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Intercell Interference Mitigation Scheme For Long Term Evolution Network Uplink Based On Quality-Of-Service Priority

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Abstract:
The continuous growth in Device-to-Device (D2D) and Machine-to-Machine (M2M) communications demands for a robust uplink Radio Resource Management (RRM) strategy. However, radio waves in a mobile cellular radio access network such as the Long Term Evolution (LTE) network are faced with the problem of Intercell Interference (ICI) which limits the achievable system throughput. Thus, this paper proposes a Quality-of-Service (QoS)-based ICI mitigation (QICIM) scheme for the LTE network uplink. The proposed QICIM scheme involves coordination among the cells that make up the network to achieve maximum system throughput via QoS priority and effective power control for interference mitigation among the User Equipment (UEs). Two target QoS uplink rates namely 200 kbps and 600 kbps were used in this study. The simulation results showed that the proposed QICIM scheme gave a maximum average ICI of -150.6309 dB on a Physical Resource Block (PRB) compared to the conventional Frequency Reuse 1 plus Power Control (FR1+PC) scheme that gives -133.1276 dB. Generally, the proposed QICIM scheme outperforms the FR1+PC scheme in terms of resource efficiency, fairness and system throughput.
Key Word: *Intercell Interference (ICI), Long Term Evolution (LTE), Physical Resource Block (PRB), Quality-of-Service (QoS), Radio Resource Management (RRM).*

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I. Introduction

The Long Term Evolution (LTE) network is a Mobile Cellular Radio Access Network (MCRAN) developed to cater for the increasing demand for higher data rates, enhanced Quality of Service (QoS) as well as Machine-to-Machine (M2M) communications [1], [2]. In the uplink (UL) of LTE, a User Equipment (UE) is allocated one or more available Physical Resource Blocks (PRBs) by its serving evolved NodeB (eNB), a Base Station (BS), to transmit in every 1 millisecond transmission time interval (TTI) [3]. A PRB consists of 12 subcarriers, and a UE is allocated a PRB that can satisfy its target Signal-to-Interference-to-Noise-Ratio (SINR). Interference is an undesirable phenomenon that is common to radio waves in MCRANs [4]. Within a cell of the LTE network, uplink intracell interference is properly mitigated by providing orthogonality among the UEs via channelization methods that are based on the Orthogonal Frequency Division Multiplexing (OFDM) [5],[6]. However, in a multicell LTE network, uplink transmission is not immune to Intercell Interference (ICI), which is caused by signals of UEs from neighboring cells transmitting on the same PRB [4],[7]. A UE becomes prone to high ICI level as it moves farther away from its serving eNB; and in consequence, it will require more transmission power to maintain the link quality [8],[9]. High ICI level, which is common to UEs located at cell edges, degrades signal quality, reduces QoS satisfaction and limits the achievable SINR and overall system capacity [10].

Further, with the continuous increase in connecting devices leading to ultra-dense and heterogeneous networks (HetNets) [11], optimum utilization of the available spectrum is key. The conventional strategy for mitigating ICI in LTE is by frequency planning [3],[12]. The major drawbacks of frequency planning are signalling overhead, wastage in spectrum and network overload [13]. Among the frequency planning methods, Frequency Reuse 1 (FR1) factor is the most spectrally efficient in a multicell LTE network. However, FR1 causes increase in ICI level which invariably reduces the achievable SINR and QoS within the network if not properly managed [4],[13]; thus, the development of a robust ICI Mitigation (ICIM) scheme is very essential.

From the literature, ICIM strategies can be categorized into four as shown in Figure 1. Randomization and cancelation strategies entail processing of the interfering signals by the receiver [14], [15]. Beamforming strategy has to do with steering of the antenna to produce desired beam pattern [16]. Management strategy is made up of two categories: Interference avoidance and Cell coordination. Interference avoidance involves frequency reuse planning [17],[18]; whereas, cell coordination involves ICI level information sharing among the eNBs in the network using the X2 interface [13]. In addition, two or more of these ICIM categories can be combined to improve system performance [16]. The cell coordination strategy is regarded as the most promising for future networks [19]; thus, the proposed QoS-based ICIM (QICIM) scheme in this paper is categorized under the cell coordination strategy.

