Evaluation Performance of Long Term Evolution Coverage and Cell Edge

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Abstract.

Historically, the domain of military communications used to be the sole initiative for the development of telecommunications systems. This is not the case anymore. Commercial telecommunications networks witnessed a revolutionary evolution in the past two decades that leads to the currently running discussion about 5G. Whilst, military communications still creeping and stocked to the old day's push to talk radios. Today, while the average commercial consumer demands for a traffic of some Mbps, the maximum achievable rate of VHF radios is 19.2 kbps. This paper proposes the use of LTE standard in military communications to bridge the gap and for a better usage of the commercially of the shelf (COTS) technologies. LTE/LTE-A promise to provide a 100 km cell coverage with a downlink capable of 3 Gbps, and uplink that can reach 1 Gbps and terminal speed of 320 km/h. The paper focuses on the coverage problems. Vienna LTE-A Link Level Simulator was used to simulate the system. Simulation results were presented as throughput versus distance instead of SNR. This was done using together the 3GPP Spatial Channel Model and the ITU-R model to predict the cell edge coverage. Results show that the downlink can meet the goals of ITU's IMT-Advanced. In the uplink, the standardized output power will not satisfy the goals.

Keywords: 4G, COTS, LTE, LTE-A, Link budget, Military networks, open architecture, public safety.

Introduction

For decades, the domain of military tactical communications used to be the driving force, and the sole initiative for the development of telecommunications systems. Defense-based technologies were decades ahead of commercial technologies. Military communications witnessed and embraced the birth of all telecommunications technologies since the invention of the telegraph up to the advanced spread spectrum techniques. But, for the last two decades this picture greatly changed. The commercial telecommunications domain gradually takes hand on leading the evolution of telecommunication, supported by gigantic scientific institutions such as IEEE and open R&D community. The technology gap between the two domains is now huge. This situation leads to frantic cries form the army people complaining about their devices being helpless. actually it is extremely painful to use legacy CNR radios after getting used to something like Galaxy phones! So if a soldier can use a lightweight, powerful smart phone in his day-to-day life, the same soldier would question the necessity of carrying a few pounds of tactical radio, with diminished capabilities and features. In fact, with the technological leaps in commercial wireless networks, expectations of tactical wireless networks increased and have yet to be fully met [1]. Moreover, features that was once an exclusively military requirement is now a common base line feature. In fact, todays military communications technologies lag behind their commercial counterpart. Hence, commercial cellular networks can provide so many benefits to the tactical theater, such as low cost, application richness, maturity, and familiarity of use.

The current generation of warfighters can greatly benefit from the use of smartphones; given the additional features they provide.

Smartphones are putting a never-before-seen communications capabilities into the hands of new tactical users. These include, but are not limited to, voice and command and control (C2) data, social networking, anthropological decision aids, real-time data feeds (from airborne and ground-based sensors), and remote controls of unmanned vehicular platforms [2]. In general, as stated in [3], mobile devices with reach-back to network-based services will allow distributed commanders and staffs to collaborate as though co-located. Developing networks that can simultaneously integrate secure and non-secure communications will widen the circle of actors who can support a given operation, allowing diverse stakeholders to contribute insights and expertise in real time.

Some commercial end user device technologies are already applied to the tactical environment [4]. In some cases, commercial smart phones are being used as is; however, in other cases they are being adapted to the special needs of the tactical environment, i.e. rigidness. Vendors are undertaking some of the adaptations, because they see a growing market for secure, ruggedized devices that can be used not only in the military domain, but also in public safety, disaster relief, humanitarian aid, and wilderness domains. Other adaptations are being pursued by the USA’s DoD and the Intelligence Community, with the essential properties of the devices being preserved. This tendency arises after the failure of the recently closed Joint Tactical Radio System (JTRS) project, which was initially intended to solve the above mentioned problems (mainly interoperability) with the logical alternative being the utilization of customized LTE network [1]. Keeping in mind that the fast pace of commercial product cycles requires any customization to be carefully considered and properly architected [2]. George F. Elmasry, an American-Egyptian famous professor in the field, addressed this problem in his book [1]. This book discussed the matter in details and describes how to re-layer the protocol-stack of LTE to satisfy tactical network’s needs. It ends up with two main requirements for a successful military communications standard:

1. To be an open standard, to grantee the maximum support from research community.
2. With an efficient interlayer communication for maximum utilization of available resources.

