Resource Management in 4G Wireless Communications at Vehicular Speeds: A Game Theory Solution

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Abstract – **Poor cell-edge throughput is a well recognized problem in wireless communication technologies including 4G. Inter-cell interference (ICI), low signal to noise ratio (SNR) and inability to use an efficient modulation scheme in a low SNR environment are major problems in cell-edge regions in a multi-cell communication environment, which severely limits the spectral efficiency and cell-edge throughput. Mobility at vehicular speeds adds another dimension of problem for cell-edge users mainly because bit error rate increases exponentially with increasing vehicular speeds due to the multipath problem. 4G standards like LTE–A and WiMAX are currently considering various options to address this problem of low cell-edge throughput. One such option is to split the total radio resource among the cell center and cell-edge region, which allows frequency reuse, reduces ICI in cell-edge area, and supports CoMP transmission. In this paper, we show that simple resource splitting strategy like this, is not sufficient to support wireless communications at vehicular speeds. We propose a game theoretic model to resource management in 4G networks, which works well with nodes moving at high vehicular speeds. The ultimate benefit of the proposed scheme includes lower connection dropping rates for mobile nodes and higher revenue return for the service providers.**

Keywords – Cell-edge, vehicular speeds, game theory, revenue index, utility.

I. INTRODUCTION

Wireless communication has revolutionized the way of our day-to-day communication and opened opportunities for many innovative applications in areas such as intelligent transportation system and multimedia entertainment system. While wireless technology has come a long way since its introduction, its adoption rate has increased significantly and new bandwidth hungry applications are evolving at the same time. Demand for a wireless technology that can support current and future emerging applications is on the rise, which has led to the introduction of 4G wireless standard and two major contenders for 4G standard include: the worldwide interoperability for microwave access (WiMAX) [1] and the 3rd generation partnership project (3GPP) long term evolution advanced (LTE-A) [2]. Both of these technologies target to deliver very high throughput with stringent quality of service (QoS), long range coverage and high spectral efficiency.

Efficient physical layer and QoS focused medium access control (MAC) layer are two major strengths in both WiMAX and LTE-A. Orthogonal frequency division multiple access (OFDMA) has been adopted as the downlink access technology for LTE-A standard while WiMAX uses it for both uplink and downlink [7-9]. OFDM is well known for its ability to reduce intra-cell interference. Inter-cell interference (ICI), however, remains as a major challenge in both WiMAX and LTE-A, particularly in the cell-edge area [3-5]. Another major problem is that in cell-edge regions, SNR remains low, which restricts the use of efficient modulation and coding (MC) scheme, leading to a poor spectral efficiency (bps/Hz). Traditionally, ICI problem is addressed by the classical cell clustering techniques [10], for example, a reuse factor of 3. These techniques reduce interference in the cell-edge region at the expense of system throughput due to resource partitioning.

Researchers have proposed a coordinated multipoint transmission scheme (CoMP) for LTE-A where more than one base station act in a coordinated fashion to help nodes in the cell-edge area [2]. Similar multipoint transmission schemes are being investigated for inclusion in the latest WiMAX standard. While CoMP partially addresses the problem of ICI, it does not significantly improve the spectral efficiency. Moreover, implementation and coordination are two major challenges in CoMP, a reason why it was not initially included into the release 9 of LTE-A standard. In literature almost all works [3-6] on cell-edge throughput focus on addressing ICI problem and thereby, improving throughput. The target groups for these schemes are either fixed or nomadic nodes. Mobile nodes that move at vehicular speeds add another dimension of problems in addition to the ICI problem, known as the multipath problem. As evident in our previous works [11] and also reported in relevant works [12], multipath problem contributes to exponential rise in average bit error rate with increasing vehicular speeds (Fig. 1). In this paper, we focus on resource management in 4G technologies at high vehicular speeds.

II. RADIO RESOURCE MANAGEMENT IN 4G AND PROBLEM DEFINITION

To address the problem of low cell-edge throughput, researchers [4-6] have recently introduced an innovative idea of resource splitting between cell center and cell edge regions in 4G (Fig. 2). In the new system, radio resource is divided into two bands, namely, cell center band and cell-edge band. The philosophy behind such splitting is: cell center region enjoys higher SNR and can benefit from

