Performance Analysis and Optimization of Downlink Multi-User MIMO LTE for Satellite Communications

Constantinos T. Angelis[1,*] and Spiros Louvros[2]

[1] Department of Informatics and Telecommunications
Technological Educational Institute of Epirus, Arta, Greece
kangelis@teiep.gr
[2] Department of Telecommunication Systems and Networks
Technological Educational Institute of Messologi, Messologi, Greece
slouvros@teimes.gr

Abstract. This article presents a theoretical analysis for packet delay and simulation results for a realistic implementation of the Multi-User MIMO LTE Release 8 downlink standard in mobile satellite systems. Two Satellites, one Ground Station and two 2x2 MIMO Channels have been used as a basic configuration in the simulation scenarios and various key characteristics of the MIMO channel and the LTE radio interface, including physical layer and radio resource management functions ware simulated and their impact on system performance is evaluated for moving terminals in wide area scenarios. Simulation results suggest that in practice multi-user LTE, when applied to the transmission over satellite links, is able to support multi stream transmission with very high data rates, even for hand held moving terminals. Moreover, the improvements of Multi-User MIMO transmissions for different system configurations are clearly shown for different number of users. Finally a theoretical approach, considering OFDMA scheduler functionality, is presented leading into an optimization procedure for MAC transport channel packet length.

Keywords: LTE, Satellite, Multi-User MIMO, OFDMA, MAC transport channel.

1 Introduction

The growing demands for broadband wireless data communications, in multihop capable interfaces, are becoming more and more intense due to their improvements of coverage and capacity. For these reasons they are proposed for the next generation cellular systems like 3G-LTE [1]. This has motivated many research efforts in the last years, puts high pressure on operators to increase the capacities of their networks and on the industry for enabling such an increase also in the long term future via more efficient and flexible communication standards. Long-Term Evolution (LTE) is an emerging radio access network technology standardized in 3GPP [1], that meets all the previous constrains, and evolving as an evolution of Universal Mobile

[*] Member ICST, IEEE, EuMA.

P. Pillai, R. Shorey, and E. Ferro (Eds.): PSATS 2012, LNICST 52, pp. 69–80, 2013.

Telecommunications System (UMTS). LTE uses Orthogonal Frequency Division Multiplexing OFDM as downlink air interface multiple access scheme [1].

The interesting research outcomes that obtained by proposed LTE techniques in terrestrial networks have engender further interest in investigating the possibility of applying the same principles in satellite networks. However, there are fundamental differences between satellite and terrestrial channels that lead this effort to a very challenging research subject. The most important restriction for the successful deployment of mobile satellite systems in the LTE networks is the overall cost minimization. In order to achieve this, the technological commonalities with the terrestrial networks have to be maximized. This can be done by considering the terrestrial radio interface as the baseline for the satellite radio interface, introducing only those modifications that are strictly needed to deal with the satellite peculiarities. The most important peculiarities are nonlinear distortion introduced by the on-board power amplifiers, long round-trip propagation times, and reduced time diversity.

Many researchers work on LTE and MIMO based systems for satellite communications. General LTE concept descriptions are available in [2-7]. In these papers, the focus is on key characteristics of the LTE radio interface. A set of such key characteristics are both qualitatively discussed and quantitatively evaluated in terms of downlink user data rates, spectrum efficiency generated by means of system level simulations and measurements. In [2] the applicability of the 3GPP Long Term Evolution standard to mobile satellite systems is investigated. In [5] the applicability of multiple-input multiple-output (MIMO) technology to satellite communications at the Ku-band and above is investigated. In [6] a three dimensional channel model for the study of distributed MIMO communication systems is presented. Finally, in [7] a novel physical-statistical generative model for the land mobile satellite (LMS), dual polarized, MIMO channel along tree sided roads is presented.

