Link Adaptation in Satellite LTE Networks

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***Abstract*—This paper investigates the impact of the Round Trip Propagation Delay (RTPD) in the satellite LTE air interface with the adoption of MIMO technology. The Satellite LTE air interface will provide global coverage and hence complement its terrestrial counterpart in the provision of LTE services to mobile users. A land mobile dual-polarized GEO satellite system has been considered for this work. The link adaption is an important module for the scheduling scheme and the satellite LTE network as a whole in order to make optimal scheduling decisions and effectively utilize the network resources respectively. However, the long RTPD experienced when Channel Quality Indicator (CQI) is reported from the User Equipment (UE) to the eNodeB via GEO satellite causes misalignment between the reported CQI at the eNodeB and the present CQI of the mobile user. The aim of this paper is to investigate the effect of the misalignment as a result of long RTPD through simulations and also investigate the effect of varying CQI reporting interval on the system performance of Satellite LTE network. The possibility of using a fixed CQI rather than an adaptive CQI is also investigated.**

***Index Terms*— CQI, RTPD, GEO satellite, LTE**

I. INTRODUCTION

The rapid growth in mobile users and continuous increment in the demands for different types of telecommunication services, like video streaming, video conferencing, Voice over IP (VOIP), web browsing, multimedia messaging, video gaming and FTP downloads have compelled the need for new technologies able to provide high data rates and also satisfy their respective Quality of Service (QoS) requirements. It is also worth to note that the available spectrum is limited and this has made high spectrum efficiency an important target that must be addressed in the future technologies.

The need to address these important challenges in future mobile networks formed the basis for ITU-R WP 8F to define the future Fourth Generation Mobile (4G). The set of transmission capacity and QoS requirements are specified which allow any technology that meets up with these requirements to be included in the IMT-Advanced family [1]. This has led to the emergence of LTE and WiMAX 802.16x. Though, these two technologies do not fulfill the requirements, they are first steps towards the 4G [2]. Advanced features are being looked into by both standards that will be included in next releases (WiMAX evolution and LTE Advanced) in order to meet up with the 4G requirements

The LTE technology, which is of interest to this paper is made up of the radio access and packet core networks. The radio access network of LTE is referred to as Evolved UMTS Terrestrial Radio Access (E-UTRA) and the core network is denoted as Evolved Packet Core (EPC). LTE uses a new multiple access technology, which is Orthogonal Frequency Division Multiple Access (OFDMA) for downlink transmission and Single Carrier Frequency Division Multiple Access (SC-FDMA) for uplink. Another important technology introduced to LTE network is MIMO. It has brought a linear increase in the capacity of the network depending on the minimum of the numbers of transmit or receive antennas [3].

In order to provide seamless mobile services to users irrespective of their locations, the satellite component of 4G systems will play a vital role, since the terrestrial component will not be able to provide a global coverage due to economic and technical limitations [4]. Therefore, future satellite air interfaces need to have a high-level of commonality with the 4G terrestrial air interface. Hence, both 3GPP LTE and WiMAX air interfaces have been proposed for the satellite scenario especially for unicast communications. Though, the satellite systems have some

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doi:10.4304/jait.5.1.37-43

peculiarities like long Round Trip Propagation Delay (RTPD), on-board amplifier and in particular specific channel models, which make it different from the terrestrial counterparts; some key technology enablers are being proposed that will allow the LTE air interface to be used in the satellite channel [5, 6]. The whole system will have both terrestrial and satellite RANs connecting to the same core network and an S-band GEO satellite system has been recommended for this purpose (land mobile users) [6].

The ambitious 4G targets in terms of QoS, data rates and fairness can only be achieved with an effective scheduling scheme that will provide an optimal balance of all these requirements. For effective resource allocation, the resource allocation scheme must be sensitive to the instantaneous channel conditions of the mobile users. This makes link adaption module a key component in the satellite LTE network. The Channel Quality Indicator (CQI) is sent from the mobile terminal to the eNodeB via the GEO satellite at intervals for the purpose of link adaptation but due to the long RTPD experienced in GEO satellite, the link adaption in satellite scenario is a major challenge towards achieving effective system utilization.

