APPLICATION OF 3G PCS TECHNOLOGIES TO RAPIDLY DEPLOYABLE MOBILE NETWORKS

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Abstract

In this paper, a rapidly deployable PCS architecture based on our novel resource management scheme, namely, virtual cell layout (VCL), is introduced. VCL is used to develop new self-organization and routing procedures, which mitigate the scalability problem of infrastructureless routing and resource management. In VCL, the communication area is tessellated with regularly shaped fixed size virtual cells. Radio resources such as frequency carriers and CDMA codes are assigned to the fixed cells of this layout. The real cells, which do not need to be the same size as the virtual cells, can move over the VCL cells. Simulation results show that the VCL based architecture satisfies the requirement for rapid deployment and can provide acceptable grade of service.

1. Introduction

Third generation PCS services (3G PCS) are already offered in limited areas, and will be used more extensively in the future [11]. 3G PCS will convey multimedia traffic in mobile and wireless environments. Universal Mobile Telecommunications System (UMTS) is a 3G PCS system which will replace GSM gradually. UMTS uses both wideband code division multiple access (WCDMA) and hybrid time division multiple access/CDMA [1][4] in the radio access network.

Since UMTS and most of the other PCS technologies are cellular architectures, they require a carefully designed and deployed infrastructure. Sometimes rapid deployment without extensive preplanning is needed. Tactical communication systems and networks used after disasters are examples of systems which require rapid deployment. In these systems, pre-deployment of a cellular infrastructure is often impossible. Therefore, infrastructureless routing algorithms and resource management schemes are needed to fulfill the rapid deployment requirement.

Ad hoc techniques have been developed to route data packets between mobile terminals through an infrastructureless network. Many ad hoc routing techniques have been proposed in the literature [9]. Available ad hoc routing algorithms however are not scalable enough to manage tens of thousands of nodes. Furthermore, they do not address the management of radio resources. Therefore, we have developed the VCL based architecture concept, which leverages both cellular and ad hoc paradigms to handle a large number of mobile terminals in a rapidly deployable network. In this paper, we use the VCL concept to adapt the UMTS terrestrial radio access network (UTRAN) to the next generation tactical communication systems.

In VCL, the communication area is tessellated with fixed size hexagons. Each hexagon represents a VCL cell to which the available spectrum is assigned. Also, the CDMA codes are distributed among the fixed VCL cells. Hence, if a mobile access point can find out its geographic location, it can also determine the available set of carriers and codes without a need for a central topology database or a central resource manager.

Based on this approach, we propose new algorithms and schemes that make the techniques used in UTRAN applicable to the radio access system of rapidly deployable mobile networks. In order to make the proposed system compatible with UMTS, we design these algorithms such that a UMTS terminal can access the proposed system or a terminal of the system can access a UMTS network.

We also complement this architecture with ad hoc procedures. These procedures enable the mobile terminals of the proposed system to self-organize in the absence of an access point in the vicinity. VCL is used to devise a distributed ad hoc clustering technique that organizes the unconnected mobile terminals into clusters and connects these clusters to an access point. We also examine handoff and routing techniques that can operate on the proposed architecture.

The rest of the paper is organized as follows: In Section 2, we describe the principles of tactical communication systems, and discuss the overall architecture envisioned for the next generation systems. In Section 3, the new VCL concept is introduced. The algorithms developed to deploy the VCL concept to the mobile subsystem of the tactical communication systems are presented in the same section. We summarize the results of performance evaluation studies in Section 4. Section 5 concludes the paper.

2. Next Generation Tactical Communication Systems

The essence of designing a good tactical communication system is to enhance survivability and rapid deployment capability. Since this goal must be often achieved in a very harsh and hostile environment, tactical communication systems are one of the most challenging application areas of communications. Other important characteristics of tactical communications are [5], [8], [10], [12]:

- Different mobility patterns: While some subscribers move at supersonic speeds, others may be fixed.
- Wide range of terminal types: A wide range of equipment such as sensors (video camera, radar, sonar, thermal camera, etc.), single channel radios and computers may be the terminals of a military communication network.
- Variable communication distances: Communication distances range from a couple of meters up to thousands of kilometers.
- Variable communication medium characteristics: Various types of media such as wires, optical fibers, the air and the sea may be used.
- Rapidly changing communication locations: The regions to be covered with extensive communication networks may be deserted and the same networks may need to be installed in different regions within days during a military operation.
- Hostile and noisy environments: Communication facilities of the opposing side are the high priority targets in a battlefield. Besides, thousands of exploding bombs, vehicles and intentional jamming cause noise in the communication media.
- Bursty traffic: Subscribers usually try to communicate simultaneously.
- Different types of applications: The military communication networks host various types of applications that need to meet different end-to-end quality of service requirements.
- Different security constraints: Unclassified data together with top-secret data flow through the same communication channels.

In order to satisfy these requirements, intensive research activities have been carried out both in the U.S. and in NATO, such as Defense Information System (DISN) [12], Post-2000 Tactical Communications (TACOMS) [10], Global Mobile Communications [8]. Figure 1 illustrates the architecture of the next generation tactical communications systems derived from DISN and TACOMS efforts.