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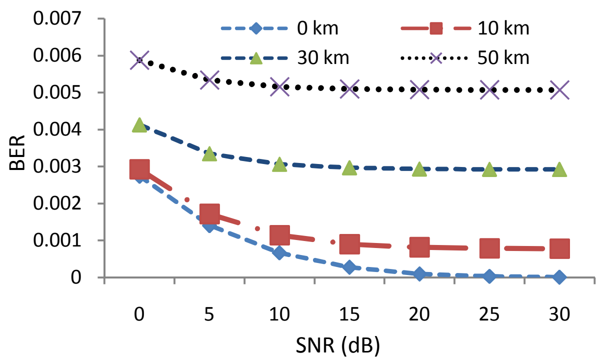

Figure 1: Bit error rate at vehicular speeds in a 2.6 GHz, 5 MHz WiMAX system for Nakagami-*m* faded channel.

the use of efficient modulation and coding schemes and as a result, spectral efficiency remains much higher in the cell center area. Spectral efficiency is much lower in the cell-edge region, which means more radio resources are required to deliver the same data rate in the cell-edge region than in the cell center region. One implication of this is: unless otherwise some radio resources are purposefully put aside for cell-edge users, they are likely to suffer from starvation of high quality services. Resource splitting among cell center and cell-edge regions also allows use of dissimilar spectrum in cell-edge regions among neighbouring cells, which reduces ICI.

While radio resource management technique, as discussed above, has some clear advantages, it is not sufficient to support mobility at vehicular speeds. Mobile nodes do not have a prior knowledge of their bandwidth requirements and as they move from cell center to cell-edge region (Fig. 2), low SNR, increasing ICI and high vehicular speeds, contribute to a high bit error rate. 4G standards attempt to address this problem by increasing error correction code size at the expense of lower spectral efficiency. This has two implications for mobile users entering to the cell-edge region from the cell center region: i) in case, not enough units are available in the cell-edge band, QoS may degrade severely, if not dropped at all, due to poor throughput, ii) if the cell-edge band is considered to be the only source for extra radio resource units required to maintain throughput for an entering high speed mobile node, the system is likely to end up in a situation where only a limited number of mobile nodes moving at very high speeds consume all resource units in the cell-edge band leaving others to face complete starvation. In a scenario like this, the research challenge becomes: how can the cell center and cell-edge bands work together to meet the demand for extra resource units for mobile nodes entering the cell-edge region so that the overall utility remains high? Finding a solution to this problem provides the motivation for this work and we propose a game theoretic model where both the cell center and cell-edge agents participate to jointly address the problem of resource management at vehicular speeds.

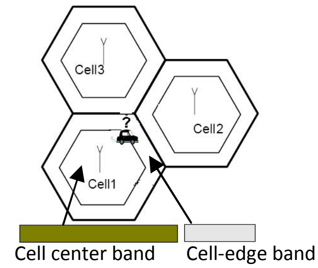

Figure 2: Frequency splitting in 4G.

III. PROPOSED GAME THEORITIC MODEL TO RADIO RESOURCE MANAGEMENT IN 4G

Game theory [16] is a tool often used in a competitive environment where rational decision makers interact to achieve their objectives. A game is described by a set of players, their strategies and payoffs for the players. In a non-cooperative game, players are unable to bind deals and try to maximise their benefits irrespective of what others are doing. The solution is the set of strategies adopted by the players such that none of the players deviate from their decisions. In this state, often known as Nash equilibrium, each player's chosen strategy is optimal given that other players choose the equilibrium strategies. An efficient method to obtain Nash equilibrium is to use the best response of the players. First the best response of each player is computed given other players strategy. The Nash equilibrium is identified as the set of best responses from all players.

The proposed game theoretic model to resource management at vehicular speeds works as follows: when a node requests for a connection when it is in the cell center region, call admission control scheme checks and reserves the requested resource units across cell center and cell-edge region. If the node is nomadic or moves at reasonably low vehicular speeds, the allocated radio resource unit proves sufficient to support the service. However, if the node moves at high speeds and reach the cell-edge region, extra radio units are required to maintain the service due to poor spectral efficiency. Here, the game theoretic model decides how much contribution will be made from the cell center and cell-edge band towards fulfilling the demand for extra units required for the mobile node. The non-cooperative game for bandwidth allocation can be attributed as follows:

Players:
Player 1: Agent for cell center band
Player 2: Agent for cell-edge band
Strategies:
The strategy of each player is to decide how much bandwidth they are happy to contribute towards fulfilling the demand for extra units required for the mobile node.
Payoffs:
Increase in revenue index per cost per bandwidth unit.