This is due to the misalignment between the reported CQI at the eNodeB and the instantaneous CQI experienced by the mobile user as a result of the long RTPD. This might result to loss of packets when the reported CQI that is used for transmission is greater than the instantaneous CQI experienced by the mobile user. Also, of interest, is continuous reporting of CQI from the UE to the eNodeB in a satellite LTE scenario, the power consumed in this process is a major concern, hence, the need to look into possible reduction of the frequency at which the CQI is reported or usage of a fixed CQI without compromising on system performance.

The aim of this work is to investigate the impact of the misalignment on the system performance as a result of the long RTPD experienced in the GEO satellite LTE network scenario through simulations. Also, to investigate the effect of varying CQI reporting intervals on system performance in a satellite LTE network and to also look at the possibilities of using fixed CQI rather than adaptive CQI. The rest of the paper is organized as follows: Section 2 provides an overview of the adaptation of LTE air interface to the satellite scenario. Channel characteristics are presented in Section 3. In Section 4 and 5, the simulation setup and numerical results are presented respectively. Finally, Section 6 concludes the paper.

II. SATELLITE LTE AIR INTERFACE

The Satellite LTE radio access technology is envisaged to use OFDMA for downlink transmission just like its terrestrial counterpart. OFDMA can be adopted for satellite as stated in [5], due to the fact that it easily exploits frequency selectivity and allows flexible bandwidth operation with low complexity receivers. It supports both Frequency Division Duplex (FDD) and Time Division Duplex (TDD) and allows for a wide range of different bandwidths (1.5, 3, 5, 10, 15 and 20 MHz) [7]. It also supports downlink multi-antenna schemes including both transmit diversity, spatial multiplexing and beamforming [8]. The spatial multiplexing, which includes single user and multi- user MIMO is of interest to this work. For the downlink of 3GPP LTE, the 2 x 2 MIMO is assumed to be the baseline configuration and 4 x 4 MIMO is also envisaged [9].

The transmission mode is selected depending on the MIMO technique of interest. The transmission modes are single antenna, transmit diversity, open-loop spatial multiplexing, closed-loop spatial multiplexing, Multiuser MIMO, closed-loop single layer precoding and single antenna (beamforming). Four of the seven transmission modes as specified for LTE are related to MIMO transmissions. The transmission mode 5 which is for MU MIMO has been considered for this work since the focus of the work is to evaluate the performance of satellite LTE in MU MIMO scenario considering the effect of RTPD. The details of these modes are presented in [9]. For this work, the evolved Node B (eNodeB), which acts as the base station in satellite LTE scenario, is located on the earth station and it is considered to be equipped with two transmit antennas; the User Equipment (UE) has two antennas as well, according to the 2 x 2 MIMO configuration.

A transparent GEO Satellite has been considered for this work. Dual-polarized antennas consisting of Right Hand Circular Polarized (RHCP) and Left Hand Circular Polarized (LHCP) antennas have been considered for both the GEO satellite and UEs. As shown in Fig. 1, the satellite eNodeB uses two satellite dishes to transmit via the dual-polarized antennas of the GEO satellite to the mobile users as proposed in [10]. This allows simultaneous transmissions from the two polarized antennas of the GEO satellite to different UEs. This transmission mode is closed loop, hence, there is a UE feedback for link adaptation purposes, which is very vital in determining the transmission rate.

The UE will send the CQI via the GEO satellite as recommended in [6] to the eNodeB on the earth station. The RTPD of approximately 540 ms is experienced in this scenario. This causes a misalignment between the reported UE’s CQI at the eNodeB and the instantaneous CQI level experienced by the UE. The reported CQI is used for transmission and scheduling purposes at the eNodeB and will either lead to underutilization of resources if a lower CQI is used or packet losses if a higher CQI is used. This occurrence makes link adaptation a serious challenge in the satellite scenario.