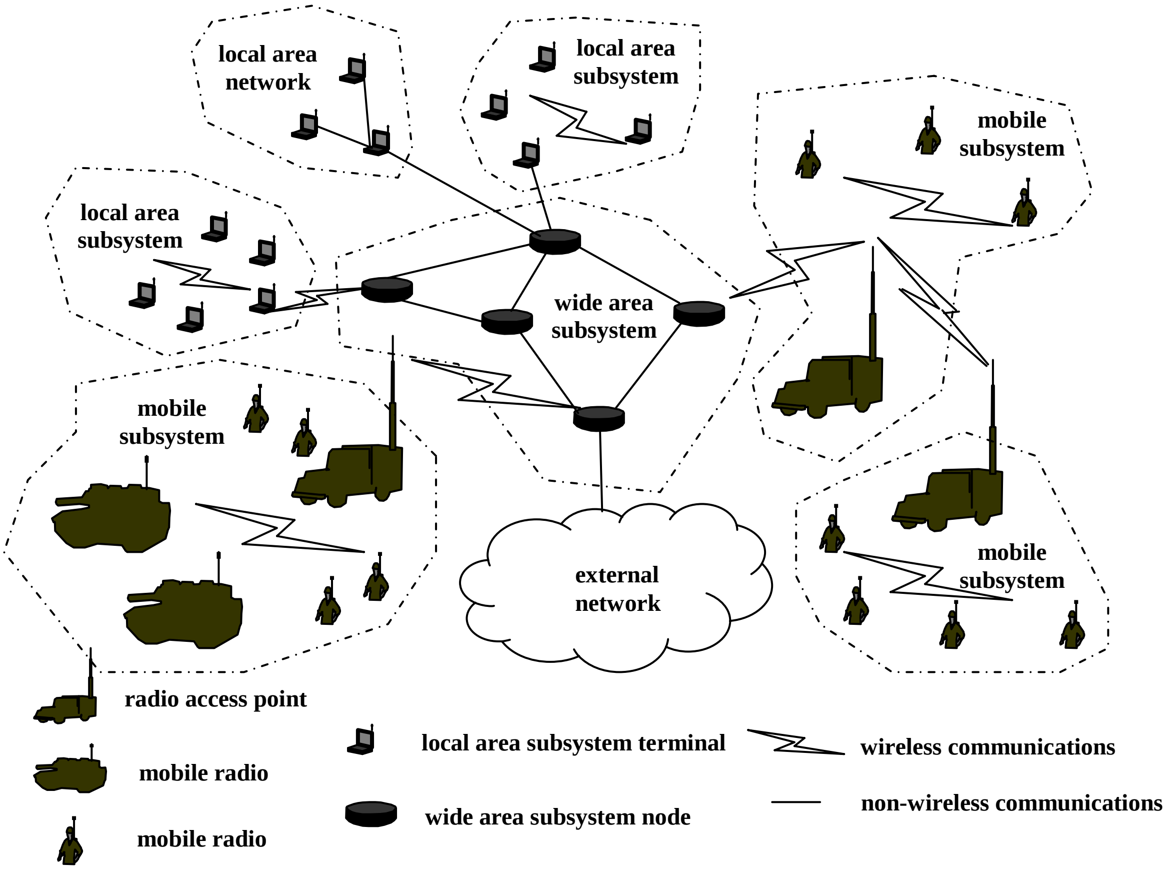


Figure 1. Tactical communications systems.

This 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 into the architecture. The WAS interconnects other subsystems as a wide area backbone. It is generally a pre-deployed high capacity network designed and managed better than the other subsystems. It may even be deployed and used in peacetime. The LAS can be considered as a nomadic *local area network* that can access the WAS or available commercial networks. Headquarters and similar organizations that sustain their presence in restricted areas are provided with local area networking support by a LAS. Mobile users in a battlefield access a tactical communication system through a MS. A MS may operate as an independent communication network or be a part of the overall tactical communication system by accessing the WAS. The SMCS, a subsystem integrated into the architecture, provides the network administrators with system management functions.

The technology components of this architecture and its subsystems are examined in detail in [12]. Among these components, radio access points (RAPs) [12] and mobile terminals have a key role in the proposed system. Users of the proposed system access the integrated services through these components. RAPs convey the multimedia traffic among mobile terminals, and between a WAS and a MS. In the rest of this paper, we use the term "man packed radio" (MPR) instead of mobile terminal. MPRs have similar capabilities with future digital radios [12]. They can transmit and receive through more than a single carrier simultaneously. Although we call them MPRs, they may be mounted on various types of vehicles.

3. System Description

The VCL based architecture is designed for the Mobile Subsystem of the next generation tactical communication systems. It has a rapidly deployable mobile infrastructure, and uses both cellular and ad hoc techniques. In Figure 2, the MS architecture envisioned for the next generation tactical communication systems is illustrated. In this MS architecture, there are four tiers:

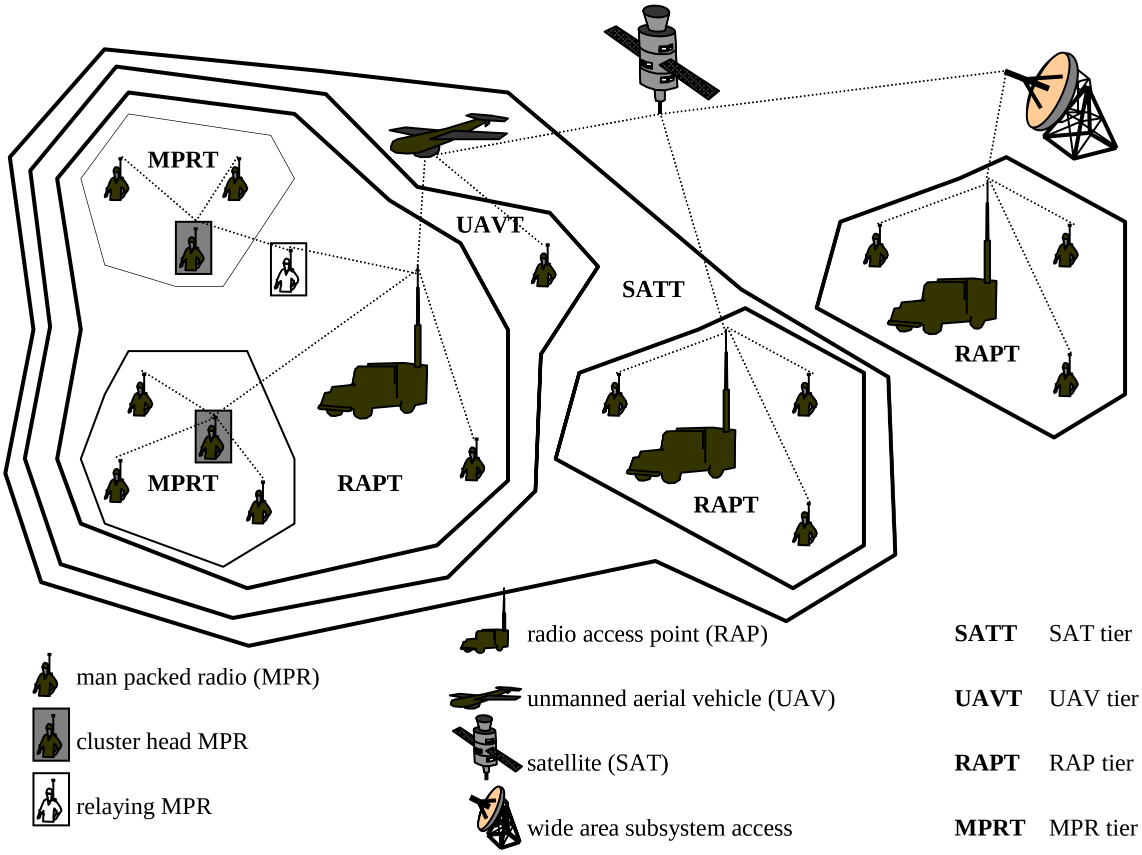


Figure 2. Multi-tier mobile subsystem.

