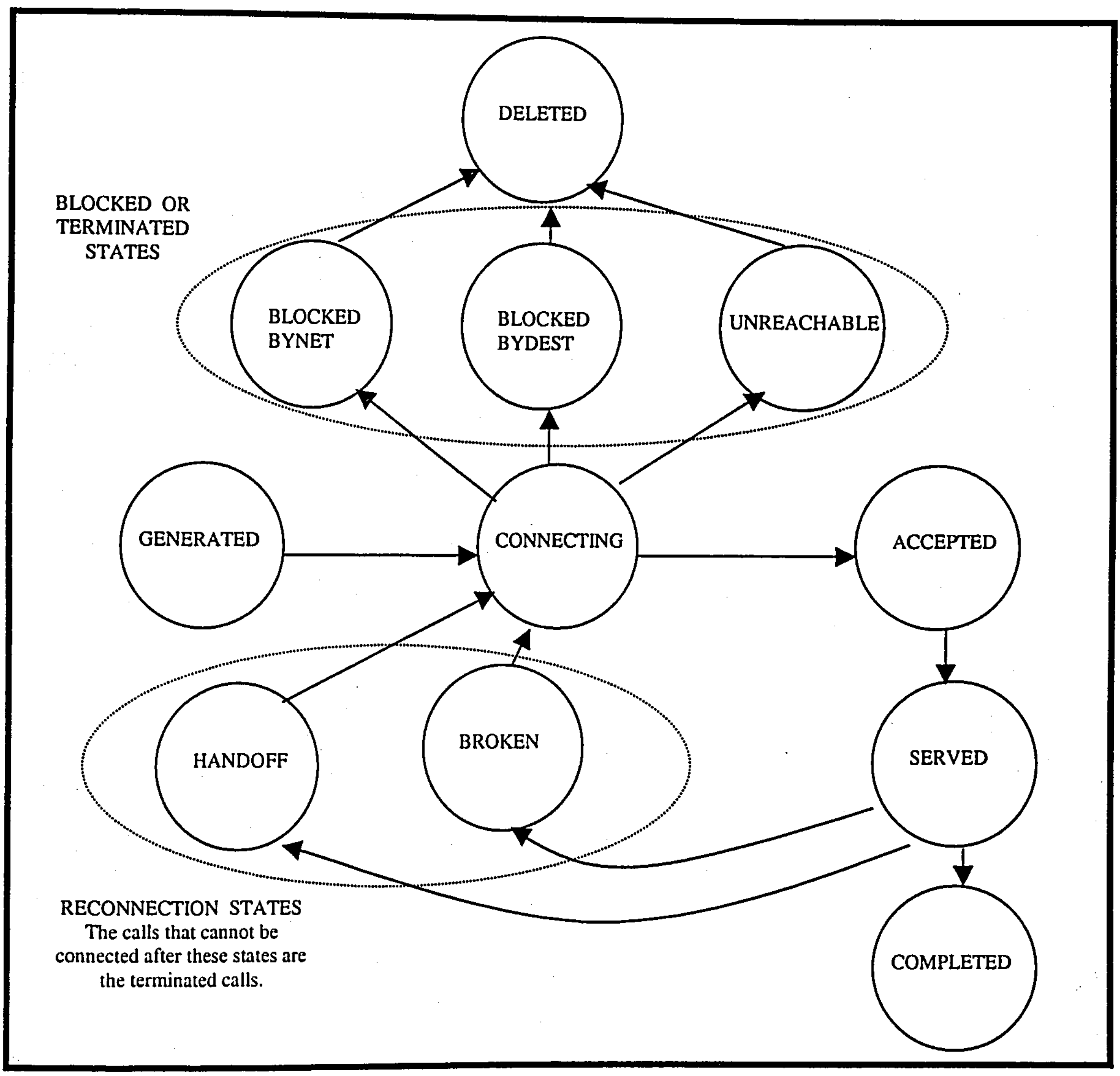


FIGURE 4.25. States of a call.

While a call is being served, one of the intermediate nodes can be destroyed or a handoff in the either ends can be needed. In the first case, the call is broken, and a new connection for the same call is tried to be established. When a handoff is made, one of the rerouting techniques (Çayırcı, 1998a) is used to reroute the call. If the resources is not enough to reestablish or reroute the call, the call is terminated.

A call can stay in *CONNECTING* mode until the end of a system defined time, If, the connection is not established during this time period, it is blocked or terminated.

4.5. Location Management

In the proposed system each cluster head and RAP has a local database (VLR) which has three fields in each record in our application as illustrated in Figure 4.26. This structure can be changed for other requirements.

The registered component id	The registering component	Hop number
124.1.1.8.0.0	Node1	0

FIGURE 4.26. The VLR record structure.

All components reaching WAS through this node has a record in the VLR database. If hop number is 0, it indicates that the component is directly registered to this node. If it is a positive number it indicates that the component reaches this node after being relayed by that many components.

When a call connection request is received by a node, it first checks its VLR and route the call to the registering node, if the destination has an entry in the VLR. Otherwise, it routes the call to a higher node which is the node that the current node is registered by. If the WAS is reached at the end of this process, the HLR is looked up, and the routing continues from the RAP that connects the tree of the destination node to the WAS. Since the components call the neighboring calls in most of the cases, this scheme runs effectively.

5. PERFORMANCE EVALUATION OF THE PROPOSED SYSTEM

The Communications Simulation Systems (CSSs) developed for civilian needs are generally not capable to simulate military networks especially the mobile ones efficiently. On the other hand, it is not easy to find a CSS for military needs. We should also investigate the usage of combat simulation systems to simulate a tactical communications system. There are hundreds of combat simulation systems (Çayırcı, 1997a). Many of them are well designed and implemented, high fidelity software and hardware systems, but we cannot use them directly because of the following shortcomings:

- There are only a few simulation systems which are designed only for modelling military communications. Even these specific models work for generic cases with some unnecessary details.
- The amount of required input parameters is high in these systems, so it requires long run times and many personnel to run a simulation to obtain a result.
- The verification of the results is cumbersome.
- The required computational power to run such systems is generally very high.
- The resolution of these systems are generally lower than the required resolution to model a tactical communications system.

On the other hand, most of these combat models have the replay capability. "Replay" means running the simulation with the previously entered commands. If we can collect the commands entered in a Computer Aided Exercise (CAX) in which combat models are used, we can run them again by replaying. Hence, we can make some simulations by using the recorded exercises without a need to have many personnel.

Three combat models, namely JANUS (a high resolution army model), IDAHEX (a highly aggregated Army model) and JTLS (a highly aggregated joint model) (Çayırcı, E., 1997a) are available for us. Among these, JTLS is a joint combat model which means it models the operations of multiple services (army, navy, air forces). It is the most commonly used joint combat model within NATO, and we have some recorded wargames played with JTLS. As a result, we used JTLS to provide some data needed to run our simulation studies.

We developed a simulation system which is illustrated in Figure 5.1. In this system, JTLS provides the mobility, event and tactical posture data for the simulated units. The most recently played wargame commands are run and a translator converts the results of this simulation into the format we need for our simulation system. Then, a simulation manager, reads the collected data, forward these data to some generators that generate calls, events and mobility in the required resolution. The resolution of the data generated by JTLS is in company, battalion and brigade level units for each minute. This resolution is enhanced to radios for each second. The simulation manager runs the implemented system according to the generated data and collects the data related to the predefined performance metrics into a database. A post processor which runs after simulation, analyzes the collected data and writes the results to the final database. The translator in this system was implemented with C in Solaris. All other components of the system were implemented by using visual C++ in MS Windows.

5.1 Translator

Translator interacts with JTLS, converts the results of the wargame run with JTLS into the format defined for the implemented simulation system. Each tuple in this database has nine fields. These fields are defined below:

- Unit name : This field represents nine character long unit names.
- Unit type :We classify the units into 10 broad categories, namely non-applicable (an entity which is not a unit), headquarter, infantry, artillery, armor, special force, squadron, support unit, signal unit, others.
- Unit size : We classify unit sizes into 10 categories, namely squad, section, platoon, company, battalion, regiment, brigade, division, headquarter, others.
- Latitudes and longitudes : This is the geographic location of the units in degrees. The accuracy is up to seconds level.

- Posture :We classify the unit postures into 10 categories, namely attack, defend, delay-withdraw, move, air operations, amphibious, formation, incapable, inactive, wiped out.
- Current power : This field indicates the current power to the full power ratio.
- Direction : This is the direction that the unit is facing. We use six directions, namely north, north-east, south-east, south, south-west, north-west.
- In-combat : Whether the unit is in combat or not in combat information is recorded into this field.

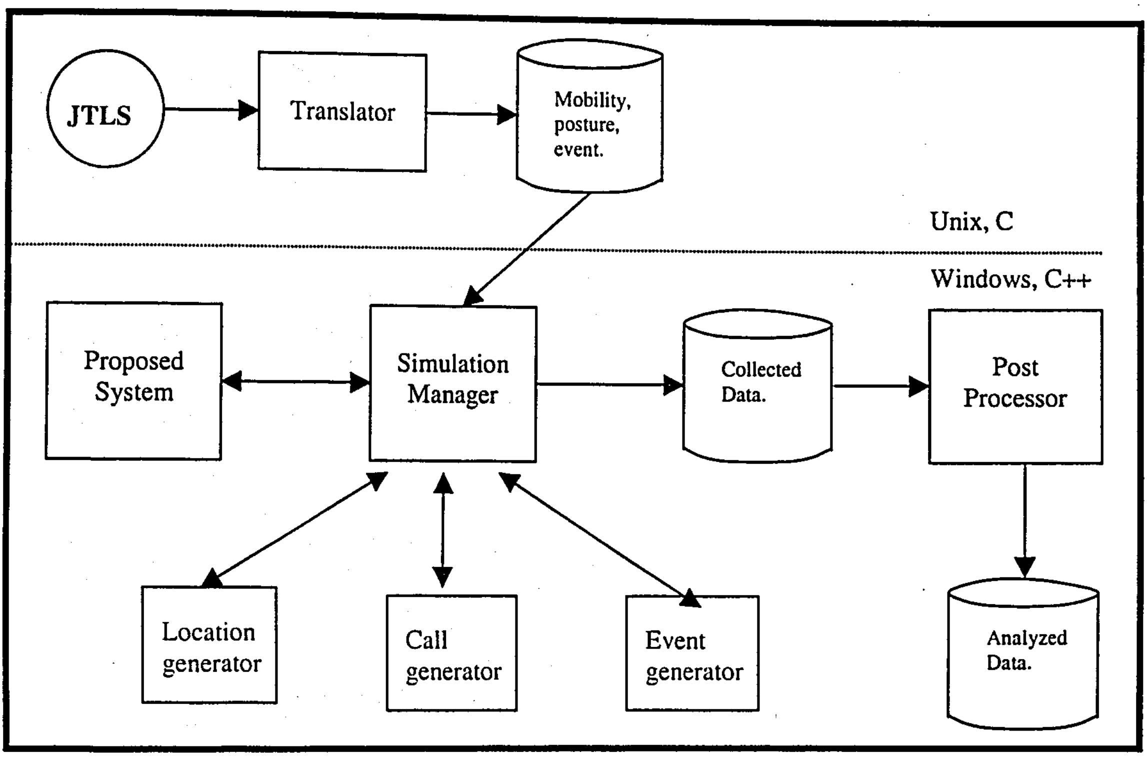


FIGURE 5.1. The layout of the developed simulation system.

There is a separate record related to each unit for each minute in this database. The simulation time information is recorded in separator records with minutes resolution. Between two time records, the records related to each unit for that minute is recorded.

5.2. Simulation Manager, Location, Call and Event Generators

The algorithm of Simulation Manager is illustrated in Figure 5.2. It reads the records related to each unit minute by minute from the database created by the translator. After reading the data of the next minute, the speeds and the lost power in the next minute is calculated, and the simulation is run until reaching the time read.

1. *Read time for the new period and calculate the time difference with the last period.*

2. *Read info from the translator database for each active unit for the new period.*

   Read info into the simulation manager data structure.
   Calculate the speed and the bearing of each unit according to the location in the last period.
   Calculate the lost power in the last period.

3. *Repeat until the simulation time reaches the time of the current period.*

   Add the time interval (the required time resolution) into the simulation time.
   Calculate the location for each component according to the speed and bearing of the unit which owns the component (location generator).
   Calculate if the components initiate a call or a call initiated in the previous intervals will last one more interval (call generator).
   Make the calculator carry the required calculations for the new situation for each component (proposed system).

4. *When the next time period is reached, calculate which components are destroyed or failured in the last period according to the lost power of the unit (event generator).*

FIGURE 5.2. The simulation manager algorithm.

Since the resolution of data created by translator is in unit size and in minutes, this resolution should be enhanced up to the radio level and seconds. This is done by the location manager.

At the initial phase, the generic unit organization illustrated in Figure 5.3 is used to determine the number of radios within a unit. We assume that each unit has one radio for the Commanding Officer (CO), four radios for the headquarter, and four subordinate units which has the same organization. This standard organization is kept down to the squad level in which we have three radios in total. These radios are deployed uniformly to the area whose center is determined from the translator database. The size of different units under different postures are given in Table 5.1. This values in Table 5.1 are determined according to the generic organization. If a unit has a RAP, the RAP is located randomly with uniform distribution within a circle whose center is the center of the unit. The radius of this circle is is equal to 10 per cent of the unit front size.

TABLE 5.1. The fronts and depths of the simulated generic units (in meters).

Unit	Bran.	Att.		Def.		With.		Move		Amp.		Other	
		Front	Depth	Front	Depth	Front	Depth	Front	Depth	Front	Depth	Front	Depth
Co	Inf.	1000	500	1500	1000	2000	2000	400	400	1000	500	1500	1000
	Art.	500	250	500	250	500	250	500	250	500	250	500	250
	Tank	1000	500	1500	1000	2000	2000	400	400	1000	500	1500	1000
	SOF	1000	500	1500	1000	2000	2000	400	400	1000	500	1500	1000
	Sup.	500	250	500	250	500	250	500	250	500	250	500	250
	Hq.	50	50	50	50	50	50	50	50	50	50	50	50
Bat	Inf.	1500	1000	3000	2500	6000	5000	400	2000	1500	1000	3000	2500
	Art.	3000	1000	3000	1000	3000	1000	3000	1000	3000	1000	3000	1000
	Tank	1500	1000	3000	2500	6000	5000	400	2000	1500	1000	3000	2500
	SOF	1500	1000	3000	2500	6000	5000	400	2000	1500	1000	3000	2500
	Sup.	1500	1000	1500	1000	1500	1000	1500	1000	1500	1000	1500	1000
	Hq.	100	100	100	100	100	100	100	100	100	100	100	100
Reg. Brig.	Inf.	4000	3000	8000	16000	16000	20000	1000	7000	4000	3000	8000	16000
	Art.	3000	1000	3000	1000	3000	1000	3000	1000	3000	1000	3000	1000
	Tank	4000	3000	8000	16000	16000	20000	1000	7000	4000	3000	8000	16000
	SOF	4000	3000	8000	16000	16000	20000	1000	7000	4000	3000	8000	16000
	Sup.	1500	1000	1500	1000	1500	1000	1500	1000	1500	1000	1500	1000
	Hq.	200	200	200	200	200	200	200	200	200	200	200	200
High	Hq.	200	200	200	200	200	200	200	200	200	200	200	200

Bran.: Branch, Att. : Attack, Def. : Defense, With.: Withdraw, Amp.: Amphibious, Co.: Company, Bat.: Battalion, Reg.: Regiment, Brig.: Brigade, Inf.: Infantry, Art.: Artilery, SOF: Special Operations Force, Sup.: Support, Hq.: Headquarter.