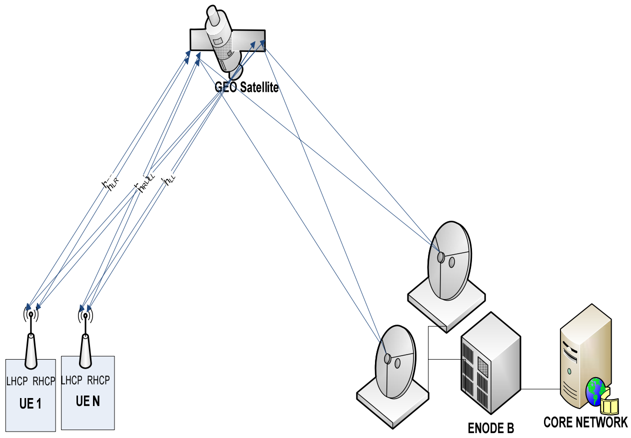

Figure 1 The system architecture of a satellite LTE network

At the MAC layer of the eNodeB, the packet scheduler works with the Link Adaptation (LA) module and Hybrid Automatic Repeat Request (HARQ) to schedule the various users allocated resources at every Transmission Time Interval (TTI) which is 1 ms, as specified in LTE.. The basic time-frequency resource that is allocated is the Physical Resource Block (PRB).

Each PRB consists of 12 consecutive subcarriers (180 kHz of the whole bandwidth) for duration of 0.5 ms for each slot [11]. Subcarrier spacing is 15 kHz and each slot contains 6 or 7 symbols depending on the type of cyclic prefix used. Assuming a normal cyclic prefix (7 symbols) is used, the PRB is made up of 84 symbols. It is worthy to note that the resource allocation is only finalized after every subframe of 1ms. This means a pair of PRBs (i.e. scheduling block) is allocated at every TTI of 1 ms.

The LTE frame is made of 10 subframes, hence, each LTE frame lasts for 10 ms or 20 slots. The smallest unit of the PRB is the Resource Element (RE). A RE can be 2, 4 or 6 bits, depending on the modulation used, that is QPSK, 16QAM or 64 QAM, respectively. The modulation type that will be used depends on the reported CQI value from UE to eNodeB.

The users selected by the packet scheduler are mapped to the available pair of PRBs at every TTI (1 ms). Hence, selected users are allocated a pair of PRB in LTE at every TTI for the two available antenna ports if a 2 x 2 MIMO is considered. The number of available PRBs in a scheduling interval depends on the size of bandwidth used and the number of antennas deployed. The number of PRBs for a single antenna ranges from 6 to 100, depending on the bandwidth size, which ranges from 1.4 to 20 MHz [12].

III. CHANNEL CHARASTERISTICS

The channel model that is considered here is an empirical-stochastic model for LMS-MIMO [13]. This is based on the fact that the model is validated and compared to other existing models [14], it considers interdependence between small scale fading. The stochastic properties of this model are derived from an S-band tree-lined road measurement campaign (suburban area) using dual circular polarizations at low elevations [13].

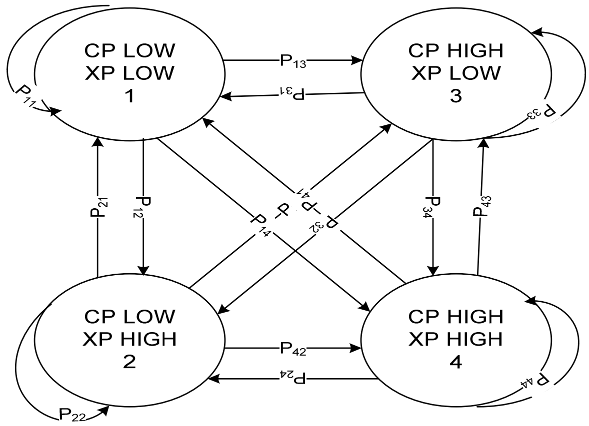

Figure 2 Four-state Markov model of an LMS-MIMO channel

The channel matrix, H, is made up of co-polar and cross-polar circularly-polarized channels and is represented as follows:

$$H = \begin{pmatrix} h_{RR} & h_{LR} \\ h_{RL} & h_{LL} \end{pmatrix} \tag{1}$$

The channel matrix, H, takes large scale fading (shadowing) and small scale fading (multipath) into account. A Markov chain is used to select between the possible regions of high and low shadowing values for both co-polar and cross-polar channels to model the mobile user movement across the buildings. There are four possible Markov states as presented in Fig. 2 below. The four possible states are due to the high or low state of both the co-polar (CP) and cross-polar (XP) channels. It is worthy to note that the transitions between the four possible states occur at every TTI.