- Man Packed Radio Tier (MPRT): An MPRT cell is a cluster of MPRs, which cannot access any RAP. In each MPRT cell (i.e., an MPR cluster), one of the MPRs becomes the head of the cell (i.e., cluster). If there is an MPR that can access a RAP and can be accessed by the MPRT cell head, then the MPRT cell is connected to the RAP via the MPR, which relays the traffic between the MPRT cell and the RAP.
- Radio Access Point Tier (RAPT): RAPs are the mobile base stations of the MS. They create the RAPT cells. The RAPT cells may also construct underlay clusters of the MPRT cells when some MPRT cells are connected to them by relaying MPRs.
- Unmanned Aerial Vehicle Tier (UAVT): This is the first level overlay tier of an MS. The UAVT cells cover the areas that are not covered by the lower tiers. The lower tier cells can also use UAVs to access the WAS.
- Satellite Tier (SATT): This is the topmost overlay tier. A SATT cell is created by a satellite and may include a number of lower tier cells. Satellites are used by lower tier cells to access the WAS and to communicate with other cells.

Before proceeding further, we first describe the mapping of the components in the VCL based MS architecture to the components in UMTS. MPRs are mobile terminals, and the other components of our architecture are the intermediate nodes. A RAP is equivalent to a UMTS radio network subsystem (RNS), and has equipment that do the same job as a radio network controller and a number of UMTS Node B’s. A RAP can also be perceived as the replacement of a GSM base station system. The wide area subsystem is the core network and a WAS access point is the access point for the core network. It is basically the mobile switching center of the system. Every WAS access point has connections to databases which have similar functionality to the home and visitor location registers. Every RAP and the MPRT cell head have their own databases, which correspond to visitor location registers. Satellites and UAVs have two different responsibilities: relaying the traffic between two terrestrial nodes and providing an overlaying access network. For the second responsibility, they construct an access network that is equivalent to a UMTS satellite radio access network (USRAN).

Similar to the components of our architecture, the procedures and especially the air interfaces between MPRs and RAPs are similar to those of UMTS. The differences come from the mobility of the infrastructure and the multi-tier architecture. MPRs select the appropriate tier and handoff among tiers and cells as they and the infrastructure move. Before describing the VCL based architecture and the procedures in detail, let us clarify the basic principles related to mobility management:

- If the tier to register is not set explicitly by operators, an MPR registers to a RAPT cell whenever possible. If there is no RAPT cell to register to, it tries to register to an MPRT cell.
- If an MPR cannot find an MPRT or a RAPT cell to register, it creates a new MPRT cell and connects this new cell to the lowest possible overlay cell.
- If required, an MPR handoffs between the cells as it moves. It can also handoff to the upper or lower tiers.
- When a number of MPRs are isolated and separate from the other MPRs and RAPs for tactical reasons, they construct an MPRT cell that is not connected to the wide area subsystem and establish communications among themselves.
- All concepts, schemes and strategies are distributed.

Virtual Cell Layout (VCL)

In the VCL based architecture, radio resources (i.e., frequency carriers and CDMA codes) are dynamically assigned to the components of a mobile infrastructure by using a VCL. A VCL eliminates the need for a central system or an accurate and timely topology database. In VCL, the communication area is tessellated with virtual cells, which are regularly shaped fixed size hexagons that are placed starting from a reference geographic location. If an access point knows its geographic location, this location information can be mapped into a VCL cell index, which can be used to determine the radio resources assigned to the fixed cells of VCL.

The real cells are mobile and created by either RAPs or cluster head MPRs (i.e., MPRT cell heads). The size of a real cell may be different from the size of a VCL cell. If a VCL cell radius is r, then the real cell radius is kr, $k \in R^+$, where k is a *multiplication factor*. When the multiplication factor is one, a real cell usually does not cover the entire virtual cell where it is located, because the access points are not necessarily at the centers of the virtual cells.

The carrier frequency set consists of a group of carriers. We assume that the frequency band allocated to this system is divided into carriers that have bandwidths between 4.4 and 5 MHz as in UMTS. 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 as illustrated in Figure 3. $N=3$ frequency reuse plan is proposed, since it is the one with the highest frequency reuse that ensures that none of the VCL cells has a neighbor VCL cell using the same carrier set. The use of CDMA is required because RAPs are mobile. Two RAPs can come too close to use the same frequency carrier even if they are in separate VCL cells.

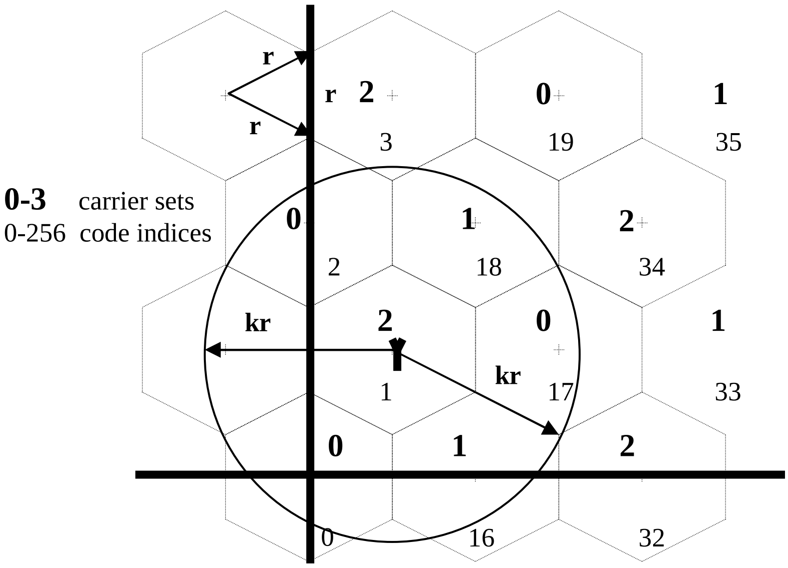


Figure 3. Virtual cell layout.