Clearly, LTE/LTE-A can meet both requirements, and more, as the standard focuses on several features that sport the special needs of the defense and public safety domains.

LTE performance enhancements strategies and mathematical models

Improved system capacity and coverage are the most important goals of the long term evolution. The standard pays a lot of attention to these requirements by the adoption of various technologies such as OFDM and MIMO techniques.

The techniques used for coverage enhancement can be divided into two categories; link level and system level enhancements. Link level enhancements include: short frame size, adoption of SC-FDMA for uplink transmission, per user power control and beam forming of control channels, time diversity of PHICH, HARQ (to be within the delay budget), subframe bundling, restricted random-access sequences (or preambles) with high transmission detection probability and low false-alarm rate (e.g. Zadoff–Chu sequence), preambles utilization for transmit diversity for different control channels. System level enhancements include MBSFN, HetNets, CoMp micro cells, Femto cells, and relaying [5].

This paper will investigate the LTE/LTE-A system to insure that it can reach the promised coverage and throughput. This will primarily justify the potential of the system over other cellular technologies and, in particular, over the extremely expensive, bulky, and limited capabilities of legacy military communications systems. The first step is to study the LTE physical layer characteristics. This was done with the aid of Vienna LTE-A Link Level Simulator [6]. The concept and the structure of the simulator is described in details in [7]. Here, will give a brief introduction of the simulator, present and discuss some of the produced results, taking into account the fact that simulated performance number should be viewed in the context that real radio network performance will depend on many parameters that are difficult to control or model, including [8]:

- The mobile environment, including channel conditions, angular spreads, clutter type, terminal speeds, indoor/outdoor usage, and coverage holes.
- User-related behavior, such as voice activity, traffic distribution, and service distribution.
- System tuning of service quality and network quality.
- Deployment aspects such as site types, antenna heights and types, and frequency planning.
- A number of additional parameters that are usually not modeled, such as signaling capacity and performance, and measurement quality.

Since simulation results are commonly presented as throughput versus signal to noise ratio, any frequency effects will be hidden and the simulator gives the same results regardless of the frequency parameters setting.

Instead of the usual way of presenting performance results versus signal to noise ratio (SNR), the relevant channel model will be used at the specific frequencies of 400MHz, 700MHz and 2.9 GHz to present the performance against distance. This will give a more insight into the system performance. The first frequency, 400MHz, is just introduced in release 13 of the standard and will offer a much better performance in terms of coverage regardless of the system technology due to inherent characteristics of EM wave propagation.

It worth noting here that, 3GPP requires the coverage issues to be discussed regardless of the carrier frequency by focusing on increasing the energy per bit, in a form stated in [9]. This is to insure that any coverage enhancements will be a benefit of all deployment frequencies. Here the interest is also in frequency as the major contributor to the path loss, and, hence, coverage.

A. Link-budget and SNR-Distance Mapping

The link budget provides the maximum allowable path-loss, which may then be mapped into cell coverage. The link budget is calculated using a path loss model suitable for the scenario in hands, as shown in figure 1.

In LTE, coverage is balanced between the different control and random-access channels, and is generally limited by the required data rate at the cell edge [5].

In terms of deployment, LTE must support a cell radius of up to 100 km, user speeds of up to 350 km/h (e.g. in a high-speed train environment). ‘Slight’ degradations are allowed for a cell radius greater than 5 km but less than 30 km. For a radius between 30 and 100 km, the requirements are further relaxed to the point that the system should be operational [5]. A lot of uncertainty to be standardized.

As can be seen from the link budget, supportable cell radius is limited by the desired uplink cell-edge data rate and the corresponding path-loss. There are many models that can be used for link budget calculation, some of which are ITU-R models, 3GPP models as well as some number of empirical models.