After the initial deployment, the simulation manager reads the data for the next time period. According to the locations that the units will be in the next period and their current locations, speed and direction of movement for each unit is calculated in degrees per second. Then simulation is forwarded second by second, and in each second location manager adds the speed of the units into the locations of the radios and the RAPs owned by that unit.

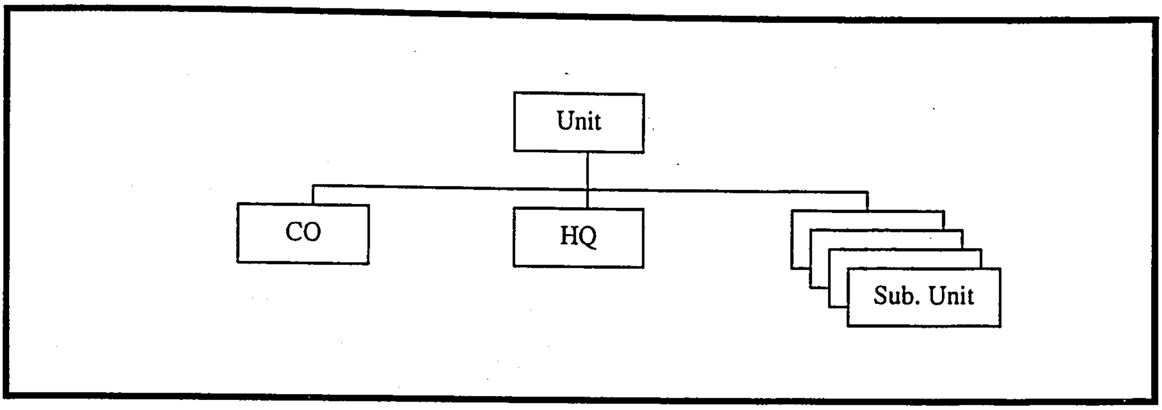


FIGURE 5.3. The generic unit organization.

Call generator generates the calls according to the unit type, unit posture and whether the unit is in combat or not. The data related with these parameters come from the translator database. Using these data together with the average arrival rates coming from a statistical work, calls are generated. The call generator decides for each radio whether the the radio initiates a call, and destination, type and duration of the call.

We performed a statistical study with 20 officers who have at least 10 years of experience on leading a combat unit. The results of this study are given in tables 5.2 through 5.5.

In Table 5.2, the call destination statistics are summarized. We asked with what probability a call is destined to where. As expected, in most of the cases the subordinate units or the COs of the leading units are called. This is very important, because it indicates that the subscribers in the vicinity of the calling subscriber are called most of the time.

TABLE 5.2. Call destination statistics.

The destination of a call.	(%)
To a subordinate unit.	61.3
To the leading HQ or CO.	22.4
The other units attached to the same higher unit.	7.8
The neighbor units attached to other units.	4.6
Anyone, any unit.	3.9

TABLE 5.3. The number of calls in an attack within one hour.

Branch	In contact			Without contact		
	Minimum	Average	Maximum	Minimum	Average	Maximum
Infantry	10.1	16.8	30.5	6.4	9	16.5
Artilery	12.5	18.1	26.8	4.6	8.4	12.4
Tank	18.7	21.1	30.2	6.6	12.1	16.6
Special Force	16.4	17	24.4	4.3	7.5	10.8
Signal	9.4	14.3	19.4	5.4	13.2	18.1
Headquarter	12.3	15.6	21.8	7.5	12.7	16
Other	9	13.3	18	7.6	11.6	15.7

TABLE 5.4. The factor to normalize the call rates for the other postures.

Posture	In contact	Without contact
Defense	0.79	0.53
Withdraw – delay	1.01	0.68
Move	0.73	0.53
Amphibious operation	1.05	0.76
Other	0.74	0.56

To decide on the call rate, the simulation manager provides the information of the type and posture of the unit together with whether it is in contact or not. Then the call manager looks up the call rate from Table 5.3 according to the unit type and in-contact information. If posture is not attack, this value is multiplied with the factor read from Table

5.4 according to the posture and in-contact information. The result is the call rate for that unit for that time period.

We assume that the call arrival pattern is Poisson. This assumption is acceptable. The exponential distribution for the call inter arrival times is a good approximation in the battlefield, because war fighters try to communicate with short time intervals in certain period of times, and if the time intervals between the calls get larger than the mean intervals, they get much larger than the mean. Since this is the same in call duration times, we assume call duration times are exponentially distributed, too. We also factorized the call duration and call rate distributions. When we tried the uniform distribution, we found that there is not a meaningful difference in call blocking and call termination rates from the results of the simulations in which we used the exponential distribution. Some other distributions which approximate bursty arrivals representing multimedia applications will be used in the future work.

TABLE 5.5. Call duration times.

	Duration in seconds
Minimum	6.7
Average	19.3
Maximum	41.3

The expected call duration for the calls are generated with exponential distribution whose mean value is read from Table 5.5.

The last thing to be determined about the calls is the type of the call. We envisioned six types of multimedia calls, and distribute the calls among these types uniformly with the percentages shown in Table 5.6. Since multimedia is a new concept for tactical communications, we could not complete a statistical study on the call types, and determined the rates intuitively. However, we factorize the ratio of multimedia calls to ordinary voice calls in our simulation studies as illustrated in Table 5.6.

TABLE 5.6. The types of calls.

Multimedia to total call rate	**# of channels**	**%37**	**%63**	**%74**	**%98**
Voice	1	63	37	26	2
Teleconference	2	18	30.6	36	47.7
Videophony	2	7.2	12.3	14.4	19.1
Videoteleconference	6	1.8	3.1	3.6	4.8
High priority data	2	1	1.7	2	2.6
Data	1	9	15.3	18	23.8

5.2.1. Soft Capacity Calculations

After the generators generate the locations and calls for the current second, simulation manager makes the implemented system run for one second with the current data. We implemented the proposed system almost as if it is a real system. Each component (MPR or RAP) tries to act as a real system in the environment created as some data structures by the simulation manager. The algorithms explained in Chapter 4 are used for this module of the developed simulation system. Here, we explain how we calculate the soft capacity of the system components.

We use bit energy to noise density ratio (E_b/N_o) equations to calculate the soft CDMA capacity of an access point. Bit energy to noise density ratio is the ratio of the signal energy per each bit to the total noise and interference per each hertz of bandwidth (Gilhousen, 1991). By using this definition, we can write Equation 5.1.

$$E_b/N_o = \frac{S / R_b}{(N \alpha S + M S + I + \eta) / B} \tag{5.1}$$

$$E_b/N_o = \frac{B / R_b}{N\alpha + M + I/S + \eta / S} \tag{5.2}$$

$$N\alpha + M = ((B / R_b) / (E_b/N_o)) - (I / S) - (\eta / S) \tag{5.3}$$

In Equation 5.1, N is the number of voice channels and M is the number of channels other than voice in the current cell, S is the signal power at the receiver, R_b is the bit rate, B is the bandwidth, I is the interference caused by the subscribers in remote cells, η is the background noise, and α is the voice activity factor. (η / S) is actually the reverse of Signal to Noise Ratio (SNR). We assume that this value is one (Gilhousen, 1991), so it reduces the capacities less than one channel.

Here, we need to find I/S which is the total inter-cell interference to the received signal strength ratio. Since we use $N=3$ frequency reuse plan, we know that there cannot be any interfering virtual cell in the first ring of the target cell, and there can be at most six interfering virtual cells in the second ring as illustrated in Figure 5.4. We assume that the interference from the other rings is negligible.

Since power control adjust the signal strength to be the same for each subscriber in their cell bases, the ratio of the interference produced by an interfering subscriber to the received signal strength of a subscriber registered to the interfered base can be modeled with Equation 5.4 (Andersen, 1995) (Gilhousen, 1991) (Muller, 1995) (Rappaport, 1997) (Stallings, 1991) (Wang, 1995).

$$I(d_o, d_m) / S = (d_m / d_o)^{\gamma}\, 10^{(\varepsilon_o - \varepsilon_m)/10} \tag{5.4}$$

In Equation 5.4, d_o is the distance between the interfering subscriber and the interfered base, d_m is the distance between the interfering subscriber and its base, γ is the slope value for the propagation model which has a value between 2 and 5 (Faraque, 1996), ε_o and ε_m are Gaussian random variables with standard deviation $\sigma = 8$ and zero mean.

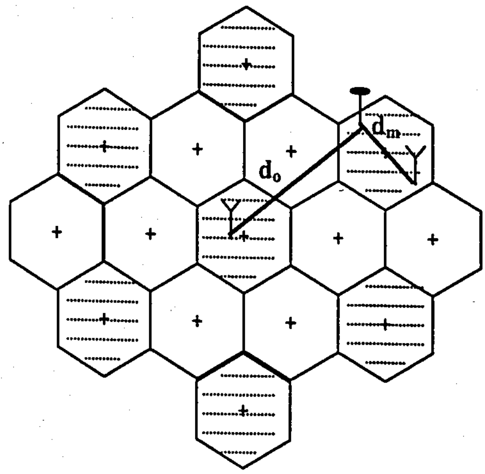


FIGURE 5.4. The interfering VCL cells.

Since Equation 5.4 gives us *I/S* for a single remote cell channel, we should sum up *I/S* values for all of the interfering channels. In our calculations, we made the following assumptions:

- Every voice communication has at least two channels, namely reverse and forward channels.
- If there is a voice communication between an MPR and an access point, there can be signal transfer only either in forward or reverse direction at a time.
- The voice activity factor in both directions are the same.

The second and the third assumptions are for the sake of tractability and simplicity. They do not change the results much and they are close to reality. Based on these assumptions, we derive Equation 5.5.

$$P(F \cup R) = 2\alpha$$
$$P(F \mid (F \cup R)) = 0.5$$
$$P(R \mid (F \cup R) \text{ and } !F) = 1 \qquad (5.5)$$

In Equation 5.5, *F* is "having traffic in forward link" and *R* is "having traffic in reverse link".

We also define several random variables for calculating the capacity. The first random variable ϕ is related to the voice activity factor. It is one if the traffic in the channel is not voice traffic. If it is voice traffic, than ϕ has the following distribution.

$$\phi = \begin{cases} 1 & \text{, with probability } P(F \cup R) \\ 0 & \text{, with probability } 1 - P(F \cup R) \end{cases} \qquad (5.6)$$

The other random variables p and q are related to the direction of the traffic. They are one for the traffic other than voice and data traffic. For data traffic, if the traffic is in forward direction, p is 0 and q is 1, and if the traffic is in reverse direction, p is 1 and q is 0. For voice traffic, they have the following distribution.

$$p = \begin{cases} 1 & \text{, with probability } 1/2 \\ 0 & \text{, with probability } 1/2 \end{cases} \qquad (5.7)$$

$$q = 1 - p \qquad (5.8)$$

From Equation 5.4, we obtain Equation 5.9 which defines the interference caused by the interfering channels in one of the interfering virtual cells.

$$\frac{I_I}{S} = \frac{3 \times I_b}{S} + \sum_{i=1}^{n} \phi i \left[\left[\frac{d_{im}}{d_{io}} \right]^{\gamma} \times p + \left[\frac{d_{im}}{t} \right]^{\gamma} \times q \right] \times 10^{(\varepsilon_{oi} - \varepsilon_{mi}) / 10} \qquad (5.9)$$

In Equation 5.9, t is the distance between the interfered base and the base of the interfering cell, and I_b/S is the interference caused by the access point in the interfering cell. There are two channels which are known to us and can cause interference in the remote cells, BCCH and SYNC channels. The I_b/S value can be calculated by applying Equation 5.10.

$$\frac{I_b}{S} = \left[\frac{kr}{t}\right]^{\gamma} \times 10^{(\varepsilon_{ob}-\varepsilon_{mb})/10} \qquad (5.10)$$

In Equation 5.10, *r* is VCL cell radius and *k* is the multiplication factor to convert the VCL cell radius to real cell radius.

Since there can be up to six interfering cells in the first three rings, the total interference becomes

$$\frac{I}{S} = \sum_{k=1}^{6} \tau_k \left[\frac{3 \times I_{bk}}{S} + \sum_{i=1}^{n} \phi i \left[\left[\left[\frac{d_{ikm}}{d_{iko}}\right]^{\gamma} \times p + \left[\frac{d_{ikm}}{t}\right]^{\gamma} \times q\right] \times 10^{(\varepsilon_{oik}-\varepsilon_{mik})/10}\right]\right] \qquad (5.11)$$

where τ_k is one if there is an interfering access point in the interfering cell, zero otherwise.

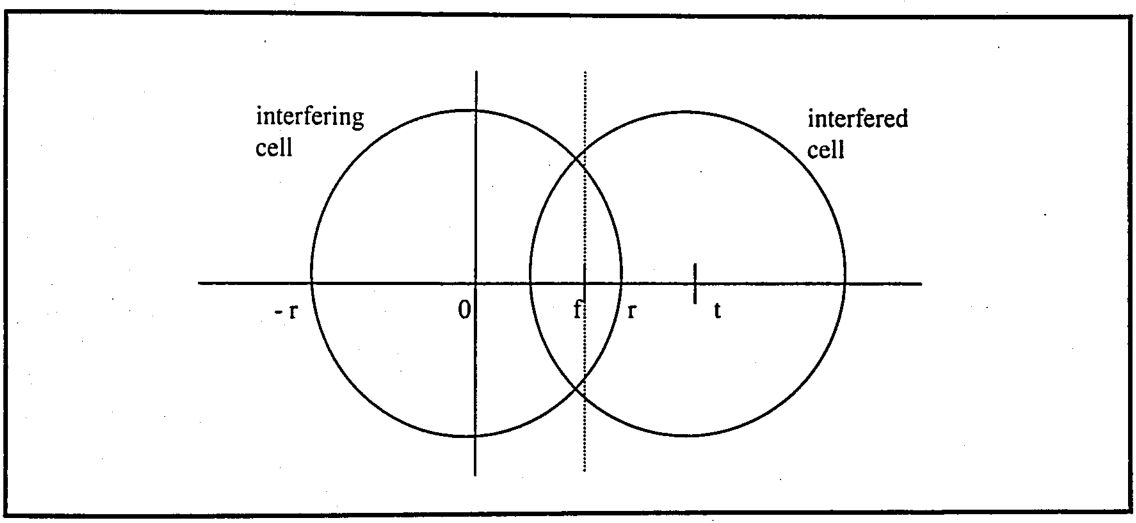


FIGURE 5.5. The geometry of remote cell interference.