UMTS uses 512 CDMA codes for identifying base stations [4]. We divide them into two groups of 256 codes. RAPs use the first 256 codes, and MPRs use the rest. We assign two codes to each VCL cell; one for RAPs and one for the MPR cluster heads. This implies that we distribute 256 code sets among the VCL cells as illustrated in Figure 3.

If a component can find out its geographic location, it can learn the most appropriate CDMA code and carrier set without the need for a central system or a database. Global Positioning System (GPS) or other location finding techniques [7] can be used to learn the current geographic location.

Radio Access Point Algorithms

We assume that each RAP has a connection to the WAS through one of the access points (i.e., WAS access point, satellite, UAV). Since the number of RAPs is relatively limited, we can use more complex algorithms in these tiers [6] or we can implement the VCL approach for these tiers as well.

A RAP can be in one of the four states illustrated in Figure 4. It runs the procedure for its current state and collects the data for calculating the required parameters by sensing the environment. When a RAP is turned on, it first discovers its current location. It then calculates the time for the next location check, which is the time required to reach to the closest edge of the current VCL cell with the current speed. This time cannot be longer than a predefined value. Initially, the next *location check time* is calculated based on the maximum speed defined for RAPs.

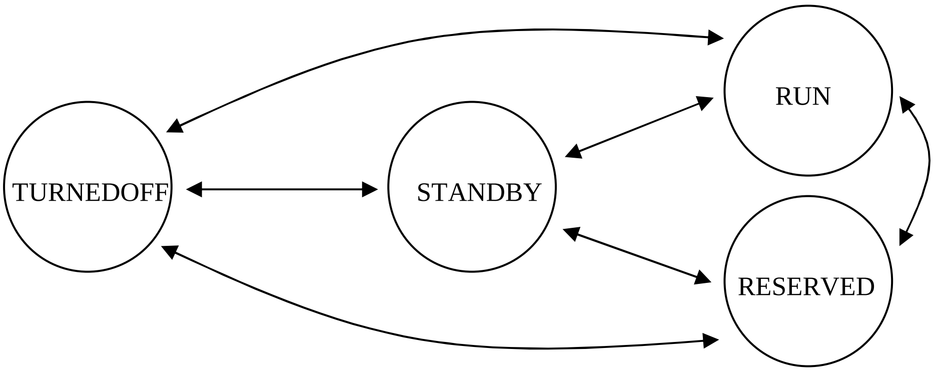


Figure 4. The state transitions for RAPs.

RAPs carry out the following procedures in the RUN and the RESERVED states:

The RUN State for RAPs: When the location is determined, this information is mapped to the VCL cell index. After the VCL cell index is found, each carrier assigned to that VCL cell is listened to in a random order. If an unused carrier is found, the control channels in that carrier are activated with the CDMA code assigned to the current VCL cell. Hence, the RAP completes its transition to the *RUN* state. The search for an unused carrier proceeds randomly. Otherwise, it is quite possible to use the same carriers in each cell and to increase the remote cell interference. This reduces the system capacity.

The RESERVED State for RAPs: If all of the carriers in the carrier set are used, RAPs using these carriers are checked for replication. If one of them is found *not replicated*, it is replicated and the RAP is put in the *RESERVED* state. If no RAPs are available for replication, the RAP goes to the *STANDBY* state. A RAP in the *RESERVED* state replicates another RAP. This means that 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 takes over the tasks of the replicated RAP. When a replicated RAP carries an inter-frequency handoff, the replicating RAP starts to use the remaining carrier.

RAPs periodically check to see if the *location check time* is reached. At the *location check time*, RAPs find out their current geographic location. If it is detected that a new VCL cell is entered, an inter-frequency handoff is conducted. Inter-frequency handoff starts with mapping the current VCL cell index to the new radio resource indices. If the RAP is in the

RUN state, it tries to find an unused carrier from the new carrier set. If it finds one, it changes the carriers and codes of the registered nodes and starts to serve with the new carrier and code set. If an unused carrier is not found in the new carrier set, the registered MPRs are forced to make inter-RAP 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 forced to handoff can find a new RAP in the vicinity. If the RAP is replicated before handoff, the replicating RAP is informed so that it can start to use the remaining resources.

Man Packed Radio Algorithms

MPRs are the mobile terminals of our architecture. They are equivalent to UMTS user equipment. They also have a few additional features such as the capability of knowing the possible codes and carriers that can be used in their current location, and the possible codes and the carriers to handoff. This is achieved as a result of the VCL approach. We also assume that they can run as a cluster head (i.e., the MPRT cell head) when required.

MPRs use the procedures related to their current status and gather the required data by sensing the environment. Hence, they can run in a distributed manner without the need for a central topology database. The basic design principle is to have a system where two MPRs can communicate with each other even if they cannot communicate with other components.

