A PCS Based Architecture for Tactical Mobile Communications

Erdal Cayirci *Cem Ersoy*

Computer Networks Research Laboratory
Bogazici University, Istanbul
cayircie@boun.edu.tr ersoy@boun.edu.tr

Abstract

There are some major distinctions between the military and commercial communications. We can enumerate the most basic two of them as the hostile environment, and the rapid deployment requirement. In our study, we discuss how to employ emerged and evolving civilian 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 reference location. The radio resources are managed in a multitier hybrid network by employing both cellular and ad hoc techniques and using VCL. The evaluated performance of the system shows that the VCL based architecture satisfies the rapid deployment requirement and gives an acceptable grade of service.

Keywords : Tactical Communications, Mobile Subsystem, Personal Communications Services, Wideband Code Division Multiple Access

1. Introduction

The next generation tactical communication systems leverage evolving and emerged technologies to provide the battle forces with an efficient, robust, flexible and tailorable network that can convey multimedia traffic [17, 52, 57]. They have four subsystems in common, namely the Wide Area Subsystem (WAS), the Local Area Subsystem (LAS), the Mobile Subsystem (MS) 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 a breakthrough in mobile battlefield communications. 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.

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 [56]. 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 UMTS. UTRA uses Wideband Code Division Multiple Access (WCDMA) [16] in the paired band, and hybrid Time Division Multiple Access/CDMA in the unpaired band [3].

In this paper, we discuss 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 us to manage the 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 $N=3$ fixed frequency reuse plan [20]. 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, too. 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 find out 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 simulations or combat models [10]. 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 simulations, 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. We implemented this system and named as CAX Interacted Tactical Communications Simulation (CITACS).

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.

In the next section, we discuss the key issues related to cellular and ad hoc paradigms and PCS technologies. After elaborating some features of the next generation tactical communications systems, we explore the algorithms used by the mobiles, and the mobile infrastructure of an architecture based on VCL in Section 4. Then the results of the performance evaluation studies are examined in Section 5. Finally, we present some concluding remarks in Section 6.

2. Wireless Networking

Two paradigms, namely cellular and ad hoc, can be distinguished in wireless networking which is the way to provide the mobile users and the mobile networks with an access to a communications network [6]. The most basic difference between these paradigms is the existence of a fixed infrastructure. Cellular networks which can be accepted as the single hop version of more general ad hoc networks require a large and carefully designed immobile infrastructure.

2.1. Multiple Access Schemes

Both in cellular and ad hoc paradigms, an efficient Multiple Access (MA) scheme is needed to fulfill the bandwidth requirements of multimedia services. Since wireless media is more error prone and has limited capacity, MA is even more critical issue in cellular and ad hoc networks. We can categorize MA schemes into two broad classes as contention based and conflict free protocols [3, 54]. In random access channels, contention based protocols such as slotted ALOHA are usually preferred. On the other hand, static or dynamic conflict free resource allocation techniques are generally used in dedicated traffic channels.

There are three well known static conflict free MA schemes, namely Frequency Division Multiple Access (FDMA) [21, 28, 37], Time Division Multiple Access (TDMA) [19, 21, 28] and Code Division Multiple Access (CDMA) [4, 21, 28, 33, 50]. The number of techniques in the class of dynamic conflict free MA schemes is higher. We can enumerate three of these techniques as, Packet Reservation Multiple Access (PRMA), Dynamic TDMA (D-TDMA) and Resource Auction Multiple Access (RAMA) [51].

CDMA studies which was started as a military communications technology initiative have gained great interest for commercial applications for two decades, since CDMA promises some advantages including the ones listed below:

- Since CDMA has a soft capacity which is interference limited, any reduction in interference cause an increase in capacity. There is no need for an extra effort to utilize the unused idle periods in voice channels, because these periods indicate a reduction in interference. Similarly spatial isolation enhance CDMA capacity. Everything that reduces interference cause an increase in the soft capacity of CDMA without a need for an extra effort.
- The overhead of channel separation is avoided in CDMA.
- Since CDMA can use the entire spectrum in every cell, advantageous soft handoffs which is explained later can be used.
- CDMA is a more secure and reliable MA technique, because it spreads the signal into a large spectrum.

In CDMA, power control is necessary because of the near-far problem [6, 30, 34, 60]. Although it seems as a disadvantage, it brings up some major advantages such as higher capacity because of lower interference and lower power consumption.

There are two CDMA techniques, namely Frequency Hoping (FH) CDMA and Direct Sequence (DS) CDMA. In FH-CDMA, an active call hop over a number of frequency channels with a hoping pattern which is named as code. If two or more hops are made for each symbol, it is called fast hoping. If two or more symbols are transferred in each hop, it is called slow hoping.

In DS-CDMA, users access to the same wide frequency channel simultaneously. Transferred signals are spread to the carrier by direct application of assigned waveforms, known as sequences or codes. Receiver is equipped with the knowledge of the spreading code, and it can decode the received signal by applying the same code [20]. Most of the next generation cellular networks will presumably use DS-CDMA technique. Because of this, it has a significant importance among the MA schemes.

2.2. Cellular Paradigm

In cellular networks, the region of communications is tessellated with cells [18, 37, 45] in which an access point often named as the base transceiver station or Radio Port (RP) provide a wireless communication path with every point within the cell. Cellular networks brings up a number of advantages [11] which can be summarized as follows:

- Since the communication distances are low because of the cellular architecture, the use of lower powered equipment with low power consumption is possible. This also indicates smaller handsets.
- Since the transmissions are carried with low power, the same frequency channels can be used in short distances which means higher subscriber density in the same spectrum.

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

- Mobility management : Since the subscribers are mobile, tracking their locations (registration strategies, deregistration 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.

Location management is another term which is often used synonymously with mobility management [7, 38, 39]. There are two parts in location management. The first of them is updating the databases related to location management. In cellular networks, databases named as Home Location Register (HLR) and Visitor Location Register (VLR) based on ITU-T Recommendation Q.1001 are used generally. The records in these databases are updated in registration and deregistration. The registration techniques are categorized into four classes in literature [7]: movement based, time based, request based and on/off based. Similarly deregistration techniques classified as explicit, timeout and implicit deregistration schemes [40]. The second part of the location management is related with subscriber notification on call arrival. This process is named as paging.

One of the unique features of cellular networks is handoffs [26, 43, 45]. In a handoff, a communicating terminal leaves an RP and continues to communicate through another RP which provides better radio transmission quality. Handoffs may require some extensive signaling which should be completed in stringent time limits. The volume of required signaling traffic and computation for handoffs is strongly related to the level in hierarchy effected from the handoff [11].

Handoff decision is made based on one of the following measurements [45]: word error indicator, received signal strength indicator and quality indicator. The handoff techniques can be classified into three groups according to the way used to decide for handoff:

- Mobile Controlled Hand Off [MAHO] : In this technique, the measurements and handoff decision are made by the mobile.
- Network Controlled Hand Off [NCHO] : In this technique, the measurements and handoff decision are made by the network.
- Mobile Assisted Hand Off [MAHO] : In this technique, the mobile makes the necessary measurements and sends the results to the network. The network decides for handoff based on these measurements.

Rerouting the traffic to a new path is a critical issue in handoffs. During handoff the path between two ends of ongoing communication is reestablished according to one of the following strategies [5]: full, incremental or multicast based reestablishment schemes.

Handoffs may end up with loops which means returning to the cell left before. If more than a single cell is visited during a loop, it is called a macro loop. If the number of cells visited in a loop is only one, it is called a mini loop. Ping-pong effect or hysterises occur when mini loops are repeated continuously with some short time intervals. Because of this, most of the systems do not decide on handoff as soon as a better RP is found, and wait until the quality difference is over a determined threshold. Incremental path re-establishment which is often named anchor based rerouting reduces the signaling traffic most notably in the case of loops

Based on the MA scheme used, we can further categorize handoff schemes as soft [61] and hard handoffs. In CDMA, soft handoffs which means establishing the new path before breaking the older one is possible. In a hard handoff, the old communication path is left and then a new communication path is established. The phase of changing the paths is critical most notably in hard handoffs. There are different methods such as marking, last sent and last received for this stage of handoff.

Capacity assignment is the most important task of resource management, especially when CDMA is not used in MA. Different capacity assignment techniques can be listed as follows [29, 62]:

- Fixed Capacity Assignment (FCA) : Each cell is assigned a number of carriers according to a reuse pattern.
- Dynamic Capacity Assignment (DCA) : All carriers are in a common pool initially. They are assigned to the cells as needed.
- Hybrid Capacity Assignment (HCA) : It is the combination of FCA and DCA.

2.3. Ad Hoc Paradigm

For ad hoc paradigm, there are three major research areas apart from the other common ones related to wireless networking, namely topology maintenance for connectivity, scheduling for interference minimisation, and routing. Routing is actually a research area which is the combination of topology maintenance and scheduling studies.

Ad hoc networks are dynamic in topology since they do not have a fixed infrastructure. Links between nodes change or even nodes of the network can change the locations which indicates changes in more than a single link. The links may fade gradually due to mobility or they may be lost suddenly due to hostile actions or failures in nodes. In such a dynamic environment, maintaining the correct graph of the network in the nodes is a both demanding and required task. Topology maintenance schemes are classified according to the following criteria in the literature [1, 2]:

- Active or passive.
- On demand (event driven) or continuous (time driven).
- Centralised or distributed.

Event driven schemes update the topology only in the event of a topology change. On the other hand, time driven algorithms carry topology maintenance tasks periodically. In centralized schemes, the topology database is maintained in a central system. In distributed schemes, every node manage its own topology database.

As a distributed topology maintenance scheme, the usage of mobile agents has been proposed in literature [9]. Mobile agents are software entities that move from one machine to another. While they are moving, they maintain their view of the current topology.

Scheduling [53, 58] is required to avoid from collisions which is also named as interference. There are two types of interference: primary interference and secondary interference. If a node is to perform multiple operations at the same time, such as receiving and transmitting, a primary interference occurs. When a transmitter interferes the receiving end of a transmission unwillingly, it is called secondary interference. Scheduling means assignment of the radio resources in a way that no interference occur. Various schemes are proposed in the literature for topology maintenance and scheduling [24, 58, 59].

Routing strategies is classified into two broad categories in literature [41, 55]: table driven routing protocols and source initiated on demand routing protocols. There are many algorithms and approaches that fall in one of these classes.

2.4. Personal Communications Services

In the American National Standards Institute (ANSI) approved standard, "Personal Communications Terminology" (ANSI T1.702-1995), PCS is defined as follows [27]: "A set of capabilities that allows some combination of terminal mobility, personal mobility, and service profile management." The ultimate goal of PCS is to be able to communicate with a person, at any time, at any place and in any form [48]. Terminal mobility requires wireless access to the PCS networks. Personal mobility is enabled by the usage of personal identification numbers. Service portability is the result of service profile management.

We can categorize PCS networks into three classes according to their evolution. The first generation includes analog systems that can transfer voice trafic. Advanced Mobile Phone Service (AMPS) in the United States, Nippon Telephone and Telegraph (NTT) in Japan, Total Access Communications System (TACS) in the United Kingdom, Nordic Mobile Telephones (NMT) in European Countries are some well known first generation systems. Their major problems were low capacity and poor quality.