Performance optimization of such a satellite network is crucial due to long propagation delays, contributing into throughput reduction. MAC layer maps the logical channels into a new channel format called transport channel [9]. MAC packet length is dynamically decided based on the service and the used Modulation and Coding scheme (MCS). Optimizing the packet length will contribute into less delays thus improving the overall performance. In [10] combination of power and time-frequency domain allocation of resources has been extensively studied and in [11] different scheduling time-frequency domain algorithm approaches have been also proposed. Finally in [12] a good algorithmic analysis has been presented exploiting simultaneously throughput optimization with QoS rate restrictions. Most important scheduling algorithms involved in existing analysis in literature are considering mostly proportional fair schemes, max CQI, min interference or round robin and performance results have been proposed based on the channel conditions. In order to make good scheduling decisions, uplink/downlink scheduler should be aware of channel quality in the time-frequency domain, as channel fading is time-frequency dependant, using channel quality reports (CQI) [13]. Although ideally, the scheduler should have exact knowledge of the channel quality for each sub-carrier and each user [14], this is not realistic due to increased signalling load and a compromise between good channel quality knowledge and CQI reports has to be decided [15]. However all previous analysis mostly focus on the scheduling algorithm performance optimization based on algorithm simulations and simple theoretical approaches for CQI, quality and MCS selection. What is still missing is an exact analytical model to combine all different aspects of scheduler functionality in order to provide an exact optimization solution for MAC transport channel length.

In this paper a realistic implementation of the Multi-User MIMO LTE Release 8 downlink standard in mobile satellite systems is investigated. Simulation results show that the performance improvement depends on the considered parameters. MAC packet length optimization analysis focuses on basic delay calculation over the LTE air interface based on scheduler and MAC layer functionality. In the basic analysis retransmissions are considered as a general drawback on the throughput optimization. The rest of the paper is organized as follows: Section 2 describes the FDD MIMO LTE system level model and an overview about the simulation model used for the investigation with description of the performed link and system level simulations; Section 3 presents the basic theoretical delay analysis; Section 4 presents the simulation results; and finally the conclusions are given in Section 5.

2 The Multi-User FDD MIMO LTE Simulation Model

This section presents the proposed Multi-User FDD MIMO LTE system level model and the simulation setup environment. The simulation results were obtained with the Agilent Advanced Design System (ADS) [8]. We performed Multi-User TDD downlink coded measurements on MIMO channels for all the combinations of the parameters discussed bellow. In our analysis we assume a scenario in which two GEO satellites broadcast services to a Ground Mobile Terminal (GMT). Both satellite and terrestrial components work at the same frequency, thus realizing a Single Frequency Network (SFN). Figure 1 shows a schematic diagram of the simulation model that consists in three main blocks for each satellite link: transmitter, channel and receiver chains.

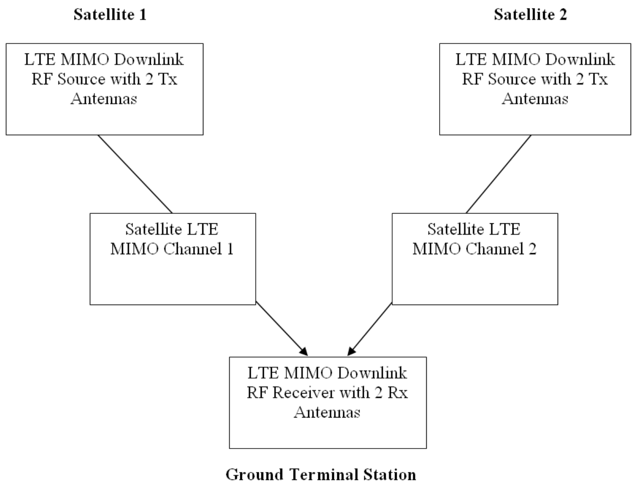

Fig. 1. The Multi-User TDD MIMO LTE simulation model

The reference channel in A.3 of TS 36.101 [1] is used as a signal source with the exception that no Physical Hybrid ARQ Indicator Channel (HARQ) transmissions are employed and a Bandwidth of 10 MHz is employed. The modulation type that we used in our simulation scenarios is the 10 MHz QPSK 1/3. Four (2 per satellite) transmitter antennas and 2 receiver antennas were used as parts of the simulation in Transmit diversity transmission mode. The correlation matrix support was set to Medium. Table 1 shows some of the most fundamental simulation conditions and parameters.