We also carried another analytical study to find out an equation that gives us the possible interference caused by a remote cell, when we know the distance (*t*) between the RAP in the remote cell and the interfered RAP, and the number of channels (*n*) served by the interfering RAP. The results of this study can be used in the simulation software to decrease the volume of the computation needed to calculate the remote cell interference, or we can calculate the possible remote cell interference analytically for other applications by using these derivations.

Since MPRs are served by the closest RAPs using the same carrier, the originating MPRs for the channels in the interfering cell can be somewhere within the interfering cell and on the left of the line passing through the point *f* in Figure 5.5. Here *f* determines the boundary between two interfering cells, and can be calculated by the following equation.

$$f = \begin{cases} t/2 & , \text{if } t < 2r \\ r & , \text{otherwise} \end{cases} \quad (5.12)$$

The probability of a channel is originated at a point in this region can be calculated by the following equation, if we assume that the MPRs are uniformly distributed in the region.

$$\psi = \begin{cases} n\,\alpha / ((\pi\, r^2 / 2) + (\pi\, r^2 \arcsin(f/r)/180) + ((r^2 - f^2)^{1/2} f)) & , \text{if } f < r \\ n\,\alpha / \pi\, r^2 & , \text{otherwise} \end{cases} \quad (5.13)$$

By using the same approach in Equation 5.9, we can derive Equation 5.14 to calculate the expected interference caused by the used channels in an interfering cell. In Equation 5.14, γ is taken as four as a typical value (Gilhousen, 1991).

$$E[I/S]=2\psi 10^{(\varepsilon o-\varepsilon m)/10}\left(\int_{-r}^{0}\int_{0}^{(r^2-x^2)^{1/2}}(x^2+y^2)^2/((t-x)^2+y^2)^2 dydx + \int_{0}^{f}\int_{0}^{(r^2-x^2)^{1/2}}(x^2+y^2)^2/((t-x)^2+y^2)^2 dydx\right) \quad (5.14)$$

$$E[I/S]=2\psi 10^{(\varepsilon o-\varepsilon m)/10}\left(D \Big|_{-r}^{0} \Big|_{0}^{(r^2-x^2)^{1/2}} + D \Big|_{0}^{f} \Big|_{0}^{(r^2-x^2)^{1/2}} \right) \quad (5.15)$$

D in Equation 5.15 is the result of the following equation.

$$D = y\left(x + \frac{t^2}{2}\right)\left(\frac{d \arctan\left(x/(a-t^2)^{1/2}\right)}{(a-t^2)^{1/2}\, a^2} - \frac{t^2}{b\, a} + \frac{g\,(2\log(b) - \log(h))}{a^2}\right) + \frac{1}{2}\arctan\frac{c}{3\, b^2} \quad (5.16)$$

In Equation 5.16,

$$a = 2\,t^2 - 2\,tx + y^2$$
$$b = x - t$$
$$c = 7\,t^5 - 7\,t^4\,x + 18\,t^3 - 8\,t^2\,x^3 - 48\,t^2\,x + 8\,t\,x^4$$
$$d = 8\,t^4 - 22\,t^3\,x + 16\,t\,x^2 + 11\,t^2\,y^2 - 16\,t\,x\,y^2 + 4\,y^4$$
$$g = 3\,t^3 - 4\,t^2\,x + 2\,t\,y^2$$
$$h = t^2 - 2tx + x^2 + y^2$$

5.3. Post Processor

The post processor runs on the data produced by the simulation manager, and prepares some summary statistics. An example summary statistics report is illustrated in Figure 5.6. Detailed information about the calls, handoffs, the connectivity and the resource utilizations are presented in these reports.

These summary reports can be produced for the desired number of periods with the desired period lengths. For instance, you can analyze the results of a simulation for one minute long periods.

The Information about Simulation

Number of Simulated Units : 153
Number of Simulated MPRs : 18529
Number of Simulated RAPs : 77

The Destroyed Components

The Number of Destroyed RAPs : 0
The Number of Destroyed MPRs : 21

The Call Statistics

Total Number of Calls : 147664
The Number of Successfully Completed Calls : 140044
The Calls Blocked by Network Resources
The Calls Blocked in Initial Setup Phase : 7361
The Calls Terminated after Being Broken : 1
The Calls Terminated after a Handoff : 1
The Calls Blocked by the Destination Node
The Calls Blocked in Initial Setup Phase : 0
The Calls Terminated after Being Broken : 0
The Calls Terminated after a Handoff : 0
The Calls Blocked When the Destination is Unreachable
The Calls Blocked in Initial Setup Phase : 255
The Calls Terminated after Being Broken : 1
The Calls Terminated after a Handoff : 1

The RAP Level Handoff Statistics

The Total Number of Handoffs : 32
The Number of Unsuccessfull Handoffs : 0
The Number of Handoffed RAPs : 14
The Minimum Cell Residency Time (in Seconds) : 25
The Maximum Cell Residency Time (in Seconds) : 2460
The Average Cell Residency Time (in Seconds) : 1138
RAP Level Handoff Rates Per Second : 0.000057720
Handoffed RAP to RAP ratio during the Simulation : 0.181818182

The MPR Level Handoff Statistics

The Total Number of Handoffs : 20373
The Number of Handoffed MPRs : 5302
The Minimum Cell Residency Time (in Seconds) : 1
The Maximum Cell Residency Time (in Seconds) : 2220
The Average Cell Residency Time (in Seconds) : 1138
MPR Level Handoff Rates Per Second : 0.000287368
Handoffed MPR to MPR ratio during the Simulation : 0.286146041

The Connectivity Statistics for MPRs

The Average Ratio of Partially Connected MPRs to Total MPRs : 0.015605545
The Average Ratio of Not Connected MPRs to Total MPRs : 0.0001632170

The Utilization Statistics for RAPs

The Average Ratio of Out of Resource RAPs to total RAPs : 0.0
The Average Ratio of Replicating RAPs to total RAPs : 0.067689574

FIGURE 5.6. Example summary report.

5.4. The Verification of the Implemented Simulation Software

The verification of the implemented software is the critical part of our work, since we evaluate the performance of the proposed system based on the results produced by this software. We use three approaches to verify the implemented software: careful debugging and tracing, software verification tools, and consistency checks.

We stopped and verified each module just after implementation by tracing and running some trials. We followed the critical variables step by step in these trials. When we complete the implementation, we run the same procedures for the complete system. We spent three times more effort for debugging compared to that for the implementation.

We also implemented some software tools to verify the implemented simulation system. One of the most important software tools is a module that randomly selects a component among the simulated components and presents some critical information about this component. We run the simulations for any time period with our system, and then use this tool to observe the information about a component, such as the current VCL cell and the resources used. We manually calculate the possible location of the component by looking at the location of the related unit in JTLS at that time. The results of our calculations match to the results produced by the simulation software.

Lastly, the consistency of results also verifies the implemented system. In summary, we believe in that the software does not have major bugs that can spoil the results.

5.5. Performance of the Proposed System

We studied the effect of different factors on the performance of the proposed system. These factors are in Table 5.7. While evaluating the performance, the following metrics are used:

- the RAPs that cannot be assigned radio resources,
- call blocking because of insufficient radio resources,
- call termination because of insufficient radio resources,
- call blocking because of unreachable destinations,
- call termination because of unreachable destinations,
- RAP level handoff rates,
- the ratio of the handoffed RAP number to the total RAP number,
- average cell residency time for RAPs,
- MPR level handoff rates,
- the ratio of the handoffed MPR number to the total MPR number,
- average cell residency time for MPRs,
- partially connected MPR ratios,
- not connected MPR ratios.

We experimented with three different scenarios to run 35 simulations. Most of the simulations are done with the first scenario. The second scenario is less and the third scenario is more mobile than the first one. The values for the factoring parameters of the second and the third scenarios are the ones which we determined as the best configuration for the first scenario.

In the first scenario, we simulate the communications of 153 ground units which are deployed over an area of 115 km. × 170 km. Seventy seven of these units are of battalion size. The others are higher headquarters or subordinate units. We deployed 77 RAPs and 18529 MPRs with these units. During 2 hours of simulations, 52 MPRs and 2 RAPs were destroyed in average by hostile actions. In our simulation studies, we assume that UAV or satellite coverage is NOT available for MPRs. If we include satellite or UAV coverage for the MPRs, the results related to the grade of service are expected to get better.

TABLE 5.7. The factoring parameters used in the simulation studies.

Test #	VCL Cell Radius (m.)	k (multiplication factor)	# of channels in a cell	E_b/N_o	Scenario	Call rate factor	Multi media
1	1000	1	3	5	1	1	%37
2	1000	3	3	5	1	1	%37
3	1000	2	3	5	1	1	%37
4	1000	2	1	5	1	1	%37
5	1000	2	7	5	1	1	%37
6	2000	1	3	5	1	1	%37
7	2000	3	3	5	1	1	%37
8	2000	2	3	5	1	1	%37
9	2000	2	1	5	1	1	%37
10	2000	2	7	5	1	1	%37
11	4000	1	3	5	1	1	%37
12	4000	3	3	5	1	1	%37
13	4000	2	3	5	1	1	%37
14	4000	2	1	5	1	1	%37
15	4000	2	7	5	1	1	%37
16	8000	1	3	5	1	1	%37
17	8000	3	3	5	1	1	%37
18	8000	2	3	5	1	1	%37
19	8000	2	1	5	1	1	%37
20	8000	2	7	5	1	1	%37
21	1000	2	3	3	1	1	%37
22	2000	2	3	3	1	1	%37
23	4000	2	3	3	1	1	%37
24	8000	2	3	3	1	1	%37
25	1000	2	3	5	1	1	%63
26	2000	2	3	5	1	1	%63
27	4000	2	3	5	1	1	%63
28	8000	2	3	5	1	1	%63
29	4000	2	3	5	1	1	%74
30	4000	2	3	5	1	1	%98
31	4000	2	3	3	1	2	%37
32	4000	2	3	3	1	3	%37
33	4000	2	3	3	1	4	%37
34	2000	2	3	5	2	1	%37
35	2000	2	3	5	3	1	%37

Firstly, we analyzed how long it takes to start up the proposed system, if we turn on all of the components at the same time. We examine the "*partially connected*" and "*not connected*" MPR ratios with one minute time intervals in Figure 5.7 and in Figure 5.8. After the first minute, the "*not connected*" MPR ratios degrade down to almost zero level, and continue steady in the following minutes. On the other hand, it takes one more minute for *the* "*partially connected*" MPR ratios to reach a steady level. Although there is another minor jump in "*partially connected*" MPR ratios for VCL cell radii 8000 m. and 4000 m. at around the eighth minute, it is scenario dependent. As a result, we conclude that the self configuration of the proposed system may take two minutes. For that reason, we omit the data collected in the first two minutes while studying the average performance of the proposed system.

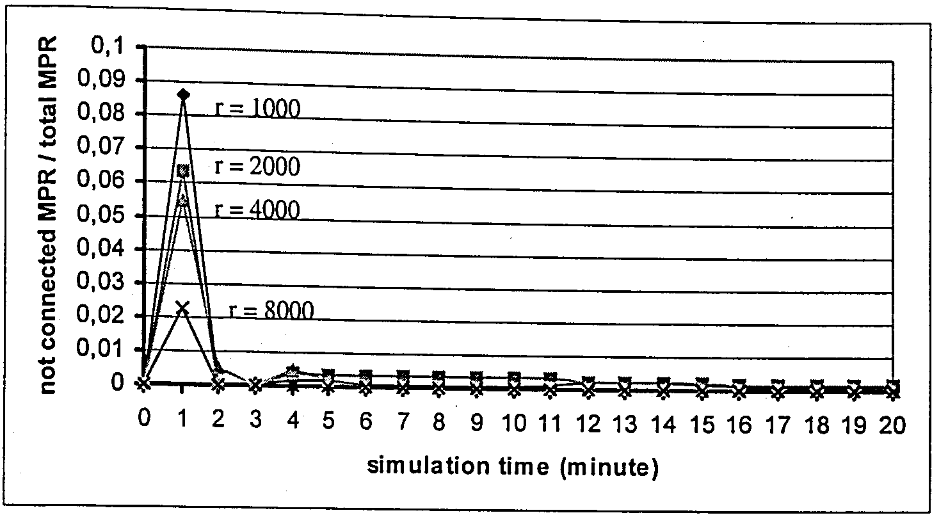


FIGURE 5.7. Not connected MPR ratios for each minute.

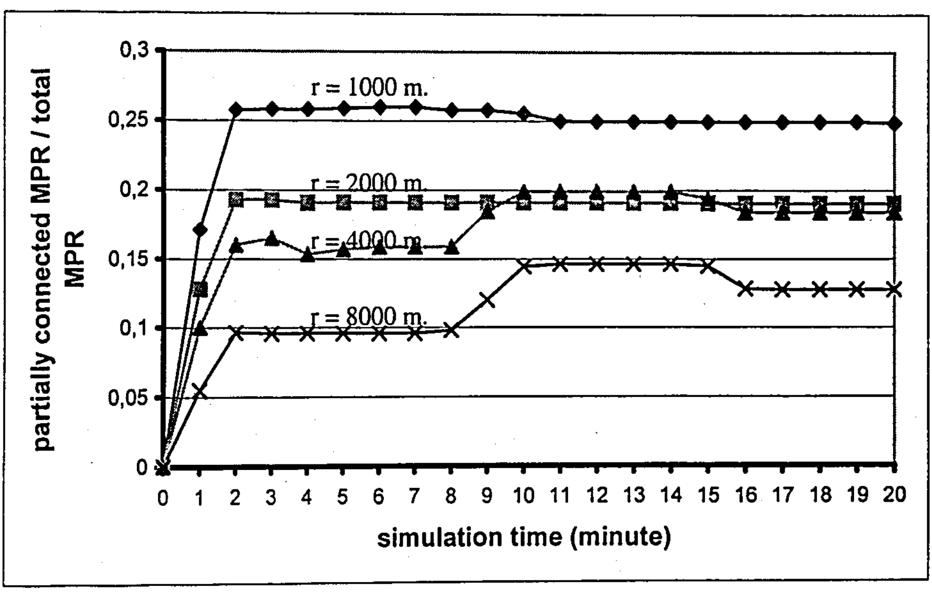


FIGURE 5.8. Partially connected MPR ratios for each minute.

The ratio of the number of replicated RAPs to the total number of RAPs for different VCL cell radii when the multiplication factor is two are illustrated in Figure 5.9. As expected, the number of active RAPs decreases while the VCL cell radii increase.

When we have three available carriers per each VCL cell, the ratio of the numbers of replicated to the total RAPs are in an acceptable level even for the VCL cell radius of 4000 m. When we have six carriers, all RAPs are active for VCL cell radii 1000 m. and 2000 m., and the ratio is lower than 0.1 for VCL cell radius 4000. We also note that none of the RAPs is ever in *STANDBY* state due to the lack of resources when we have three of more carriers for each VCL cell.