The second generation systems like digital cellular and cordless telecommunications systems have deployed for the last decade. The best known three examples of digital cellular systems are Global System for Mobile Communications (GSM) in Europe [22], Personal Digital Cellular (PDC) in Japan, and Interim Standard 54/136 (IS 54/136) and IS 95 in North America. In these systems, TDMA is used as an access technique, except for IS-95 which is based on CDMA. All of these digital cellular systems are high tier systems. A mass market has been achieved through the second generation networks.

Since the third generation (3G) systems are expected to evolve from the existing second generation systems, there will be different standards in different regions of the World. However, International Mobile Telecommunications-2000 (IMT-2000) family concept promise the required base for global roaming capability of 3G terminals. International Telecommunications Union (ITU) develops IMT-2000 standards [8, 49]. Universal Mobile Telecommunications System (UMTS) [15, 31, 36, 42] which is expected to be deployed in Europe starting from the year 2002 is being developed by European Telecommunications Standardization Institute (ETSI). The 3G systems differ from the second generation systems most notably with multimedia communications and global roaming capabilities.

ETSI selected UMTS Terrestrial Radio Access (UTRA) technique in January of 1998. The key characteristics of UTRA is summarized in [32, 44, 46, 47] as follows:

- For the paired bands (1920-1980 and 2110-2170) Wideband CDMA (WCDMA) will be used in Frequency Division Dublexing (FDD) operation (UTRA/FDD Mode).
- For the unpaired bands of total 35 MHz time division CDMA (TD-CDMA) will be used in Time Division Dublexing (TDD) operation (UTRA/TDD Mode).
- UTRA/FDD is based on 5 MHz WCDMA with a basic chip rate of 4.096 Mchips/s. Higher chip rates are intended for the future evolution of the WCDMA 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.
- WCDMA physical layer Transport Channels (TrCh) which are very similar to GSM TrChs are Synchronization Channel (SYNC), Broadcast Control Channel (BCCH), Forward Access Channel (FACH), Paging Channel (PCH), Random Access Channel (RACH), Dedicated Physical Control Channel (DPCCH) , Dedicated Physical Data Channel (DPDCH). Each TrCh has a Transport Format (TF) which is simply a transfer rate set from which Medium Access Control Layer (MAC) can choose one for each connection.

3. The Next Generation Tactical Communications Systems

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 communication 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 communication medium characteristics: The communications may be carried via the tethered or untethered nodes through the wires, the optical fibers, the air or even through the sea.
- Rapidly changing communication locations: The regions covered with extensive communication 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 applications: 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 [17, 35, 52, 57]:

- 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.

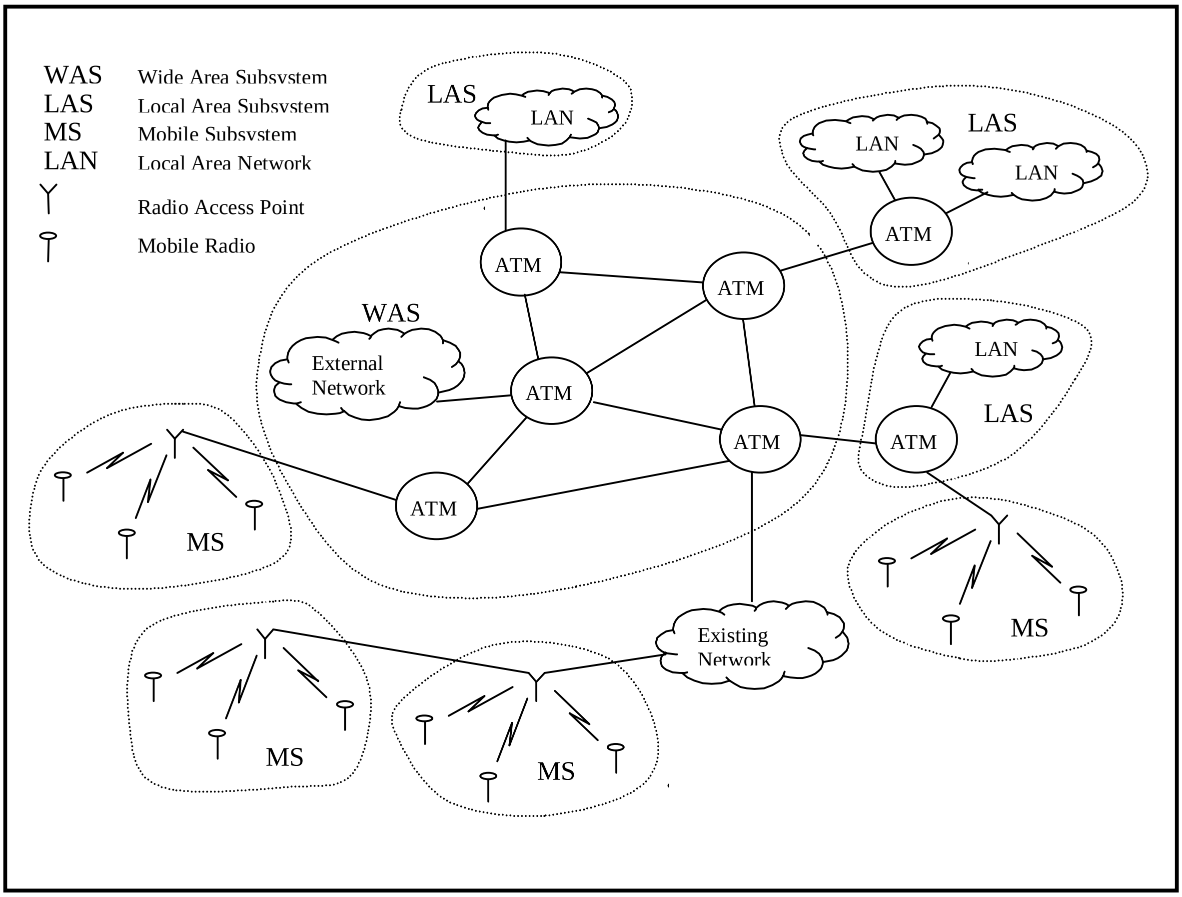


Figure 1. The next generation tactical communications systems.

In order to satisfy these requirements by using evolving technologies, intensive research activities are carried out both in the U.S. and in NATO, such as Defense Information System

(DISN) [57], Post-2000 Tactical Communications (TACOMS) [52], Global Mobile Communications [35]. Figure 1 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). A security system is also integrated to the architecture to provide the security services related to the communications.

The WAS connects other subsystems as a wide area backbone. ATM serves as the multiplexing and switching architecture of this subsystem.

The LAS can be considered as a nomadic Local Area Network that can access to WAS or available commercial networks. Headquarters and similar organizations that sustain in restricted areas are provided with networking support by the LAS.

Mobile users such as warriors in battlefield access to the tactical communications system through the MS. The MS may operate as an independent communications network or be a part of the overall tactical communications system through an access to the WAS.

The SMCS which is a subsystem integrated to the architecture provides the network administrators with system management functions.

The technology components of this architecture and its subsystems are examined in detail in [57]. Among these components RAPs and mobile radios have a key role in the proposed system. Mobile subscribers in the battlefield can access the integrated services through these components. RAPs will convey the multimedia traffic among its subscribers and between the WAS and the MS that it creates. In the rest of this paper, we use the term Man Packed Radios (MPR) instead of Mobile Radios. We envision MPRs as the equipment that has similar capabilities with Future Digital Radios (FDR) [57]. They can transmit and receive through more than a single carrier simultaneously. Although we call them MPR, they may be mounted on various types of vehicles.

4. The Proposed Architecture

We propose VCL as a resource management aid in an MS that uses both cellular and ad hoc techniques with a mobile infrastructure. In Figure 2, the MS that we envisioned is illustrated. In this MS architecture, there are four tiers:

- Man Packed Radio Tier (MPRT): This is the low tier part of the MS. One of the Man Packed Radios (MPRs) act as a cell head, and the cell head or one of the other MPRs act as a gateway to the other tiers, the other cells or directly to a WAS access point.

- Radio Access Point Tier (RAPT): This is the high tier macrocellular part of the MS. The Radio Access Points (RAPs) which act as mobile base stations should have the same capabilities with the ones defined in [57]. 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.
- Unmanned Aerial Vehicle Tier (UAVT): This is the first level overlay tier of the MS. The 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.
- Satellite Tier (SATT): This is the topmost overlay tier over the UAVT.

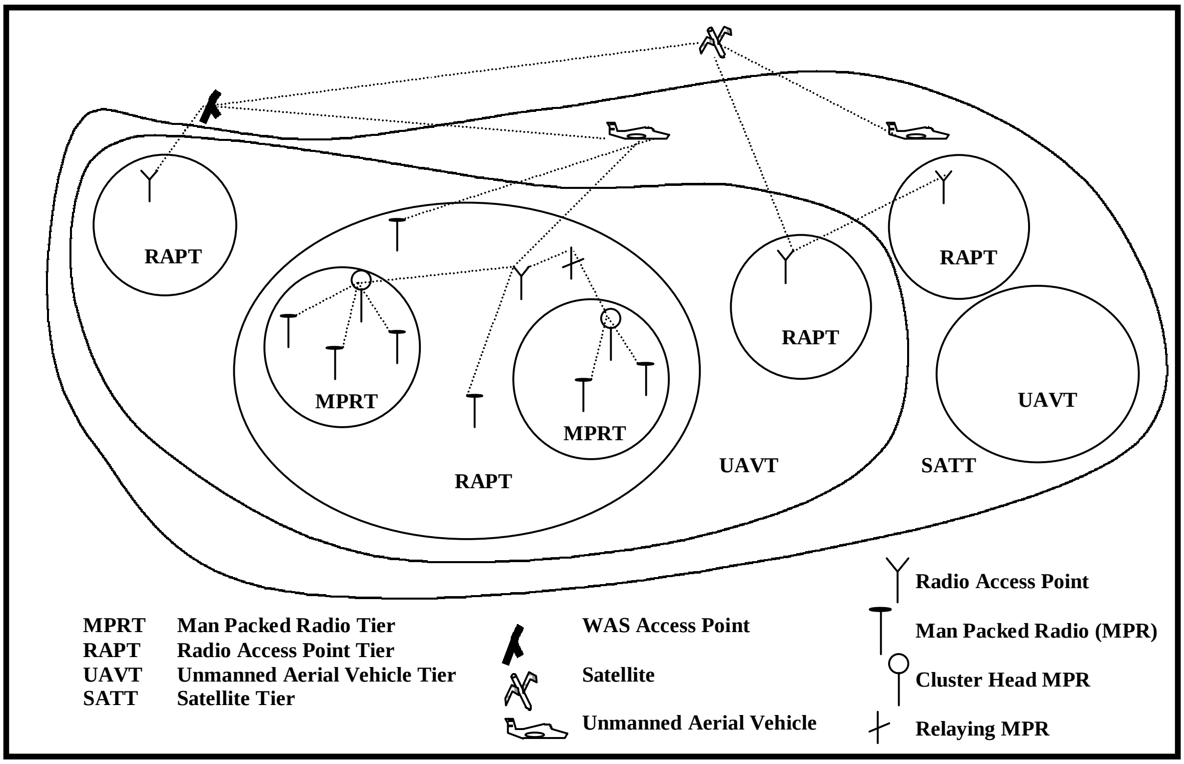


Figure 2. Multitier mobile subsystem.

