Analysis of the use of LTE-A in Mission Critical Communications among armoured vehicles in operational scenarios

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***Abstract*— The main objective of this thesis was the study of the coverage and capacity of a D2D LTE-Advanced network among military vehicles. The study was made considering the most recent Portuguese Army vehicles, PANDUR II and considering the characteristics inherent in military communications as distance between vehicles or the vehicle's height. A model was developed to evaluate the coverage and capacity of these communications. The model considers three frequencies that are available to the Portuguese Army: 65 MHz, 896 MHz and 1685 MHz and three modulations: 4-PSK, 16-QAM and 64-QAM. For these frequencies, four environments were analysed: Urban, Suburban, Rural and Forest. The most effective frequency to perform all services was the frequency 65 MHz. The case of the forest environment is quite critical when using the 1685 MHz frequency. In terms of coverage, for the scenario with the highest throughput (Rb = 144.166 Mbit/s), frequency 65 MHz obtained the best results. In the Forest environment, which is the worst case, this frequency allows communicate up to 3776 meters. In terms of capacity, for the greater distance between vehicles (600 meters) the frequency 65 MHz could in the worst case transmit with a throughput of 380 Mbit / s. The results obtained show that the technology proves to be quite satisfactory, being able to carry out the communications much more effectively than with the technology used nowadays.**

***Index Terms*— LTE-Advanced, D2D, Ad hoc networks, PANDUR vehicles.**

I. Introduction

Mobile communications from the outset have already greatly changed their paradigm. Although in their genesis they were created to support voice services, the truth is that today the big challenge for operators is to ensure an effective data communication system. According to international reports the penetration rate of mobile communications has been growing exponentially as well as the information circulating in networks [Eric16]. Data traffic grew by a factor of 3.6x over a period of two years, which corresponds to an annual growth of 90%. This growth is an argument for the development of Long Term Evolution (LTE) networks and the need to expand the spectrum available for LTE. In Figure I.1. one can observe this growth.

As for the Portuguese Army, the PRC 525 radio is currently in use and has a data transfer rate of 72 kbps using OFDMA modulation [EID16]. This value is substantially lower when compared to LTE technology. It is then very clear the advantage of using this technology in the face of current needs. The major challenge in the application of this technology in a military environment is with the additional security and availability requirements in relation to the commercial environment. However, about security, the Army has means of encryption independent of the medium of transmission, so in the study of this dissertation it will not be necessary to consider procedures in terms of information security. Another important reason is that the military environment is a much smaller market compared to the civilian medium, which for the companies that develop technology is not profitable, consequently the investment that the Armed Forces so desire is not made.

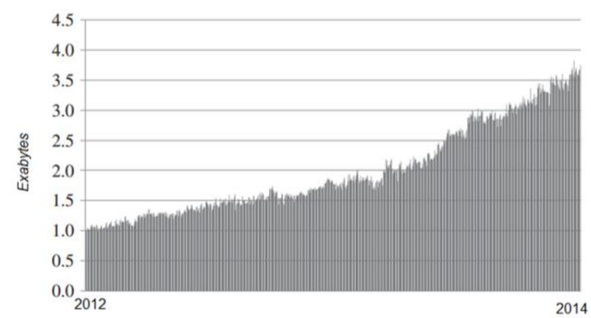


Figure I.1 Data traffic between 2012-2014 (adapted from [HotoRe16]).

The mission of the Army is very extensive and includes participating in international missions in the framework of International Organizations namely the North Atlantic Treaty Organization (NATO) and the United Nations (UN), to carry out technical-military cooperation actions or to cooperate in missions of civil protection [Exe16]. To date, the Army maintains operational training missions and operations in the following countries: Kosovo, Iraq, Mali, Central African Republic, Somalia, and Afghanistan. In all scenarios, regardless of the type of operation it is necessary to establish and maintain military communications for the normal operation of the Outstanding Force. As you can expect, the Army finds completely different scenarios in these countries, but regardless of this, communications must work in the same way, so it is a great challenge to be able to standardize the technologies knowing that the scenarios vary drastically. Environments range from roads and rural roads where there is no impediment to the connection, highly wooded areas or even urban areas where the density of buildings can be high and vehicles are no longer in sight. It is therefore a challenge to study the applicability of LTE in such different scenarios and atmospheric conditions.