The remaining sections of this paper are as follows: Section II presents the review of related works. In Section III, the system model for ICI in a multicell LTE environment as well as the proposed LTE uplink ICI mitigation scheme are presented. In Section IV, the numerical results obtained from the simulation of the system are discussed. Finally, Section V gives the conclusion of the paper.

II. Related Works

Until recently, majority of the proposed ICIM schemes for LTE networks have focused on the downlink (DL) [20],[21],[22]. However, owing to the increasing mixed and dynamic QoS UL traffic caused by emerging new services such as the Internet-of-Things (IoT) and edge computing, the uplink (UL) interference management is gaining more attention in recent times [23][24]. Thus, this section focuses on the ICIM schemes for the LTE uplink. An ICIM scheme that utilizes network measurements to centrally coordinate the cells in adjusting the UL powers of UEs was proposed in [15]. Mao et al (2008) [18] proposed a dynamic frequency reuse scheme for ICI avoidance. The scheme partitions PRBs between cell-edge and cell-center users and then dynamically distributes PRBs among neighboring cells based on load demands. Mei et al (2018) [25] presented a centralized and a decentralized ICIC schemes for the uplink communication. The schemes achieved significant improvement in the network's throughput.

Authors in [13] proposed a cell coordination strategy based on UL power control and cooperative pricing among neighboring cells in the LTE network. Fan et al. (2014) [26] presented field test results on ICI coordination methods for time-division LTE. Cell coordination strategy was also employed in [27], whereby the UEs within a cell are grouped into four sets which are assigned different Power Control (PC) scaling coefficients. Some other ICIM schemes that are based on adjusting the UL powers of small cell UEs for protecting the macrocell UEs from interference in LTE HetNets are presented in [28],[29].

All the referenced related works provide some level of improvement to LTE network uplink; however, to the best of our knowledge, none took into account QoS priority levels as the basis for cell coordination. Thus, this paper presents a QoS-aware cell coordination ICIM strategy for optimal spectrum utilization and network throughput maximization.

III. System Model

Figure 2 illustrates the uplink ICI scenario in an LTE network. The network is presented in hexagonal grid cell layout consisting of 7 cells, and each having a serving eNB. The UEs have different QoS classes, and are scattered within the network. It is assumed that the network adopts the FR1 factor in which all the cells are allowed to utilize the available PRBs at the same time. The eNB 1 is taken as the reference cell, which is surrounded by 6 neighboring cells with the potential of causing ICI to eNB 1. The UE 1 is located at the cell edge of eNB 1 that is serving it, and it is experiencing high ICI level caused by neighboring UE 2 and UE 7 on its allocated PRB. Consequently, the link gain of UE 1 is negatively affected, and will invariably reduce its achievable effective SINR. The effective SINR $\Gamma_{u,b}^{eff}$ achievable by any UE u over its allocated b^{th} PRB in a reference cell c is given as:

$$\Gamma_{u,b}^{eff} = \left(\frac{1}{\frac{1}{N_{sc}} \sum_{n}^{N_{sc}} \frac{\Gamma_{u,n}}{\Gamma_{u,n} + 1}} - 1 \right)^{-1} \qquad (1)$$