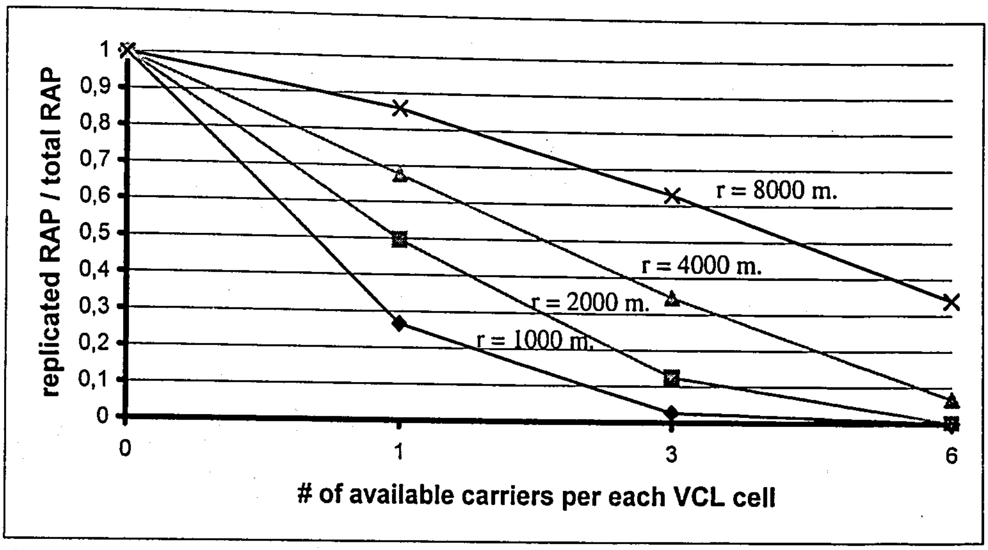
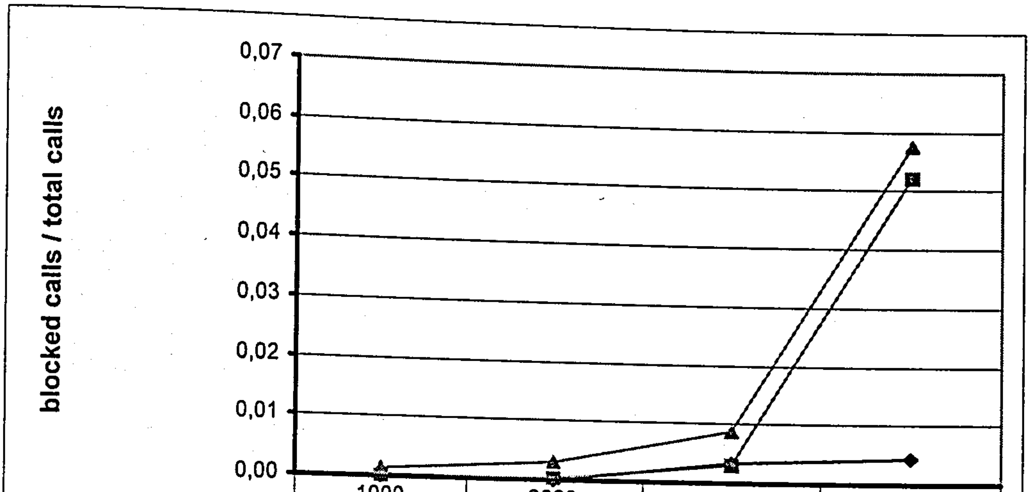


FIGURE 5.9. The ratio of replicated RAPs according to different available carrier numbers.

5.5.1. Call Blocking and Call Termination

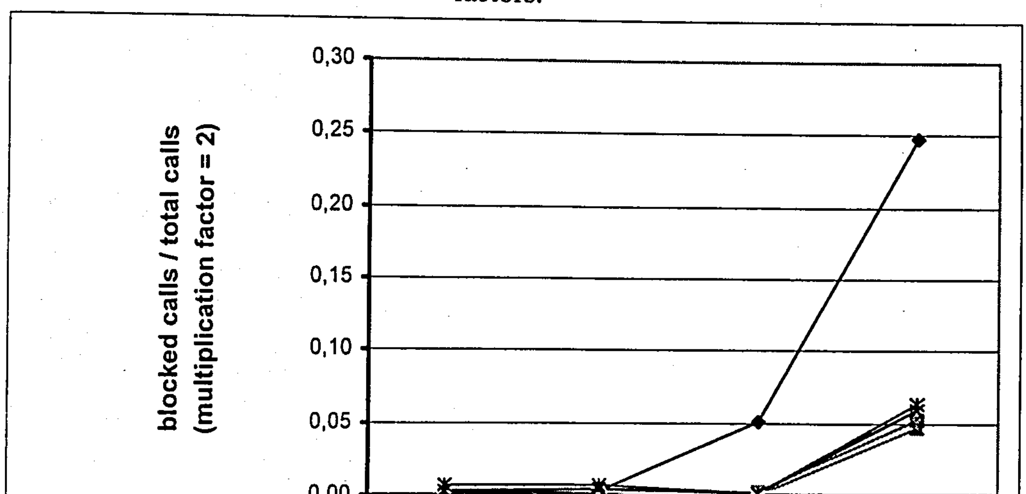
Figure 5.10 illustrates that the call blocking because of insufficient radio resources increases when the VCL cell to real cell multiplication factor gets higher. When the range of RAP transmission equipment gets larger, their interference on the RAPs using the same frequency carriers gets higher, too. This negative effect is even more observable in larger radii. RAPs broadcast in BCCHs and SYNC channels without power control, and a RAP may be within the communications range of another RAPs, when the multiplication factor is larger than one. The effect of the multiplication factor and the radius is analytically examined in Section 5.2.1.



	1000	2000	4000	8000
mult factor=1	0,0E+00	0,0E+00	3,4E-03	4,5E-03
mult factor=2	4,8E-06	4,7E-04	3,0E-03	5,2E-02
mult factor=3	1,5E-03	3,1E-03	8,7E-03	5,8E-02

VCL cell radius (meters)

FIGURE 5.10. Call blocking (because of the lack of resources) for different multiplication factors.

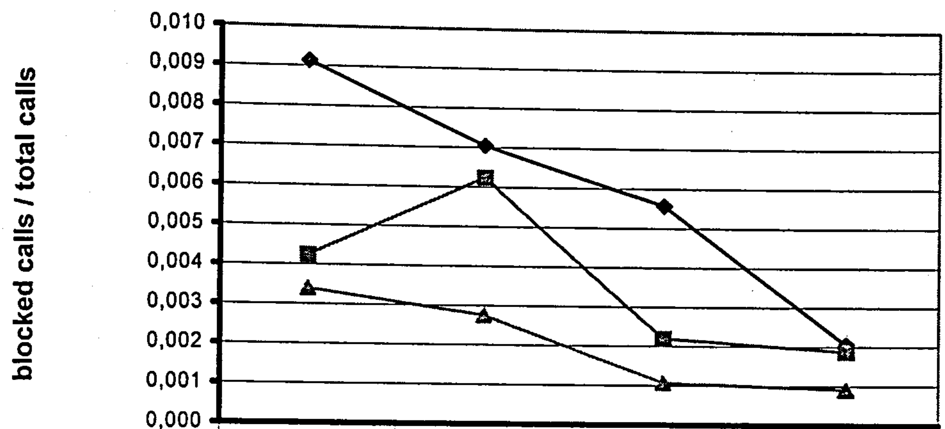


	1000	2000	4000	8000
1 carrier	2,1E-03	2,3E-03	5,1E-02	2,5E-01
3 carriers	4,8E-06	4,7E-04	3,0E-03	5,2E-02
6 carriers	4,5E-03	2,5E-03	0,0E+00	4,7E-02
Eb/No=3	3,0E-03	4,0E-03	7,3E-04	6,0E-02
higher multimedia	7,0E-03	6,5E-03	7,6E-04	6,3E-02

VCL cell radius

FIGURE 5.11. Call blocking (because of the lack of resources) for different number of carriers and media characteristics.

In Figure 5.11, the results obtained by factoring the number of carriers, the percentage of multimedia traffic, and E_b/N_o are illustrated. The change in call blocking rates can be easily noticed only when we decrease the number of carriers per VCL cell down to one. In the other cases, the changes can be accepted negligible which indicates that there is some spare capacity when we have three or more carriers per each VCL cell. In Figure 5.11, the multiplication factor is two for all five curves, and the number of carriers per cell is three for E_b/N_o=3 and "*higher multimedia*" curves. In the higher multimedia curve, the ratio of video and data traffic is 60% of the overall traffic.

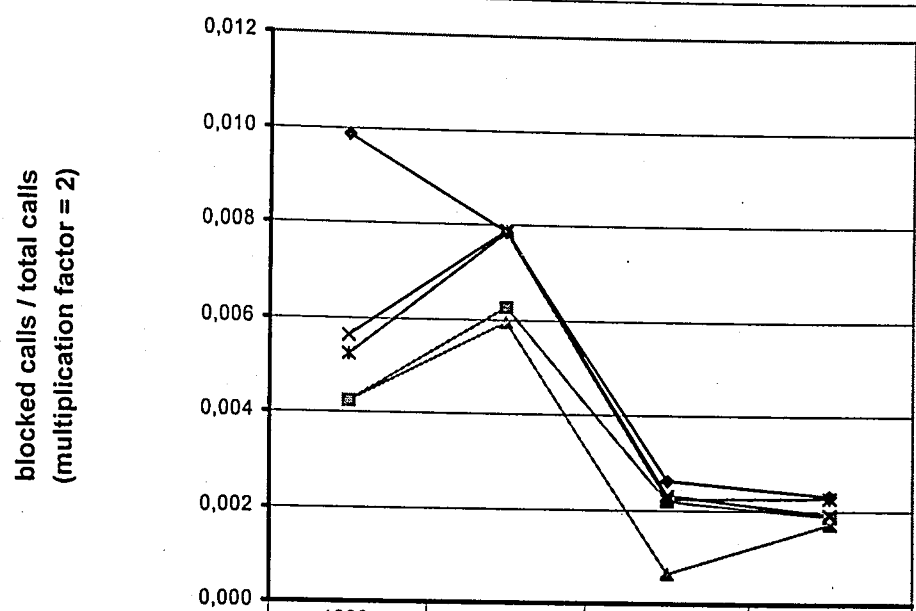


	1000	2000	4000	8000
mult factor=1	9,1E-03	7,0E-03	5,6E-03	2,0E-03
mult factor=2	4,2E-03	6,2E-03	2,2E-03	1,9E-03
mult factor=3	3,4E-03	2,8E-03	1,1E-03	9,1E-04

VCL cell radius (meters)

FIGURE 5.12. Call blocking (because of unreachable destinations) for different multiplication factors.

In Figure 5.12, we can make some observations which are opposite of the observations we made for the call blocking rates because of the lack of resources. The call blocking rates because of unreachable destinations get lower when the multiplication factor gets higher. Since the number of "*not connected*" or "*partially connected*" MPRs decreases when the range of RAPs increases, the probability of having an unreachable destination is lower in higher multiplication factors. Some of the unreachable destinations may be the ones which are destroyed by hostile actions, but the percentage of these is not high. As we stated before, in average only 52 out of 18529 MPRs are destroyed during two hours of simulations. For the multiplication factor two, the call blocking rate gets higher going from VCL cell radius 1000 m. to 2000 m. This is not normal and scenario dependent. We may sometimes decrease the connectivity by increasing the real cell radius, since the multihop connectivity is happened to be limited. We can make the same observation in Figure 5.13, because the multiplication factor is two for all of the curves in Figure 5.13.



	1000	2000	4000	8000
1 carrier	9,9E-03	7,8E-03	2,6E-03	2,3E-03
3 carriers	4,2E-03	6,2E-03	2,2E-03	1,9E-03
6 carriers	4,2E-03	6,0E-03	6,5E-04	1,7E-03
Eb/No=3	5,6E-03	7,9E-03	2,3E-03	1,9E-03
higher multimedia	5,2E-03	7,8E-03	2,2E-03	2,2E-03

VCL cell radius (meters)

FIGURE 5.13. Call blocking (because of unreachable destinations) for different number of carriers and media characteristics.

Having more capacity has more effect on the call blocking rates due to the unreachable destinations compared to those due to the lack of resources as illustrated in Figure 5.13. However, we note that the call blocking rates because of the unreachable destinations are much lower than the call blocking rates because of the lack of resources. The more carriers we have for each VCL cell, the lower call blocking rates we observe, because the more RAPs become active when we have more resources and the larger areas are covered by RAPs.

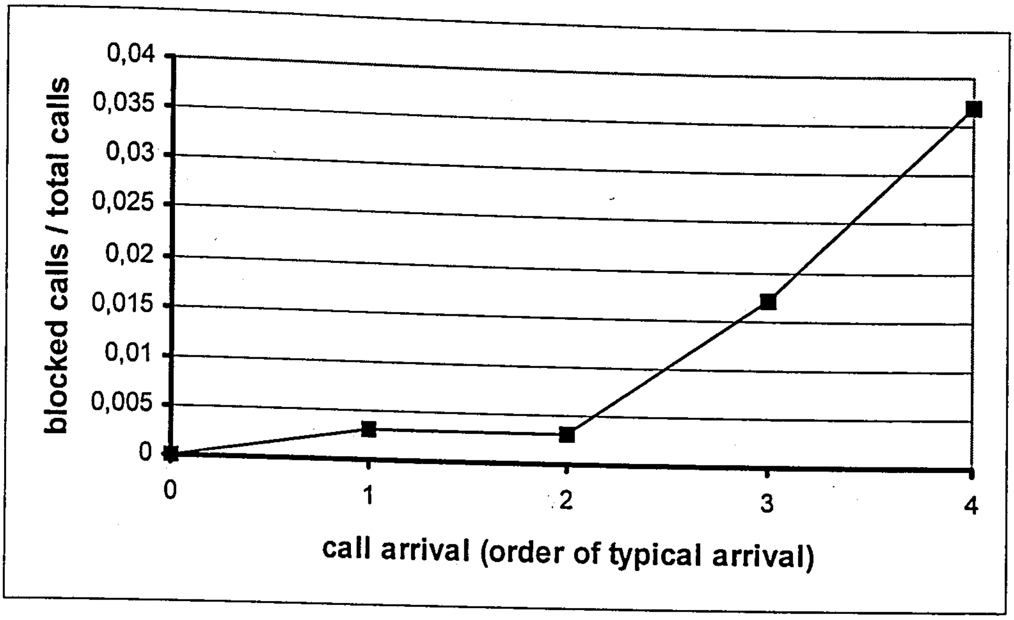


FIGURE 5.14. Call blocking (because of the lack of resources) for different traffic loads.