Nowadays time is an essential factor, on the battlefield it is indispensable that the Commander, who is in the rear, obtain the information of the front of combat as fast as possible and that his decisions are spread in the minimum possible time. Therefore, obtaining such detailed information requires a timely return [TTG13].

II. FUNDAMENTAL CONCEPTS

A. Network Architecture

LTE was introduced by the Third Generation Partnership Project 3GPP in Release 8 and developed in Release 9. According to the company there were several motivations that led to the development of this technology, among which, the user's requirement for higher and higher binary throughput rates. Service (QoS). [3GPP8]. These publications were launched in 2008 and 2009 respectively, so in recent years the evolution of technology has had to accompany the abrupt growth of data usage. Faced with these requirements, the driving force behind the development of LTE-Advanced was to attempt to provide binary throughput rates that would meet the needs of users. More recently the goals that were specified in Release 10 were to increase the peak of the binary throughput rate in downlink (DL) to 3 Gbps and uplink (UL) to 1.5 Gbps and increase the number of active users simultaneously.

The LTE network was designed to support packet switching services, unlike previous networks that use circuit switching. It encompasses the evolution of radio access through the Evolved Universal Terrestrial Radio Access Network (E-UTRAN) and is accompanied by the evolution of non-radio aspects through System Architecture Evolution (SAE) which includes the Evolved Packet Core (EPC) network. LTE and SAE form the Evolved Packet System (EPS). Figure 2.1. shows the overall architecture including the elements of the network and the communication interfaces between them. The elements of the network are detailed below.

The architecture of a direct-mode communication system has some specifications that differ from a conventional LTE system. Release 12 emphasizes public safety communications in 3 different cases: with coverage, this scenario indicates that the EU considered is covered by eNBs, without coverage, this scenario indicates that the EU considered is out of eNB coverage, partial coverage, this scenario indicates that some US are under eNB's coverage and others are not. In Figure II.1 we can observe an exemplary scheme.

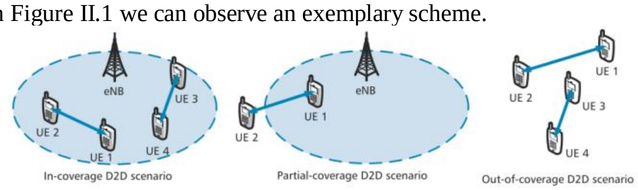


Figure II.1 Division of D2D communications according to Release 12 ([extracted from [LCTH16].

B. Radio Interface

It is quite relevant to note the interface aspects that underpin communications, from the possible frequency bands to the details of multiple access techniques. This section addresses the aspects of the radio interface, namely frequency bands, multiple access techniques, modulation schemes, control and information channels, and MIMO. The sources on which the section was based were [HoTo11], [HoToRe16] and [3GPP13].

Military communications differ in the frequency bands used since frequencies are assigned in the order of tens or few hundreds of MHz. One of the main reasons is that with lower frequencies it is possible to perform communications over longer distances. As for the transmission equipment already used by PANDUR vehicles, it has been found that these are equipped with several antennas, which serve several telecommunications systems.

Table II. Bandwidth of PANDUR antennas (adapted from [Exe13])

Antenna	***Bandwidth [MHz]***
HF Vehicular antenna	2 – 30
VHF Vehicular Antenna	33 – 108
VHF/UHF Vehicular Antenna	30 – 512
UHF Antenna	225 – 450

C. Coverage and Capacity

To better understand the coverage and capacity of the network that would be required to support a military unit, it is necessary to specify the organic and functioning of a platoon that moves assembled. The Army has several strengths with respect to armored vehicles or personnel transport. The mechanized platoons of the Army are mostly composed of PANDUR II or M113 vehicles. Each platoon consists of 4 vehicles that are distanced according to the probability of contact with the enemy.