The 4 x 4 transition matrix, P, is used to predict the next possible state. The columns of the matrix represent the probability of one state moving to another listed in the right hand column while the rows represent the probability of moving to the state on the right hand column from the previous state on the bottom row. State 1 is CP Low XP Low, Sate 2 CP Low XP High, State 3 is CP High XP Low and State 4 is CP High XP High. The probability matrix below is derived from the measurements obtained in [13]. The top right corner value of 0.1037 is the probability of “CP High, XP High” to “CP Low XP Low”.

$$P_{ij} = \begin{bmatrix} 0.6032 & 0.1579 & 0.0561 & 0.1037 \\ 0.2887 & 0.2474 & 0.0447 & 0.4192 \\ 0.1682 & 0.0966 & 0.1745 & 0.5607 \\ 0.0098 & 0.0199 & 0.0150 & 0.9554 \end{bmatrix} \tag{2}$$

The large scale (shadowing) fading generation depends on the Markov chain. A high or low shadowing is generated on the basis of the state. The small scale fading is modelled using Ricean distribution. The Ricean fading for each of the MIMO branch is generated using

Ricean factors. The details on how the large scale and small scale fading are obtained are shown in [13].

Though the varying distance is of less significance to the total path loss, the path loss (in dB) at 2 GHz is computed as follows:

$$L_{Fs} = 190.35 + 20\log\left(\frac{38500 + D}{35788}\right) \quad (3)$$

The large scale fading and small scale fading obtained above are considered together with the path loss (L_{FS}) and polarization loss as part of the total loss experienced in the channel. The Signal-to-Noise-Interference Ratio (SNIR), which is obtained on a subchannel basis by dividing the received power by the noise power, can be expressed as follows;

$$SNIR(dB) = EIRP + G_R - L_{Total} - N - I\,(dB) \quad (4)$$

The EIRP value of 63 dB, Polarization loss of 3.5 dB and a noise of -148.95 dBm for each subchannel is used to compute the SNIR. It is worthy to note that EIRP value of 53dB is also considered for the purpose of this work. Also, considered, it's the inter-spotbeam interference, *I*, as a result of power received from eNodeBs sharing the same frequency. The SNR-CQI mapping derived from [15] for a BLER of 10^{-3} is used to determine the CQI from obtained SNR. This can be presented as follows;

$$\begin{gathered} if\ SNR < -4.8;\quad CQI = 1 \\ if -4.8 \le SNR \le 21.6;\quad CQI = (0.55 * SNR) + 4 \\ if\ SNR > 21.6;\quad CQI = 15 \end{gathered} \quad (5)$$

The CQI distribution of a mobile user with speed of 30 km/h for EIRP value of 63 dB is presented in Fig. 3.

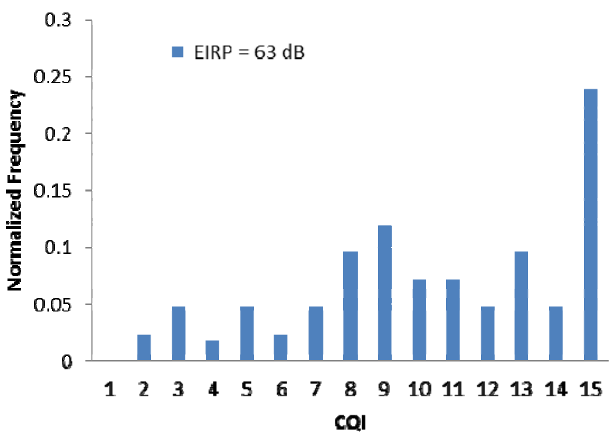

Figure 3. The CQI distribution of a UE at 30km/h

Based on the reported CQI, an appropriate Modulation and Coding Scheme (MCS) is used to transmit the packets of the selected mobile users. The BLER is determined by taking into account the MCS used and the estimated SNR at the UE for each subchannel. A much lower BLER target of 10^{-3} has been considered as compared to the BLER target of 10^{-1} that is considered for the terrestrial scenario since if the first transmission is unsuccessful in the terrestrial scenario, retransmission can quickly be employed to recover the lost packets. However, this is not the case for satellite scenario due to the long RTPD experienced in the satellite scenario. This practically prevents the use of retransmission to recover lost packets.