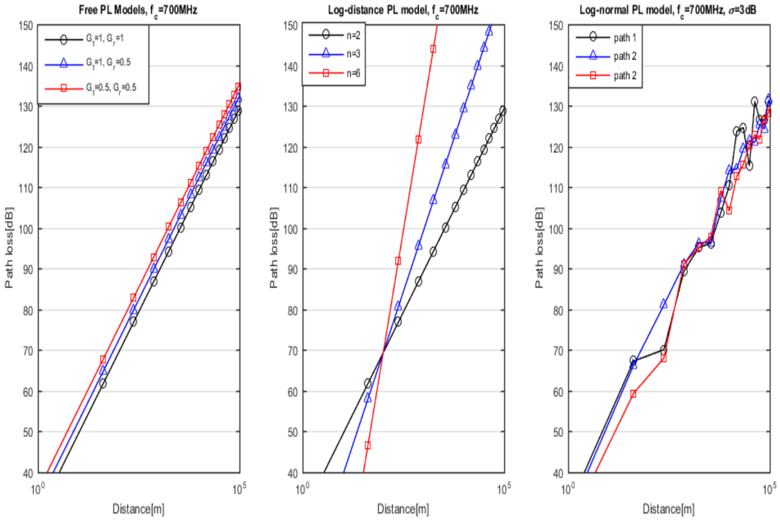

Figure 1: path loss versus distance using (a)Free Space Model(b) log-distance and (c) log-normal

B.The 3GPP Spatial Channel Model

With the restriction that, the bandwidth of the tested systems should not exceed 5 MHz, the 3GPP and 3GPP2 Spatial Channel Model approximates the path loss of the urban and suburban macrocells, a by [10]:

$$PL[dB] = \left(44.9 - 6.55\, log_{10}(h_{eNB})\right) log_{10} d + 45.5 \quad + (35.46 - 1.1h_{UE})\, log_{10}(fc) \; - 13.82\, log_{10}(h_{eNB}) + 0.7h_{UE} + C$$

Where h_{eNB} is the eNB antenna height in meters, h_{UE} the UE antenna height in meters, f_c is the carrier frequency in MHz, d is the distance between the eNB and UE in meters (has to be at least 35 m), and C is a constant factor (C = 0 dB for suburban macro and C = 3 dB for urban macro).

For h_{eNB} = 50 m, h_{UE}=1.5 m and in terms of fc, the suburban macro cell path loss will be:

$$PL = 33.7717\, log_{10} d + 23.07 + 33.81\, log_{10}(fc) \quad (1)$$

$$d = 10^{\frac{PL - 23.07 - 33.81\, log_{10}(fc)}{33.7717}} \quad (km) \quad (2)$$

For fc = 700 MHz:

$$PL = 33.7717\, log_{10} d + 119.263 \quad (3)$$

The distance d will then be given by:

$$d = 10^{\frac{PL-119.263}{33.7717}} \quad (4)$$

Similarly, the distance for 400 MHz and 2.1GHz is

$$d = 10^{\frac{PL-111.046}{33.7717}} \quad (5)$$

$$d = 10^{\frac{PL-135.394}{33.7717}} \quad (6)$$

Respectively.

A. *The ITU-R Models*

The ITU model also specifies the path loss (in dB) depending on the distance d, for three environments: indoor, pedestrian and vehicular.

Pedestrian path loss is given by:

$$PL = 40\ log_{10} d + 49 + 30\ log_{10}(fc) \qquad (7)$$

Rearranging, the equation will be:

$$d = 10^{\frac{PL - 49 - 30\ log_{10}(fc)}{40}} \qquad (8)$$

While the vehicular case path loss is given by [10]:

$$PL = 40(1 - 4 \times 10^{-3} \times \Delta h_b) log_{10}\, d - 18\ log_{10} \Delta h_b + 21\ log_{10} f_c + 80 \qquad (9)$$

Where Δh_b is the BS height measured from the rooftop level; the model is valid for $0 < \Delta h_b < 50\, m.$