There are three levels of probability, unlikely, probable, and imminent. For each level, the vehicles differ in different ways to better respond to enemy attacks. In a situation of unlikely contact, the squad progresses continuously, in which case the speed of the vehicles is higher than in the other levels. The vehicles proceed alternately with a lateral distance of about 50 m and spaced between 50 and 100 meters in the direction of travel. When the contact becomes probable, the progression happens to be on supported, in this case the distance between the vehicles increases to 400 to 600 meters. In the latter case, with imminent probability, the distances are reduced because the vehicles assume combat positions. It will then be concluded that in a displacement on supported the peloton is positioned more distally. This is a relevant fact when it is intended to communicate between the first and the last vehicle. As the squad consists of 4 vehicles, the distance between the first and last will be about 1800 meters. In Figure II.2 we can visualize the device in alternating progression and progression on supported.

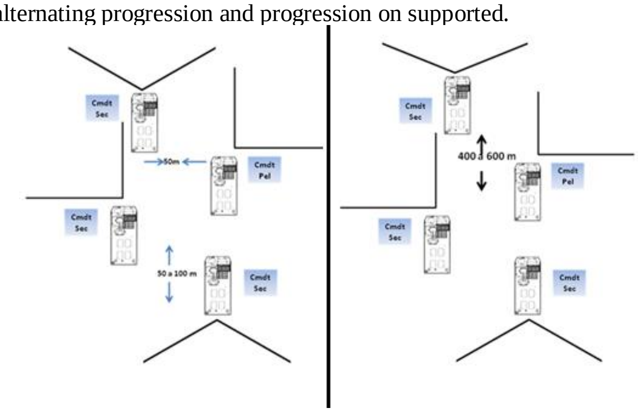


Figure II.2 Distances between moving vehicles (extracted from [Exe15]).

There are two families of models for distances of more than 5 km. The models of the family are used in urban, suburban or rural settings. For distances of less than 5 km the family COST 231 - Walfish-Ikegami (CWI) is used. As for the classification of the environments it is necessary to consider these parameters: ripple of the terrain, density of vegetation, density of buildings and height, density of open areas and density of aquatic areas. All models are defined for a certain frequency band, connection distance and environment.

D. Ad hoc networks

Ad hoc networks are especially attractive for military communications, since on the battlefield mobility is a determining factor and in this typology the nodes may be in constant motion. Table II.1. we can observe the main advantages that an ad hoc network and that are especially attractive in the scope of military communications.

Table II.1 Advantages of Ad hoc networks (extracted from [COTS11].

Advantage	**Description**
Self forming	Nodes that enter in the network coverage can establish communication without any pre-configuration or manual intervention
Self healing	Nodes can join or leave the network without affecting the operations of the other nodes.
Without infrastructure	Nodes form their own network and form essentially the structure itself.
Peer-to-peer	Nodes can change information without previously agreement and depending on centralized resources.
Wireless	This networks are in majority wireless but can be extended to support wire communications.
Mobility	Nodes are in constant movement and the network topology is constantly changing.

E. State of Art

When we talk about the use of LTE for communication between military vehicles, derived to the specification of the subject there is little investigation of the subject. However, LTE for public security services and D2D communications has already been the subject of investigation since Release 12 in which 3GPP stated that this strand should be investigated.

In article [VFS13] the improvement that a D2D system brings in terms of coverage and capacity compared to a traditional system is analyzed. It claims that the use of the UE as mobile relayers increases the coverage by about 150%, since in this way it manages to get signal to places that would not otherwise arrive. In Figure 2.10. we observed the clear improvement in the covered area that exists with the use of mobile relays.

[RWLLL15] makes a study about the use of LTE - D2D with support for communication between vehicles. The model is applied in a typical scenario of a motorway by varying the distance from the eNB to the motorway. Comparing two models of power control, uniform control and control based on geolocation, concludes that the model based on geolocation by varying the distance from the eNB to the motorway is always better.