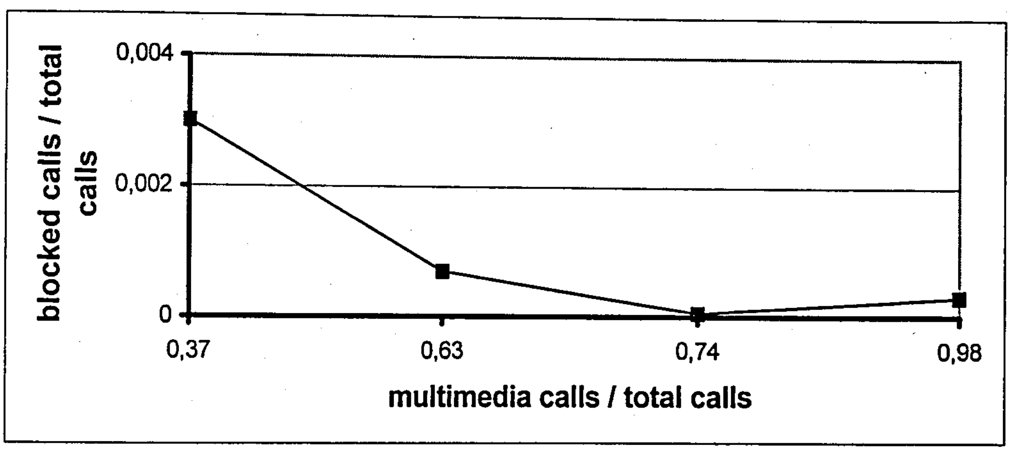
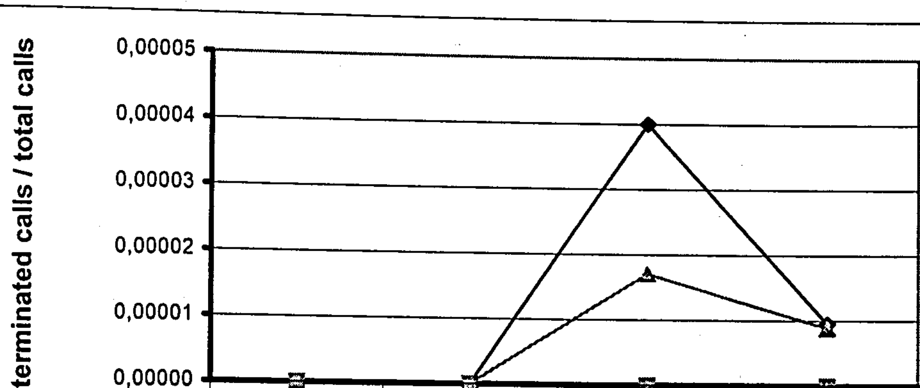


FIGURE 5.15. Call blocking (because of the lack of resources) for different multimedia traffic rates.

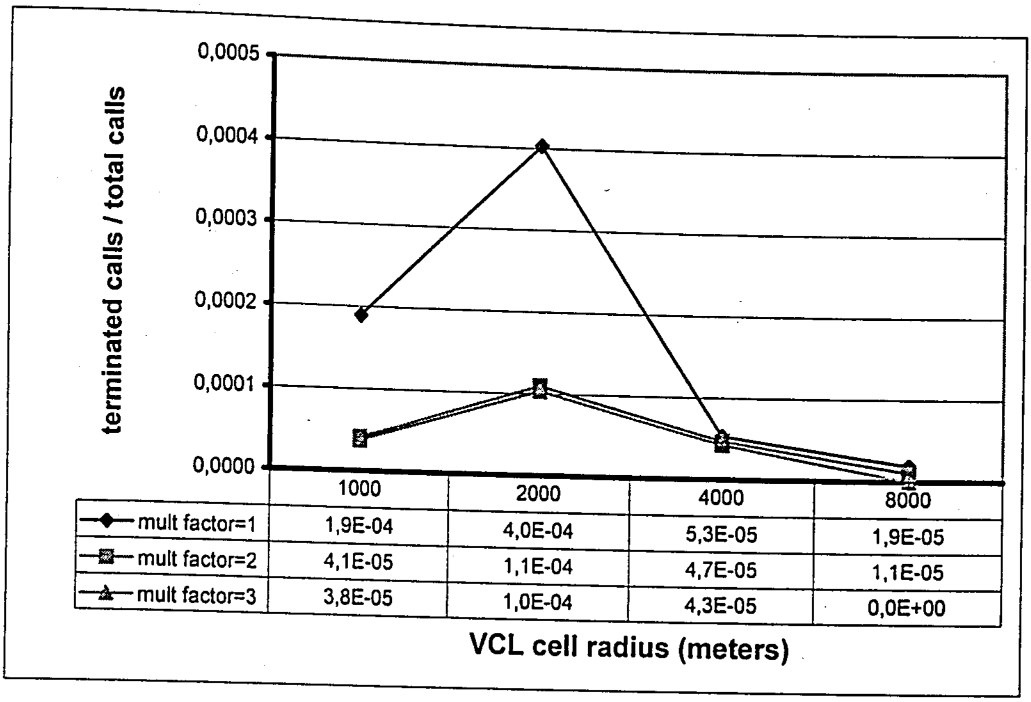
In Figure 5.14 and Figure 5.15, the call blocking rates due to the lack of resources with respect to different call arrival rates and multimedia traffic to total traffic rates are illustrated. In these simulations, the VCL cell radius is 4000 m., the multiplication factor is two, and the number of frequency carriers in each carrier set is three. The call arrival rates determined during the statistical study are accepted as the typical rates. When the call arrival rates which are two times more then the typical rate is simulated, the call blocking rates does not change. This indicates that the system has a spare capacity in this combination of factoring parameters for the typical rates. When the rates are three or four times more than the typical, an increase in call blocking rates is observed. When the rates of multimedia traffic to total traffic is changed, the call blocking rates change less than10^{-3}. Since the system has spare capacity, the change in call blocking rates related to multimedia traffic rates is small. The ratios of different traffic types to total traffic for these scenarios are written in Table 5.6.



	1000	2000	4000	8000
mult factor=1	0,0E+00	0,0E+00	4,0E-05	9,5E-06
mult factor=2	0,0E+00	0,0E+00	0,0E+00	0,0E+00
mult factor=3	0,0E+00	0,0E+00	1,7E-05	8,8E-06

VCL cell radius (meters)

FIGURE 5.16. Call terminations because of the lack of resources.



	1000	2000	4000	8000
mult factor=1	1,9E-04	4,0E-04	5,3E-05	1,9E-05
mult factor=2	4,1E-05	1,1E-04	4,7E-05	1,1E-05
mult factor=3	3,8E-05	1,0E-04	4,3E-05	0,0E+00

FIGURE 5.17. Call terminations because of the unreachable destinations.

As illustrated in Figure 5.16, the call termination due to the lack of resources is zero in most of the cases. It is a little different for the call terminations because of the unreachable destinations. Figure 5.17 illustrates that as the multiplication factors get higher, the call termination rates due to the unreachable destinations become lower.

5.5.2. Handoffs and Cell Residency Times

In Figure 5.18, the number of handoffed RAPs in an hour to the total number of RAPs ratio is plotted. Approximately 13 per cent of the RAPs move more than eight km. in one hour. Although the scenario that we used in our simulation study is accepted as a dense and mobile one, the number of RAP level handoffs recorded during the simulation is low.

The handoff rates and the average cell residency times for different cell radii are illustrated in Figure 5.19 and Figure 5.20 respectively. Multiplication factor does not have an effect on the statistics related to the RAP level handoffs, since we accept the VCL cell crossings as a RAP level handoff. Only the handoffed RAPs are counted in average cell residency time calculations. We also note that we did not record any RAP which cannot find available radio resources in the newly entered VCL cell in a RAP level handoff.

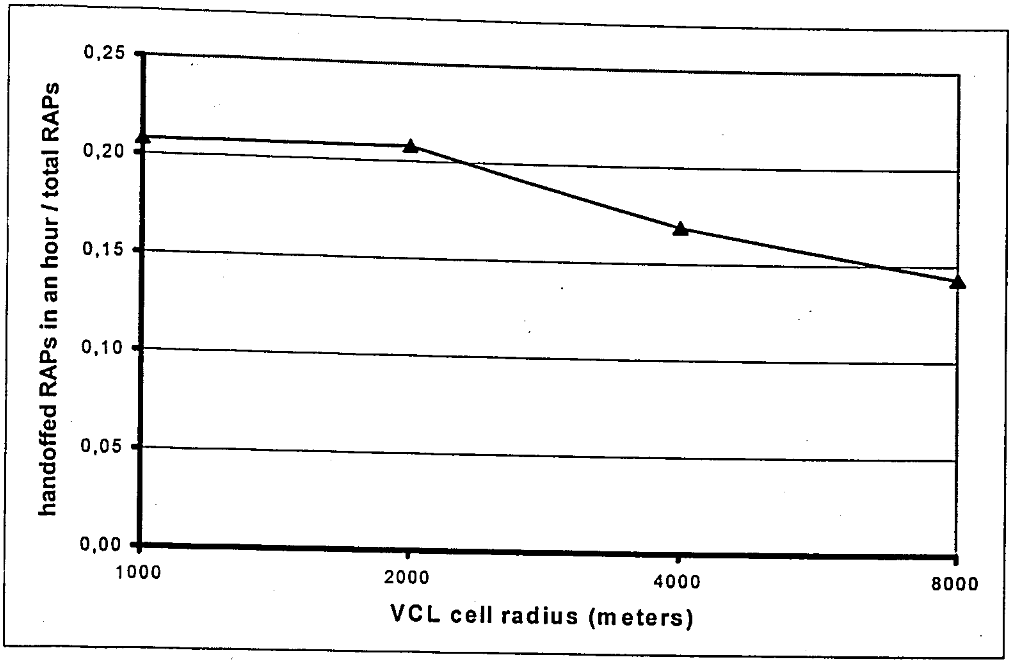


FIGURE 5.18. The rate of handoffed RAP numbers to the total number of RAPs.

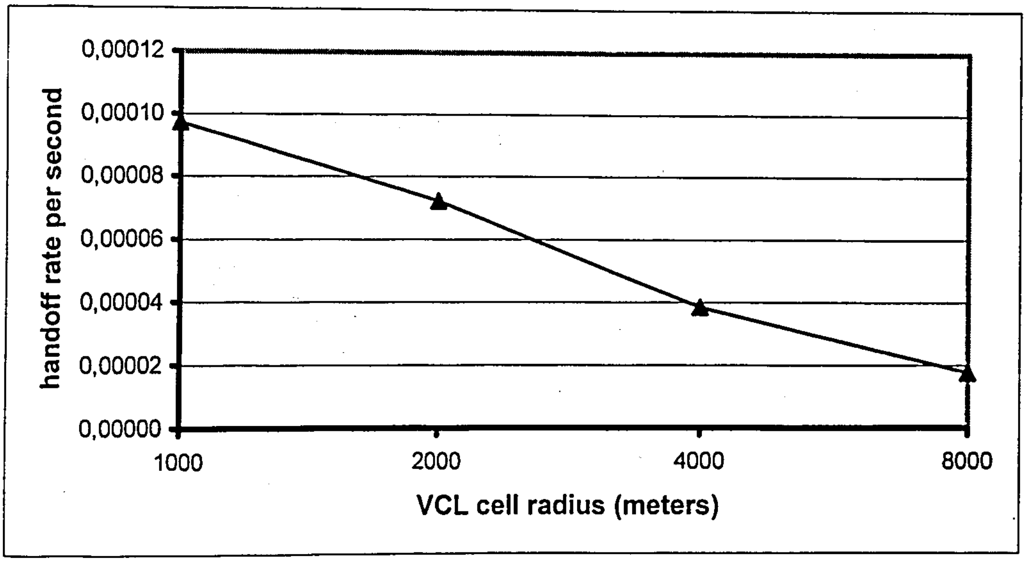


FIGURE 5.19. The RAP level handoff rates.

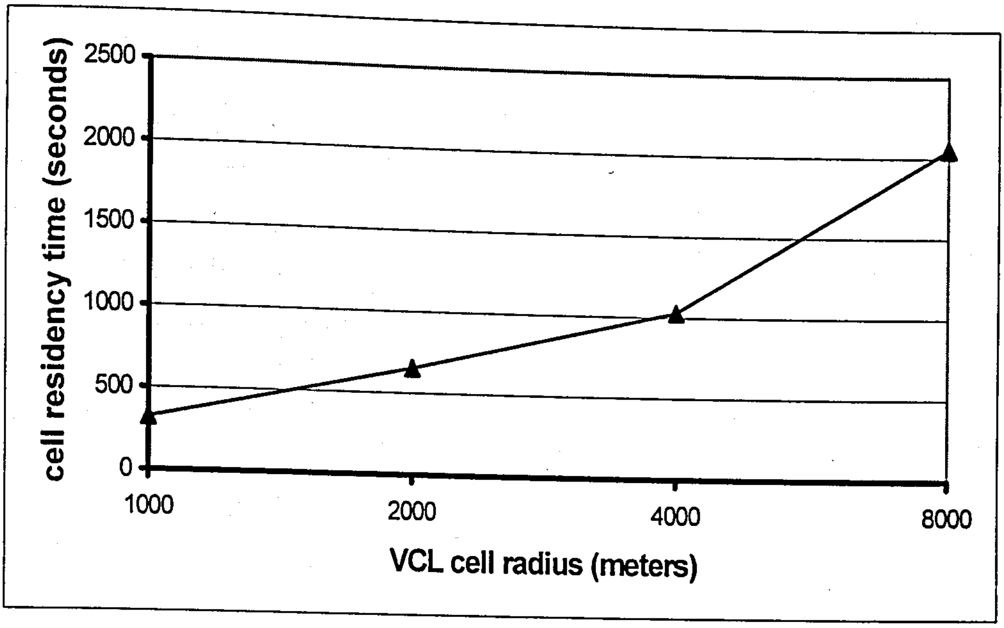
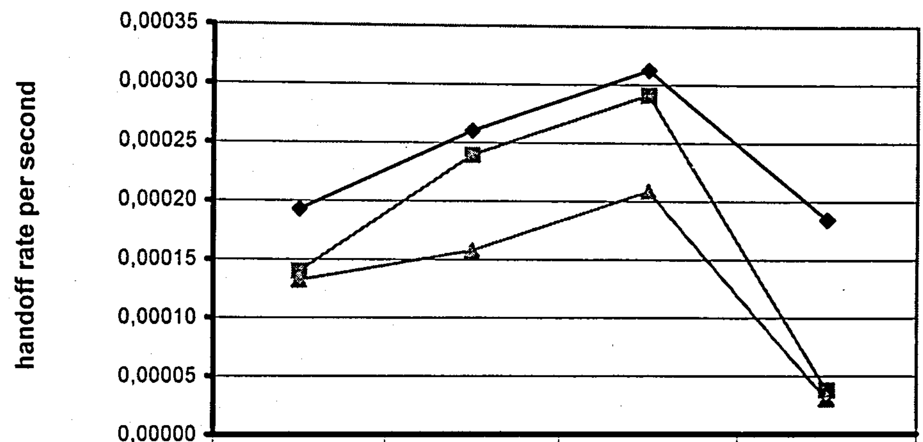


FIGURE 5.20. The average cell residency times for RAPs.