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 get registered by 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. They can handoff to the upper or the lower tiers, too.
- MPRs may reach to one of the tiers by multihop since we utilize ad hoc techniques 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.

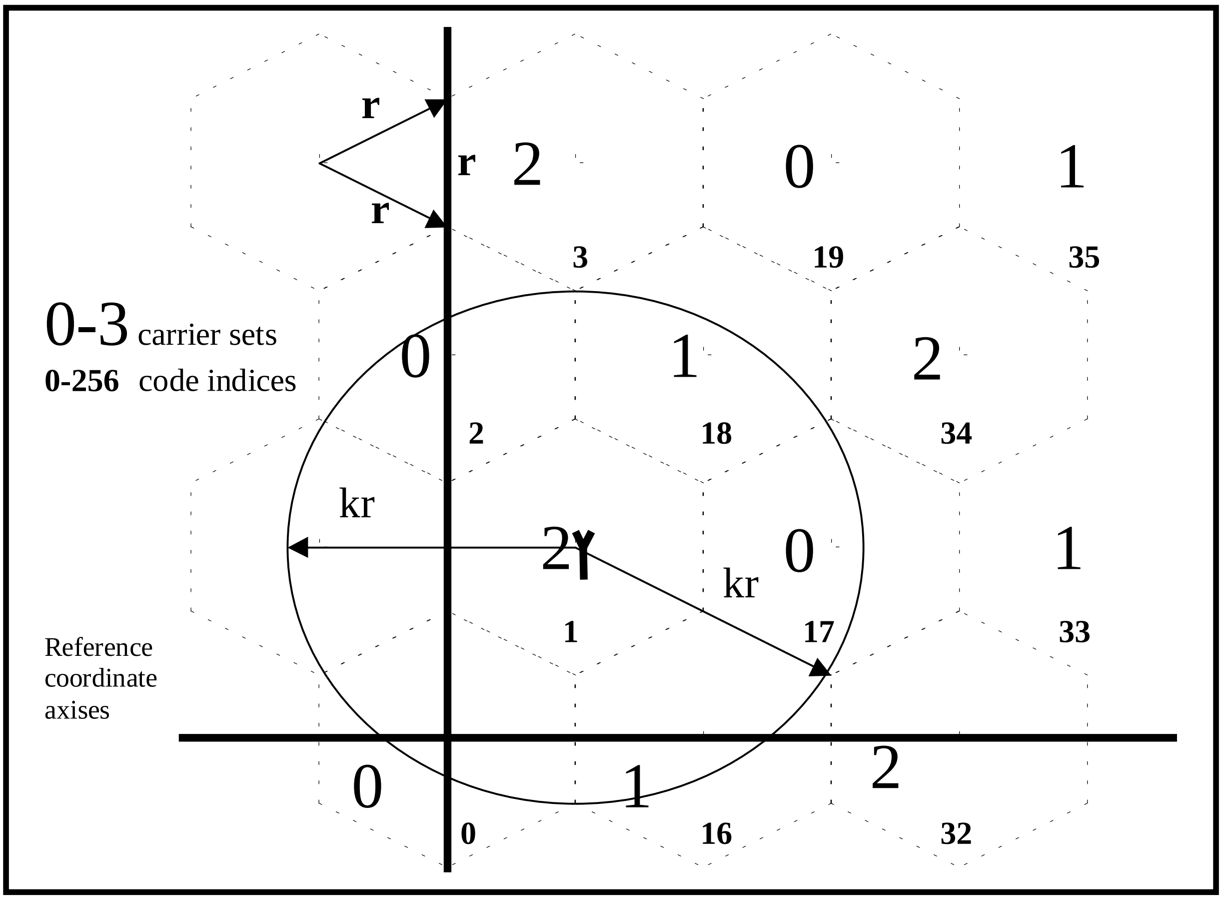


Figure 3. Virtual cell layout.

In VCL, the communications area is tessellated with virtual cells which are regularly shaped and sized hexagons that are placed starting from a reference geographic location. 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.

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.

The carrier frequency set is a set of carriers. 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 $N=3$ fixed frequency reuse plan [20] as illustrated in Figure 3. $N=3$ 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.

UTRA uses 512 short (scrambling) codes. We divided them 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; one for RAPs and one for MPR cluster heads. This implies that we distribute 256 code sets among the VCL cells as illustrated in Figure 3. Each code is also related with one preamble code used to access the Random Access Channel (RACH) in UTRA [16].

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 (GPS), the use of other location finding approaches [25], and manual entry of the location information if the previous approaches are not applicable.

Based on VCL approach we devised some mobility and resource management algorithms for a cellular network with a mobile infrastructure. The details of these algorithms and approaches are in [12, 13].

5. Performance Evaluation of the Proposed Architecture

We use the data collected in Computer Aided Exercises (CAX) to evaluate the performance of the proposed approach. The commands entered during these exercises are replayed in Joint Theater Level Simulation (JTLS) to produce realistic mobility and event patterns. JTLS is a highly aggregated joint combat model [10]. It is the most commonly used constructive model in the joint exercises of NATO. Although JTLS can provide us with the most realistic mobility, posture and status data related to a large number of units, its resolution should be enhanced to evaluate the performance of a system that requires high resolution. We developed a tactical communications simulation system that interacts with JTLS and enhance it's outcomes to create and move the communication components owned by the units modeled by JTLS. Then, these components are assigned with calls which are generated by models related to call destinations, call arrivals and call duration based on a statistical study. We implemented this software system in the computer networks research laboratory (NETLAB) of Bogazici University and named as CAX Interacted Tactical Communications Simulation (CITACS). CITACS uses JTLS results to drive a simulation that accumulate data for some performance metrics determined for the analyzed tactical communications system.

5.1. CAX Interacted Tactical Communications Simulation

The architecture of CITACS [14] is illustrated in Figure 4. In this architecture, JTLS provides the mobility, event and tactical posture data for the simulated units. The commands entered during a previous CAX are replayed and a translator converts the results of this simulation into the format needed for CITACS. Then, a simulation manager, reads the collected data, and 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 for each minute. This resolution is enhanced to radios for each second. The simulation manager runs the implemented algorithms 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.

A large set of factoring parameters are used in our performance studies. A separate simulation is run for each combination of the factoring parameters by using CITACS. Then, reports related to the determined performance metrics are generated by the post processor. For the performance evaluation of the proposed architecture, the factoring parameters we use are cell radius, multiplication factor (k), bit energy to noise density ratio (E_b/N_o), available bandwidth, the ratio of voice traffic to multimedia traffic, and different distributions for call arrival rate and call duration. Our performance metrics are call blocking and termination rates, handoff rates per second, cell residency times, the ratio of handoffed components to the total number of components, the ratio of components that can not get connected to the network.

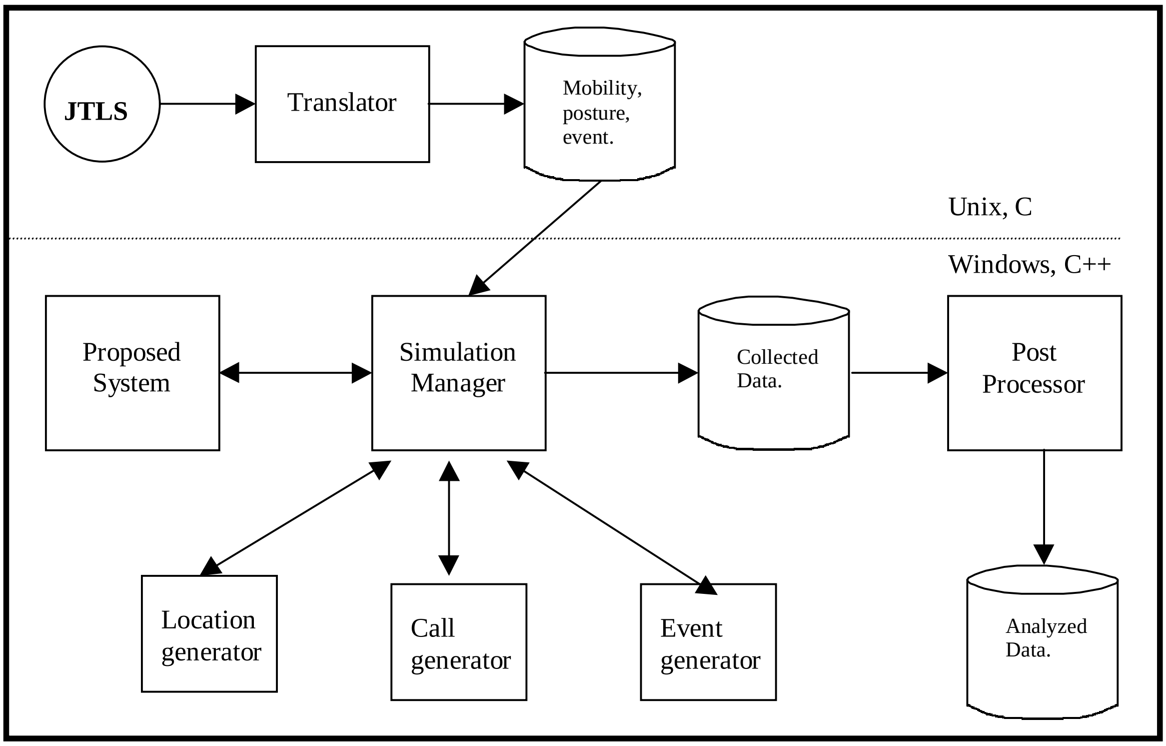


Figure 4. The architecture of CITACS.

We use two military scenarios in our performance studies. We run most of the simulations by using the first scenario. The second scenario is run for the best configuration of the first scenario to compare the effects of different scenarios on the performance. The geographical regions in both of the scenarios are the same in size. 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 deploy 77 RAPs and 18529 MPRs with these units. During 2 hours of simulations, 52 MPRs and 2 RAPs are 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.

5.2. Self Organization Performance of the Proposed System

Firstly, we analyze 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 and in Figure 6. "*Partially connected*" MPRs belong to an MPR cluster that can not communicate with the other clusters or the higher tiers. These MPRs can communicate only to the MPRs in the same cluster with them. "*Not connected*" MPRs are isolated MPRs. They are out of the range of any other MPR or RAP. 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.