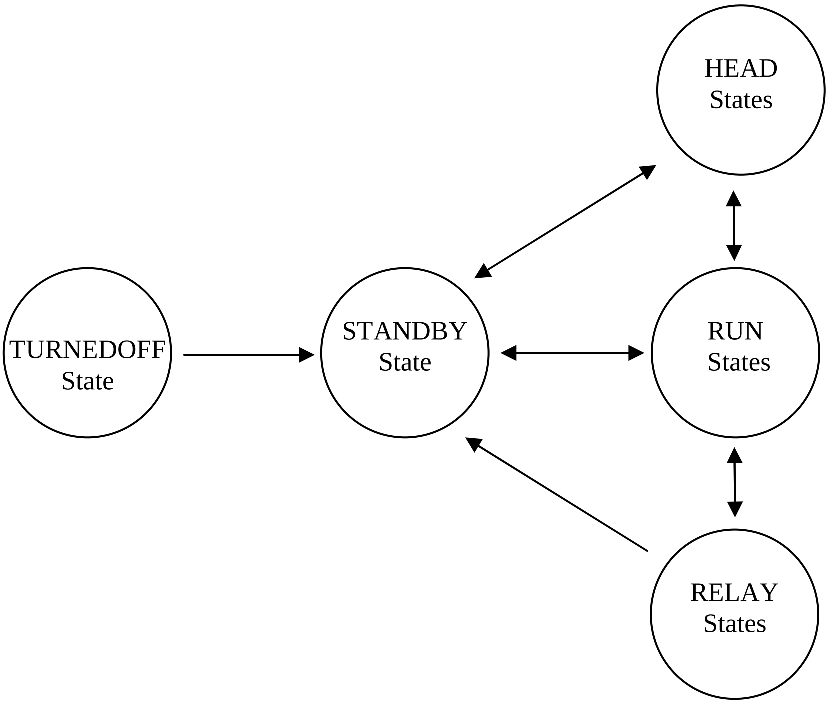
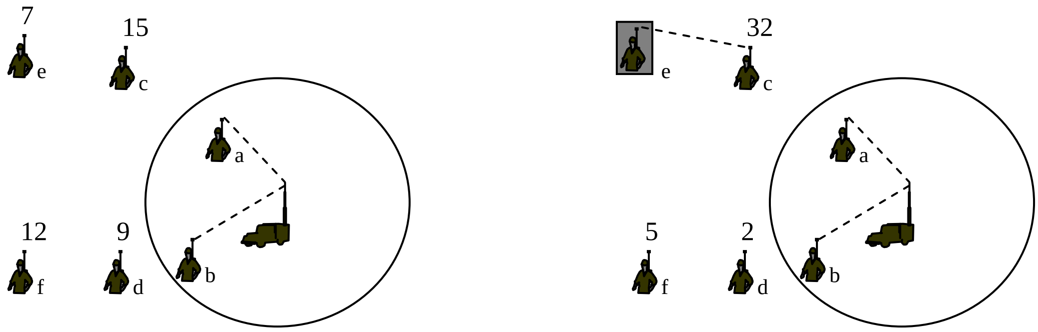


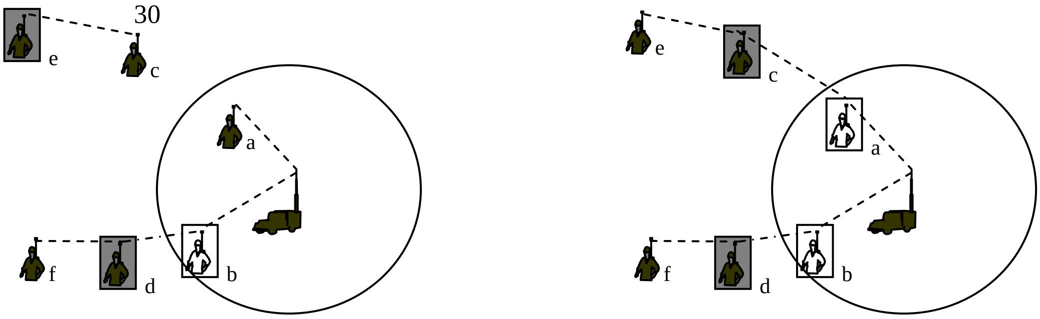
Figure 5. The state transitions for MPRs.

The state transition diagram of an MPR is shown in Figure 5. It is more complex than the diagram for RAPs because MPRs may sometimes become cluster heads or relay the traffic between a RAP and a cluster. In Figure 5, the *HEAD* and the *RUN* states represent a group of states. The details about each of these states are given below:

The RUN States for MPRs: When an MPR is powered on, it tries to go to the most appropriate state by sensing the environment. It prefers being in one of the run states. There are three types of run states: *RUN*, *RUN_LINKED*, *and RUN_LINKED_PARTIAL*. In the *RUN* state, which is the most preferred state, the MPR registers directly to an RAP. If a RAP to register is not found, but there is an MPR acting as a cluster head, the MPR registers to this cluster head. If the registered *HEAD* is relayed to a RAP or a WAS, the state entered is *RUN_LINKED*. Otherwise, the state entered is *RUN_LINKED_PARTIAL*.



(a) The topology after second 1. (b) The topology after second 7.



(c) The topology after second 9. (d) The topology after second 39.

Figure 6. An example scenario.

The RELAY States for MPRs: An MPR in the *RUN* or *RUN_LINKED* state senses the environment to find a cluster head that is not connected to upper layers. If it finds one, it connects to that cluster head and starts to relay the traffic between the cluster and the RAP that it is connected to. The relaying MPR also makes a state transition to one of the *RELAY* states. If it is connected to a RAP, its state becomes *RELAY_RUN*. Otherwise it goes to the *RELAY_LINKED* state.

The HEAD States for MPRs: If an MPR cannot find any node to register during a time period that is determined randomly after the transition to the *STANDBY* state, it enters the *HEAD_ALONE_NO_USER* state. An MPR in a *HEAD* state acts as a cluster head. If it is not connected to the higher tiers, its state is *HEAD_ALONE*. If it is connected to a RAP or another cluster head MPR, its state is *HEAD_RELAYED*. An MPR in the *HEAD_ALONE_NO_USER* state has no MPR registered to it. The *HEAD_ALONE_NO_USER_DUP* state is a special state where one of the MPRs in a cluster checks whether there is an MPR that can relay its traffic or not.