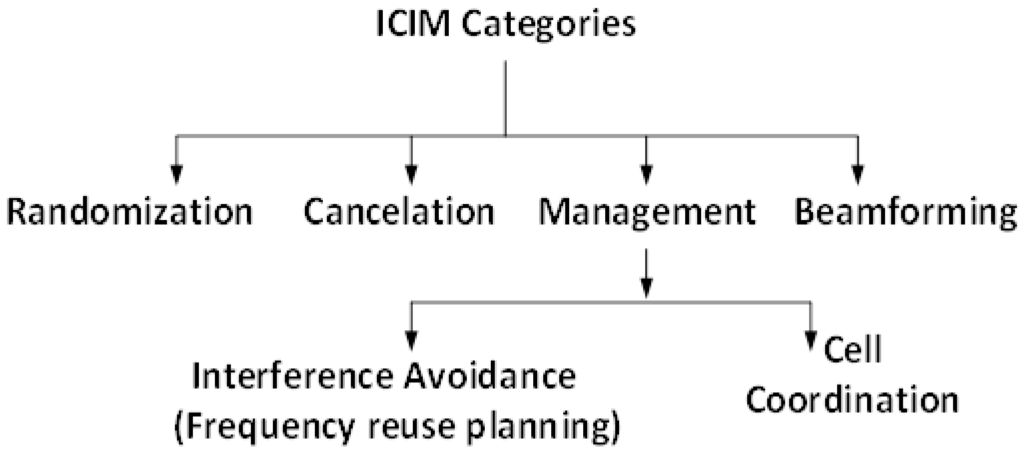

Figure 1. Categorization of ICI mitigation strategies

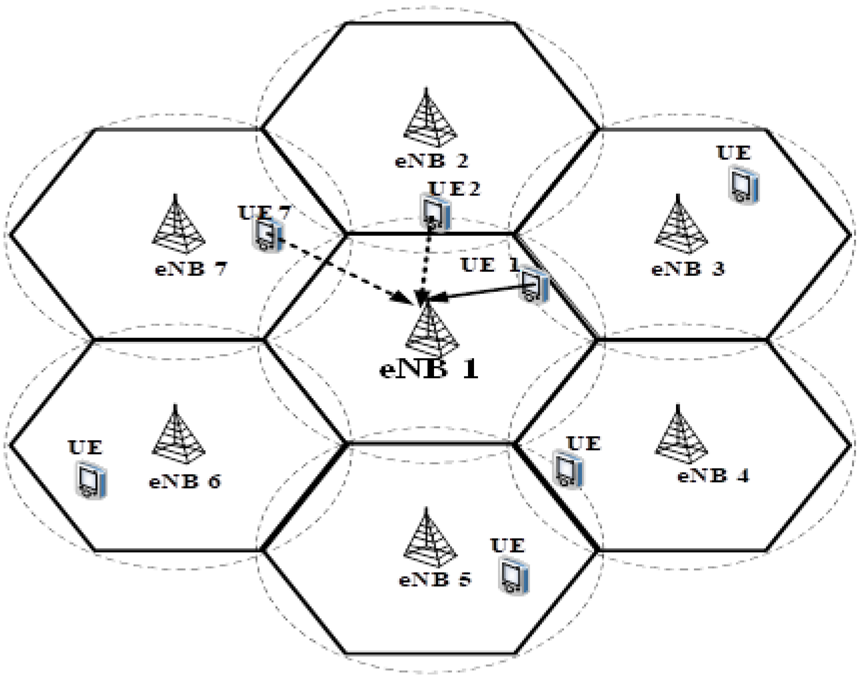

Figure 2. The uplink intercell interference scenario in an LTE network.

where N_{sc} is the number of subcarriers contained in the PRB and $\Gamma_{u,n}$ is the SINR achieved on the n^{th} subcarrier, and is obtained as:

$$\Gamma_{u,n} = \frac{P_{u,n} H_{u,n}}{\sigma_{c,n}^2 + I_{c,n}} \quad (2)$$

where $P_{u,n}$ is the UL transmission power on the n^{th} subcarrier, $H_{u,n}$ is the link gain of the UE on the subcarrier, $\sigma_{c,n}^2$ is the noise power on the subcarrier and $I_{c,n}$ is the total ICI level on the subcarrier in cell c, which is expressed as:

$$I_{c,n} = \sum_{j=1}^{|N|} \delta_j P_{j,n} H_{j,n} \quad (3)$$

where $|N|$ is the cardinality of the set of neighbouring cells to cell c; $\delta_j = 1$ if cell j interferes with the UE u and $\delta_j = 0$ if otherwise; $P_{j,n}$ and $H_{j,n}$ are the transmission power and link gain of the interfering UE from neighbouring cell j, respectively.

It can be observed from Equation (2) that the total ICI level must be acceptably low for the UE to achieve its desired SINR. In addition, the effect of ICI can be appropriately managed by controlling the UL transmission powers of the interfering UEs as shown in Equation (3).