Then

$$d = 10^{\left(\frac{PL + 18\ log_{10} \Delta h_b - 21\ log_{10} f_c - 80}{40(1 - 4 \times 10^{-3} \times \Delta h_b)}\right)} \qquad (10)$$

B. Total path loss calculation

To calculate the path loss, the first step is to start with the calculation of the received signal strength for each SNR point using the effective noise power given by [9]:

$$N_{effective} = Thermal\ noise\ density\ (dBm/Hz) + Receiver\ noise\ figure\ (dB) + Interference\ margin\ (dB)$$

$$+10\,log\,(Occupied\ channel\ bandwidth\ (Hz))\ (dBm) \quad (11)$$

Received signal is then calculated from:

$$P_{received}\,[dB] = SNR + N_{effective} \qquad (12)$$

Finally, the path loss is calculated using

$$PL\ = P_{Tx\_effective} - P_{received}\ \ [dB] \qquad (13)$$

Where:

$$P_{Tx_{effective}} = P_{transmitted} + T_x\ antenna\ gain(dBi)$$
$$+R_x\ antenna\ gain\ (dBi).$$

PL is then substituted in the model equation to get the distance d. The path loss should be equal to or less than receiver sensitivity as given by the standard for each transmission band, mode and bandwidth. The receiver sensitivity dictates the maximum coupling loss (MCL). Therefore, the maximum coupling loss is the limit value of the coupling loss at which the service can be delivered. Hence, any distance corresponds to a path-loss value that exceeds the MCL should be excluded.

The minimum requirement for UE and eNB sensitivities are given in [11] and [12], respectively, for each supported transmission bandwidth. Parameters used in simulation are listed in table 4.1. Table 4.2 list the eNB sensitivity as per the standard, together with the calculated $N_{effective}$ and MCL.

Table 4.1: Parameters Used in link-budget and link-level Simulation

Quantity	Value	Units
eNB transmit power	46	dBm
UE transmit power	24	dBm
UE antenna gain	0	dBi
Body loss	0	dB
Equivalent isotropic radiated power	24	dBm
Noise spectral density	−174	dBm
eNB Rx noise figure	5	dB
UE Rx noise figure	9	dB
eNB antenna gain	18	dBi
Interference margin	2	dB
Penetration loss	12	dB
eNB antenna height	50	m
UE antenna height	1.5	m
Carrier frequency	400,700 and 1200	MHz
Environment	Pedestrian and vehicular	

Table 4.2: Maximum Coupling Loss and Effective Noise

BW	UL-Rx sensitivity (Wide Area eNB) [14]	Neffective (dBm)	MCL
1.4	-106.8	-105.54	153.8
3	-103.0	-102.23	151
5	-101.5	-100.01	148.5
10	-101.5	-97	148.5
15	-101.5	-95.24	148.5
20	-101.5	-94	148.5

E. Vienna LTE-A Link Level Simulator

The LTE-A link level simulator is MATLAB-based simulator published under a non-commercial academic use license with some parts of the code under the GNU Lesser General Public License [13], and the MIT License [14]. The simulator can be downloaded from the publisher, Institute of Telecommunications, Vienna University of Technology.

Most parts of the LTE simulator are written in plain Matlab-code. Only computationally intensive functions like soft-sphere or channel decoding are implemented in ANSI-C as MEX functions. Since the source code of all functions is also provided, highest flexibility for modification (customization), as well as support of different platforms is guaranteed [7].

Using this simulator, the performance of a single user Long Term Evolution (LTE) transmission on an uncorrelated TU channel for several transmission modes and antenna configurations (number of transmit antennas Nt times number of receive antennas Nr) was tested. All simulated transmission modes (Single-Input Single-Output (SISO), Transmit Diversity (TxD), Open Loop Spatial Multiplexing (OLSM) and Closed Loop Spatial Multiplexing (CLSM)) utilize UE feedback to adapt important transmission parameters (code rate, modulation alphabet, Multiple-Input Multiple-Output (MIMO) pre-processing) to the channel quality.