Table 1. LTE System fundamental simulation conditions and parameters

Parameter	Value
Carrier Frequency	2.5 GHz
Bandwidth	10 MHz
Frame Mode	TDD Configuration
Oversampling	Ratio 2
Cyclic Prefix	Normal
Antenna Configuration	2x2 for each Satellite
Number of code word(s)	2 (Spatial multiplexing)
Number of layer(s)	2 (Spatial Multiplexing)
Correlation	Medium (α=0.3, β=0.9)

Table 2. UEs and GMT fundamental simulation conditions and parameters

Parameter	Case 1 1 User per Satellite	Case 2 2 Users per Satellite	Case 3 3 Users per Satellite
Velocity	**(a)** 5km/h, **(b)** 50km/h	**(a)** 5km/h, **(b)** 50km/h	**(a)** 5km/h, **(b)** 50km/h
Number of Subframes	10	10	10
Modulation	QPSK	QPSK	QPSK
UEs Payload	1/3	1/3	1/3
Preconding	Yes	Yes	Yes
Channel Estimator	2D MMSE	2D MMSE	2D MMSE
Number of RBs for each 2D-MMSE interpolation	5	5	5
Turbo decoder iteration	6	6	6

The basic configuration of the MIMO channels is in accordance to the specifications of Annex B - TS 36.101 [1]. The MIMO satellite channel was modeled as a normal MIMO LTE channel with medium correlation and the Doppler frequency was taken into account. In addition, to accurately model the MIMO satellite channel, a High Power Amplifier (HPA) is introduced within each satellite channel [2-4]. The HPAs are assumed to work with an Input Back-Off (IBO) of 4dB. Both Satellite channels assumed to be identical for simplicity. Moreover the proposed inter-TTI interleaving technique that was proposed in [2] is used in order simulate the satellite propagation conditions.

In the proposed scenario the Ground Mobile Terminal (GMT) motion is taken into account by considering the Doppler spread. Two different speed values are analyzed, that are ν = 5km/h and ν = 50km/h. The GMT receiver uses a 2D MMSE channel estimator with 5 RBs for each 2D-MMSE interpolation and the Turbo decoder iteration number was set to 6. Simulations were performed for both Single and Multi User UEs. The parameters used in the simulations are given in Table 2.

3 Basic MAC Delay T_{delay} Analysis

In LTE services traffic is based on IP technology [1]. Between UE and Nodeb (terrestrial or satellite) each MAC packet is supposed to be transmitted completely over the air interface before starting transmission of next MAC packet in a duration of Time Transmission Interval TTI=1ms. In such a case the advantage is that LTE could provide error detection and retransmission not only on TCP/UDP IP level on the core network but also on the air interface resulting into better correction techniques improving thus the throughput and minimizing delays [1]. In each downlink TCP/UDP IP initiation session, scheduling decisions are mostly decided based on QoS service profile and Channel Quality Index (CQI) measurements. A number of variable length MAC packets arriving at the destination will be acknowledged by sending back a short acknowledgment packet of length M_{ack} bits size on the PDSCH downlink channel. There is supposed to be a window size of length W, meaning that on the eNodeB receiver an acknowledgment is created only when a total number of W MAC packets are received. One interesting question that arises then is which is the optimum MAC packet length size in order to improve throughput per connection. Suppose that a TCP/UDP IP packet of M_I bits per packet be framed in such a way that resulting MAC packets of variable length M_{mac} bits per packet contains a fixed number of M_{over} header bits per packet [16]. In such a model then one M_I packet will be segmented into Int[M_I / M_{mac}] MAC packets. Definitely the division will never allocate an integer number and hence padding should be applied in order to be able to fix the leftover bits into exactly Mmac packet size. The total number of MAC packets out of one M_I size TCP/UDP IP packet are Int[M_I / M_{mac}] +1, the total number of MAC bits to be transmitted out of one M_I size TCP/UDP IP packet are M_I + {Int[M_I / M_{mac}] +1}M_{over}, where the factor {Int[M_I / M_{mac}] +1}M_{over} is the overhead created by MAC layer for the M_I size TCP/UDP IP packet transmission. What is then interesting to measure is the total transmission time (as a measure of expected delay) and the error performance as functions of MAC packet size M_{mac} and to find the best compromise. Expected whole TCP/UDP IP packet transmission time in ideal conditions, without retransmissions, is:

$$T_{delay} = \frac{\left\{ M_I + \left[\text{Int}\left(\frac{\text{M}_\text{I}}{\text{M}_\text{mac}} \right) + 1 \right] M_{over} + F \right\}}{M \cdot N \cdot r_{TTI}} T_s + \langle n \rangle T_s \quad (1)$$

where $M_I + \left[\text{Int}\left(\frac{\text{M}_\text{I}}{\text{M}_\text{mac}} \right) + 1 \right] M_{over} + F$ is the total number of TCP/IP bits to be transmitted considering also overhead M_{over} and padding bits, $F = M_{mac} + \left(\text{int}\left[\frac{M_I}{M_{mac}} \right] + 1 \right) \cdot M_{mac} - M_I$ considering always that M_{mac} packet size is always less than the M_I IP packet size. Also $\left[Int\left(\frac{M_I}{M_{mac} W} \right) + 1 \right] A$ is the number of bits to be transmitted on the downlink PHICH physical channel per W window size which is not delayed by scheduling decisions ($\left\langle t_{sch}^{ack} \right\rangle = T_s$ =1 ms). r_{TTI} is the number of transmitted bits per scheduled block (TTI = 1ms and bandwidth of 180 kHz) which depends on Link Adaptation Modulation Scheme, N is the average allocated number of 180 kHz radio block (RB) units of bandwidth per TTI considering also the constraint that $0 \le N \le BW$ where BW is the allocated bandwidth in the cell planning (minimum 1.8 MHz up to maximum 20 MHz) and M is the number of antenna ports (in case of MIMO implementation). In this analysis then we consider, for average $N \cdot 180kHz$ allocated RB, $N \cdot r_{TTI}$ bits out of total o be transmitted simultaneously in TTI = 1 ms and finally if we have spatial multiplexing of $M \times M$ MIMO antenna ports then $M \cdot N \cdot r_{TTI}$ bits are expected to be transmitted simultaneously in TTI = 1 ms. Finally $\langle n \rangle \cdot T_s$ is the average schedule time by scheduler, where n is an integer value to indicate the number of subframes (Time Transmission Interval $T_s = 1ms$) that one MAC packet is not scheduled by scheduler in a total scheduling period T. Remember that n for downlink scheduling decisions depends mainly on the QoS Guaranteed Bit Rate (average) GBR parameter, on Channel Quality Index CQI measurement report and also on UE transmitter mean packet waiting time on the buffer. Substituting F into equation (1) we get:

$$T_{delay} = \frac{\left\{ \left[\text{Int}\left(\frac{\text{M}_\text{I}}{\text{M}_\text{mac}} \right) + 1 \right] M_{over} + M_{mac} + \left(\text{int}\left[\frac{M_I}{M_{mac}} \right] + 1 \right) \cdot M_{mac} \right\}}{M \cdot N \cdot r_{TTI}} T_s + \langle n \rangle T_s \quad (2)$$

Considering then that its MAC packet could be retransmitted maximum v times and the average transmission rate is m_{mac} from (1) TCP/IP packet transmission delay time could be recalculated as:

$$T_{delay}^{retr} = \frac{\left\{ m_{mac} \cdot M_I + m_{mac} \cdot \left[\operatorname{Int}\left(\frac{\mathrm{M_I}}{\mathrm{M_{mac}}} \right) + 1 \right] M_{over} + F \right\}}{M \cdot N \cdot r_{TTI}} T_s + \langle n \rangle T_s \tag{3}$$

Substituting then F padding bits from previous analysis TCP/IP packet transmission delay time could be recalculated as:

$$T_{delay}^{retr} = \frac{\left\{ M_I \left(m_{mac} - 1 \right) + m_{mac} \cdot \left[\operatorname{Int}\left(\frac{\mathrm{M_I}}{\mathrm{M_{mac}}} \right) + 1 \right] M_{over} + M_{mac} + \left(\operatorname{int}\left[\frac{M_I}{M_{mac}} \right] + 1 \right) \cdot M_{mac} \right\}}{M \cdot N \cdot r_{TTI}} T_s + \langle n \rangle T_s \tag{4}$$