The achievable throughput R_u by UE u during a transmission period is obtained as:

$$R_u = B_u \log_2\left(1+\Gamma_u^{eff}\right) \quad (4)$$

where Γ_u^{eff} is the effective SINR achieved by UE u over its allocated PRBs, B_u is the bandwidth occupied by all the PRBs allocated to the UE, and is given as:

$$B_u = B_{sc} \cdot N_{sc} \cdot \Lambda_u \quad (5)$$

where Λ_u is the number of PRBs allocated to UE u, N_{sc} is the number of subcarriers contained in one PRB, and B_{sc} (= 15 kHz) is the bandwidth occupied by each subcarrier. The implication of Equation (4) is that a relatively high SINR would result in corresponding high achievable throughput needed to satisfy the QoS requirement of the UE.

Proposed QICIM Scheme

The proposed QICIM scheme is a variant of the scheme in [13]. It involves cell coordination strategy utilizing FR1 factor in a multicell LTE network serving Macrocell UEs (MUEs). However, the scheme can be adapted to HetNets when small cells are grouped into virtual macrocell eNBs [17]. Assuming the link gain remains constant for 10 ms, the proposed QICIM scheme can be performed every 10 TTIs so as to limit the signalling overhead. The UL transmission power adjustment is carried out based on the priority index of the scheduled UEs. The priority index is obtained from the QoS rate class; that is, whether it is Guaranteed Bit Rate (GBR) or None GBR [30].

The priority index consists of two levels: Low (None GBR) and High (GBR). The priority index ρ_u^c of a given UE u being served by a reference cell c can take any of the two levels as:

$$\rho_u^c = \begin{cases} 1, & Low \\ 2, & High \end{cases} \quad (6)$$

In this study, the target QoS rates assigned to the “Low” level priority and “High” level priority are 200 kpbs and 600 kbps, respectively. The QICIM scheme is presented in Algorithm 1. The inputs to the QICIM scheme are: the maximum transmission power for uplink ($P_{UL_{\max}}$); the maximum number of PRBs needed to satisfy the target QoS rate of UE u ($\Lambda_u^{\max}$); the set of ICI levels estimated on all the available PRBs (**L)**; ICI level threshold above which the highest price is obtained (I_{th}); and the set of neighboring cells causing ICI to the reference cell c (**Q**). The output of the scheme is the set of adjusted uplink transmission powers (**P**).

The threshold I_{th} is computed as:

$$I_{th} = 10^{-p/10}\left(0.1D_{ref}\right)^{-q/10} \quad (7)$$

where $0.1D_{ref}$ is a reference distance, and the values for p and q are taken from [31]. The value of D_{ref} is chosen to be 85 m because it was found to be the maximum value that makes an UL transmission power reduction not to go below the minimum acceptable level, which is 14% of $P_{UL_{\max}}$ [31]. The ICI threshold I_{th} was calculated to be approximately -169 dB.

Initially, all UEs are allowed to transmit at maximum transmission power $P_{UL_{\max}}$. Then, the set **L** is first obtained by all the eNBs in the network using Equation (3). If the ICI level on a PRB b used by a given UE u is above the threshold, then the reference eNB c computes the price $\beta_{c,b}$ on the PRB b as:

$$\beta_{c,b} = \min\left(\frac{I_{c,b}}{I_{th}}, 1\right) \quad (8)$$

where $0 \leq \beta_{c,b} \leq 1$, $I_{c,b}$ is the ICI level estimated on PRB b and I_{th} is the specified ICI threshold. After $\beta_{c,b}$ has been determined then the reference cell c sends the average ICI price $\overline{\beta}_{c,b}$ to the neighbouring cells. The average ICI price $\overline{\beta}_{c,b}$ is calculated as:

$$\overline{\beta}_{c,b} = \frac{\beta_{c,b}}{6} \quad (9)$$

where 6 is the number of neighbouring cells in hexagonal grid cell layout. Then, the eNB of the interfering cell checks the value of the priority index ρ_u^c.

If the priority index $\rho_u^c = 1$ (i.e. Low), the eNB of the interfering cell, l, upon receiving $\overline{\beta}_{c,b}$, signals the UE v causing ICI on PRB b to adjust its transmission power as [13]:

$$P_{l,b}^v = \frac{P_{UL_{\max}} \cdot \max\left(1 - \overline{\beta}_{c,b}, 0\right)}{\Lambda_u^{\max}} \quad (10)$$

where $P_{UL_{\max}}$ is the maximum transmission power for uplink, $\Lambda_v^{\max}$ is the maximum number of PRBs needed to satisfy the target QoS rate of UE u.