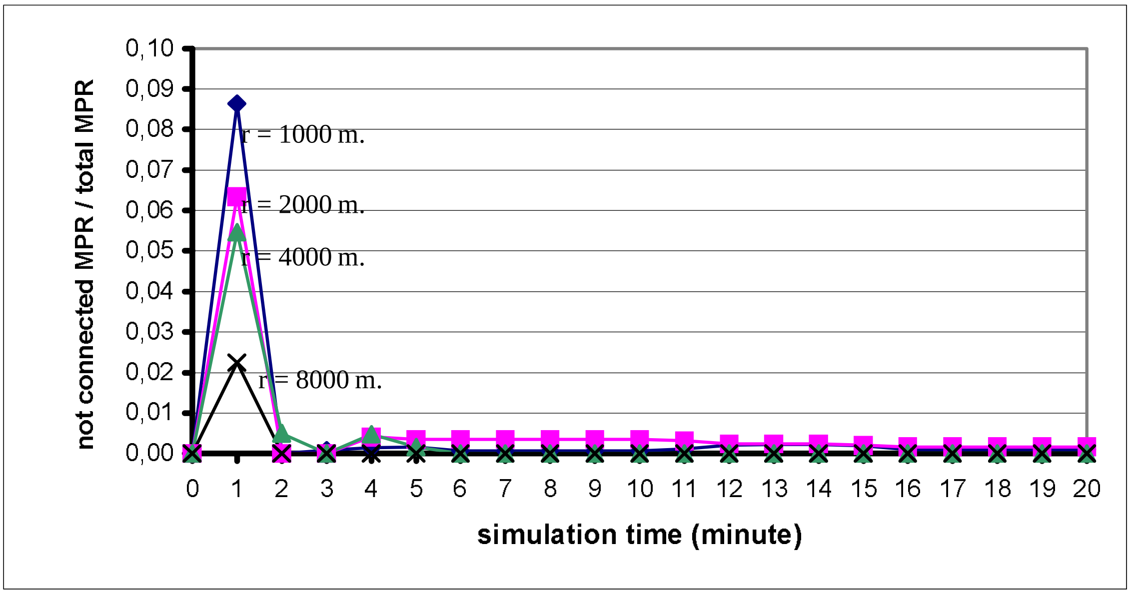


Figure 5. Not connected MPR ratios for each minute.

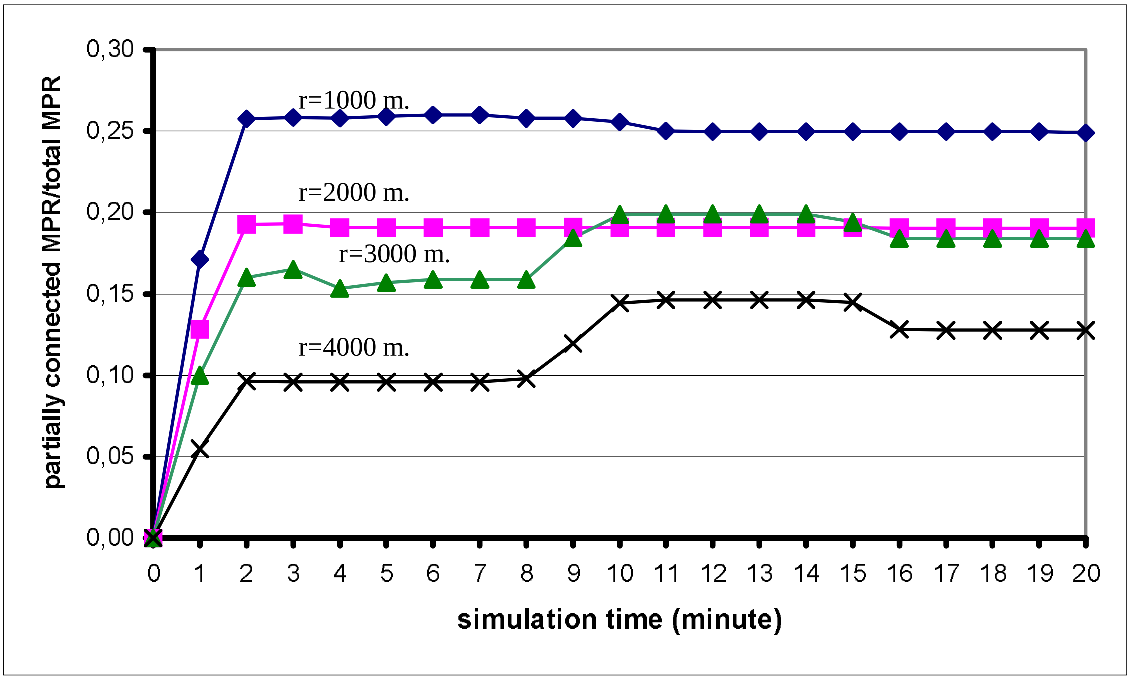
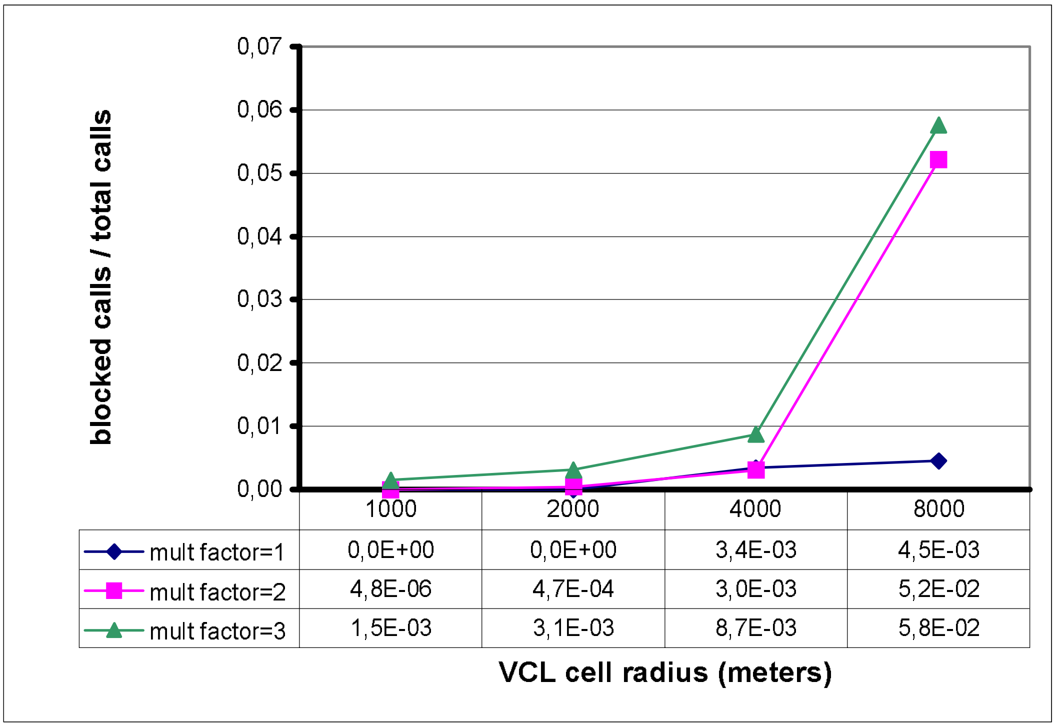


Figure 6. Partially connected MPR ratios for each minute.

5.3. Call Performance of the Proposed System

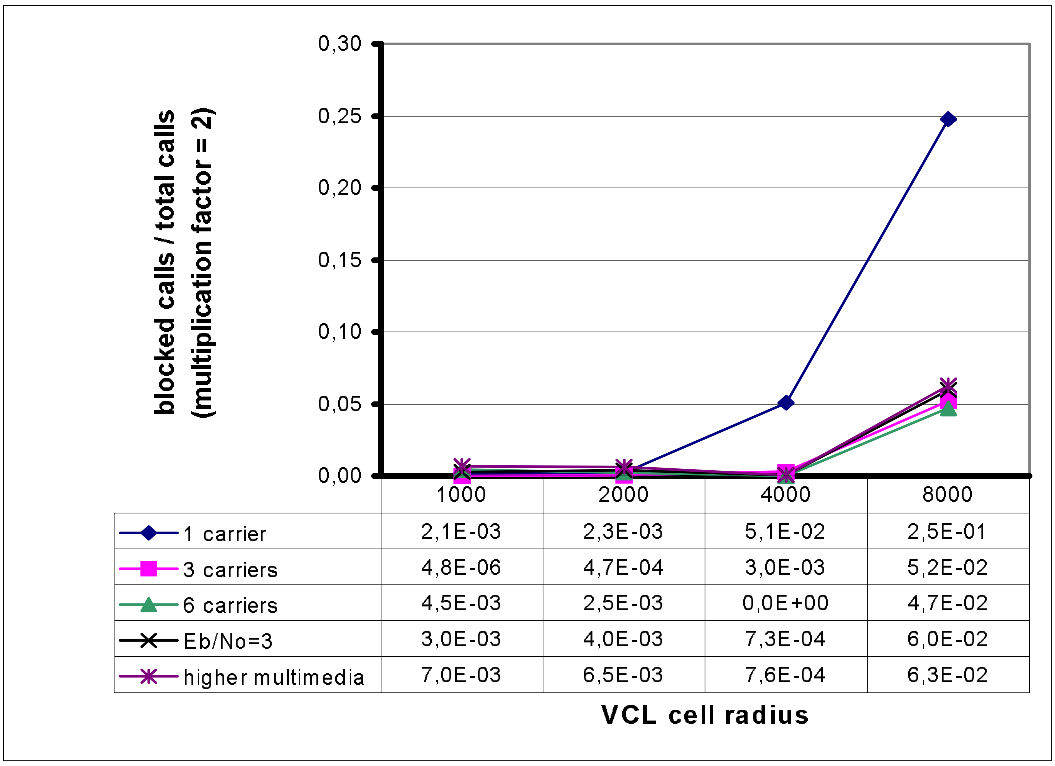
Figure 7 illustrates that the call blocking because of insufficient radio resources increases when the VCL cell to real cell multiplication factor gets higher. When the range of RAP transmission equipment gets larger, their interference on the RAPs using the same frequency carriers gets higher, too. 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 RAP, when the multiplication factor is larger than one. The effect of the multiplication factor and the radius is analytically examined in Appendix A.

In Figure 8, 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 8, 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.