Table II.2 Results obtained by [VFS13].

$R_{b\,[Mbit/s]}$	**Coverage area without D2D (%)**	**Coverage area with D2D (%)**	**Increase of coverage area (%)**
0.384	96.29	100	3.71
1.0	93.28	100	6.72
5.0	85.28	100	14.72
10.0	79.5	100	20.50

III. Models

A. Operational Scenarios

The fact that Portugal belongs to institutions such as NATO or the UN entails additional responsibilities in respect of international conflicts, so it is important that the Armed Forces, in this case the Army, are prepared to act in any type of environment. Involving communications to operate in any environment under any conditions. Several typical scenarios can be derived from NATO's various commitments:

- Urban environment with high density of buildings, tall buildings, narrow streets. This environment is increasingly common with the existence of conflicts in the center of cities. An example is NATO's commitment to the peacekeeping mission in Addis Abada, Ethiopia, a city with a high density of buildings.
- Suburban environment with 3 or 4-story buildings, spaced apart, are typically residential neighborhoods in the outskirts of major cities.
- Tunnel or metal bridge environment, where communication between both terminals is done within a tunnel or bridge, the attenuations in connection to the metal or to the surrounding soil are necessary to consider.
- Rural environment where the density of buildings is much lower than previous environments with buildings of 1 or 2 floors and often very spaced apart.
- Forest environment This environment is characterized by the presence of trees, undergrowth and absence of buildings. Taking as an example the Pinhal of Leiria with a density around 250 trees / hectare, a higher density of trees would not allow the vehicles to move in this environment, soon lose the interest of the study.
- Lowland environment, this environment is characterized by the absence of buildings and great obstacles to propagation, typically plains with large areas of low vegetation. Examples are the interior areas of Europe such as Germany or Poland.

• Hilly environment where there are no buildings, but there are natural obstacles such as large cliffs or mountainous formations. Examples are the interior parts of Afghanistan or Iraq.

• Desert environment, this environment is also characterized by the absence of buildings. The obstacle to communications in this case will be the natural formations of dunes for example.

• Arctic environment, this environment derives from a mountainous or desert environment, but in this case, it is necessary to consider the attenuations derived from snow and very low temperatures. Examples are northern regions of countries such as Norway or Sweden.

These scenarios were chosen to analyze environments as close to reality as possible.

The 1st Scenario would be an urban zone, with buildings of about three floors with wide streets and equivalent distances between streets. The 2nd Scenario would be suburban, this scenario only differs from the previous one at the height of the buildings, the distance between them and the width of the streets. Of course, it will be possible to achieve superior coverage, since there will not be the same propagation attenuation values. The third scenario is the rural scene, where it is quite common in countries in conflict in the Middle East and in which NATO is involved. In such a scenario, the vehicles will be further apart from each other, on the one hand, it will guarantee more safety to the vehicles and from the point of view of the propagation, the attenuation is lower so the vehicles may be further apart. Finally, the forest scenario with low vegetation density. This scenario is based on an environment like the Pinhal of Leiria with trees spaced apart, where vehicles can patrol. Scenario typically found in many army engagements.

Once the scenarios are defined, it is necessary to specify the working frequencies and their respective bandwidths. There are frequency bands allocated especially to the military and in which only these can operate. The Army provided three bands for study and possible use. These three bands to be evaluated are located in very different areas with different coverage and capacity. The bands are divided into a VHF band (61-68 MHz), and two UHF (895-898 MHz) and (1675-1695 MHz). Table III.1 shows the frequency and its bandwidth. These bands have specific characteristics that allow you to perform different tasks. Frequencies that use narrower bandwidth will be more suitable for services that require a low throughput, such as for example voice calls for group communication purposes. On the other hand, there are services that require higher bandwidth (streaming video, group video calls and file transfer) that require a higher bandwidth to perform these services.

Table III.1 Frequencies in study and its bandwidth.