If the priority index $\rho_u^c = 2$, (i.e. high), the eNB of the interfering cell signals the UE v causing ICI on PRB b to adjust its transmission power using a closed-loop power control (PC) [23] given as:

$$P_{l,b}^v = \min\left\{P_{UL_{\max}}, (\Lambda_u \cdot P_0 \cdot PL^{\alpha} \cdot \delta_{mcs})\right\} \quad (11)$$

where Λ_u is the number of PRBs assigned to the UE, PL is the pathloss, α is the pathloss exponent, δ_{mcs} is a modulation and coding scheme (MCS)-dependent power offset and P_0 is the ICI level given as [12]:

$$P_0 = I_u \Gamma_u \quad (12)$$

where I_u is the ICI level experienced by the UE u and Γ_u is the target effective SINR of the UE u. The implication of Equations (10) and (11) is that an interfering UE reduces its transmission power more when $\rho_u^c = 1$ and less when $\rho_u^c = 2$. The proposed QICIM scheme is presented in Algorithm 1.

System Simulation and Performance Evaluation

The proposed QICIM scheme was simulated in MATLAB. the system simulation parameters are contained in Table no 1. The LTE multi-cell network was simulated to investigate the effect and mitigation of ICI in the network. System bandwidth of 5 MHz was provided for each cell. The sampling frequency, number of subcarriers, and PRBs were taken from the LTE uplink specification [3]. The assumed traffic model is full buffer, which means that every UE in the network always has data to transfer. A target QoS rate is the throughput that every scheduled UE desires to achieve in 1 TTI. The system was run for 1000 TTIs (or channel realizations) so as to get good statistical average of the results. The central cell in the network was taken as the reference cell and the impact of the QICIM scheme was investigated in the reference cell. The scheduling scheme presented in [31] was used in the simulated network.

Algorithm 1 QICIM Scheme (proposed)
Inputs: $P_{UL_{\max}}$, $\Lambda_u^{\max}$, **L**, I_{th}, **Q** **Output: P**

1: **Initialization:**
2: $\mathbf{P} = \{\ \}$
3: $c \leftarrow$ reference cell that initiates the ICI coordination
4: **while L** $\neq \{\ \}$ **do**
5: $I_{c,b} \leftarrow$ ICI level of next PRB b, $\forall I_{c,b} \in \mathbf{L}$
6: Calculate the price $\beta_{c,b}$ on PRB b by (8)
7: Calculate the average ICI price $\bar{\beta}_{c,b}$ by (10)
8: Cell c sends $\bar{\beta}_{c,b}$ to the neighbouring cells in **Q**
9: The interfering UE in cell $l \in \mathbf{Q}$ controls its transmission power on PRB b by (11)
10: Update the set of adjusted transmission powers:
$\mathbf{P} = \mathbf{P} \cup \{P_{l,b}^{u}\}$
11: Remove $I_{c,b}$ from
$\mathbf{L} = \mathbf{L} \setminus \{I_{c,b}\}$
12: **end while**

Table no 1 System simulation parameters and specifications

Parameter	Specification
Cell layout	19 cells in hexagonal grid with 3 sectors per cell
Number of UEs per cell	10
eNB to eNB distance	1000 m
Minimum UE to eNB distance, d_{min}	35 m
Maximum UE to eNB distance, d_{max}	500 m
UE distribution	Uniform
Carrier frequency	2.6 GHz
System bandwidth	5 MHz
Number of available PRBs	25
Bandwidth of 1 subcarrier	15 kHz
Traffic model	Full buffer
Transmission Time Interval (TTI)	1 ms
Target QoS rate	250 kbps, 600 kbps
Maximum UE transmission power, $P_{UL_{max}}$	125 mW (21 dBm)
Minimum UE transmission power, $P_{UL_{min}}$	2.1 mW (3.22 dBm)
Multipath channel model	ITU EPA
Noise power	-162 dBm
MCS set	QPSK, 16QAM, 64QAM [available rates are 1/2, 2/3 and 3/4]

System Throughput

The system throughput is a measure of achievable data rate of all the scheduled UEs in a cell or an entire network. In other words, the system throughput in a given TTI is the sum of all the achievable throughputs of the UEs. The system throughput, R_{tot}, measured in bits per second (bps), is calculated as:

$$R_{tot} = \sum_{u=1}^{N_{UE}} R_u \qquad (13)$$

where R_u is the achieved throughput by the u^{th} UE, and N_{UE} is total number of UEs in the network.