Average number of retransmissions m_{mac} is a function of the MAC packet error rate. In this analysis we do consider p to be the MAC packet successful acceptance probability rate. If after maximum v transmissions the MAC packet is still corrupted it will be finally forwarded to the upper RLC layer with probability $v \cdot (1-p)^v$ since MAC layer does not discard corrupted packets even after the maximum v number of retransmissions. Hence overall average retransmission rate is calculated as:

$$m_{mac} = v(1-p)^v + \sum_{k=1}^{v} kp(1-p)^{k-1} = \frac{1-(1-p)^v}{p} \tag{5}$$

Since $(1-p) = 1-(1-p_b)^{M_{mac}}$ where p_b is the bit error rate which could be substituted with BER and should be calculated from simulations (as we did on section 4 in Fig. 6a) or real channel measurements.

$$m_{mac} = \frac{1-(1-p)^v}{p} = \frac{1-\left(1-\left(1-p_b\right)^{M_{mac}}\right)^v}{\left(1-p_b\right)^{M_{mac}}} \tag{6}$$

Retransmission rate m_{mac} depends on number of attempts v and on the size of the MAC packet M_{mac}. LTE MAC Scheduler follows rules of priorities on scheduled packets per TTI. Basic priority rule assigns retransmission packets with highest priority rather than new packets on the transmitter bucket when they are scheduled by scheduler. Expected delay budget equals:

$$\max \tau_{delay}^{budget} = v_{\max} T_s + \langle n \rangle T_s \Rightarrow v_{\max} = \frac{\max \tau_{delay}^{budget} - \langle n \rangle T_s}{T_s} \tag{7}$$

and equation (6) finally becomes:

$$m_{mac} = \frac{1-\left(1-\left(1-BER\right)^{M_{mac}}\right)^{\frac{\max \tau_{delay}^{budget} - \langle n \rangle T_s}{T_s}}}{\left(1-BER\right)^{M_{mac}}} \tag{8}$$

4 Results and Discussion

Performance of the simulated schemes is compared in terms of Tx and Rx Signal Spectrum, Complementary Cumulative Distribution Function (CCDF), BER and BLER measurements. Simulations were conducted taking into consideration the number of users in each Satellite Link. Figure 2 presents indicative Signal spectrums in the 4 transmit antennas (2 per Satellite) and in the 2 receive antennas for $E_b / N_o = 20dB$. The modulation scheme in figure 2 is QPSK 1/3, while the correlation was set to medium. Figures 3 and 4 present CCDF measurements of the TDD Downlink LTE signals in the 2 receive (Rx) antennas. The modulation scheme is QPSK 1/3. As it is seen for figure 3 the number of EUs increment does not affect the CCDF measurements for both ground terminal velocities of 5km/h and 50 km/h. On the other hand the ground terminal velocity affects the CCDF measurements as it is seen in figure 4.