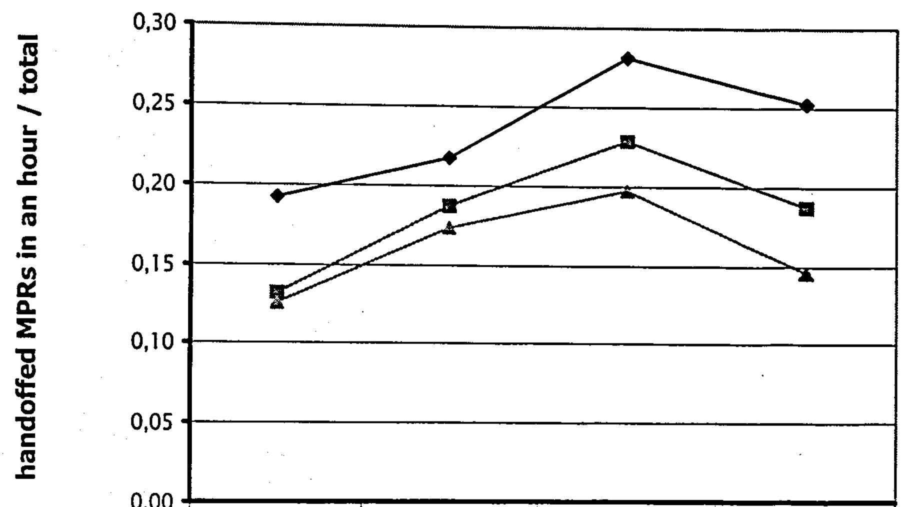


	1000	2000	4000	8000
mult factor=1	1,9E-04	2,6E-04	3,1E-04	1,8E-04
mult factor=2	1,4E-04	2,4E-04	2,9E-04	3,8E-05
mult factor=3	1,3E-04	1,6E-04	2,1E-04	3,0E-05

VCL cell radius (meters)

FIGURE 5.21. The MPR level handoff rates.

The results related to MPR level handoffs are illustrated in Figure 5.21, Figure 5.22 and Figure 5.23. The multiplication factor has a major effect in the MPR level handoff rates. As the multiplication factor gets higher, the real cell size gets larger. This normally decrease the handoff rates and increase the average cell residency times. However, we observe in the figures related to the MPR level handoffs that the handoff rates get higher as the VCL cell radii get larger until 4000 m. The number of MPRT cells is higher in small VCL cell radii, because the coverage of RAPs is less than the area covered by units when they are deployed. Since the MPRT cells move together with the registered subscribers in most of the cases, the need for an MPR level handoff decreases. That is the reason of the increase in MPR level handoff rates until 4000 m. When the radius is larger than 4000 m., a larger percentage of the handoffed MPRs become registered by RAPs. Though, the larger the real cell size gets, the lower the MPR level handoff rates become.

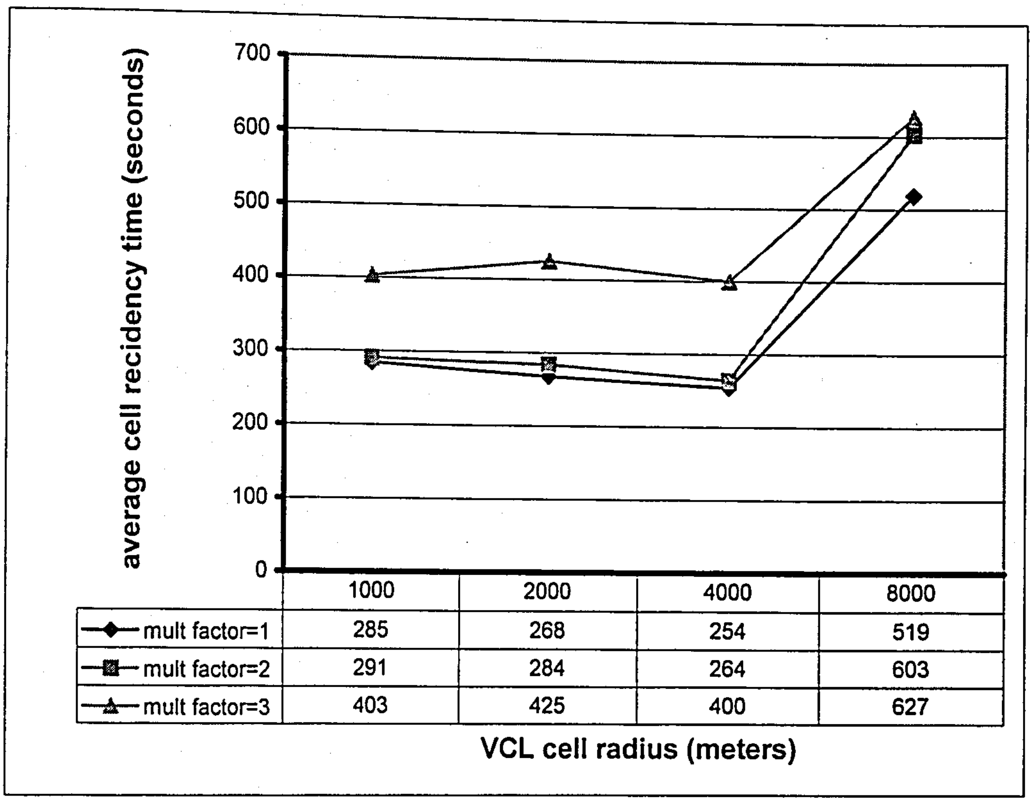


	1000	2000	4000	8000
mult factor=1	1,9E-01	2,2E-01	2,8E-01	2,5E-01
mult factor=2	1,3E-01	1,9E-01	2,3E-01	1,9E-01
mult factor=3	1,3E-01	1,7E-01	2,0E-01	1,5E-01

VCL cell radius (meters)

FIGURE 5.22. The rate of handoffed MPRs to the total number of MPRs.

The MPR level handoff rates per second is in the level of 10^{-4} as plotted in Figure 5.21. This indicates that most of the MPRs do not handoff even once. This can be observed also in Figure 5.22. After one hour of simulation less than 30 per cent of MPRs make handoff in the worst case. For that reason, the results related to cell residency times produced by the developed simulation system is not ample to have a good intuition about the speeds of MPRs relative to the bases by which they are registered, because this software calculates the average cell residency times of the handoffed MPRs. Since it takes hours for the most of the MPRs to handoff, and some of them even never handoff, these cell residency times should be much longer for overall average cell residency times than they are illustrated in Figure 5.23. For this reason we carried an analytical study and a simulation study specific to cell residency times.



	1000	2000	4000	8000
mult factor=1	285	268	254	519
mult factor=2	291	284	264	603
mult factor=3	403	425	400	627

FIGURE 5.23. The average cell residency times for MPRs.

In the analytical study, we examine the mobility of an MPR and RAP together to devise a cell residency time distribution model. In this model, the MPR and the RAP move at different directions with different speeds, but their speed and movement direction are determined according to the movement direction and speed of the owning unit. However, we assume that these directions and speeds remain constant during the modeling process. This assumption is made for the sake of tractability.

In Figure 5.24, the mobility patterns of the RAP and the MPR are illustrated, in which

Pb_o : Original position of the RAP.

Pb_d : Destination position of the RAP.

Pm_o : Original position of the MPR.

Pm_d : Destination position of the MPR.

β : The angle between the reference line and the line that connects two original positions.

α_b : The movement direction of the RAP according to the reference line.

α_m : The movement direction of the MPR according to the reference line.

V_b : The velocity of the RAP.

V_m : The velocity of the MPR.

T : The cell residency time.

R_t : The range of the transceiver equipments.

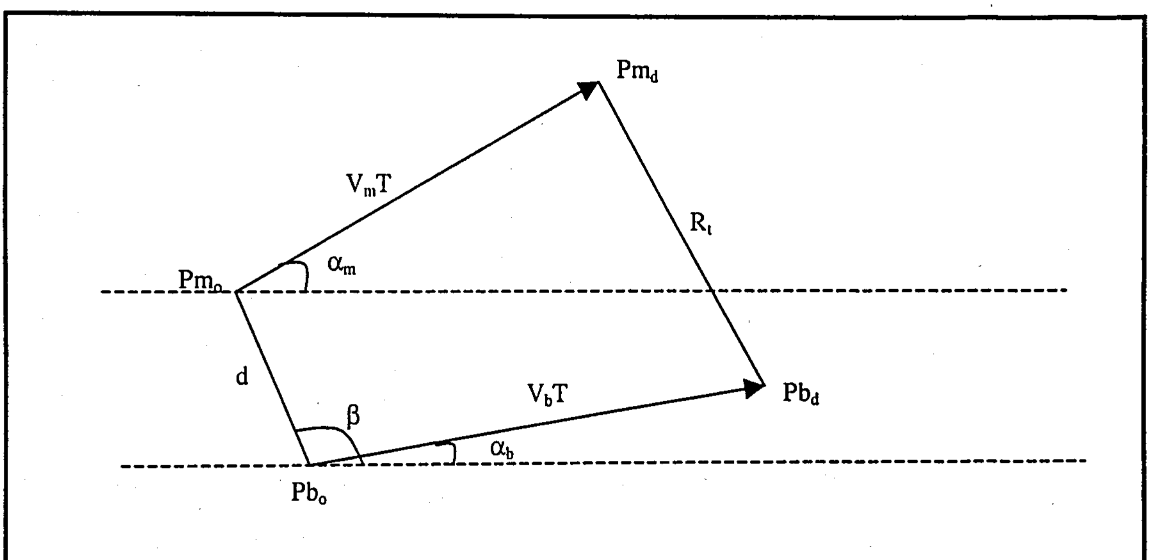


FIGURE 5.24. The illustration of the mobility pattern of two terminals.

The positions of the RAP and the MPR can be defined using a referential grid coordinate system:

$$Pb_o = \{ Xb_o, Yb_o \}$$
$$Pb_d = \{ Xb_d, Yb_d \}$$
$$Pm_o = \{ Xm_o, Ym_o \}$$
$$Pm_d = \{ Xm_d, Ym_d \} \tag{5.17}$$

Equation 5.18 is the geometric definitions of the destination positions according to the same coordinate system.

$$Xm_d = Xb_o + d\cos\beta + V_m T \cos\alpha_m$$
$$Ym_d = Yb_o + d\sin\beta + V_m T \sin\alpha_m$$
$$Xb_d = Xb_o + V_b T \cos\alpha_b$$
$$Yb_d = Yb_o + V_b T \sin\alpha_b \tag{5.18}$$

The distance between the destination positions in *X* and *Y* axis are determined by Equation 5.19.

$$Xdif = V_b T \cos\alpha_b - V_m T \cos\alpha_m - d\cos\beta$$
$$Ydif = V_b T \sin\alpha_b - V_m T \sin\alpha_m - d\sin\beta \tag{5.19}$$

We can derive the range from Equation 5.20.

$$R_t^2 = T^2 (V_b^2 + V_m^2 - 2V_bV_m \cos(\alpha_b - \cos\alpha_m)) -$$
$$T (2V_b\, d \cos(\alpha_b - \beta) - 2V_m\, d \cos(\alpha_m - \beta)) + d2 \tag{5.20}$$

T has two different values that can be found by Equation 5.21. If the both RAP and the MPR move at the same direction with the same speed, they stay within the range of each other forever.

$$T = \begin{cases} \infty & \text{, when } \alpha_m = \alpha_b \text{ and } V_b = V_m \\ \dfrac{V_b\, d\, \psi - V_m\, d\, \phi + \Delta}{V_b^2 + V_m^2 - 2V_bV_m\, \alpha} & \text{, otherwise} \end{cases} \tag{5.21}$$

where

$$\phi = \cos(\alpha_m - \beta)$$

$$\psi = \cos(\alpha_b - \beta)$$

$$\alpha = \cos(\alpha_b - \alpha_m)$$

$$\Delta_\alpha = d^2(\psi\phi - \alpha)$$

$$\Delta_\phi = d^2(\phi^2 - 1)$$

$$\Delta_\psi = d^2(\psi^2 - 1)$$

$$\Delta = \sqrt{V_m^2(\Delta_\phi + R_t^2) + V_b^2(\Delta_\psi + R_t^2) - 2V_m V_b(\Delta_\alpha + \alpha R_t^2)}$$

In Equation 5.21, the following are random variables: α_m, α_b, β, d, V_m, V_b. We assume that, among these random variables, β and d are independent and uniformly distributed random variables. Their probability distribution functions (pdf) are as follows:

$$f_d(d) = \begin{cases} 1/R & \text{, for } 0 \le d \le R \\ 0 & \text{, elsewhere} \end{cases} \qquad (5.22)$$

$$f_\beta(\beta) = \begin{cases} 1/2\pi & \text{, for } 0 \le \beta \le 2\pi \\ 0 & \text{, elsewhere} \end{cases} \qquad (5.23)$$

The direction of terminals are dependent on a central direction of movement *(α_c)* which can be accepted as a gravitation point. The pdf of the central movement direction and the equations for the movement directions of the RAP and the MPR *(α_b, α_m)* are as follows:

$$f_{\alpha c}(\alpha_c) = \begin{cases} 1/2\pi & \text{, for } 0 \le \alpha_c \le 2\pi \\ 0 & \text{, elsewhere} \end{cases} \qquad (5.24)$$

$$\alpha_b = \alpha_c + \theta\, \sigma_\alpha \qquad (5.25)$$

$$\alpha_m = \alpha_c + \theta\, \sigma_\alpha \qquad (5.26)$$

Similarly, the velocity of the RAP and the MPR are dependent on a central velocity *(V_c)*. The pdfs and equations for the velocities are as follows:

$$f_{V_c}(V_c) = \begin{cases} 1/V_{max} & \text{, for } 0 \le V_c \le V_{max} \\ 0 & \text{, elsewhere} \end{cases} \qquad (5.27)$$

$$V_b = V_c + \theta\,\sigma_v \qquad (5.28)$$

$$V_m = V_c + \theta\,\sigma_v \qquad (5.29)$$

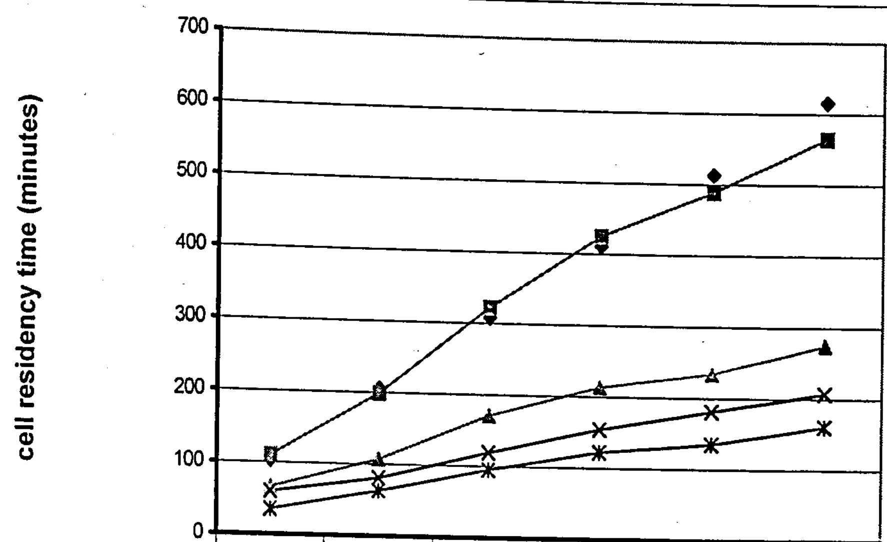
In equations 5.24 through 5.29, σ_v and σ_α are exponentially distributed random variables whose mean values are scenario dependent, and θ is a random variable with the following distribution.

$$\theta = \begin{cases} 1 & \text{, with probability } 1/2 \\ -1 & \text{, with probability } 1/2 \end{cases} \qquad (5.30)$$

By using these equations, we run some Monte-Carlo simulations for a case of V_c=10 km/h. In this study, we assume that the mean value for σ_v is typically 1 km/h (10 per cent of central velocity) and the mean value for σ_α is typically 5^0. The central movement of direction is assumed as 45^0. The value of central movement direction has no effect on the results. We run different simulations for the transceiver ranges from 500 m. to 6000 m. The results are plotted in Figure 5.23 as Monte-Carlo curve together with some other results.