In Figure 6, we illustrate the transitions between the states by an example. In our scenario, there are six MPRs and a RAP. MPRs *a* and *b* are in the range of the RAP, so they immediately go to the *RUN* state when they are turned on. However, the other MPRs are out of range, so they are in the *STANDBY* state after being turned on. The MPRs determine a random period, when they make a state transition to the *STANDBY* state. These random periods are shown at the upper right side of the MPR symbols in Figure 6. They try to find an MPR in one of the *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 the *HEAD_ALONE_NO_USER* state. This transition is illustrated in Figure 6(b). MPR *e* makes a state transition to the *HEAD_ALONE_NO_USER* state. Then MPR *c* detects MPR *e*, registers to it, and makes a state transition to *RUN_LINKED_PARTIAL* state, which also indicates a state transition to the *HEAD_ALONE* state for MPR *e*. MPR *c* determines a time period that it will wait in *RUN_LINKED_PARTIAL* state when it enters to this state. In Figure 6(c), MPR *d* makes similar transitions. However, the ultimate state of *d* is *HEAD_RELAYED*, since it is in the range of MPR *b*, which can connect it to the RAP. An MPR determines a random period when its state becomes *RUN_LINKED_PARTIAL*. If it is still in the *RUN_LINKED_PARTIAL* state at the end of this period, it makes a state transition to the *HEAD_ALONE_NO_USER_DUP* state. This is illustrated in Figure 6(d). Since MPR *c* is still in the *RUN_LINKED_PARTIAL* state after 39 seconds, it handovers MPR e. MPR *c* is in the range of MPR *a*, which can connect it to the RAP. Therefore the ultimate state of MPR *c* becomes *HEAD_RELAYED*. At the end of these stages, all components of the network are 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. Performance of the System

In order to evaluate the performance of the proposed system, Computer Aided Exercises Interacted Tactical Communications Simulation (CITACS) [3] was used. CITACS is a simulation system developed in the Network Laboratory (NETLAB) at Bogazici University. CITACS interacts with real computer aided military exercises to obtain data related to the movement and the posture of military units. This data was used to generate the mobility and call patterns. We experimented with three different scenarios in our performance evaluation studies. Two of these scenarios are from real military exercises where the operations of an army corps made up of the armored and mechanized infantry brigades are simulated in a joint theater. The corps is attacking in the first scenario, and defending in the second scenario. The third scenario is generic, and publicly available [13]. In the first scenario, 153 ground units deployed over an area of 115 km. × 170 km were simulated. 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. All simulation results presented in this paper use the first scenario. The other scenarios were used to compare the performance metrics for the three scenarios. In the second scenario, which is also a real scenario, 49 units were simulated in an area that is the same in size as the first scenario. These units do not move as much as the units in the first scenario. 30 RAPs and 5721 MPRs are deployed with them. In the last scenario, 20 RAPs and 3452 MPRs are deployed with 28 units over an area that is 85 km × 40 km in size. This is the scenario that has the highest mobility.

Since our system runs mainly in an open rural area, we used in our simulations a free space propagation model with a 2 dB pathloss exponent up to the Fresnel breakpoint, and shadowed propagation with a 4 dB pathloss exponent and a 4 dB shadow fading standard deviation after the Fresnel breakpoint. Antenna heights were assumed to be 185 cm because our mobile terminals are mainly man packed. The soft capacity of the system was determined by the bit energy to noise density ratio (E_b/N_o) where the interference made by each active terminal (i.e., a terminal that is making a transmission at that instant) was calculated according to its location. Simulations were run for both $E_b/N_o=5$ and $E_b/N_o=3$. A sensitivity analysis was carried out for varying radio ranges between 1 and 8 km. In the simulations, we assumed that the UAV or satellite coverage was not available for MPRs.

The mobility patterns of the terminals are based on real data. MPRs and RAPs move with the military unit that owns them. The mobility patterns of the units were taken directly from realistic military exercises. Node failures were determined by using the posture and event data from these exercises. Based on this data, 52 MPRs and 2 RAPs were destroyed on average in a two-hour simulation with the first scenario.

Table 1. The call rates (call/hour) in the attack posture.

Branch	In contact	Not in contact
Infantry	17	9
Artillery	18	8
Tank	21	12
Special Force	17	7
Signal	14	13
Headquarter	15	13
Other	13	12

Similarly, call models were based on real data. Posture, contact (i.e., the contact with the opposing side) and unit type data determined the call rate of a unit. For instance, the call rate for an infantry unit in the attack posture was higher than that of an infantry unit in the tactical move posture. The typical call rates for varying postures and unit types were determined from a statistical study [3] performed among 50 experienced officers. The call rates used for the attack posture are given in Table 1. The call rates for other postures are calculated by multiplying the typical call rates for the attack posture with the normalization factors in Table 2. The details about call generation can be found in [3]. A sensitivity analysis was also carried out by changing the typical call rates. We used the exponential distribution for call inter-arrival times in the majority of the experiments. Note that the mean call inter-arrival time is different for each unit and each posture. We also did a sensitivity analysis by changing call inter-arrival time distributions [3]. Call durations are 19.33 seconds on the average, which was also determined from the statistical study. In general, we can characterize call related parameters for tactical communications as bursty, frequent and short. The type of calls can be voice, teleconference, videophony, video-teleconference, high priority data, or data [3]. In most of the simulations, the ratio of the number of voice calls to the total number of calls was 0.63. We also checked the sensitivity of call blocking rates to a higher rate of multimedia calls, where the voice calls constituted 37% of the calls. The source-destination pairs for calls were found using the same statistical study [3]. Most of the calls are directed to the parent or children units in the command hierarchy. Another important group of destination nodes are terminals owned by the neighboring units. Fewer calls are destined to other units.

Table 2. The call rate normalization factors.

Posture	In contact	Not in contact
Defense	0.79	0.53
Withdraw-Delay	1.01	0.68
Move	0.73	0.53
Amphibious	1.05	0.76
Other	0.74	0.56

Table 3. The average call intensity for an MPR in Erlangs.

Scenario 1	Scenario 2	Scenario 3
0.103 Erlangs	0. 082 Erlangs	0.109 Erlangs

The average call intensities, (i.e., the ratio of the call arrival rate to the call departure rate) observed in our simulations are shown in Table 3. Since call arrival rates are based on the posture of units, the average call intensity is different for each scenario. Although call holding times are usually short in tactical communications, call arrival rates are high especially when the units are in contact with the opposing units. Therefore, the traffic that we observed in our simulations is higher than that of a typical commercial system. The total offered load in the three scenarios are, respectively, 1908.49 Erl, 469.12 Erl, and 376.27 Erl.