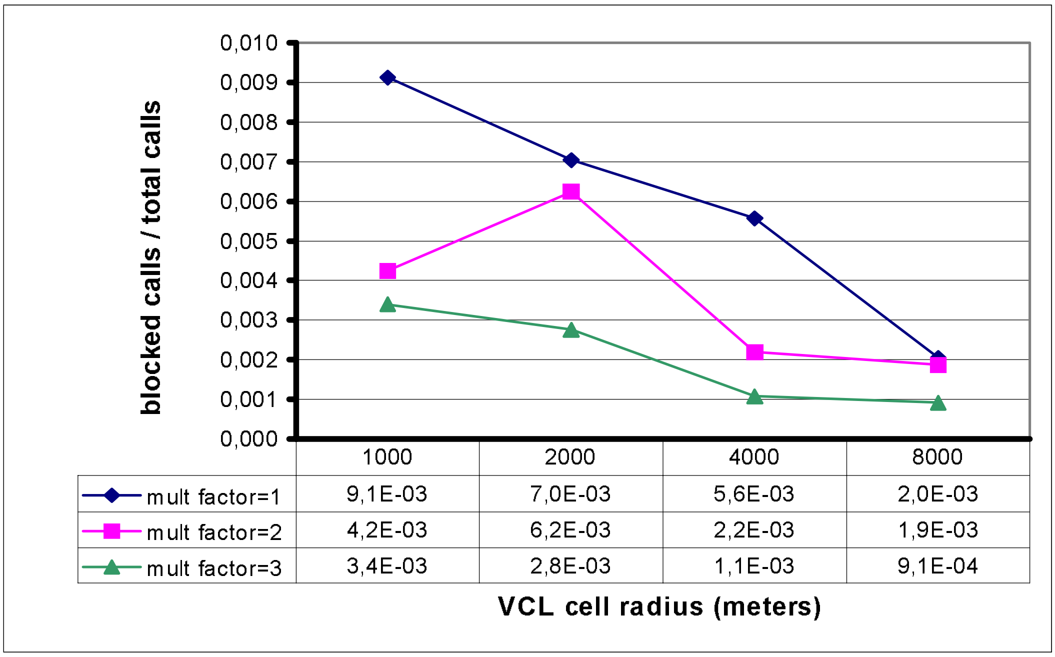
	1000	2000	4000	8000
mult factor=1	0,0E+00	0,0E+00	3,4E-03	4,5E-03
mult factor=2	4,8E-06	4,7E-04	3,0E-03	5,2E-02
mult factor=3	1,5E-03	3,1E-03	8,7E-03	5,8E-02

Figure 7. 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

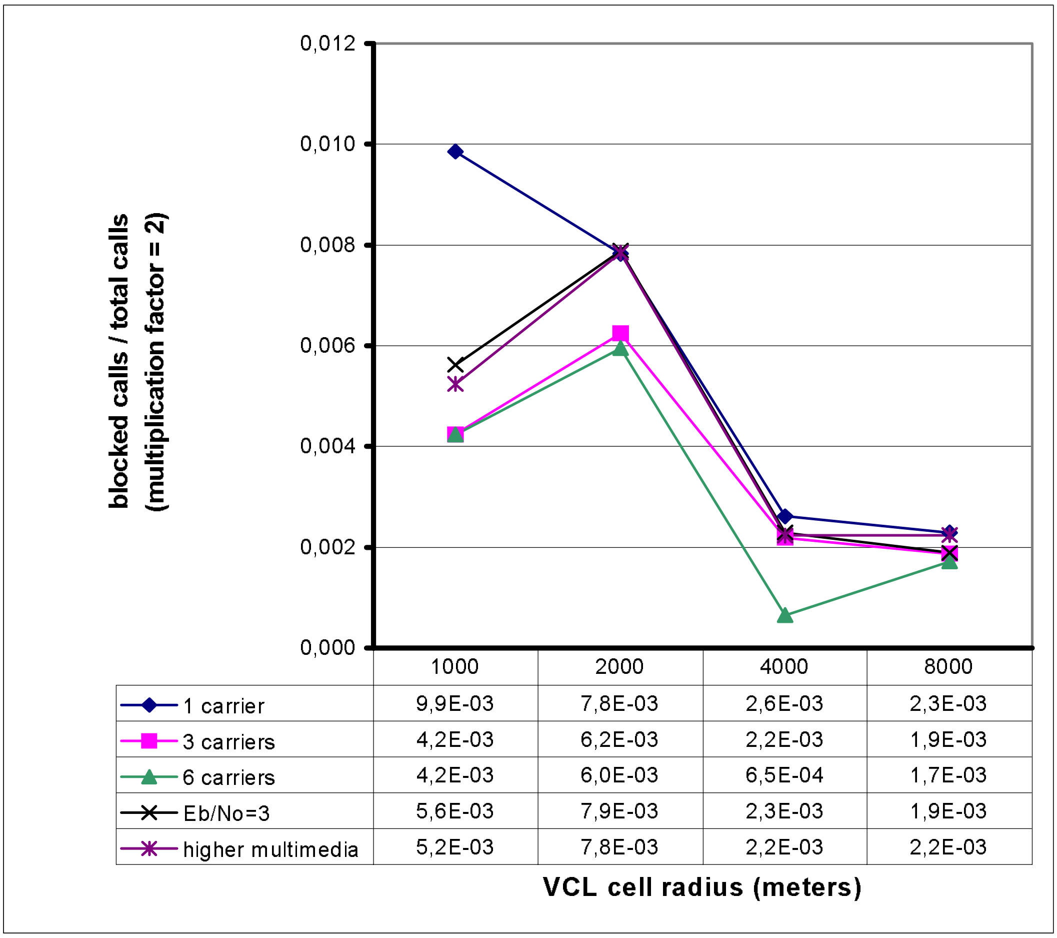
Figure 8. Call blocking (because of the lack of resources) for different number of carriers and media characteristics.



	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

Figure 9. Call blocking (because of unreachable destinations) for different multiplication factors.

In Figure 9, 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 due to 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. 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 10, because the multiplication factor is two for all of the curves in Figure 10.

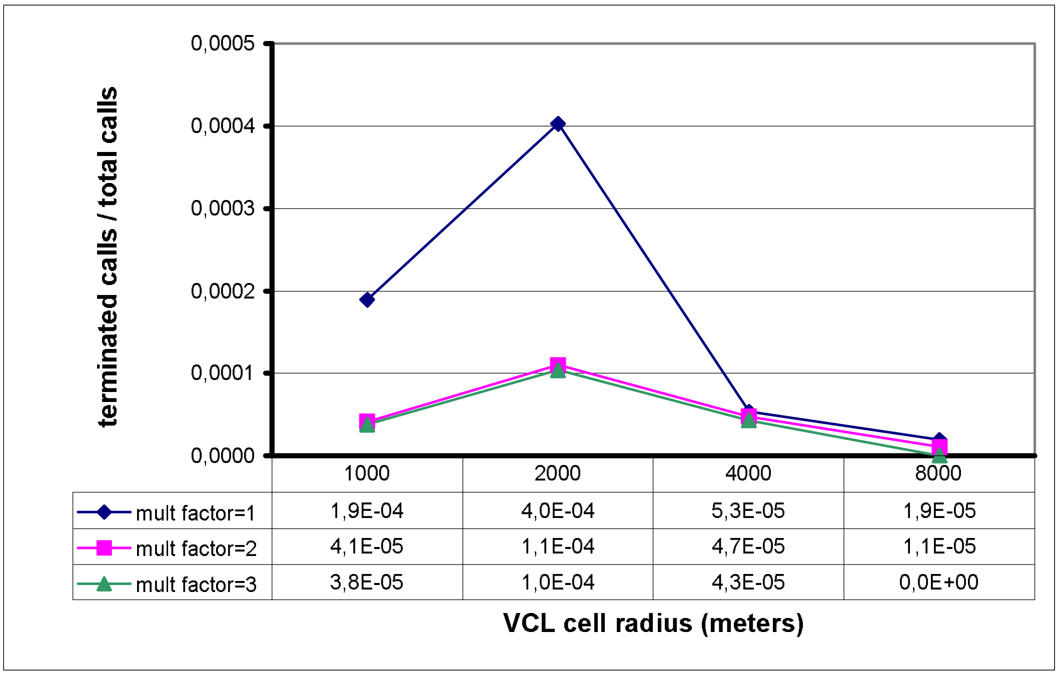


	1000	2000	4000	8000
1 carrier	9,9E-03	7,8E-03	2,6E-03	2,3E-03
3 carriers	4,2E-03	6,2E-03	2,2E-03	1,9E-03
6 carriers	4,2E-03	6,0E-03	6,5E-04	1,7E-03
Eb/No=3	5,6E-03	7,9E-03	2,3E-03	1,9E-03
higher multimedia	5,2E-03	7,8E-03	2,2E-03	2,2E-03

Figure 10. 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 10. 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.

The call termination rates 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. It is illustrated in Figure 11 that the higher the multiplication factors get, the lower rates of call termination due to the unreachable destinations become.



	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 11. Call terminations because of the unreachable destinations.

5.4. Handoff Performance of the Proposed System

In Figure 12, the number of handoffed RAPs in an hour to the total number of RAPs ratio is plotted. Approximately 13% 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 statistics related to handoff rates and the average cell residency times for different cell radii are given in [13]. 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. We also note that we do not record any RAP which cannot find available radio resources in the newly entered VCL cell during a RAP level handoff.

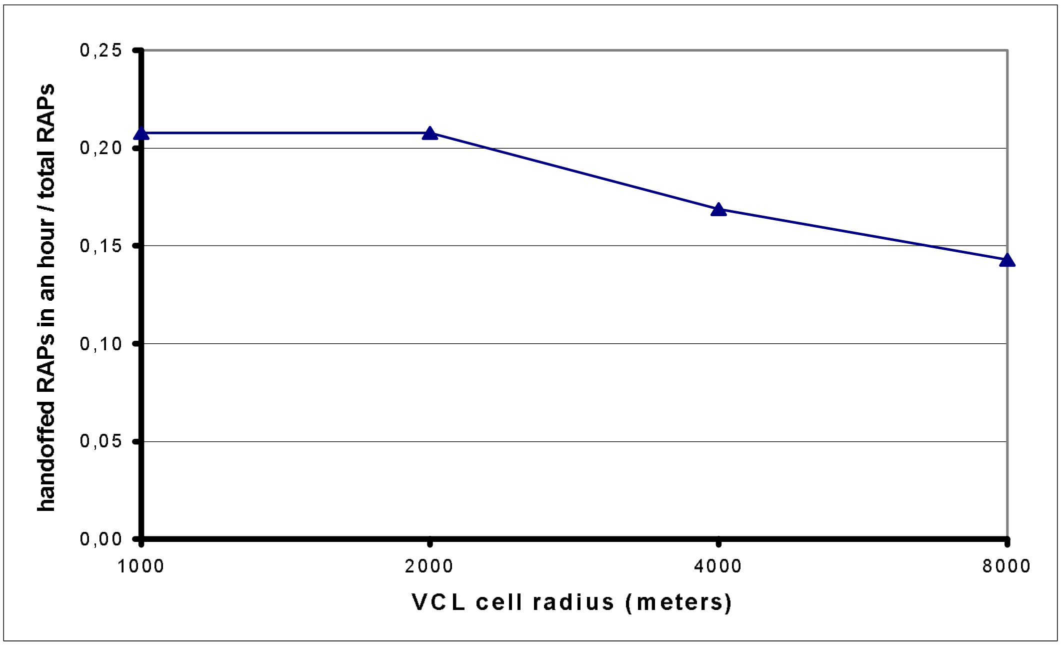
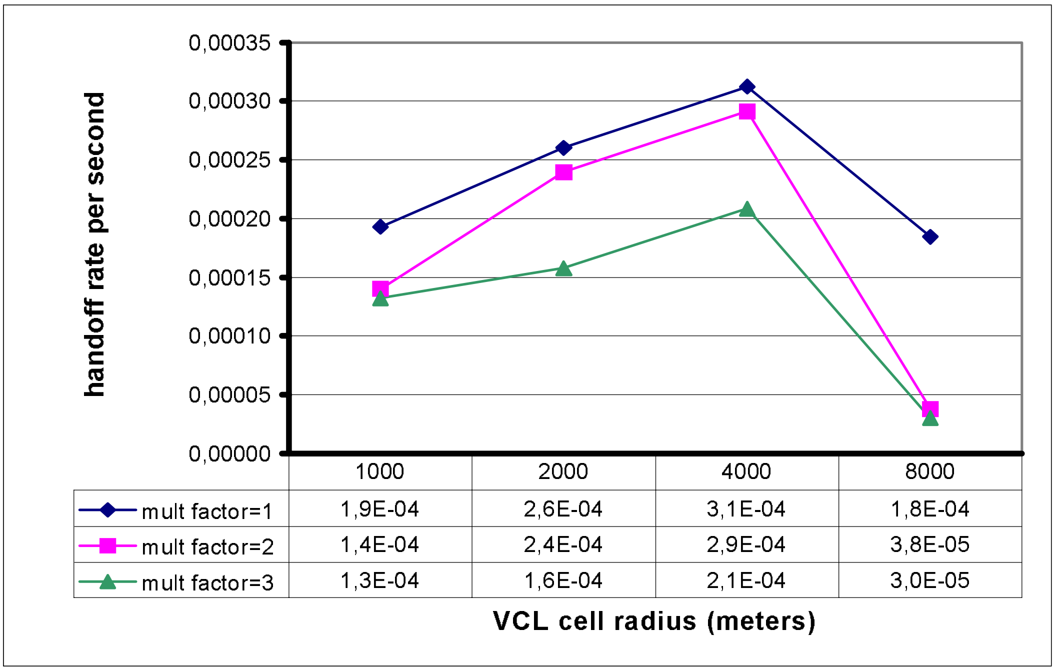