Fairness

In this study, two different methods were used to measure the fairness among UEs. The first method was the average number of UEs that the RRM scheme schedules in one TTI. This is very important in order to know whether the ICIM technique has been able to increase the chances of some cell-edge UEs to be scheduled. The second fairness metric was in terms of individual achievable throughput of the scheduled UEs, and the Jain's fairness index was used to compute this. The Jain's fairness index, F_S, is calculated as [32]:

$$F_S = \frac{(R_{tot})^2}{N_{UE} \cdot \sum_{u=1}^{N_{UE}} R_u^2} \qquad (14)$$

where R_{tot} is the system throughput, R_u is the achieved throughput by the u^{th} UE, and N_{UE} is total number of UEs in the network.

IV. Results And Discussion

Numerical results obtained from the simulation of the proposed QICIM scheme are hereby presented. The QICIM scheme is compared with the conventional frequency reuse 1 plus the LTE power control (FR1+PC) [13]. Figure 3 presents the comparison of the average ICI level on a PRB achieved by the QICIM scheme and the FR1+PC at 2, 6, 10, 14, 18, 22, 26 and 30 UEs per cell. These results showed that with the QICIM scheme, the average ICI level becomes negligible as the number of UEs per cell increases above 22 compared to the FR1+PC scheme which suffers from increasing average ICI level. Further, the maximum average ICI level obtained with the proposed QICIM scheme was -150.6309 dB whereas the QOEA scheme gave -133.1276 dB. This reveals that the QICIM scheme reduced the level of ICI on the PRBs by controlling the transmission powers used on the PRBs.

Figure 4 shows the average number of allocated PRBs for each of the target QoS uplink rates (i.e. 200 kbps and 600 kbps) by the QICIM and FR1+PC schemes for 10 UEs per cell. The results showed that the QICIM scheme allocates relatively higher PRBs to the UEs compared to the FR1+PC. The QICIM scheme gave an average of 21.25 PRBs whereas the FR1+PC gave 18.34 PRBs. The results reveal that the QICIM scheme is able to reduce PRB wastage due to its ICI mitigation mechanism. The comparisons of the fairness of the two schemes are presented in Figures 5 and 6. In Figure 5, the average numbers of scheduled UEs achieved by the QICIM scheme are relatively higher than those achieved by the FR1+PC. For instance, UEs in the 600 kbps class were scheduled more by the QICIM scheme compared to the FR1+PC scheme with an average of 7.33 and 5.24, respectively.

The Jain's fairness index results in Figure 6 are in agreement with results obtained in Figure 5. The QICIM achieved 0.9695 and 0.5484 for 250 kbps and 600 kbps, respectively; whereas the FR1+PC achieved 0.8283 and 0.5243 for 250 kbps and 600 kbps, respectively. The results of the system throughput versus target QoS uplink rate are presented in Figure 7. The results show that QICIM scheme delivers relatively higher throughput compared to the FR1+PC scheme. For the 200 kbps class, 1.89 Mbps and 1.85 Mbps were achieved by the QICIM scheme and FR1+PC scheme, respectively. For the 600 kbps class, the QICIM scheme achieved 2.52 Mbps and the FR1+PC scheme achieved 2.31 Mbps.