In the performance studies, we first evaluated how long the system needs to configure itself if all the components are turned on at the same instance. Among all cases studied, self-configuration took two minutes at worst as illustrated in Figure 7. These results demonstrate that the proposed system is highly scalable and rapidly deployable. Note that the number of terminals involved in this initial self-configuration is more than 18000. We checked the sensitivity of this value in three different scenarios for different cell sizes and multiplication factors. The system always required less than two minutes for the initial configuration. Based on this finding, we omit the simulation data related to the first two minutes while studying the average performance of the system for the other performance metrics.

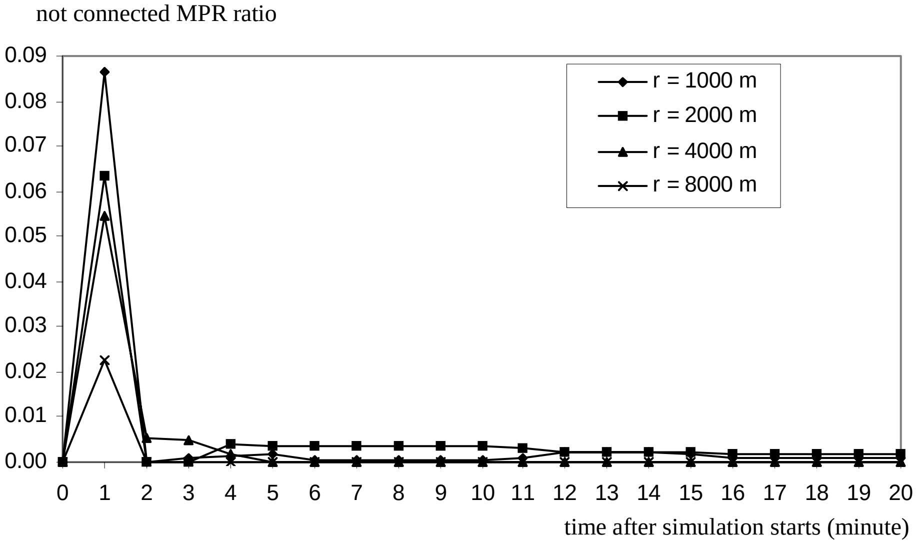
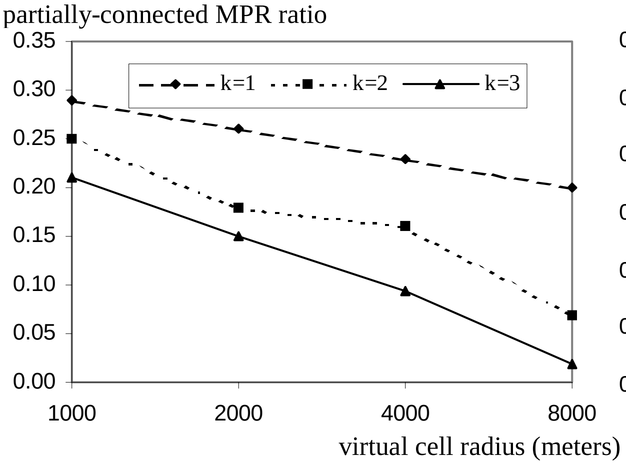


Figure 7. Not connected MPR ratios for each minute.



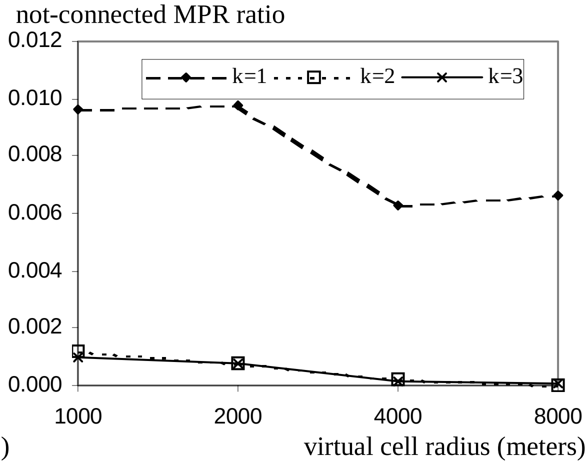


Figure 8. Average partially-connected MPR ratio.

Figure 9. Average not-connected MPR ratio.

In Figure 8, the average ratio of the number of partially connected MPRs to the total number of MPRs is illustrated for varying cell sizes. A partially connected MPR is an MPR that registers to a cluster head that is not connected to the WAS. Since the coverage area of RAPs enlarges as the cell size increases, the partially-connected MPR ratio reduces with higher cell sizes. In Figure 9, the average not-connected MPR ratio is illustrated. A not-connected MPR is an isolated MPR that does not have any connection with any other component. This ratio is low even for small cell sizes. It is almost zero if the virtual cell size is 2000 m or larger for multiplication factors larger than one. Since increasing *k* enlarges the real cells, partially-connected and not-connected MPR ratios decrease for higher *k*'s as shown in Figures 8 and 9.

In Figure 10, each of the curves represents the average call blocking rates for a given *k*. The call blocking rate is the ratio of the number of blocked calls to the total number of calls. Since the inter-cell interference gets higher and the frequency reuse gets lower when the cell radius gets larger, the call blocking rate is higher for the larger real cell radii. The average call blocking rate is lower than 0.01 when the real cell radius is lower than 12000 m. The number of carriers assigned to each virtual cell is three for all of the curves in Figure 10.

We examine the sensitivity of the call blocking rates to the changes in the number of carriers assigned to the virtual cells, channel characteristics and call types in Figure 11. Unless the number of carriers assigned to a virtual cell is lower than three, we do not observe much difference in call blocking rates. In Figure 11, *k* is 2 for all of the curves.

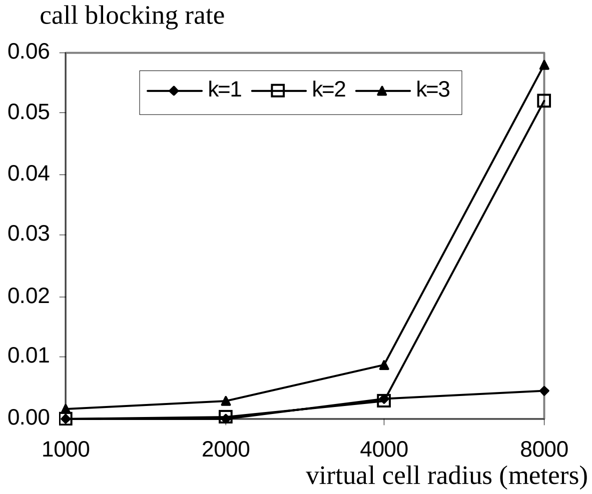


Figure 10. Call blocking rate for different multiplication factors.