IV. Simulation Setup

The impact of the long RTPD is analysed through simulations. An event-driven-based open source simulator called LTE-Sim [16] is used for simulations in this paper. It is a standalone version of the LTE module in NS-3 and is written in C++. The simulator has been adapted for the satellite scenario by making necessary changes to both its physical layer and propagation delay. The web traffic model presented in the previous section is also added to this simulation software.

A single spotbeam has been considered with users capable of making video streaming and web surfing uniformly-distributed within a serving eNodeB footprint. The channel and traffic model presented in the previous section are adopted for the simulations.

A Queue-Aware Fair (QAF) scheduler [17] is considered for the purpose of this simulation. Each set of users is made of 60% of web browsers and 40% of video streamers. Each user is assumed to be reporting its channel condition at certain intervals to the eNodeB. Two channel reporting scenarios have been considered. A RTPD is experienced in one while we assume there is RTPD experienced in the other scenario. The details of the simulator parameters are provided in Table 1 below.

Table 1
Simulation Parameters

Parameters	Value
Simulation Time	500 seconds
RTPD	540 ms
Channel Model	4 state Markov model
TTI	1 ms
Frequency Re-use	7
Mobile user Speed	30 km/h
RLC Mode	AM
Web Traffic Model	On/off Pareto
Video Traffic Model	Trace based @ 242 kb/s
Schedulers	QAF
Bandwidth	15 MHz

The investigation of the impact of varying the CQI reporting intervals and possible usage of fixed CQI instead of an adaptive CQI is analysed through semi-analytical approach. The channel trace generated using MATLAB is used for this analysis. The channel trace for different speed 0 km/h, 30 km/h and 300 km/h using EIRP of 63 dB are generated.

V. Numerical Results

From results obtained, there is significant impact as a result of the long propagation delay experienced when the channel condition is reported to eNodeB by the UE. The throughput performance for when there is no RTPD experienced is better than when RTPD is experienced for both video and web traffic as shown in figure 4 and 5 respectively. The difference becomes more significant as the number of users increases.

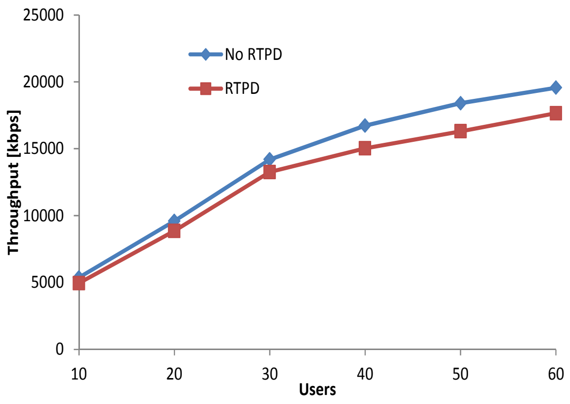

Fig.4. The average throughput for video users

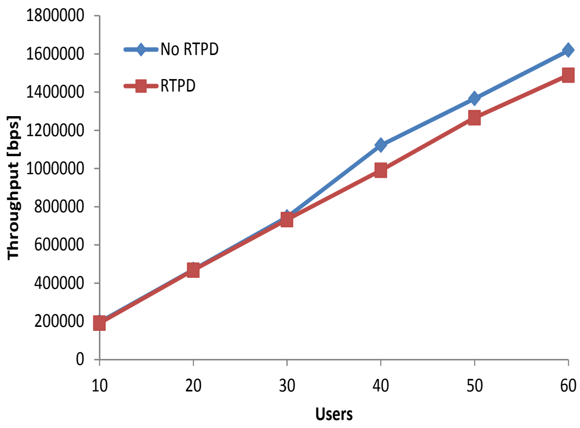

Fig.5. The average throughput for web users

The delay performance follows the same trend. The delay performance for cases when RTPD is experienced while reporting channel status is worse than cases when there is no RTPD experienced for both video and web traffic as shown in figure 6. Expectedly, the delay experienced by the web traffic users is higher than that of the video traffic users since the scheduler considers QoS factors while taking scheduling decisions.