We also implemented a simulation software specific for cell residency times with C that runs the model defined above with a difference. In the implemented software, the speeds and the directions of the terminals can change with some time intervals. With this software, we examine the cell residency times for different speeds and ranges. The results of these simulation runs are in Figure 5.25.

It is intuitively clear that the cell residency times should get shorter in higher average speeds. This also can be observed in our simulation results.



	1000	2000	3000	4000	5000	6000
◆ MonteCarlo Vc=10 km/h	103	205	308	411	513	616
Vc=10 km/h	110	199	322	425	489	565
Vc=20 km/h	66	107	171	213	234	274
Vc=30 km/h	60	81	119	154	181	207
Vc=40 km/h	35	63	95	122	135	161

cell radius (meters)

FIGURE 5.25. The illustration of cell residency simulation results.

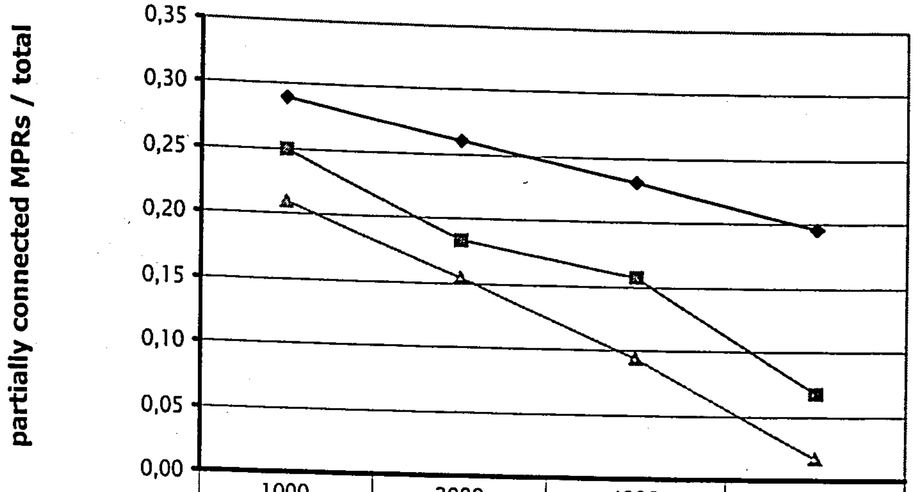
In Figure 5.25, we illustrate that the results of the Monte-Carlo simulations in which we used our analytical model match with the results of the simulation implemented specifically for cell residency times. This verifies our analytical study.

The average cell residency times calculated by these studies can be defined in the unit of hours. We believe that the real cell residency times should be even longer, because in the analytical study, we assume that the movement directions and speeds are constant. This is not a very accurate assumption, because the components of a unit are likely to keep the same pace and the same direction with the other components of the same unit. Because of this, even they move in different directions with different speeds on and off, they presumably change their courses with the one common for the unit that they belong to eventually. This makes the average cell residency times even larger.

In the second study, the average cell residency time is plotted as 122 minutes for the cell radius 4000 m. and the average speed 40 km/h. This indicates that the speeds of MPRs relative to the RAPs by which they are registered, are actually lower than 2 km/h (less than the pedestrian speed) which means that the mobiles in military cellular systems behave like the ones expected in low tier systems. This is a major advantage, because it indicates lower handoff signalling traffic and better radio transmission characteristics.

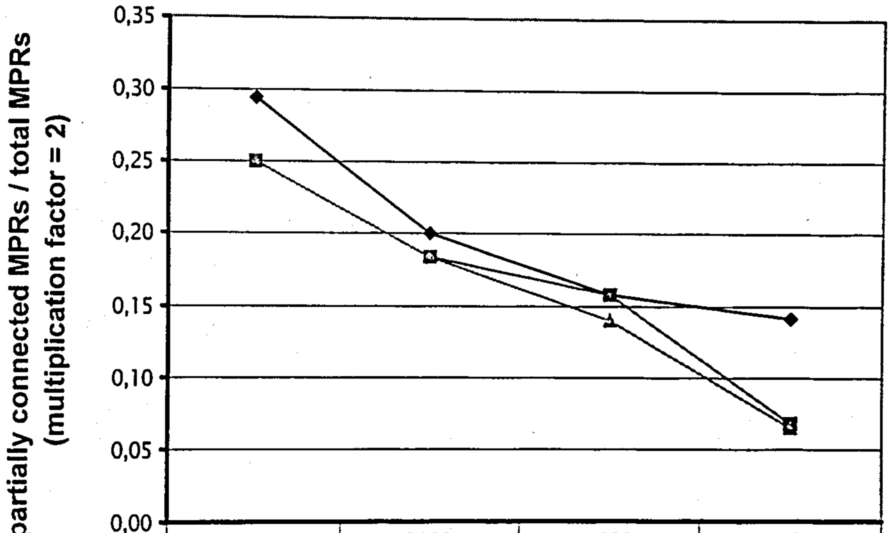
5.5.3. The Rates of Not Connected MPRs

In Figure 5.26 and Figure 5.27, the ratio of the number of partially connected MPRs to the total number of MPRs are plotted with respect to the multiplication factor and the number of available carriers respectively. Since the higher multiplication factor indicates that the larger areas are covered by real cells, the number of partially connected MPRs decreases in higher multiplication factors. Similarly, the more the available resources are, the more RAPs become active, and the larger areas are covered by the RAPT cells. When larger areas are covered by the RAPT cells, the number of partially connected MPRs decreases.



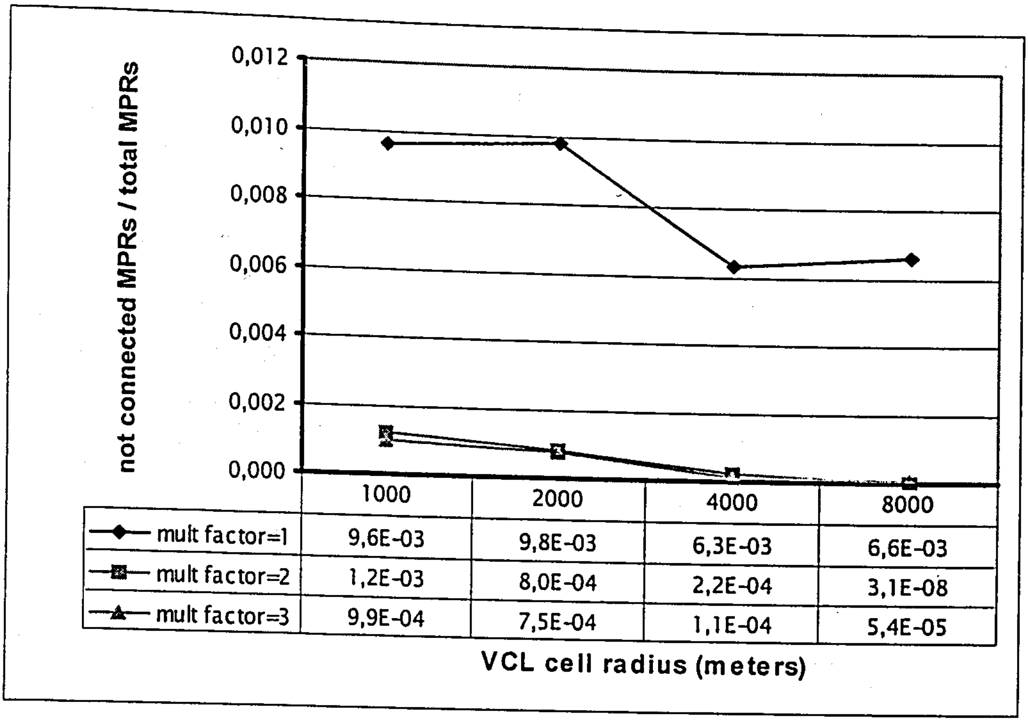
	1000	2000	4000	8000
mult factor=1	2,9E-01	2,6E-01	2,3E-01	2,0E-01
mult factor=2	2,5E-01	1,8E-01	1,6E-01	6,8E-02
mult factor=3	2,1E-01	1,5E-01	9,3E-02	1,8E-02

FIGURE 5.26. The partially connected MPR rates for different multiplication factors.



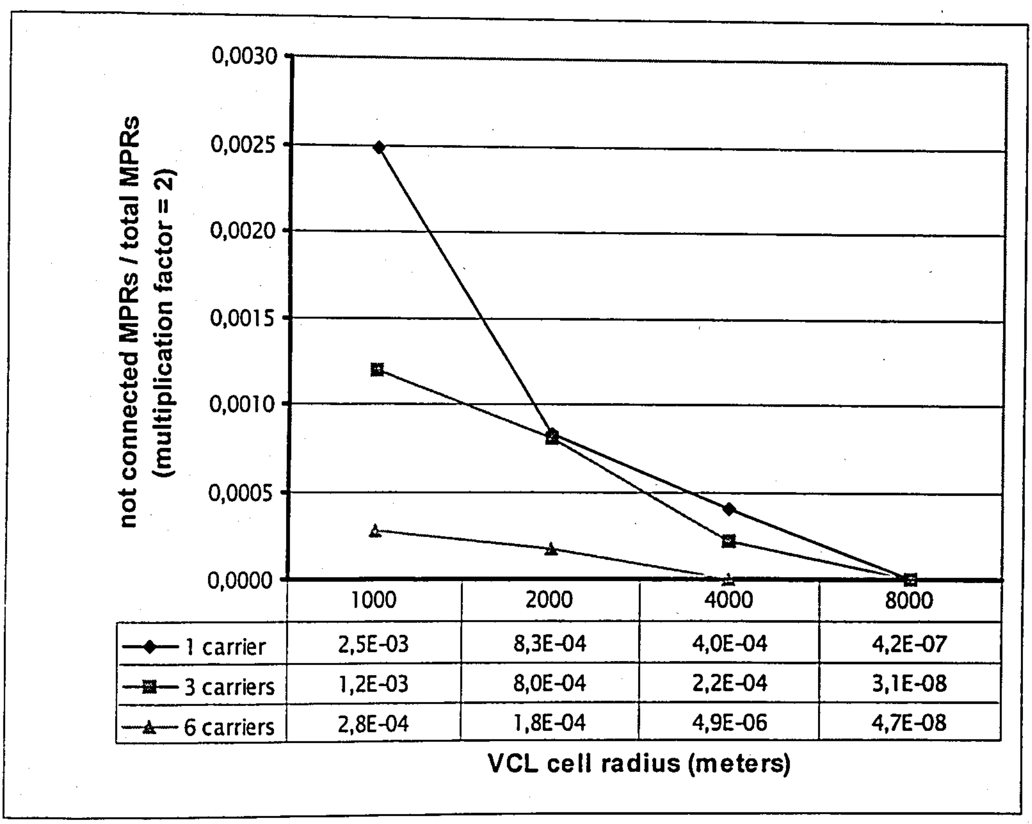
	1000	2000	4000	8000
1 carrier	3,0E-01	2,0E-01	1,6E-01	1,4E-01
3 carriers	2,5E-01	1,8E-01	1,6E-01	6,8E-02
6 carriers	2,5E-01	1,8E-01	1,4E-01	6,5E-02

FIGURE 5.27. The partially connected MPR rates for different number of carriers.



	1000	2000	4000	8000
mult factor=1	9,6E-03	9,8E-03	6,3E-03	6,6E-03
mult factor=2	1,2E-03	8,0E-04	2,2E-04	3,1E-08
mult factor=3	9,9E-04	7,5E-04	1,1E-04	5,4E-05

FIGURE 5.28. The not connected MPR rates for different multiplication factors.



	1000	2000	4000	8000
1 carrier	2,5E-03	8,3E-04	4,0E-04	4,2E-07
3 carriers	1,2E-03	8,0E-04	2,2E-04	3,1E-08
6 carriers	2,8E-04	1,8E-04	4,9E-06	4,7E-08

FIGURE 5.29. The not connected MPR rates for different number of carriers.

The observations that can be made on the not connected MPR rates are similar to the observations made for the partially connected MPR ratios with the following differences. The not connected MPR ratios are much lower than the partially connected MPR ratios. The effect of changing the multiplication factor from one to two is much more pronounced.

5.5.4. Different Scenarios

Based on the evaluated performance of the system, certain values are preferred for several parameters. We prefer using 2000 m. VCL cell radius and multiplication factor two with at least three carriers per each VCL cell for this scenario, because this configuration provides the best combination of call termination rates, call blocking rates and "*partially*" and "*not connected*" MPR ratios according to our priorities. However, this is an engineering decision depending on the scenario and the available equipment. For instance, if we have satellite and UAV cover which makes the "*partially*" and "*not connected*" MPR ratios less important, we may prefer a different VCL cell radius and a different multiplication factor.

The results of two different scenarios are compared with the results of the scenario we examined above. The second scenario includes less number of units which are less mobile. These units are deployed over an area which is the same in size with the first scenario. In the second scenario, the number of units is 49; the number of MPRs is 5721; and the number of RAPs is 30.

In the third scenario, 28 units are simulated during 30 minutes. Twenty RAPs and 3452 MPRs are deployed over a region which is 85 km × 40 km in size. This scenario which is a generic one is illustrated in Figure 5.30. The data related to this scenario is in "mercan.cmpe.boun.edu.tr". The name of the file which includes the data is "jtlsveri.dat". The details about the format of the data file is written in "readme.doc" file which is in the same directory with "jtlsveri.dat".