Revenue return, which reflects overall utility of a service, is one of the main driving forces for any network service provider. In economics, the prospect of revenue earning is dominated by the level of user satisfaction. User satisfaction is highly crucial specially when the long term future of the enterprise is considered. In a relevant study, Lewis *et al.* [15] proposed a measurement of the relationship between customer satisfaction and revenue prospects for any service provider. A metric called the Revenue Index (RI) was proposed by Lewis that reflects the relationship between customer satisfaction and revenue return. A two step calculation of the RI index was proposed as follows [13-15]:

Step 1: Calculate the % of each of the four satisfaction groups of survey respondents for a specific service, where the groups are: (i) totally satisfied (ii) somewhat satisfied (iii) somewhat dissatisfied and (iv) totally dissatisfied.

Step 2: Multiply those % of the four categories by weighting factors. The weighting factors are obtained using the multivariate linear regression over a large scale surveyed data. Final expression for RI is given as follows: RI = 1.0 × % of totally satisfied respondents + 0.38 × % of somewhat satisfied respondents + 0.068 × % of somewhat dissatisfied respondents - 1.80 × % of totally dissatisfied respondents[13-15].

The rationale behind such a calculation is based on the analysis that a fully satisfied customer pays 100% of revenue for the specific product or service. A somewhat satisfied customer pays 38% of the revenue that a fully satisfied customer pays. A somewhat dissatisfied customer pays 6.8% while a fully dissatisfied customer subtracts 180% of the revenue (by leaving the service provider and discouraging others to join). The numerical figures were obtained from the relationship that emerged between customer satisfaction and revenue earning based on practical data collected and analysed over a long period of time.

In this work, increase in revenue index per cost per unit bandwidth (i.e., investment cost) is considered as the pay off for each player. As revenue index is directly related to user satisfaction, we define a utility function (modelled after a sigmoid function – Fig. 3) that models the utility gain in response of various radio resource unit allocations. The utility function U_i for connection i can be modelled as:

$$U_i(b(i)) = \frac{1}{1+\exp\left(-g\times(b(i)-d_{\min})\right)} \tag{1}$$

Here, $b(i)$ is the bandwidth unit allocated for connection i, d_{min} is the unit below which the service quality drops rapidly, g is a service dependent co-efficient that may vary from service to service.

The rationale behind such a utility function can be given as follows: surely, a user is satisfied if the requested demand (d_{max}) (i.e., ($b(i)$-d_{min}) ≥ (d_{max} - d_{min})) is always met. If the bandwidth allocation is less than the maximum

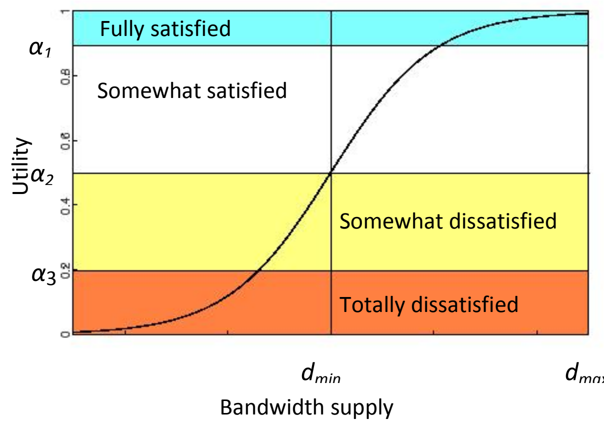

Figure 3: Utility curve vs. bandwidth supply.

demand, utility drops which is followed by a drop in user satisfaction. As shown in Fig. 3, a user is somewhat satisfied if the maximum demand is not met and utility remains within the range of α_2 to α_1. A user is somewhat dissatisfied if the utility is between α_3 and α_2. The utility below α_3 is negligible and in that case, the user is totally dissatisfied. To explain further on the rationality of this model, let us assume a video application. When the maximum bandwidth is supplied, video quality remains very good (e.g., HD quality) and the user remains fully satisfied. As the supply of bandwidth falls, quality starts degrading (due to higher compression ratio) and the utility drops. After one stage, the quality becomes so poor that the user has zero utility and is totally dissatisfied.

In context of the problem definition in this paper, the challenge that the proposed system attempts to address is – if there is a demand for extra radio resource units due to mobility of a node at vehicular speeds, how much units agent A (player 1) and agent B (player 2) need to contribute so that overall revenue index (user satisfaction) remains high. This is rather a conflicting situation since both agent A and B try to conserve resources for customers in their own areas and increase their own customers' satisfaction and revenue prospect. For example, let us consider a scenario where a high speed node entering the cell-edge region requires 4 radio resource units in order to maintain the service. Agent A has 10 units available in a pool of 60 units (cell center