Frequency (f) [MHz]	**Bandwidth (Δf) [MHz]**
65	5
896	3
1685	20

B. Model Parameters

To be able to perform the communication it is necessary to have a capable transmission medium. Research was done on antennas that met the needs. The antennas chosen to carry out the simulations are special antennas that meet the technological needs covering the available frequencies as well as the military needs of being robust to face adverse weather conditions. The antennas in question are designed to operate in vehicles, and at desired frequencies [RoSch14]. These antennas are designed with NATO standards and therefore guarantee a wide range of frequencies, discrete design, high efficiency and capable of operating in harsh environments with large thermal amplitudes. The antennas are omnidirectional that in the case study of this dissertation is of extreme importance that they have this standard once the vehicles move. In the supplier's catalog, you can remove the values that are relevant to the calculation of coverage and capacity, such as transmission power, gains and losses in cables. The HK056 antenna is designed for the bandwidth from 600 MHz to 3 GHz and the HK055L antenna is designed for the bandwidth from 27.5 to 600 MHz so this two ones cover the frequencies needed.

Figure III.1 Antenna R&S HK056 and Antenna R&S HK055L, extracted from [RoSch14].

The choice of antennas is essential because they provide values essential for the calculation of coverage, such as antenna gains or maximum transmit power. The characteristics of the antennas have been taken from the manual [RoSch14] and are presented in Table III.2.

Table III.2 Caracteristics and antenna values, adptadem from [RoSch14].

Parameter	**Value**		
Frequency [MHz]	65	896	1685
Bandwidth [MHz]	5	3	20
RB	25	15	100
Transmission Power [dBm]	50	50	50
Antenna Gains[dBi]	1	2	2
Cable Losses [dB]	2	2	2
EIRP [dBm]	47	50	50
Noise factor[dB]	7	7	7
Slow fade margin[dB]	8.8	8.8	8.8
Average Power Decay (CWI)	3.8	3.8	3.8
Average Power Decay (ITUR)	4	4	4
Average Power Decay (Weissberger)	3.28	3.28	3.28

C. Coverage Model

One of the main objectives of this thesis is to evaluate the use of LTE technology in hostile environments considering the needs of a Portuguese contingent committed to a mission. One of the main characteristics to evaluate is the coverage, in other words calculate until distance these technologies can be used without any communication failure. The reasoning followed to calculate the coverage is represented in Figure III.2.

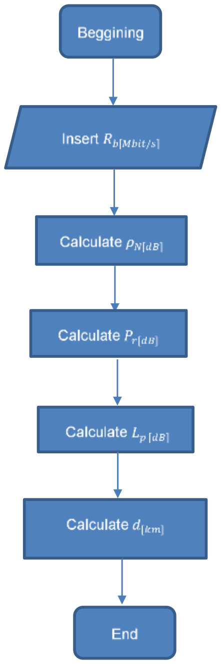
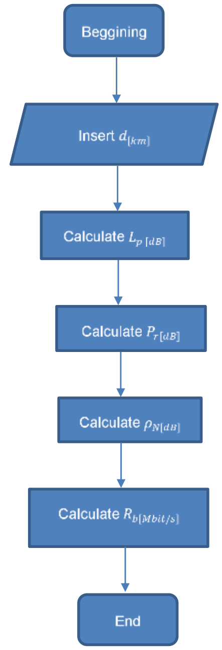


Figure III.2 Coverage model flowchart.

D. . Capacity Model

Evaluated the coverage according to the various frequencies and the different modulations, it will now be essential to assess the capacity of the system. At a given distance a car will have access to a certain transfer rate ($R_{b\,[Mbit/s]}$) and depending on that rate it can perform certain services for a limited number of users. It is extremely important for the Commander to have the perception of which services he can carry out and which ones he will be more limited.