The LTE simulator supports standard compliant transmission from up to four transmit antennas in one of the following transmit modes:

- Single antenna port scheme (mode 1): transmission from a single antenna port only.
- Transmit diversity scheme (mode 2): transmission from two antenna ports utilizing the Alamouti transmit diversity scheme.
- Open loop transmit diversity scheme/large delay CDD scheme (mode 3): transmission from 2 or 4 antenna ports, utilizing large delay Cyclic Delay Diversity (CDD).
- Closed loop spatial multiplexing (mode 4): transmission from 2 or 4 antenna ports, utilizing UE feedback for choosing the appropriate precoding matrix. Corresponds to the single and dual layer transmission schemes defined in the LTE spec.

These features were used throughout this study and some of the results are presented in figures 5,6 and 7.

Results and Analysis

To evaluate and verify the system performance in a simulated real life environment, a 700 MHz carrier, 5 MHz BW transmitter and receiver models were developed using SystemVue system design software and fed to the system tool kit (STK) software, then a communication link analysis simulation was performed for a single eNodeB and one vehicle travelling at 350 km/h.

Figure 2 was created using the 3GPP spatial suburban model of equation (1), applied to a carrier frequency of 2.1GHz and 400MHz, where the maximum attainable cell radios is around 6 and 18 km, respectively, for a bandwidth of 1.4MHz and SNR level of -10 dB. In case of 20 MHz bandwidth, the radios shrink back to less than 3 km for the same SNR level at fc 2.1GHz and 8 km for fc 400 MHz.

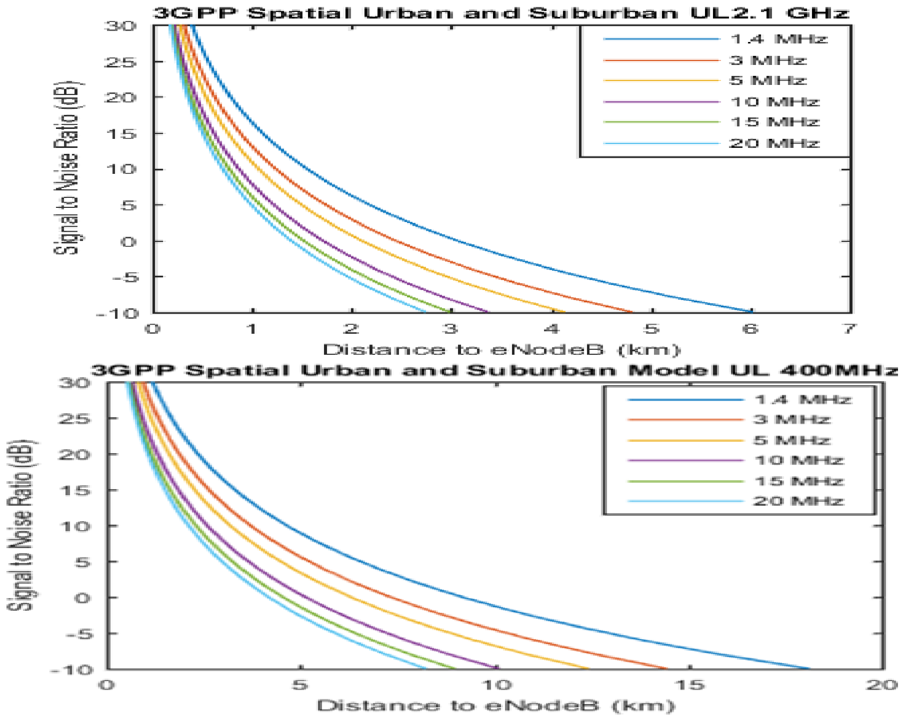

Figure 2: 3GPP Spatial Suburban Model, applied to UL @ 1.2 GHz and 400MHz

In figure 3 the ITU-R Vehicular model is used to calculate the SNR against the cell radios for the UL case. This is 21 km for an SNR of -10 dB at fc 700MHz, and 30 km for fc 400 MHz @ 1.4MHz bandwidth, with the assumption of full-band transmission. The coverage should be better in realistic scenarios, since the UE will inject its power in a less bandwidth (two RBs) as shown in figure 4.