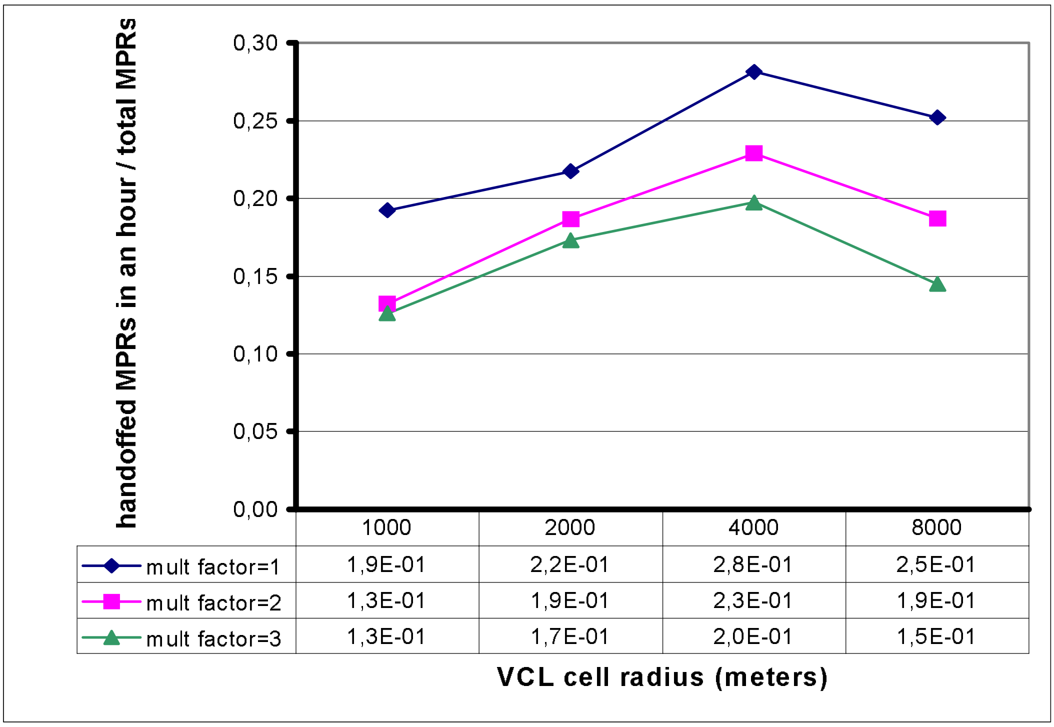
Figure 12. The rate of handoffed RAPs with respect to the total number of RAPs.



	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

Figure 13. The MPR level handoff rates.

The results related to MPR level handoffs are illustrated in Figure 13, Figure 14 and Figure 15. 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.



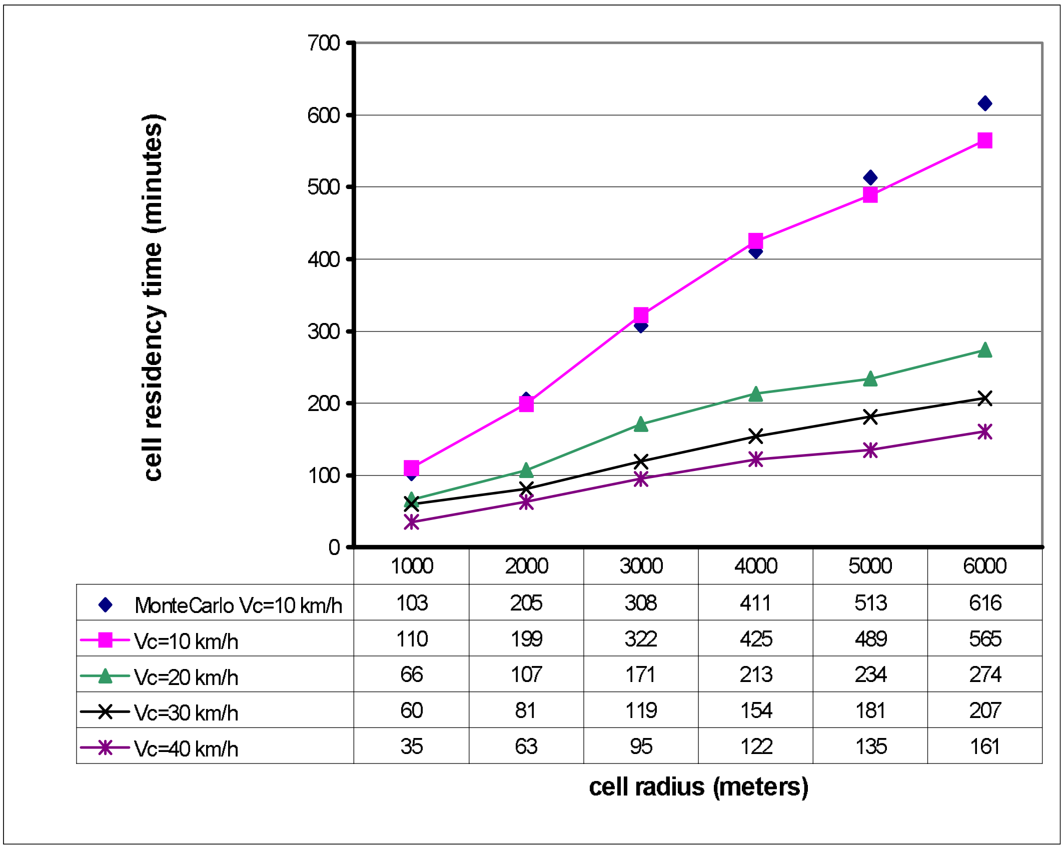
	1000	2000	4000	8000
◆ mult factor=1	1,9E-01	2,2E-01	2,8E-01	2,5E-01
■ mult factor=2	1,3E-01	1,9E-01	2,3E-01	1,9E-01
▲ mult factor=3	1,3E-01	1,7E-01	2,0E-01	1,5E-01

Figure 14. 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 13. This indicates that most of the MPRs do not handoff even once. This can be observed also in Figure 14. After one hour of simulation less than 30% of MPRs make handoff in the worst case. For this reason, we carried an analytical study and a simulation study specific to cell residency times.

In the analytical study (See Appendix B), 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 directions are determined according to the movement direction and speed of the unit that the MPR and the RAP belong to. We assume that these directions and speeds remain constant during the modeling process. This assumption is made for the sake of tractability.

By using the devised analytical model, we run some Monte-Carlo simulations. In these simulations, the average speed of the unit (V_c) is accepted as 10 km/h. The difference in speed from the unit speed (σ_v) is exponentially distributed with mean value 1 km/h (10% of central velocity) for the MPRs and RAPs. Similarly, the difference in movement direction (σ_α) is exponentially distributed with mean value 5^0. Here, exponential distribution is used, since it represents real tendencies well. 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 shown as Monte Carlo simulation values in Figure 15.



	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

Figure 15. The illustration of cell residency simulation results.

We also implemented a simulation software specific for cell residency times that runs the model defined above with a difference. In the implemented software, the speeds and the directions of the terminals may change every second. With this software, we examine the cell residency times for different speeds and ranges. The results of these simulation runs are in Figure 15. 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.

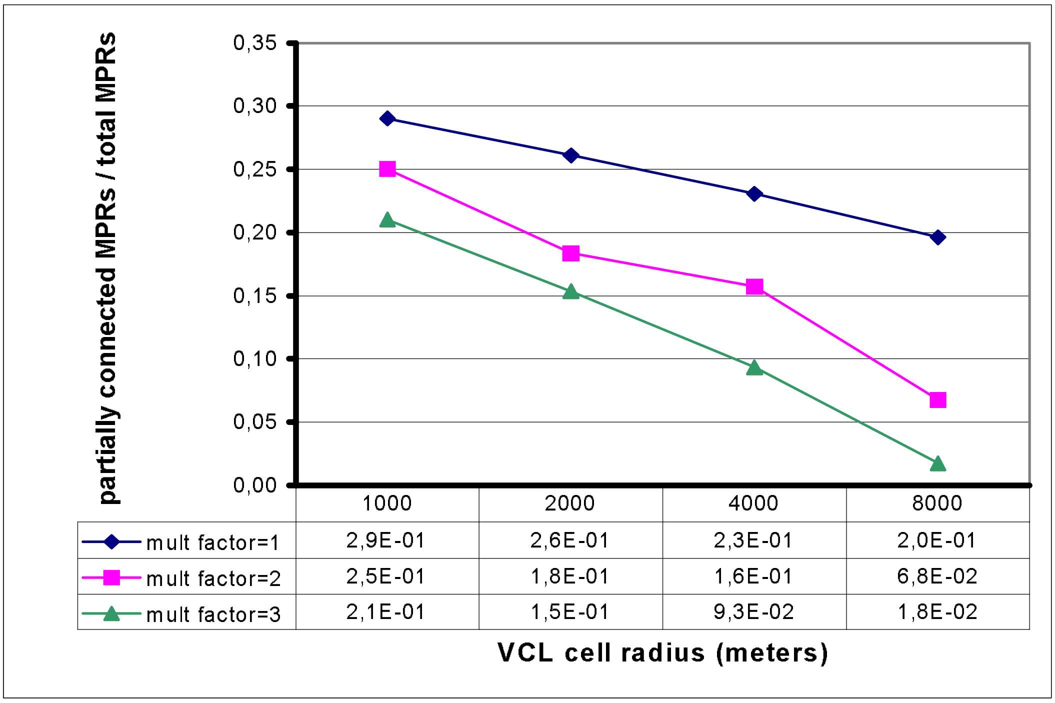
As illustrated in Figure 15, the results of the Monte-Carlo simulations based on our analytical model match with the results of the simulation implemented specifically for cell residency times. This increases our confidence in our simulation results.