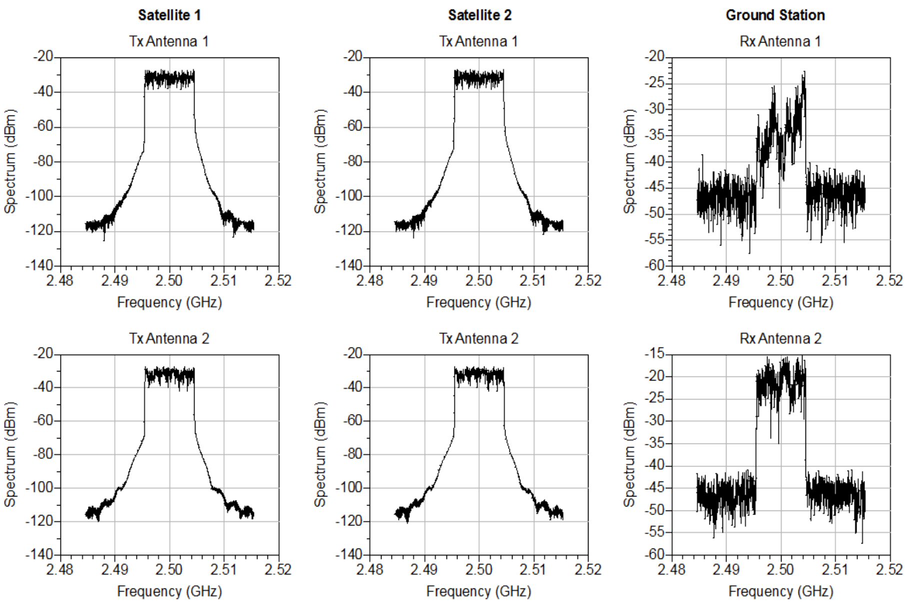

Fig. 2. Signal spectrums in the 4 transmit (Tx) antennas and in the 2 receive (Rx) antennas for $E_b / N_o = 20dB$

BER, BLER and Throughput measurements where performed for the case of QPSK 1/3 modulation scheme. The throughput was evaluated using the proposed specifications of the LTE radio interface, where the modulation was fixed at QPSK. The turbo code that was used and the mapping from code words to layers ware according to LTE specifications. The throughput was calculated as the product:

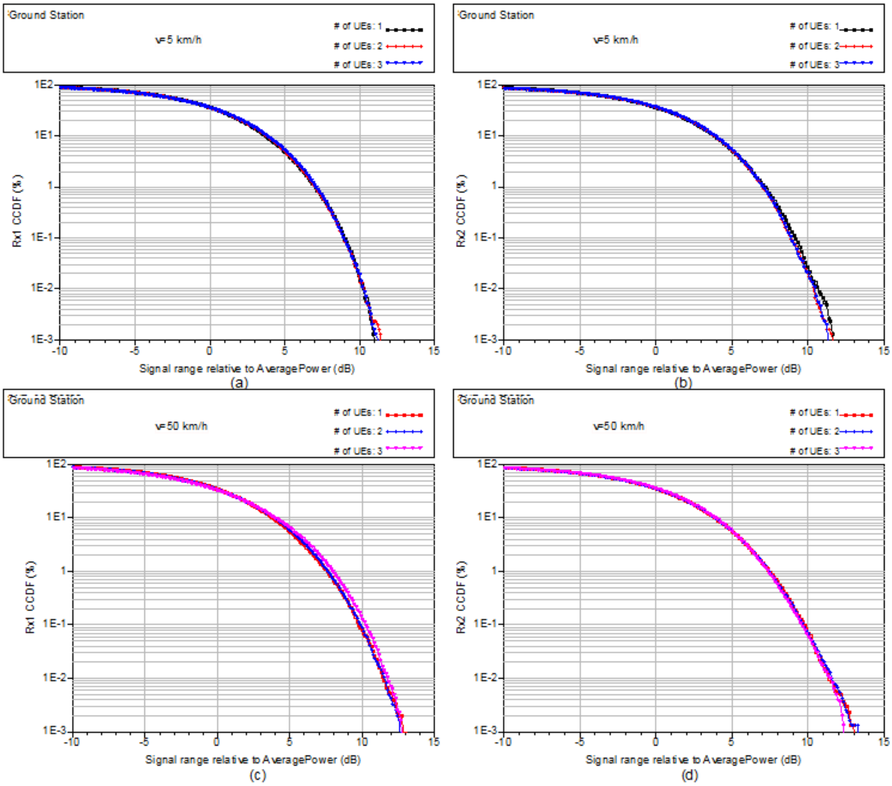

Fig. 3. CCDF measurements of the TDD Downlink LTE signals in the 2 receive (Rx) antennas. (a) and (b) stands for v=5km/h, (c) and (d) stands for 50km/h