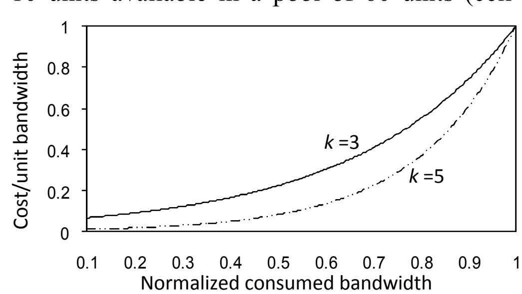

Figure 4: Cost of bandwidth unit vs. bandwidth supply.

band size = 60 units) and Agent B has 10 units available in a pool of 40 units (cell-edge band size = 40 units). If agent A decides to contribute 4 units from its 10 available units, only 6 units will remain available and should there be any sudden rush of calls, they will experience deprivation of service resulting user dissatisfaction. It is therefore, important for both agent A and B to check their investment cost and anticipated return before making a decision on the amount of contributions. To address this issue, following the popular demand supply model, we propose to use the following equation to measure investment cost per unit resource (Fig. 4):

$$\delta\left(T\ /\ D\right)=\exp\left(k\left(T\ /\ D-1\right)\right) \tag{2}$$

Here, D indicates the total capacity of radio units in a band (e.g., cell center band) and T indicates the units allocated for existing connections. k determines the relative cost of radio units in different regions. For example, k =3 for cell-edge region and k =5 for cell center region are rational assumption because for the same service, a node requires more units in the cell-edge region than in the cell center region (i.e, demand drives cost per unit). Equation 2 shows that when an agent has plenty of units available, the cost per unit is low and it is worth investing for any revenue earning from the mobile node. On the other hand, if the supply is low, investment should only be made when the revenue prospect compared to investment cost looks attractive. This is why, we propose to use the increase in revenue index per cost per unit bandwidth as the payoff function for the players. Increase in RI is computed as:

$$\phi_A(b_A,b_B)=\Delta RI(b_A,b_B)\frac{b_A}{b_A+b_B} \tag{3}$$

$$\phi_B(b_A,b_B)=\Delta RI(b_A,b_B)\frac{b_B}{b_A+b_B} \tag{4}$$

where

$$\Delta RI\left(b_A,b_B\right)=RI(b_A+b_B+b(i))-RI(b(i)) \tag{5}$$

$$RI(b(i))=\begin{cases}1 & ;\ if\ U(b(i))\geq\alpha_1\\ 0.38 & ;\ if\ \ \alpha_1>U(b(i))\geq\alpha_2\\ 0.06 & ;\ if\ \ \alpha_2>U(b(i))\geq\alpha_3\\ -1.8 & ;\ if\ U(b(i))<\alpha_3\end{cases} \tag{6}$$

Here, $\phi_A(b_A,b_B)$ indicates the increase in RI for agent A when agent A and B agree to contribute b_A and b_B units respectively. *b(i)* is the bandwidth currently allocated for connection *i* in consideration. Pay off function (φ) therefore, takes the form of:

$$\varphi_A\left(b_A,b_B\right)=\phi_A\left(b_A,b_B\right)/\ \delta\left(T_A\ /\ D_A\right) \tag{7}$$

$$\varphi_B\left(b_A,b_B\right)=\phi_A\left(b_A,b_B\right)/\ \delta\left(T_B\ /\ D_B\right) \tag{8}$$

We consider the Nash equilibrium as the solution of this game. Nash equilibrium is a set of points where best response functions for both Agent A and B intersect. These intersecting points indicate how much radio resource units agent A and B are happy to contribute. The best response function for Agent A given Agent B's decision to contribute b$'$ is defined as:

$$BR_A(b_B^{'})=\max\phi_A(b_A,b_B^{'}) \tag{9}$$

Similarly the best response function for Agent B given Agent A's decision to contribute b$'$ is defined as

$$BR_B(b_A^{'})=\max\phi_B(b_A^{'},b_B)\,. \tag{10}$$

The decision pair (b_A^*,b_B^*) is considered to be at Nash equilibrium if and only if

$$b_A^*=BR_A(b_B^*)\text{ and }b_B^*=BR_B(b_A^*)\,. \tag{11}$$

In practice, cell-edge regions are large geographical areas (i.e., in kms) which means that, by the time a two player limited space Nash equilibrium solution is reached, the communication scenario does not change abruptly (i.e., a vehicle remains in the same region and may change its position by few hundred meters, if not few meters).

IV. PERFORMANCE EVALUATION

Table I: Simulation parameters.