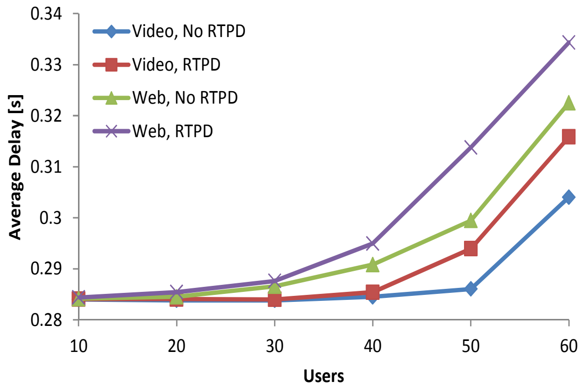

Fig.6. The average delay for all users

The spectral efficiency when the channel reporting has no RTP delay experienced is better than when the RTP delay is experienced in channel reporting as shown in figure 7.

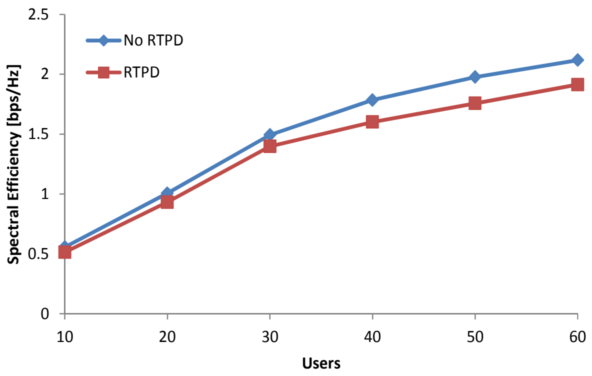

Fig.7. The spectral effiecency for all user

The performance of the investigation of varying CQI reporting intervals is measured in terms of effective spectral efficiency. The BLER is computed considering that a PRB is not correctly received when it uses a CQI value that is higher than the actual CQI needed at the UE. The effective spectral efficiency is considered to be the effectively used spectral efficiency after considering the loss as a result of this misalignment and is determined as follows:

$$S_{effective} = (1\text{-}BLER) * S \ [bit/s/Hz] \qquad (6)$$

Where $S_{effective}$ is the effective spectral efficiency and S is the spectral efficiency. The CQI value of the UE depending on the SNIR is considered to be reported at every T TTI intervals to eNodeB via the GEO satellite. The reduction of the frequency of CQI reporting will be useful to the mobile terminal since the power consumption will be reduced. The impact of the increasing value of reporting intervals on the satellite LTE performance is investigated for different speeds and the results are provided below in Fig 8.

The point 1-5 of the x-axis represents 1TTI, 20TTI, 60TTI, 100TTI and 160TTI respectively, while point 6-8 of the same axis represents 1 RTPD, 3RTPD and 7RTPD respectively.