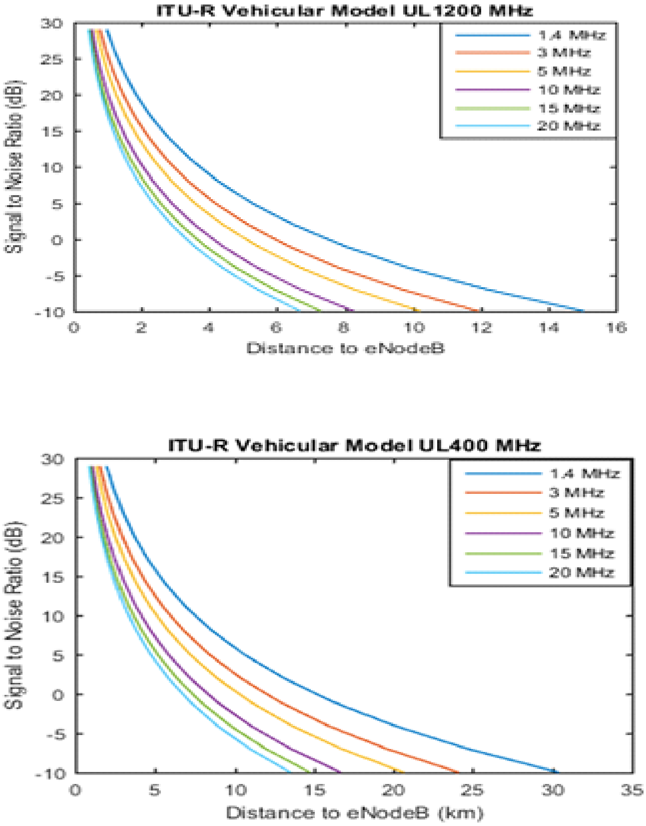

Figure 3: ITU-R Vehicular Model applied to the UL @ 1.2 GHz and 400MHz

For the system parameters shown, figure 4 plots the results obtained using the 3GPP Spatial Urban and Suburban Model for the case of suburban propagation. The tow left most curves reflect the effect of partial transmission for the standard UE power of 24 dBm.

The effect of increasing the output power of the UE to 37 dBm instead of the standardized value of 24 dBm is also shown in figure 4. For the partial transmission case (2 RBs) the coverage will jump from 28 km to 65 km. For the case of full band transmission of 1.4 MHz, the coverage will be raised from 19 km to 43 km.

The cell edge performance of the system, for four different scenarios is presented in figure 5. No matter how sophisticated the modulation scheme is, the gain will be minor at cell edge.

This divergence of the system performance at the cell edge is quite obvious from figure 6 and 7. This agrees with the Power-Bandwidth Problem as can be extracted from Shannon’s theorem for white Gaussian noise channel since we are working at the power limited region.

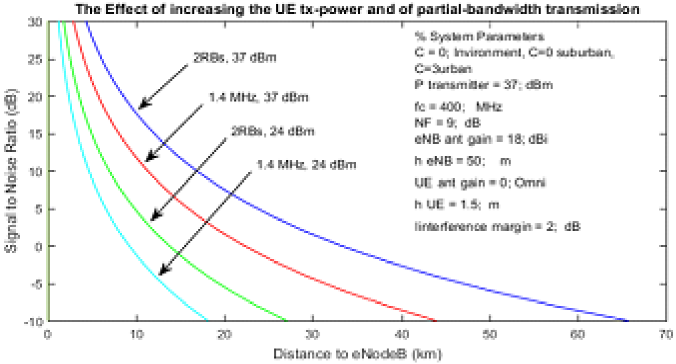

Figure 4: Effect of increasing the UE’s tx-power and of partial-bandwidth transmission