The average cell residency times calculated by these studies are in the order 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 owning unit 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 signaling traffic and better radio transmission characteristics.

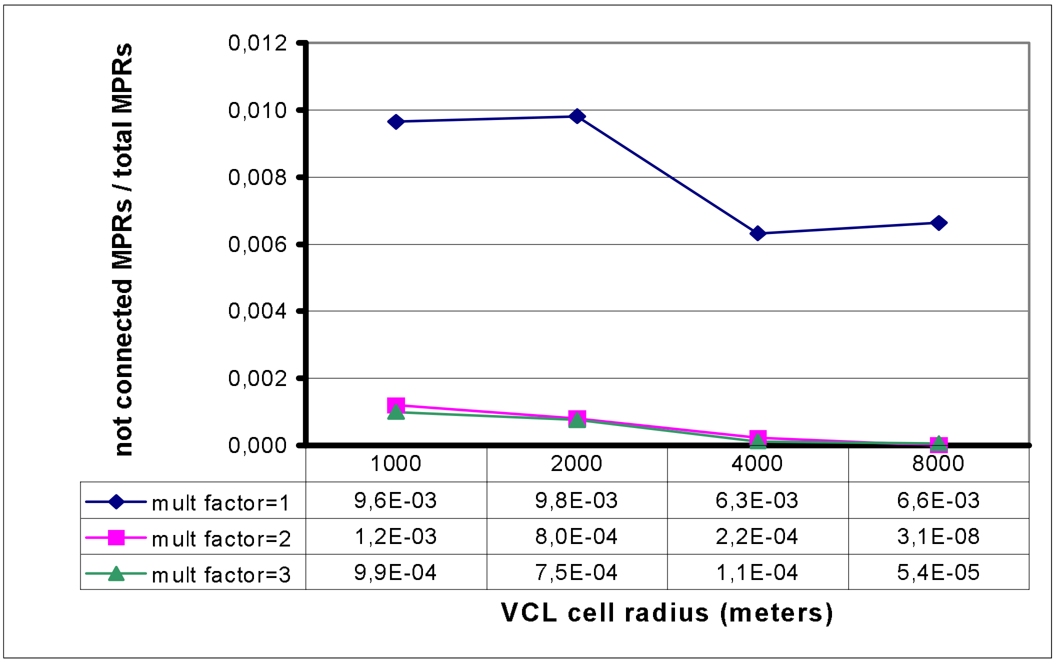
5.5. Connected MPR Rates in the Proposed System

In Figure 16, the ratio of the number of partially connected MPRs to the total number of MPRs are plotted with respect to the multiplication factor. 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 [13].



	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 16. The partially connected MPR rates for different multiplication factors.



	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 17. The not connected MPR rates for different multiplication factors.

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 as illustrated in Figure 17, and the effect of changing the multiplication factor from one to two is much more pronounced.

5.8. Different Scenarios

Based on the evaluated performance of the system, certain values are preferred for several parameters. We prefer using 4000 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 a different scenario is 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.

The value axis does not have any unit in Figure 18. The values for the performance metrics are normalized to be able to visualize all performance metrics in a single figure. For the second scenario, the proposed system perform much better than the previous scenario. Since the scenario is less mobile, the handoff rates are lower than the first scenario. Most notably MPR level handoff rate is much lower in the second scenario, because the supporting units and the headquarters are close to the maneuver units and the most of the components are registered by appropriate RAPs in the second scenario. We can observe the effect of this in "*not connected*" and "*partially connected*" MPR ratios, too. Similarly, call blocking rates get better in the second scenario, because the network is better configured, and the number of units is less which indicates fewer interfering components.

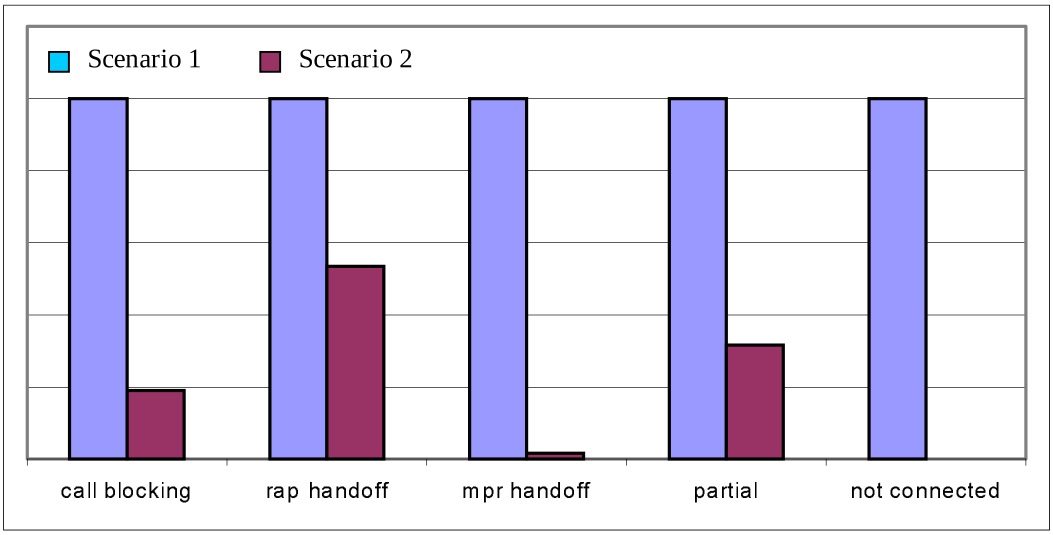


Figure 18. The results of the second scenario.

5.9. 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 the 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.

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 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 average 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.

We believe in that the scenario we used in most of our studies is one of the worst scenarios for such a system, since it includes high number of units heavily concentrated in some regions. When we use a moderate scenario, we found out that the system performed much better.

We still work on some issues related to the proposed architecture such as the integration with the higher tiers, service outage detection and handover procedures for replicating RAPs, profiling alternative handoff schemes for the proposed architecture, rerouting techniques during handoffs, the effects of more bursty call arrival patterns and call arrival rates higher than typical.

Appendix A Capacity Calculations for the Proposed System

We use bit energy to noise density ratio (E_b/N_o) equations to calculate the capacity of an access point. Bit energy to noise density ratio can be defined as follows.

$$E_b/N_o = \frac{S / R_b}{(N \alpha S + M S + I + \eta) / B} \tag{1}$$

$$E_b/N_o = \frac{B / R_b}{N \alpha + M + I / S + \eta / S} \tag{2}$$

$$N\alpha + M = ((B / R_b) / (E_b/N_o)) - (I / S) - (\eta / S) \tag{3}$$

In Equation 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 the reverse of Signal to Noise Ratio (SNR). We assume that this value is one [23], so it reduces the capacities less than one channel.

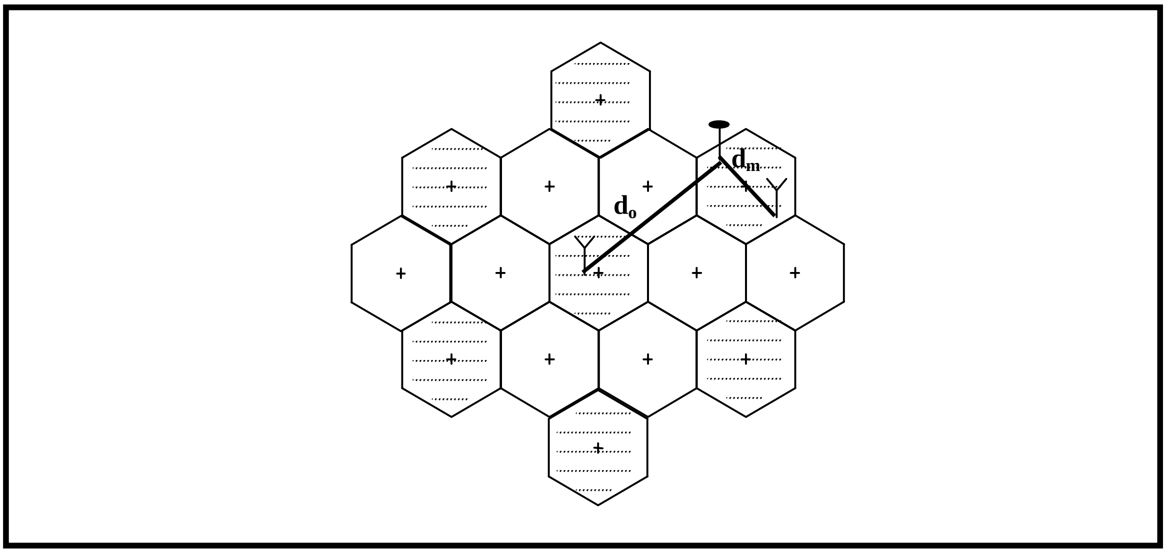


Figure 19. The interfering VCL cells.

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 19. We assume that the interference from the other rings is negligible.

Since the signal strength is the same for each subscriber in their cell bases because of power control, 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 4 as stated in [23].

$$I(d_o, d_m) / S = (d_m / d_o)^{\gamma} \, 10^{(\varepsilon o - \varepsilon m)/10} \qquad (4)$$

In Equation 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 [20], ε_o and ε_m are Gaussian random variables with standard deviation $\sigma = 8$ and zero mean.

Since Equation 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.

$$
\begin{aligned}
&P\,(F \cup R) = 2\,\alpha \\
&P\,(F \mid (F \cup R)) = 0.5 \\
&P\,(R \mid (F \cup R) \text{ and } !F) = 1 \qquad (5)
\end{aligned}
$$

In Equation 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 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.

$$
\phi = \begin{cases} 1 & \text{, with probability } P\,(F \cup R) \\ 0 & \text{, with probability } 1 - P\,(F \cup R) \end{cases} \qquad (6)
$$

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.

$$p = \begin{cases} 1 & \text{, with probability } 1/2 \\ 0 & \text{, with probability } 1/2 \end{cases} \qquad (7)$$

$$q = 1 - p \qquad (8)$$

From Equation 4, we obtain Equation 9 which defines the interference caused by the interfering channels in one of the interfering virtual cells.

$$\frac{I_1}{S} = \frac{m \times I_b}{S} + \sum_{i=1}^{n} \phi i \left[\left(\frac{d_{im}}{d_{io}} \right)^{\gamma} \times p + \left(\frac{d_{im}}{t} \right)^{\gamma} \times q \right] \times 10^{(\varepsilon_{oi}-\varepsilon_{mi})/10} \qquad (9)$$

In Equation 9, *t* is the distance between the interfered base and the base of the interfering cell, *I*$_b$*/S* is the interference caused by the access point in the interfering cell, and *m* is the number of channels broadcasted by RAPs without power control. The *I*$_b$*/S* value can be calculated by applying Equation 10.