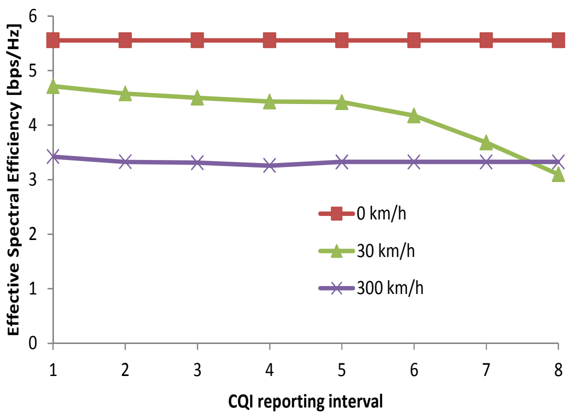

Figure 8 The spectral efficiency across varying CQI reporting intervals

From Fig. 8, a consistent and high effective spectral efficiency is obtained, this is due to the fact that a BLER value of 10^{-3} is obtained at user speed of 0 km/h since the user is stationary (the channel condition is consistent). The effective spectral efficiency at 30 km/h decreases gradually at low CQI reporting intervals and significantly decreases at high reporting interval (RTPD and above). While for 300 km/h (high user speed), the effective spectral efficiency shows no significant decrease across different CQI reporting intervals. The effective spectral efficiency obtained at user speed 30 km/h is higher than that of 300 km/h except at very high reporting intervals (close to 7 RTPD and above). This is as a result of the relatively high BLER experienced at user speed of 300 km/h as compared to 30 km/h.

Since, the CQI reporting at different intervals does not have any significant effect on the system performance at 300 km/h (high speed) as shown in Fig. 8, the effect of using a fixed CQI at eNodeB rather than frequent CQI reporting is also investigated. The result obtained which shows the effective spectral efficiency of all the 15 possible value of CQIs is presented in Fig. 9 below.

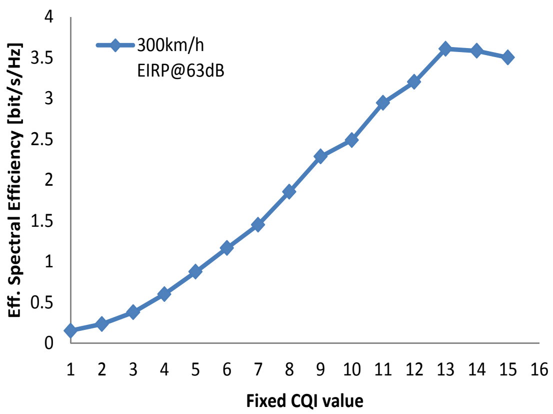

Figure 9 The eff. spectral efficiency across different fixed CQI values

From the results shown in Fig. 9, an effective spectral efficiency of 3.6 can be obtained at fixed CQI of 13 which is greater than the effective spectral efficiency obtained when using an adaptive CQI as depicted in Fig. 8. This shows that at high speed like 300 km/h, using a fixed CQI is a valuable option since it provides better system perofrmance and reduces power consumption.

VI. Conclusion & Future Works

The CQI reporting plays an important role in link adaptation especially at lower speed. The investigation of the impact of the RTPD on the performance of satellite LTE network has been presented. The RTPD experienced during channel reporting can be said to be of significance to satellite LTE network. This can be deduced from the results presented which shows that the RTPD experienced during CQI reporting reduces the performance of network when compared to when the RTPD is not experienced.

The investigation of the impact of the RTPD on the performance of satellite LTE network for both adaptive and fixed CQI at different user speeds have been presented. The frequent CQI reporting can be said to be of no significance to the network at high user speed (300 km/h) due to very frequent channel variation, while, at low user speed (30 km/h), CQI reporting is of significance; a CQI reporting interval of less than half of the value of the RTPD is recommended for low user speed (30 km/h) since at values close to RTPD, a significantly lower spectral efficiency is obtained. A fixed CQI of value of 13 is recommended for higher speed (300 km/h).

Acknowledgment

This research work is partly funded by Telkom, Alcatel-Lucent and Exotic Systems. It is also partly funded by the Coimbra Group Scholarship programme for young researchers.