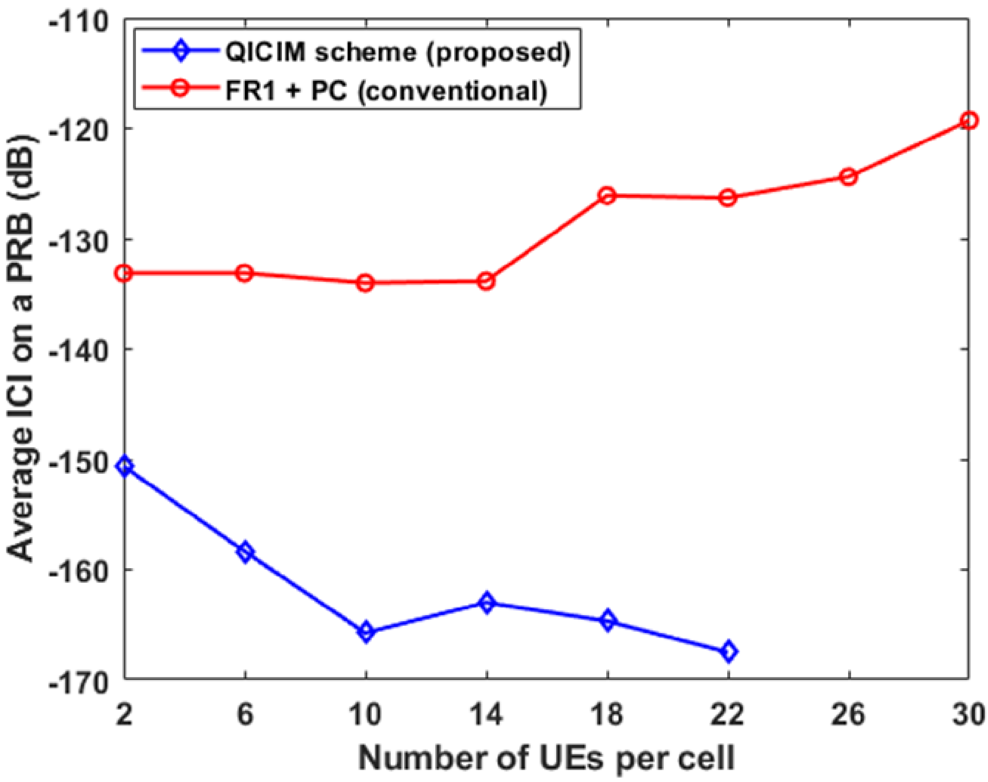

Figure 3: Average ICI level on a PRB versus Number of UEs per cell.