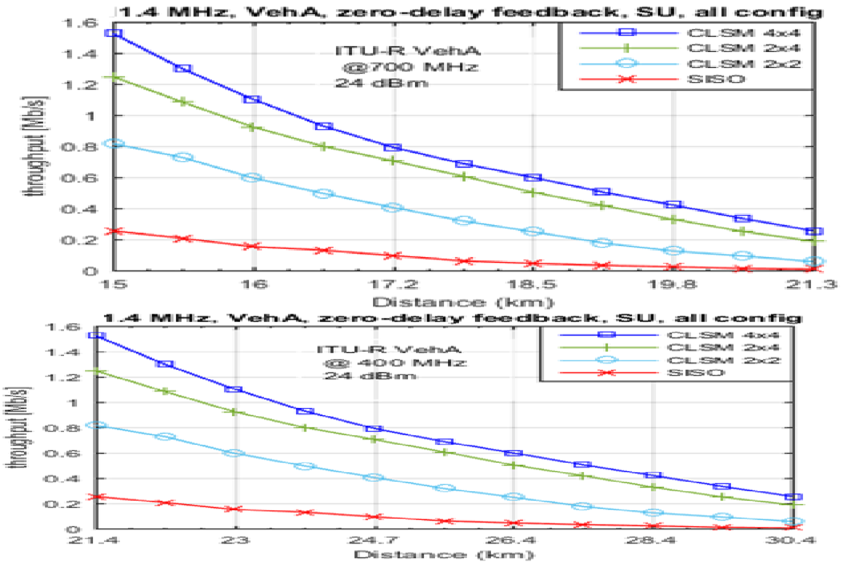

Figure 5: Cell edge performance of 1.4 MHz bandwidth for 700 and 400 MHz carriers

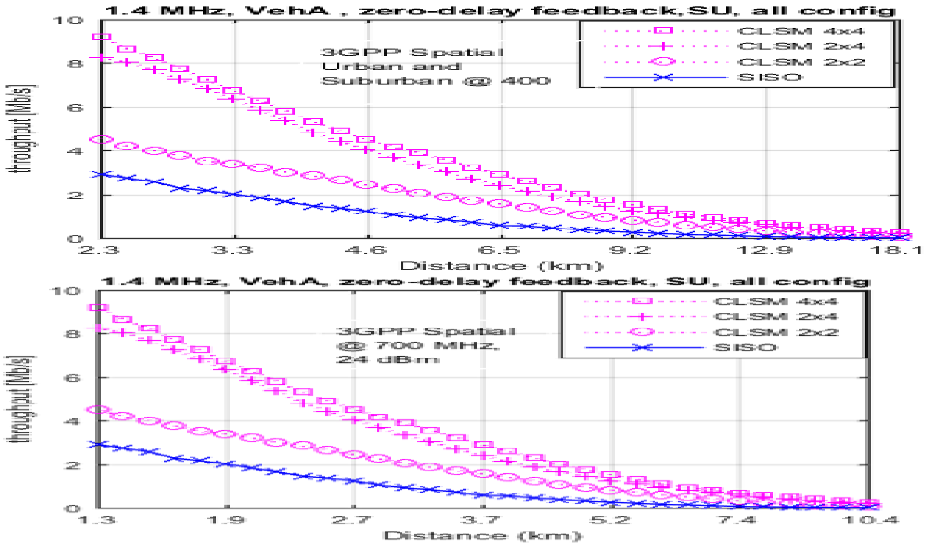

Figure 6: Throughput over distance for 700 and 400 MHz carriers, 1.4 MHz bandwidth