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- **Environmental Management** - climate change management, environmental impacts of events such as rapid urbanization and mass migration, air and water pollution (e.g. flow patterns of water or airborne pollutants), deforestation (e.g. processing and management of satellite imagery), depletion of natural resources, exploration of resources (e.g. using geographic information system analysis).
- **Popularization of Ubiquitous Computing** - foraging for computing / communication resources on the move (e.g. vehicular technology), smart / 'aware' environments, security and privacy in these contexts; human-centric computing; possible legal and social implications.
- **Commercial, Industrial and Governmental Applications** - how to use knowledge discovery to help improve productivity, resource management, day-to-day operations, decision support, deployment of human expertise, etc. Best practices in e-commerce, e-commerce, e-government, IT in construction/large project management, IT in agriculture (to improve crop yields and supply chain management), IT in business administration and enterprise computing, etc. with potential for cross-fertilization.
- **Social and Demographic Changes** - provide IT solutions that can help policy makers plan and manage issues such as rapid urbanization, mass internal migration (from rural to urban environments), graying populations, etc.
- **IT in Education and Entertainment** - complete end-to-end IT solutions for students of different abilities to learn better; best practices in e-learning; personalized tutoring systems. IT solutions for storage, indexing, retrieval and distribution of multimedia data for the film and music industry; virtual / augmented reality for entertainment purposes; restoration and management of old film/music archives.
- **Law and Order** - using IT to coordinate different law enforcement agencies' efforts so as to give them an edge over criminals and terrorists; effective and secure sharing of intelligence across national and international agencies; using IT to combat corrupt practices and commercial crimes such as frauds, rogue/unauthorized trading activities and accounting irregularities; traffic flow management and crowd control.

The main focus of the journal is on technical aspects (e.g. data mining, parallel computing, artificial intelligence, image processing (e.g. satellite imagery), video sequence analysis (e.g. surveillance video), predictive models, etc.), although a small element of social implications/issues could be allowed to put the technical aspects into perspective. In particular, we encourage a multidisciplinary / convergent approach based on the following broadly based branches of computer science for the application areas highlighted above:

Special Issue Guidelines

Special issues feature specifically aimed and targeted topics of interest contributed by authors responding to a particular Call for Papers or by invitation, edited by guest editor(s). We encourage you to submit proposals for creating special issues in areas that are of interest to the Journal. Preference will be given to proposals that cover some unique aspect of the technology and ones that include subjects that are timely and useful to the readers of the Journal. A Special Issue is typically made of 10 to 15 papers, with each paper 8 to 12 pages of length.

The following information should be included as part of the proposal:

- Proposed title for the Special Issue
- Description of the topic area to be focused upon and justification
- Review process for the selection and rejection of papers.
- Name, contact, position, affiliation, and biography of the Guest Editor(s)
- List of potential reviewers
- Potential authors to the issue
- Tentative time-table for the call for papers and reviews

If a proposal is accepted, the guest editor will be responsible for:

- Preparing the "Call for Papers" to be included on the Journal's Web site.
- Distribution of the Call for Papers broadly to various mailing lists and sites.
- Getting submissions, arranging review process, making decisions, and carrying out all correspondence with the authors. Authors should be informed the Instructions for Authors.
- Providing us the completed and approved final versions of the papers formatted in the Journal's style, together with all authors' contact information.
- Writing a one- or two-page introductory editorial to be published in the Special Issue.

Special Issue for a Conference/Workshop

A special issue for a Conference/Workshop is usually released in association with the committee members of the Conference/Workshop like general chairs and/or program chairs who are appointed as the Guest Editors of the Special Issue. Special Issue for a Conference/Workshop is typically made of 10 to 15 papers, with each paper 8 to 12 pages of length.

Guest Editors are involved in the following steps in guest-editing a Special Issue based on a Conference/Workshop:

- Selecting a Title for the Special Issue, e.g. "Special Issue: Selected Best Papers of XYZ Conference".
- Sending us a formal "Letter of Intent" for the Special Issue.
- Creating a "Call for Papers" for the Special Issue, posting it on the conference web site, and publicizing it to the conference attendees. Information about the Journal and Academy Publisher can be included in the Call for Papers.
- Establishing criteria for paper selection/rejections. The papers can be nominated based on multiple criteria, e.g. rank in review process plus the evaluation from the Session Chairs and the feedback from the Conference attendees.
- Selecting and inviting submissions, arranging review process, making decisions, and carrying out all correspondence with the authors. Authors should be informed the Author Instructions. Usually, the Proceedings manuscripts should be expanded and enhanced.
- Providing us the completed and approved final versions of the papers formatted in the Journal's style, together with all authors' contact information.
- Writing a one- or two-page introductory editorial to be published in the Special Issue.

More information is available on the web site at http://www.academypublisher.com/jait/.