The process starts by entering a distance with the first goal of calculating losses in the path ($L_{p\,[dB]}$). To perform this calculation, it is necessary to consider a frequency and a modulation. Losses are calculated according to the model appropriate to the scenario. The next step is to calculate the sensitivity. Knowing the value of the losses and considering the gains of the antennas and the losses in the cables, the available power is obtained in the antenna. Next the noise power value is calculated by considering the bandwidth associated with the chosen frequency and the noise figure, which takes a default value of 7 dB. Knowing the value of the noise power and considering a minimum interference margin (1 dB), it is calculated the SNR. Finally, and considering the reference values of the modulations, the value of $R_{b\,[Mbit/s]}$ is calculated. This whole process is plotted in the flowchart of Figure III.3.



} Figure III.3 Capacity model flowchart.

IV. Results Analysis

A. . Scenario: Baghdad city

The reference scenario chosen was the city of Baghdad because it is a theater of current and conflicting operations that counts on the presence of Portuguese military personnel, especially the Portuguese Army. They are members of the Combined Joint Task Force (OPERATION INHERENT RESOLVE), which was formed in October 2014 in a NATO coalition aimed at eliminating the Islamic state of Iraq.

The city of Baghdad is in the center of the country on the banks of the tiger river, its metropolitan area has about 9 million inhabitants, being one of the largest cities in southwest Asia. With the help of Google Maps (Figure 4.1), one can quickly see that the center of the city is organized in neighborhoods with straight and perpendicular streets, like Lisbon downtown on a much larger scale. Derived from the particularities of the city of Baghdad, the city center is characterized as an urban environment.

On the outskirts of the city there are residential neighborhoods that resemble suburban environments, with smaller buildings, narrower streets and distances between the center of smaller buildings. The most suitable propagation model to be applied in the city center and suburban areas is the Cost 231 Walfish Ikegami model The parameters are shown in Table III.3.

Moving away from the city center it begins to appear some small villages that I can be characterized as rural areas with few houses and of reduced height. The best model to use in this condition is ITU-terrain and the parameters are shown in Table III.4

Finally, along the banks of the Tigris River, there is a great density of vegetation, mainly palm trees, which can be characterized as a forest environment. To study the attenuations suffered in this environment was chosen the model of Weissberger.

Table III.3 Urban and Suburban model parameters.

Parameter	Urban	Suburban
User height [m]	2.5	2.5
Building height[m]	25	15
Street width [m]	15	10
Distance between buildings [m]	100	50
Incidence Angle [°]	90	90

Table III.4 Rural model parameters.

Parameter	Rural
User height [m]	2.5
p [%]	10
ΔL_{LoS} [dB]	-7.9
ΔL_{NLoS} [dB]	-9.0

B. Coverage model results

Four scenarios were defined that consider different situations, so different transfer rates, Table III.5 presents in detail the services used in each scenario. In the first scenario, we simulate the execution of services that lead to low traffic, such as voice calls and emails. The following scenarios arise with a parallel service increment that significantly increases the total throughput. Making a total of:

- A: R_b = 3.366 Mbit/s
- B: R_b = 12.326 Mbit/s.
- C: R_b = 63.526 Mbit/s.
- D: R_b = 144.166 Mbit/s.

Table III.5 Paralel services

Service	Voice call	Email	Video Streaming	File Transfer
A	30	30	-	-
B	30	30	10	5
C	30	30	10	50
D	30	30	100	100

Scenario D represents the highest increase in the transfer rate, as well as the greater number of cases with the impossibility of performing the communications. With a transfer rate of 144,166 Mbit / s the frequency of 1685 MHz proves to be inefficient since it does not allow communication in the Urban and Forest environments and approaches the maximum value in Suburban and Rural environments

Table III.6 Distance between vehicles in Scenario D using 4-PSK modulation.

$d_{[km]}$	65 [MHz]	896 [MHz]	1685 [MHz]
Urban	8.761	1.727	0.530
Suburban	10.729	2.116	0.650
Rural	39.984	2.815	0.861
Forest	3.776	0.683	0.323

Table III.7 Distance between vehicles in Scenario D using 16-QAM modulation.