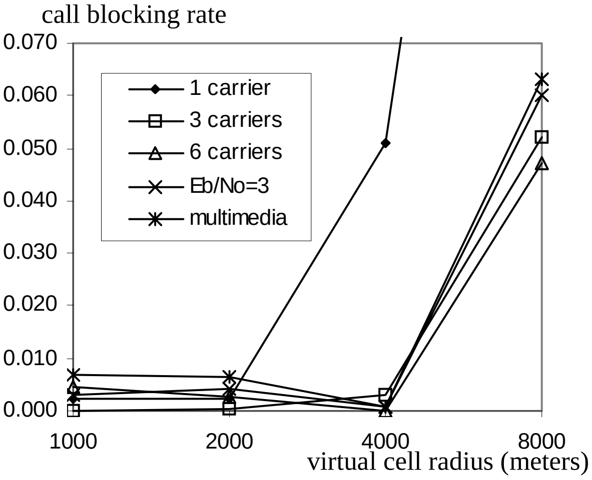


Figure 11. Call blocking rate for different number of carriers, channel characteristics and traffic types.

In our simulations, system performance was also evaluated for handoff related performance metrics. Based on the average cell residency time, we found that the average speed of an MPR relative to the registered RAP is lower than the pedestrian speed (i.e., 4 km/h). This is because RAPs move with the units to which they are attached. Hence, when the average speed of a unit is 50 km/h, the average relative speed of an MPR is less than 4 km/h according to the position of the RAP serving it. This is a major advantage, since it indicates better radio transmission characteristics and lower handoff signaling traffic. When the virtual cell radius is 2000 m and *k* is 2, the MPR handoff rate per second is 10^{-4}, which is very low. The RAP handoff rate per second is 10^{-5}, which is even lower. More detailed results of the performance studies related to handoff rates can be found in [2].

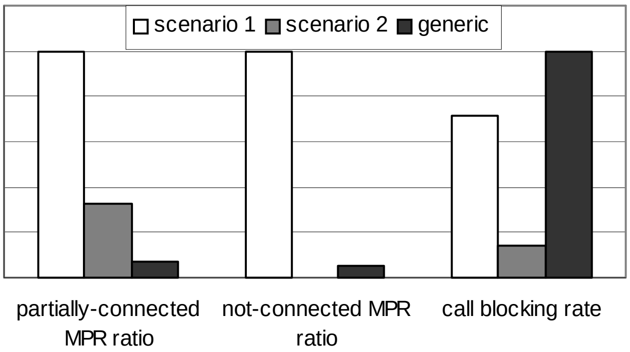


Figure 12. The comparison of three scenarios.

The three scenarios described in the beginning of this section are compared in Figure 12, where the linear vertical axis does not have any units. The values for the performance metrics are normalized to be able to visualize three performance metrics in a single figure. The cell size is 2000 m., *k* is 2, and the number of carriers in each cell is 3 in these simulations. In the first scenario, there are many units in company or lower levels deployed in a distance from battalions. Since only battalions are equipped with RAPs, the partially-connected and not-connected MPR ratios in the first scenario are the highest. The call blocking performance of the generic scenario is the worst because the units in this scenario have the highest mobility and most of them are in the attack posture. The call generation rates in the attack posture are higher than the call generation rates in most of the other postures. On the other hand, the second scenario has the best call blocking performance because almost all of the units in this scenario are fixed and in the defense posture.

5. Conclusion

In this article, we have proposed a novel resource management scheme named Virtual Cell Layout (VCL). In VCL, the communication area is covered with fixed virtual cells to which the radio resources such as the frequency carriers and the CDMA codes are assigned. The real cells are mobile over the VCL cells. RAPs use the radio resources assigned to the virtual cells where they are located to create real cells that are not necessarily the same size as the virtual cells.

We use this architecture to adapt the 3G PCS technologies for tactical communications systems. We modify the initial cell search and registration procedures of UMTS for VCL, and develop new procedures such as an RAP level handoff where an RAP makes an inter-resource handoff when it changes virtual cells. We also propose some ad hoc clustering algorithms based on VCL. These ad hoc algorithms are used to organize MPRs into cells in the absence of a RAP in the vicinity.

The performance of the proposed system was evaluated by using CITACS, which is a simulation system for tactical communication systems. In our simulation studies, we observed that it takes two minutes at most to start the system if we turn on more than 18000 mobiles at the same time. Since the system does not require a fixed infrastructure and much preplanning, this observation indicates a highly scalable and rapidly deployable architecture. The results related to performance metrics such as call blocking and handoff rates demonstrate that our system can meet even the grade of service requirements expected from an immobile infrastructure.

We continue to work on issues related to the proposed architecture such as the integration with the higher tiers, service outage detection, handover procedures for the replicating RAPs, comparison of different handoff schemes for the proposed architecture, rerouting techniques during handoffs, and the effects of more bursty call arrival patterns.

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Acronyms

3G	Third generation
CITACS	Computer aided exercise interacted tactical communications simulation
DISN	Defense information system
GSM	Global system for mobile communications
LAS	Local area subsystem
MPR	Man packed radio
MPRT	MPR tier
MS	Mobile subsystem
PCS	Personal communications services
RAP	Radio access point
RAPT	RAP tier
RNS	Radio network subsystem
SATT	Satellite tier
SMCS	System management and control subsystem
TACOMS	Tactical communications
UAV	Unmanned aerial vehicle
UAVT	UAV tier
UMTS	Universal mobile telecommunications system
USRAN	UMTS satellite radio access network
UTRAN	UMTS terrestrial radio access network
VCL	Virtual cell layout

WAS	Wide area subsystem
WCDMA	Wideband code division multiple access