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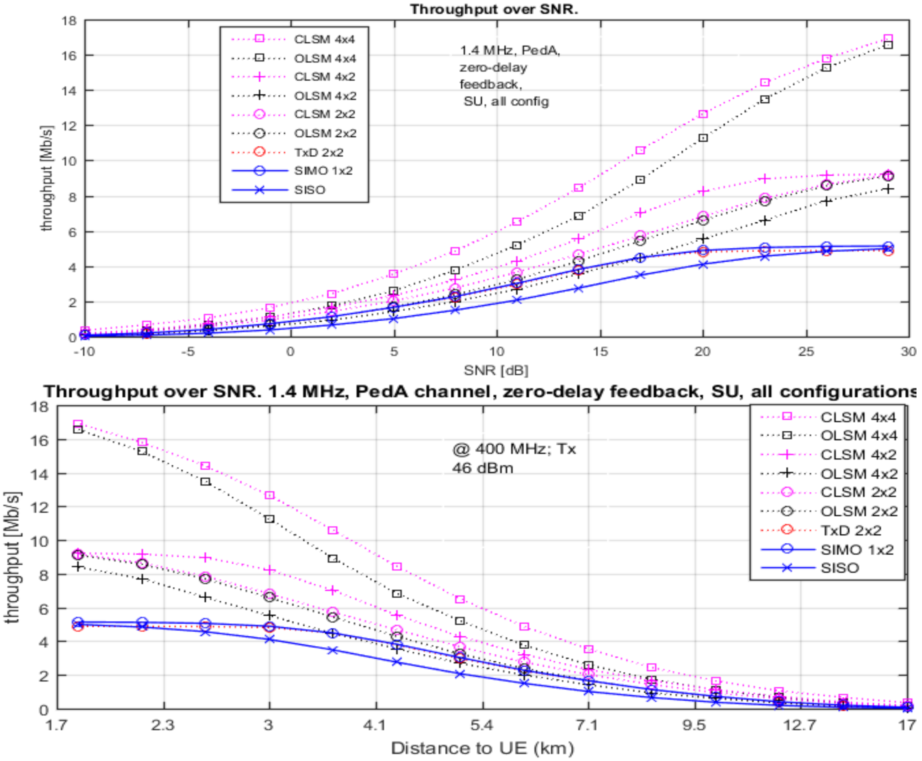

Figure 7: Overall cell performance over SNR and distance, all configurations, 400 MHz

The results show that the downlink meets these goals. For the uplink case, the standardized output power will not or actually very far from satisfying the goals unless a relatively low frequency (400 MHz) is used with a higher mobile terminal output power and sacrificing the throughput (down to some kbps).

Conclusion

LTE/LTE-A was promoted as the most promising, prominent, and evolving cellular technology

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that can reach up to 100 km with a downlink capable of 3 Gbps, and uplink that can reach 1 Gbps and terminal speed of 320 km/h. An astonishing performance in sum.

This paper focuses on the performance in terms of coverage and throughput. As a result of the executed simulations, it is clear that, although the DL can reach the cell radius specified, this will be of no value for the actual cell coverage, since the major player here is the UL limited power terminals that will eventually shrink the useful range of the cell.

Results show that by increasing the UE terminal output power, the coverage can be extended to a never reachable before range (Such a scenario was simulated using 37 dBm output power for the UE terminal). The range will be increased from around 20 km for 24 dBm to over 50 km for 37 dBm, but, as can be seen in simulation results, this increase in the UE output power will not help in enhancing throughput (Shannon-power limited region), yet will provide enough throughput (considering a VoIP application as the minimum requirement) at the cell edge. Such increase of terminal power is helpless in urban areas, and will of course increase interference levels, and may be faced be regulatory laws. In suburban and rural areas or for any low density deployment, the case is different and such relatively high power terminals (built in or with external PAs) will be very valuable to extend the range for special purpose scenarios. The standard also introduced relay terminals to extend the coverage. This of course will also help in dynamic deployment scenarios.

The standard specifies the receiver sensitivity for each transmission mode and the permitted service degradation at that point, but never mentioned the receiver noise figure. The UL simulations was carried on using a receiver with a 9 dB noise figure. The DL simulations was carried on using a receiver with a 5 dB noise figure, both are typical values found in the literature. Any enhancements in this figure, even a fraction of dB, will be of great advantage for the cell coverage, especially in the UL.

The system air interface can also be implemented in HF frequency band to provide a gateway for long haul communications.

To conclude, the LTE system with minor modifications in the mobile terminal power, can be used as the primary system for military communications and first responder networks.

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