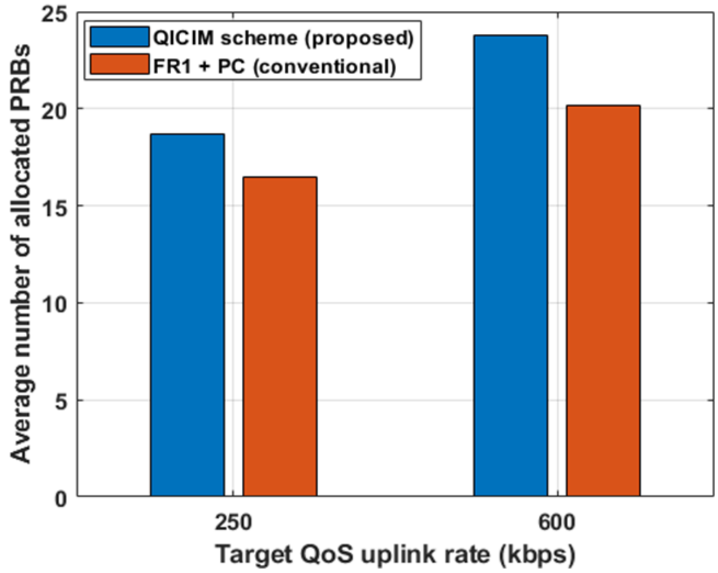

Figure 4: Average number of allocated PRBs versus Target QoS uplink rate

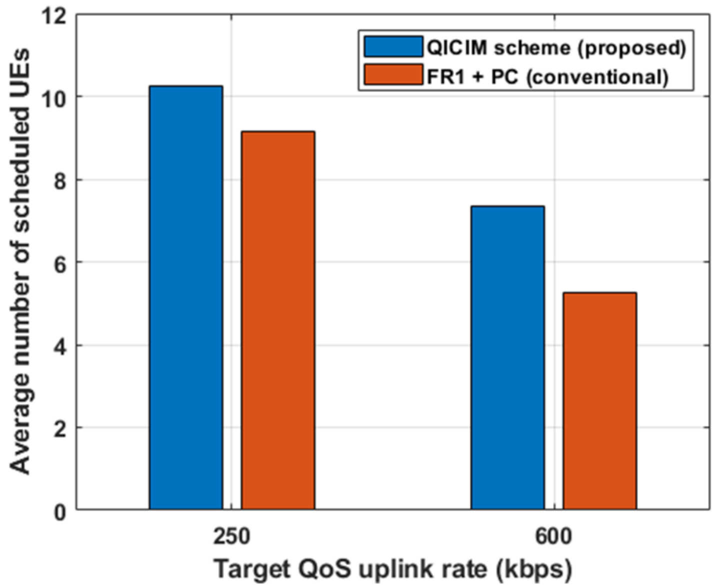

Figure 5: Average number of scheduled UEs versus Target QoS uplink rate

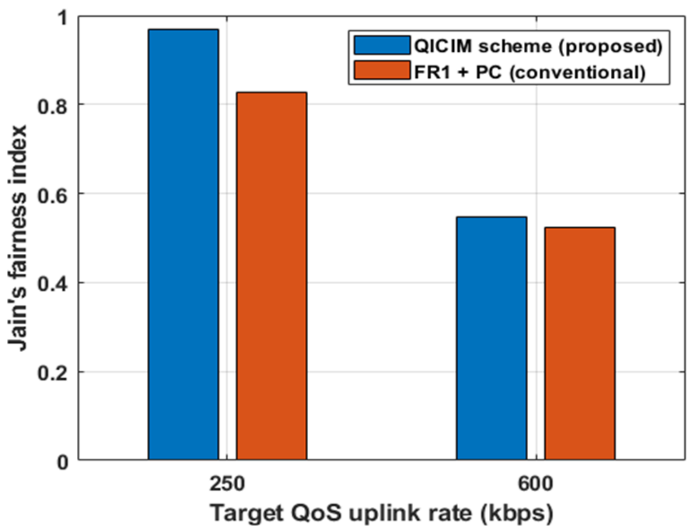

Figure 6: Jain's fairness index versus Target QoS uplink rate

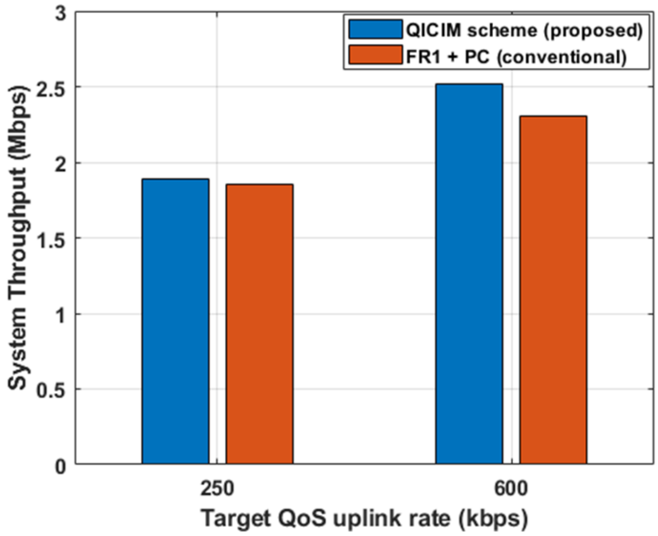

Figure 7: System throughput versus Target QoS uplink rate.

V. Conclusion

Interference is an undesirable phenomenon that is common to radio waves in a Mobile Cellular Radio Access Network such as the LTE network. A QoS-based ICI mitigation (QICIM) scheme for the LTE network uplink has been proposed in this paper. A QoS-priority power control with opportunistic scheduling strategy was investigated in the presence of signal interferences on the network. Simulation results showed that the proposed QICIM scheme outperforms the conventional frequency reuse 1 plus power control (FR1+PC) scheme in terms of resource efficiency, fairness and system throughput. The proposed scheme can be adapted to LTE-based systems such as the Narrowband-IoT (NB-IoT) and LTE-M.

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