$d_{[km]}$	65 [MHz]	896 [MHz]	1685 [MHz]
Urban	8.876	1.750	0.537
Suburban	10.870	2.143	0.658
Rural	40.391	2.851	0.872
Forest	3.794	0.687	0.325

Table III.8 Distance between vehicles in Scenario D using 64-QAM modulation.

$d_{[km]}$	65 [MHz]	896 [MHz]	1685 [MHz]
Urban	8.990	1.773	0.544
Suburban	11.010	2.171	0.667
Rural	40.884	2.885	0.882
Forest	3.798	0.691	0.328

C. Capacity model results

The study of capacity was obtained through the explicit reasoning in chapter 3, for this analysis three standards were defined (50, 200 and 600 meters) considering the minimum, average and maximum distance between vehicles.

Table III.9 Bit rate between two vehicles distanced by 600 m using 4-PSK modulation.

$R_{b\,[Mbit/s]}$	65 [MHz]	896 [MHz]	1685 [MHz]
Urban	380.680	379.707	142.966
Suburban	380.680	379.707	155.161
Rural	380.680	380.580	313.790
Forest	380.980	348.390	1.3585

Table III.10 Bit rate between two vehicles distanced by 600 m using 16-QAM modulation.

$R_{b\,[Mbit/s]}$	65 [MHz]	896 [MHz]	1685 [MHz]
Urban	1128.513	1082.785	149.988
Suburban	1128.517	1087.256	164.4459
Rural	1128.560	1121.580	496.031
Forest	1128.555	680.744	1.695

Table III.11 Bit rate between two vehicles distanced by 600 m using 64-QAM modulation.

$R_{b\,[Mbit/s]}$	65 [MHz]	896 [MHz]	1685 [MHz]
Urban	1500.00	1461.521	159.771
Suburban	1500.987	1465.849	178.087
Rural	1500.0	1495.599	653.204
Forest	1500.0	932.82	2.941

V. Conclusion

The main objective of this thesis was to study the use of LTE in military communications, especially among PANDUR military vehicles. The study placed emphasis on coverage and capacity.

About the coverage model, it is found that the results obtained for the 65 MHz frequency are very satisfactory. In all cases the distances between the vehicles, always with a considerable margin, are fulfilled. The frequency 896 MHz is also an option for use and always meets the distances, however for high transfer rates it is not recommended to use this frequency in the Forest environment. Finally, the 1685 MHz frequency has proved an option that can cause problems for the Commander if it intends the intensive use of services that entails a high transfer rate. For lower transfer rates (Scenario A and B) the 1685 MHz frequency is feasible in all scenarios except the Forest scenario. The same can not be guaranteed as the transfer rate rises and the distance between the vehicles is increasingly reduced, not being fulfilled the stipulated 600 meters.

When analyzed the capacity model in relation to the number of users in parallel it is verified that services that require low transfer rate as is the case of voice calls or email, it is possible to guarantee a number of users in the order of thousands. Exception made for the isolated case of the use of the 1685 MHz frequency with the 4-PSK modulation in the Forest environment, in this case the voice service can guarantee 111 calls in parallel. The e-mail service like the voice call service is also guaranteed by all frequencies in the order of the thousands of users, the worst case is recorded in the same way as the previous one being 14 users in parallel. The analysis is similar for video calls and file transfers. The minimum value of parallel calls is 372, except once again the Forest environment where a maximum of 8 users could simultaneously use. In the case of file transfers, the minimum value is 139 transfers in parallel, except the forest environment that allows to make at most two transfers in parallel.

When the platoon of vehicles serves as a support for infantry platoons, in most cases this technology proves to be a great advantage for the transmission of information, being very efficient in the most varied environments and in the most varied frequencies and modulations.

The greatest limitations are in Forest environments where the signal suffers great attenuation mainly for high frequencies. The frequency 65 MHz proved to be very useful in all cases, with little variation in their values when increasing distance or transfer rate. It can also be concluded that the frequency 1685 MHz in some cases is not a better option and can compromise communications mainly at high distances.

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