Simulator	Network Simulator(NS)-2.34
Number of BS	3
Carrier frequency	2.6 GHz
Bandwidth	5 MHz
Cell-center band	60% of BS spectrum
Cell-edge band	40% of BS spectrum
Radio unit (bin)	11.25 kHz
Connection arrival	Poisson dis. (100ms mean arrival)
Connection lifetime	Exponential dis. (300s mean)
Bandwidth demand per connection	Uniform dis.(128 kbps - 1.5 Mbps)
Static/nomadic nodes	70%
Mobile nodes	30%
Vehicular speed	Normal dis. (mean 60 km/h)

In simulation, we observed call dropping rate, call blocking rate, and revenue index. Figure 5 shows the call dropping rate of mobile nodes moving at vehicular speeds. Since we conducted the simulation in NS2, there was no traffic at zero simulation time. As the traffic starts to accumulate in the system, resources become scarce and as a result, dropping rate increases for mobile nodes moving at high vehicular speeds. The proposed game theoretical (GT) method, attempts to support mobile nodes by supplying extra bandwidth from both cell center and cell-edge band while existing schemes ([4]-[6]) try to supply bandwidth from a particular band (i.e., either cell center or cell-edge) depending on which region the node is in. As evident in the figure, the GT model outperforms existing scheme by a margin of upto 8% in terms of

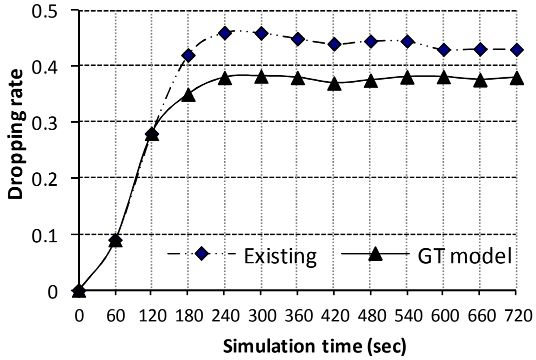

Figure 5: Call dropping rate of mobile nodes.

call dropping rate. Revenue index and revenue return reflect overall service utility to the end users and in Figure 6a, we show the % revenue return in GT and existing scheme for all nodes. As the figure suggests, GT model clearly outperforms the existing model. This is because the GT model takes the RI vs. investment cost into account while sourcing extra bandwidth and provides better service continuity for mobile nodes. Figure 6c confirms that the GT scheme consistently outperforms existing scheme for various mean vehicular speeds at the cost of minimal sacrifice in terms of call dropping rate (Fig. 6b).

V. CONCLUSION

Existing resource management schemes in 4G are not suitable for high speed mobile nodes, particularly when they move towards cell-edge region. Mobility at high vehicular speeds causes the multipath problem which when added with ICI and low SNR, severely limits spectral efficiency and throughput. Standard schemes that split radio resources among cell center and cell-edge band partly addresses the problem of ICI, but provides no real support for truly mobile nodes. In this work, we presented a game theoretic approach of resource management that intelligently tries to provide support for mobile nodes. The proposed scheme follows market based strategy where both cell center and cell-edge bands consider the demand supply status and participate in a game to increase the user utility and revenue index. Simulation results justify the usefulness of the proposed scheme.

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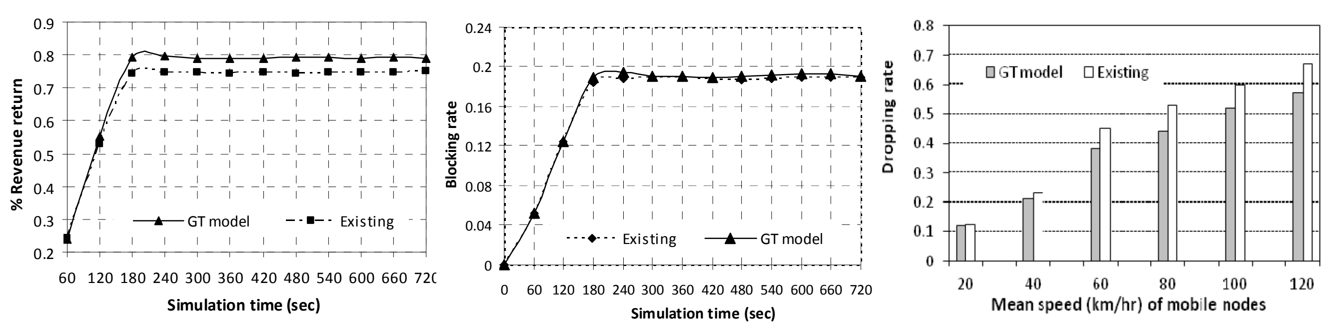

(a) (b) (c)

Figure 6: Performance comparison of (a) % revenue return (b) call blocking rate and (c) call dropping rate.