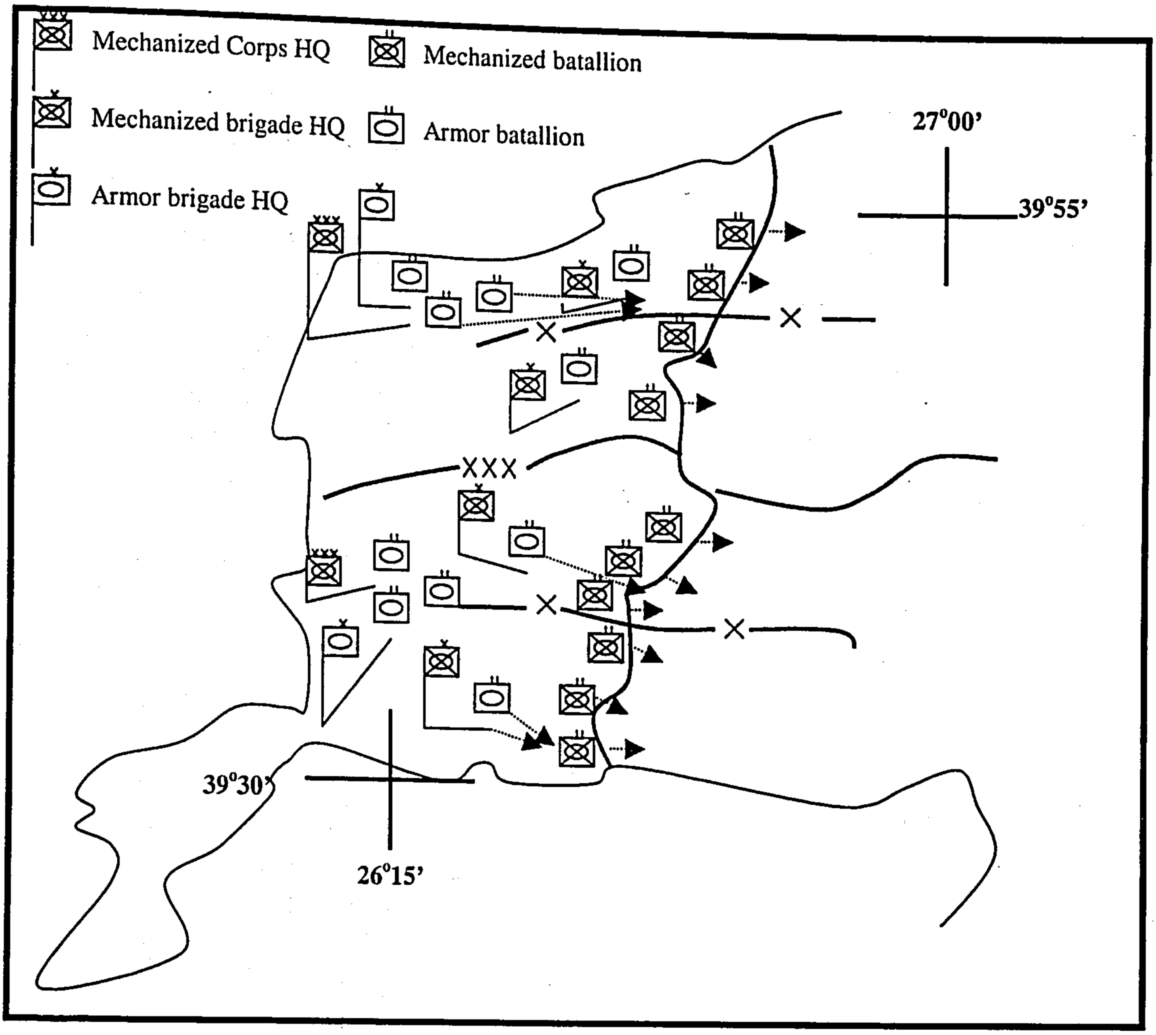


Figure 5.30. The illustration of the generic scenario.

The generic scenario is the most mobile one of the three scenarios. Almost every unit is moving in this scenario. It is also a dense one. However, headquarters are located close to battalions, and there are not units in company or lower level which are deployed in a distance from the battalions in the generic scenario. This changes the results, because we equip the battalions with RAPs. The results of the simulations made with these three scenarios are compared in Figure 5.31. The value axis does not have any unit in this figure. The values for the performance metrics are normalized to be able to visualize all performance metrics in a single figure.

Call blocking and RAP handoff performance of the generic scenario is the worst, because it is the most mobile scenario, and most of the units are in attack posture. Call rates in attack posture is higher than the others. On the other hand, the second scenario has the best call blocking and RAP handoff performance, because almost all of the units are fixed and in defend posture.

The MPR level handoff and partially connected MPR rates of the generic scenario are the lowest. In the first scenario, there are many units in company or lower levels which are deployed in a distance from the battalions. Since only battalions are equipped with RAPs, the partially and not connected MPR rates in the first scenario is the highest. In the generic scenario, the battalions have some distance from each other. This ensures that the RAP of a battalion registers most of the components owned by the battalion. Since the components of a unit moves together, the MPR level handoff rates decrease in this deployment scenario.

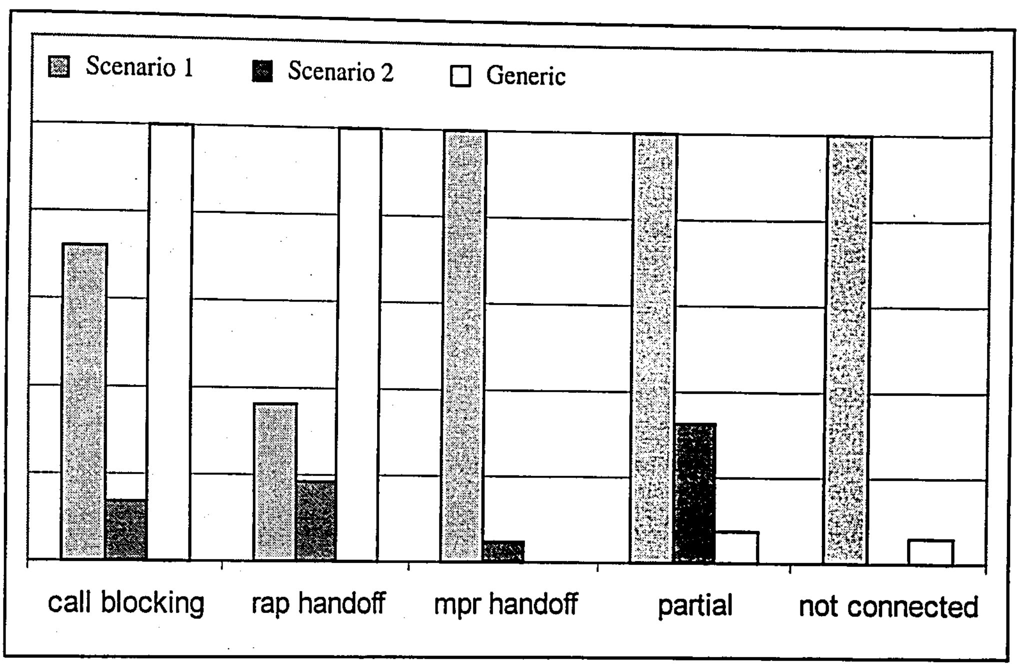


FIGURE 5.31. The comparison of three scenarios.

These comparisons indicate to some simple ways to enhance the performance of the proposed system. One of these techniques may be the possession and the deployment of extra RAPs. If we have such RAPs, we can deploy them to hot spots, and the locations where the units that do not own RAPs are present. Hence, we can eliminate some of the scenario dependent weak points such as the ones we have in the first scenario.

5.5.5. Summary of the Performance Evaluation

In our performance studies, we firstly evaluate how long the system needs to configure itself if all the components are turned on at the same instance. We found out that in the worst case, this takes two minutes for the scenario we used in our performance evaluation. Based on this finding, we omit the data related to the first two minutes while studying the average performance of the proposed system.

We found that call blocking rates are related with the VCL cell radius and the multiplication factor used to convert VCL cell radius to real cell radius. Since the intercell interference gets higher when the cell radius gets larger, the call blocking rates due to the lack of radio resources are higher in larger real cell radii. The multiplication factor has the same positive relation. Especially, the effect of changing multiplication factor from two to three is high. However, this positive relation turns to negative, when we examine call blocking rates due to unreachable destinations. Since the larger cell radii indicate that more MPRs can connect to the network, the call blocking rates due to unreachable destinations gets lower in larger radii. Call termination rates have the similar relations with the cell radii and the multiplication factor. However, call termination rates are almost zero in most of the cases. The call blocking rate due to the lack of resources is 10^{-3} with three carriers per VCL cell when the VCL cell radius is 4000 m., and the multiplication factor is two. Call termination rate is zero for the same configuration. We believe in that these are good results for even immobile infrastructures.

Based on the average cell residency times, we found that the average speeds of MPRs relative to the RAPs are lower than pedestrian speeds in our design. This is a major advantage, since it indicates better radio transmission characteristics. For the network configuration above, the MPR handoff rates per second is 10^{-4} which is very low. RAP handoff rates per second is 10^{-5} which is even lower.

When we are evaluating the rate of MPRs connected to the network, we assume that we do not have any UAV and satellite cover in the region. With the availability of higher tiers the results will get even better. However, although we assume the absence of overlay tiers, the call performance is of very good standards as stated above. The connection performance is of good standards, too. The rate of partially connected MPRs is 0.15, and the rate of not connected MPRs is 10^{-4} for the above configuration.

We believe in that the scenario we used is one of the worst scenarios for such a system, since it includes high number of units which are concentrated in some regions. These units are also more mobile than the units in an average scenario. When we apply our design to a moderate scenario, we found out that the system performs much better.

5.5.6. The Robustness of the Proposed System

The proposed system fulfills the rapid deployment requirement. It completes self-organization within two minutes in the case of all components are turned on at the same time without a requirement for much preparation prior to the deployment. After initial self-organization phase, it keeps a steady level in connected MPR ratios even if some of the components are destroyed by hostile actions. These are achieved with a mobile infrastructure. Since the infrastructure is mobile, it is more difficult to locate and destroy the infrastructure components, so the proposed system is more survivable compared to a fixed infrastructure one.

The evaluated call blocking rates and call termination rates are of good standards. Although the overlay tiers do not exist in our performance evaluation studies, the average ratio of not connected or partially connected MPRs are low. Based on the discussion related to call and connection performance, we can conclude that the proposed system gives an acceptable grade of service.

The system is designed as a distributed one. None of the components rely on another component to run. The components need to know their current state and to be able to sense the environment for the radio resources. Based on these information, they can access the communication network or at least a sub-network. The system ensures the communication between two nodes if this is physically possible.

Rapid deployment, survivability, reliability and acceptable grade of service are provided in a hostile environment through a mobile infrastructure with dense subscriber numbers. This indicates that the proposed system is robust.

6. CONCLUSION

Some of the dominating requirements for the next generation Tactical Communications Systems (TACOMS) determined based on the experience gained during the recent military conflicts can be enumerated as follows:

- More efficient spectrum utilization,
- Integrated communications,
- Both horizontal and vertical communications in and out of the command hierarchy,
- Lower power emission and consumption.

The next generation TACOMS which has been being developed for NATO has three major subsystems: namely Local Area Subsystem (LAS), Wide Area Subsystem (WAS), Mobile Subsystem (MS).

The MS should convey the multimedia communications among its subscribers who are the warriors in tactical battlefield, and provide both its subscribers with an access to the other subsystems of TACOMS and other subsystems with a connectivity with its subscribers. The basic characteristics of MS such as mobility, and hostile environment make the necessary MS requirements such as broadband integrated communications more difficult to be fulfilled.

It is believed that the evolving digital cellular systems, wireless computer networks, computer systems, global positioning and other technologies will cause a new breakthrough in the military communications systems. Among these, digital cellular networks come up as an approach that can fulfill all the requirements enumerated above. However, since the cellular paradigm stipulates a well designed immobile infrastructure to run, ad hoc approaches are preferred most notably in designing mobile tactical data communications networks. However, a true cellular MS which is compatible with the third generation mobile communications systems would be more efficient to fulfill the dominating requirements listed above.

We envisioned a multitier cellular MS in which Unmanned Aerial Vehicles (UAV) and satellites provide umbrella tiers for Radio Access Point (RAP) tier cells. In RAP tier, we devised some procedures and approaches to be able to use UMTS Terrestrial Radio Access (UTRA) as the radio access technique for the mobile terminals. These procedures are based on an approach that we devised and named as Virtual Cell Layout (VCL). In VCL approach, the communication area is tessellated with virtual cells by starting from a reference location. When a RAP (behaves like a mobile base station) enters into a virtual cell, it figures out its current cell from its current location, and grabs the resources according to it if the resources are not used up, then begins to broadcast in BCCHs and SYNC channels. The transmission range of the RAPs is found out by multiplying the VCL cell radius with a multiplication factor. We modified the initial cell search, registration, call and handoff procedures of UTRA by using this approach, and developed some new procedures such as RAP level handoff by which a RAP makes an inter resource handoff when it changes virtual cells.

We evaluate the performance of our design using some metrics such as call blocking and termination rates by a simulation software. The simulation software interacts with a constructive combat model, namely Joint Theater Level Simulation (JTLS), which runs by applying the commands entered during the previous Computer Aided Exercises (CAX), and retrieve the mobility, status, posture, and other related information for a number of units. These data is very realistic, since they are retrieved from the real exercises. Then the software enhances the resolutions and generates the calls by using the retrieved information, and run the designed system.

In the simulation studies, we found out that the VCL cell radius and multiplication factor has a major impact on the performance of the proposed system. When VCL cell radius and the multiplication factor get larger, the connectivity gets better. However the larger the multiplication factor gets, the higher the rates of call blocking due to the lack of radio resources become. The system performance related to the call blocking and termination rates are believed to be of good standards even for immobile infrastructures.

When we examine the cell residency times and handoff rates, we found out that the speeds of MPRs related to the RAPs by which they are registered is even lower than pedestrian speeds. Handoff rates per second are in the level of 10^{-4} for MPRs and 10^{-5} for RAPs. These are very good results, because they indicate low rates of handoff signaling traffic and better radio transmission characteristics.

The performance of the system is mainly based on the scenario. We believe that the scenarios which we used include high number of units heavily concentrated in some regions. When we use moderate scenarios, the system performance is expected to get better.

6.1. Future Work

In our study, we work on our proposal as a complete system, and leave the development of some procedures mostly related to the physical layer and the detailed performance studies on some components as future work.

We assume that the system works properly in satellite and UAV tiers, and the multiple tiers are integrated. The integration of the multiple tiers requires careful work for better performances.

In RAPT, RAPs replicate some other RAPs when there is not enough wireless resources. We assume that the replicating RAPs can detect the outages in the services of the replicated RAP, and if they do, they handover the tasks of the replicated RAP. The procedures and schemes related to outage detection and handovers must be studied in detail.

When the work on outage detection is carried for RAPs, a study that makes the system evolve towards a more fault tolerant and self healing architecture can be carried. Previous self healing studies for the ATM architecture promise some approaches for this work.

VCL approach can be applied to develop some more robust and distributed ad hoc network schemes without the existence of RAPT or other overlay tiers.

Timing and rerouting algorithms for interfrequency handoffs for RAPs are not studied in detail in our thesis. The details related to the execution stage of the RAP handoffs which are hard handoffs must be studied. Alternatives such as marking, last sent and last received techniques must be compared against some metrics such as required signaling traffic and execution time.

Alternative handoff techniques such as MCHO, NCHO and MAHO for MPR handoffs which can be both soft and hard must be compared and studied in detail, too. Since, the distributed techniques are preferred for military technologies, we used MCHO in our implementation.

Rerouting during the handoffs, most notably in RAP handoffs, is critical and must be designed very carefully. Rerouting work carried for wireless ATM offers some approaches. These approaches together with some alternatives can be examined to develop some efficient and robust rerouting techniques.

HLR-VLR approach is adapted for our architecture. Since the destinations of the calls are generally in the vicinity of the originating terminals in battlefield, equipping each access point with a VLR is justified. This also make the system more robust. However, this approach increase the signaling traffic and the hardware costs of the components. Because of this, some alternative techniques for location management is also another field for future work.

Lastly, the application of the distributed election algorithms (Silberschatz, 1992) to the self organization schemes of the proposed system, and the usage of the directional antennas for capacity enhancement are left as future studies.

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