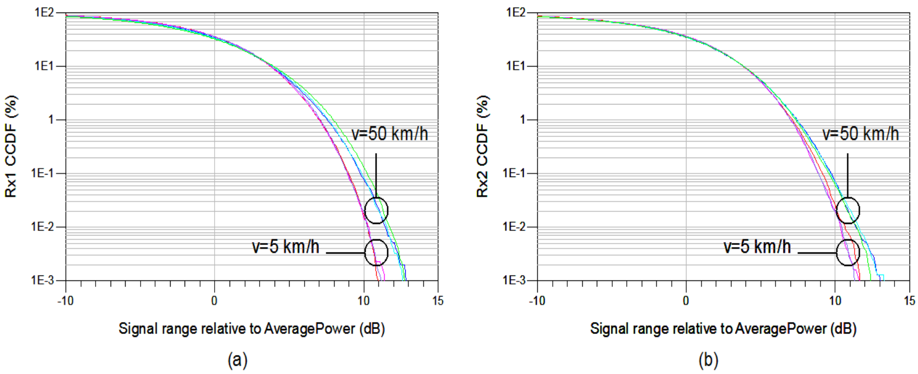

Fig. 4. CCDF measurements of the TDD Downlink LTE signals in the 2 receive (Rx) antennas

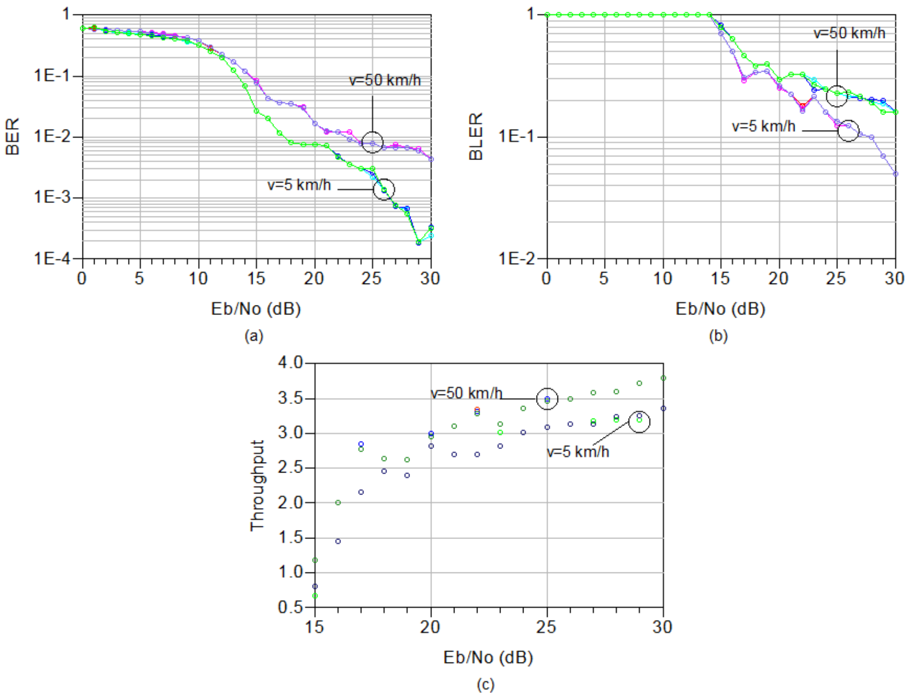

Fig. 5. (a) BER, (b) BLER and (c) Throughput measurements for different UEs and GMT velocities

$$Throughput = (1 - FER) * N_{layers} * CodingRate \tag{9}$$

where FER denotes the frame error rate, N_{layers} denotes the number of layers and CodingRate is the rate of the Turbo code. Figure 5 shows BER, BLER and Throughput measurements of the TDD Downlink LTE signals in the first Satellite link. As it is seen BER and BLER measurements are degraded when the velocity of the GMT increases, while when the number of UEs increases the BER and BLER values remain unchanged. On the other hand Throughput practically remains unchanged. These results indicate that the increment of the multi-users number, from one to tree, does not have any impact in the overall performance for the given configuration. The CCDF, BER, BLER and Throughput simulation results that derived from figures 3 to 5 indicate that the proposed Multi-User MIMO LTE downlink can handle up to 3 UEs per Satellite link.

Substituting results of BER into equation (9), for a specific service maximum allowed delay $\max \tau_{delay}^{budget}$, for specific channel conditions (thus scheduler average scheduling instances $\langle n \rangle$ and for T_s = 1ms as the sub-frame time transmission interval we could calculate the average number of retransmissions m_{MAC}. Then substituting into equation (4) we could calculate the optimum M_{mac} length to keep delay T_{delay} into the desired bounds.