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

In Equation 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

$$\frac{I}{S} = \sum_{k=1}^{6} \tau_k \left[\frac{m \times I_{bk}}{S} + \sum_{i=1}^{n} \phi i \left[\left(\frac{d_{ikm}}{d_{iko}} \right)^{\gamma} \times p + \left(\frac{d_{ikm}}{t} \right)^{\gamma} \times q \right] \times 10^{(\varepsilon_{oik}-\varepsilon_{mik})/10} \right] \qquad (11)$$

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

We use Equation 11 in CITACS to calculate the inter-cell interference. To be able to use Equation 11, we locate each interfering channel and sum up its interference. We also have 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 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.

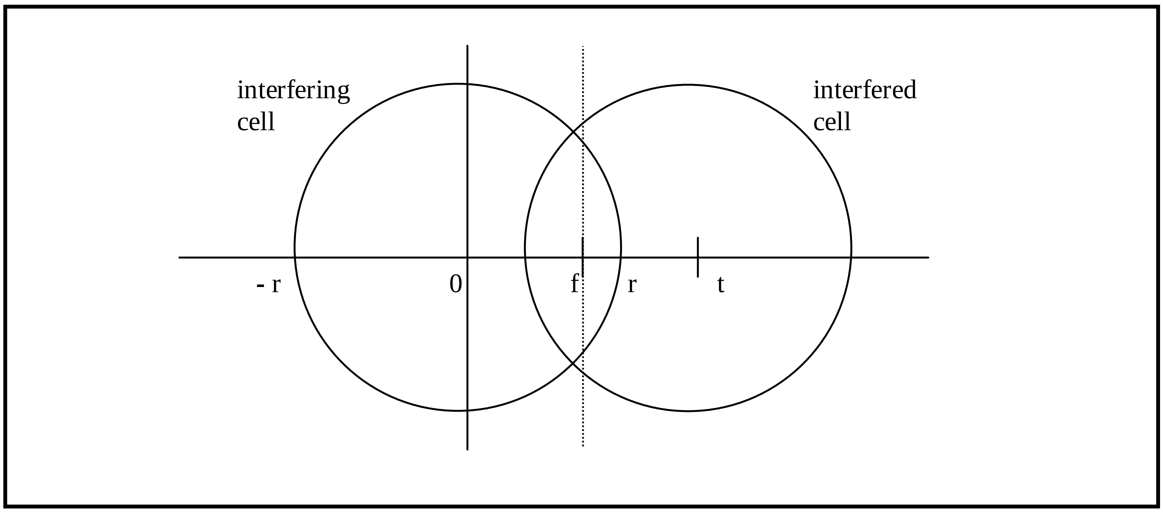


Figure 20. The geometry of remote cell interference.

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 20. Here *f* determines the boundary between two interfering cells, and can be calculated by the following equation.

$$f = \begin{cases} t / 2 & \text{, if } t < 2r \\ r & \text{, otherwise} \end{cases} \qquad (12)$$

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.

$$\psi = \begin{cases} n\,\alpha / ((\pi\, r^2 / 2) + (\pi\, r^2 \arcsin(f / r) / 180) + ((r^2 - f^2)^{1/2} f)) & \text{, if } f < r \\ n\,\alpha / \pi\, r^2 & \text{, otherwise} \end{cases} \qquad (13)$$

By using the same approach in Equation 9, we can derive Equation 14 to calculate the expected interference caused by the used channels in an interfering cell. In Equation 14, γ is taken as four as a typical value [23].

$$E[I/S]=2\,\psi 10^{(\varepsilon o-\varepsilon m)/10}\left(\int_{-r}^{0}\int_{0}^{(r^2-x^2)^{1/2}}(x^2+y^2)^2/((t-x)^2+y^2)^2dydx+\int_{0}^{f}\int_{0}^{(r^2-x^2)^{1/2}}(x^2+y^2)^2/((t-x)^2+y^2)^2dydx\right) \quad (14)$$

$$E[I/S]=2\psi 10^{(\varepsilon o-\varepsilon m)/10}\left(D\,\Big|_{-r}^{0}\,\Big|_{0}^{(r^2-x^2)^{1/2}}+D\,\Big|_{0}^{f}\,\Big|_{0}^{(r^2-x^2)^{1/2}}\right) \quad (15)$$

D in Equation 15 is the result of the following equation.

$$D=y\left(x+\frac{t^2}{2}\right)\left(\frac{d\arctan(x/(a-t^2)^{1/2})}{(a-t^2)^{1/2}a^2}-\frac{t^2}{b\,a}+\frac{g\,(2\log(b)-\log(h))}{a^2}\right)+\frac{1}{2}\arctan\frac{c}{3b^2} \quad (16)$$

In Equation 16,

$a = 2t^2 - 2tx + y^2$

$b = x - t$

$c = 7t^5 - 7t^4x + 18t^3 - 8t^2x^3 - 48t^2x + 8tx^4$

$d = 8t^4 - 22t^3x + 16tx^2 + 11t^2y^2 - 16txy^2 + 4y^4$

$g = 3t^3 - 4t^2x + 2ty^2$

$h = t^2 - 2tx + x^2 + y^2$

Appendix B An Analytical Approach to Calculate Cell Residency Time in the Proposed System

In Figure 21, 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.

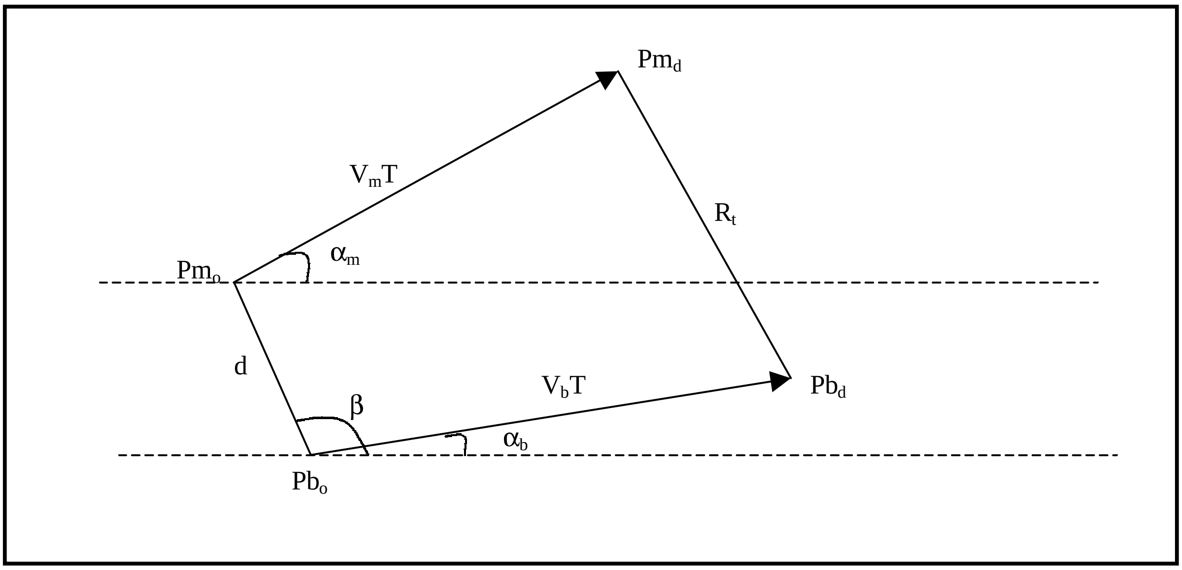


Figure 21. The illustration of the mobility pattern of two terminals.

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

$$
\begin{aligned}
Pb_o &= \{ Xb_o, Yb_o\} \\
Pb_d &= \{ Xb_d, Yb_d\} \\
Pm_o &= \{ Xm_o, Ym_o\} \\
Pm_d &= \{ Xm_d, Ym_d\}
\end{aligned} \tag{17}
$$

Equation 18 is the geometric definitions of the destination positions according to the same coordinate system.

$$
\begin{aligned}
Xm_d &= Xb_o + d\cos\beta + V_m T\cos\alpha_m \\
Ym_d &= Yb_o + d\sin\beta + V_m T\sin\alpha_m \\
Xb_d &= Xb_o + V_b T\cos\alpha_b \\
Yb_d &= Yb_o + V_b T\sin\alpha_b
\end{aligned}
\tag{18}
$$

The distance between the destination positions in *X* and *Y* axis are determined by Equation 19.

$$
\begin{aligned}
Xdif &= V_b T\cos\alpha_b - V_m T\cos\alpha_m - d\cos\beta \\
Ydif &= V_b T\sin\alpha_b - V_m T\sin\alpha_m - d\sin\beta
\end{aligned}
\tag{19}
$$

We can derive the range from Equation 20.

$$
\begin{aligned}
R_t^2 = {} & T^2 \left(V_b^2 + V_m^2 - 2V_bV_m\cos(\alpha_b - \cos\alpha_m)\right) - \\
& T\left(2V_b\, d\cos(\alpha_b - \beta) - 2V_m\, d\cos(\alpha_m - \beta)\right) + d2
\end{aligned}
\tag{20}
$$

T has two different values that can be found by Equation 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.

$$
T = \begin{cases} \infty & \text{, when } \alpha_m = \alpha_b \text{ and } V_b = V_m \\ \dfrac{V_b\, d\, \psi - V_m\, d\, \phi + \Delta}{V_b^2 + V_m^2 - 2V_bV_m\, \alpha} & \text{, otherwise} \end{cases}
\tag{21}
$$

where

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

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

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

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

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

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

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

In Equation 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:

$$f_d(d) = \begin{cases} 1/R & \text{, for } 0 \le d \le R \\ 0 & \text{, elsewhere} \end{cases} \tag{22}$$

$$f_\beta(\beta) = \begin{cases} 1/2\pi & \text{, for } 0 \le \beta \le 2\pi \\ 0 & \text{, elsewhere} \end{cases} \tag{23}$$

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:

$$f_{\alpha c}(\alpha_c) = \begin{cases} 1/2\pi & \text{, for } 0 \le \alpha_c \le 2\pi \\ 0 & \text{, elsewhere} \end{cases} \tag{24}$$

$$\alpha_b = \alpha_c + \theta\,\sigma_\alpha \tag{25}$$

$$\alpha_m = \alpha_c + \theta\,\sigma_\alpha \tag{26}$$

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:

$$f_{Vc}(V_c) = \begin{cases} 1/V_{max} & \text{, for } 0 \le V_c \le V_{max} \\ 0 & \text{, elsewhere} \end{cases} \tag{27}$$

$$V_b = V_c + \theta\,\sigma_v \tag{28}$$

$$V_m = V_c + \theta\,\sigma_v \tag{29}$$

In equations 24 through 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.

$$\theta = \begin{cases} 1 & \text{, with probability } 1/2 \\ -1 & \text{, with probability } 1/2 \end{cases} \tag{30}$$

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