5 Conclusion

In this paper system performance of a Multi-User MIMO LTE downlink for Satellite Communications which consists of Two Satellites, one Ground Station and two 2x2 MIMO Channels was investigated and various key characteristics of the MIMO channel and the LTE radio interface, including physical layer and radio resource management functions ware simulated and their impact on system delay and performance metrices is evaluated for moving terminals in wide area scenarios. Simulation results indicate that the proposed Multi-User LTE system, when applied to the transmission over satellite links, is capable of supporting multi stream transmission with very high data rates, even for hand held moving terminals for up to 3 UEs per Satellite link.

Acknowledgments. The Author would like to thank Agilent, Inc. for the license to use ADS for educational and research purposes.

References

1. TS 36.101 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception (Release 8)
2. Papaleo, M., Neri, M., Vanelli-Coralli, A., Corazza, G.E.: Using LTE in 4G Satellite Communications: Increasing Time Diversity through Forced Retransmission. In: 10th International Workshop on Signal Processing for Space Communications, Rhodes Island, Greece, October 6-8 (2008)
3. Neri, M., Salmi, P., Corazza, G.E.: Fractional Predistortion Techniques with Robust Modulation Schemes for Fixed and Mobile Broadcasting. In: 13th IST Mobile and Wireless Communications Summit, IST 2004 (2004)
4. Berdondini, M., Neri, M., Corazza, G.E.: Adaptive Fractional Predistortion Techniques for Satellite Systems based on Neural Networks and Tables. In: Proceedings of IEEE 65th Vehicular Technology Conference, VTC SPRING 2007, pp. 1400–1404 (2007)
5. Liolis, K.P., Panagopoulos, A.D., Cottis, P.G.: Multi-Satellite MIMO Communications at Ku-Band and Above: Investigations on Spatial Multiplexing for Capacity Improvement and Selection Diversity for Interference Mitigation. EURASIP Journal on Wireless Communications and Networking, Article ID 59608, 11 pages (2007)
6. Li, X., Liu, Y.: A 3-D Channel Model for Distributed MIMO Satellite Systems. In: IEEE Global Communications Conference (Globecom 2010), Miami, Florida, USA, December 6-10 (2010)
7. Cheffena, M., Perez-Fontan, F., Lacoste, F., Corbel, E., Mametsa, H.-J.: Land Mobile Satellite Dual Polarized MIMO Channel along Roadside Trees, Roma, Italy, April 11-15 (2011)
8. Agilent Advanced Design System (ADS), `http://www.agilent.com`

9. 3GPP TS 25.104 ‘Base Station (BS) radio transmission and reception (FDD)’
10. Liu, H., Li, G.: OFDM-Based Broadband Wireless Networks, Design and Optimization. John Wiley & Sons (2005)
11. Monghal, G., Pedersen, K.I., Kovacs, I.Z., Mogensen, P.E.: QoS Oriented Time and Frequency Domain Packet Schdulers for the UTRAN Long Term Evolution. In: Proc. of IEEE Vehicular Technology Conference, Spring, pp. 2532–2536 (2008)
12. Wunder, G., Zhou, C., Bakker, H.-E., Kaminsk, S.: Thoughput Maximization under Rate Requirements for the OFDMA Downlink Channel with Limited Feedback. Article ID 437921, EURASIP Journal on Wireless Communications and Networking (2008)
13. Homayounfar, K., Rohani, B.: CQI Measurement and Reporting in LTE: A New Framework, IEICE Tech. Rep. 108(445), RCS2008-244, 191–196 (2009)
14. Kawser, M.T., Hamid, N.I.B., Hasan, M.N., Alam, M.S., Rahman, M.M.: Downlink SNR to CQI Mapping for Different Multiple Antenna Techniques in LTE. In: International Conference on Future Information Technology (ICFIT), Changsha, China (December 2010)
15. Kolehmainen, N.: Channel Quality Indication Reporting Schemes for UTRAN Long Term Evolution Downlink. In: Proc. of IEEE Vehicular Technology Conference, Spring, pp. 2522–2526 (2008)
16. 3GPP TS 36.321 v8.1.0