Seamless Wireless Connectivity for Multimedia Services in High Speed Trains

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Abstract—The recent advent of high speed trains introduces new mobility patterns in wireless environments. The LTE-A (Long Term Evolution of 3GPP - Advanced) networks have largely tackled the Doppler effect problem in the physical layer and are able to keep wireless service with 100Mpbs throughput within a cell in speeds up to 350 km/h. Yet the much more frequent handovers across cells greatly increases the possibility of service interruptions, and the problem is prominent for multimedia communications that demand both high-throughput and continuous connections.

In this paper, we present a novel LTE-based solution to support high throughput and continuous multimedia services for high speed train passengers. Our solution is based on a *Cell Array* that smartly organizes the cells along a railway, together with a femto cell service that aggregates traffic demands within individual train cabins. Given that the movement direction and speed of a high-speed train are generally known, our Cell Array effectively predicts the upcoming LTE cells in service, and enables a seamless handover that will not interrupt multimedia streams. To accommodate the extreme channel variations, we further propose a scheduling and resource allocation mechanism to maximize the service rate based on periodical signal quality changes. Our simulation under diverse network and railway/train configurations demonstrates that the proposed solution achieves much lower handover latency and higher data throughput, as compared to existing solutions. It also well resists to network and traffic dynamics, thus enabling uninterrupted quality multimedia services for passengers in high speed trains.

Index Terms—Cellular Networks, LTE, Multimedia, High Speed Vehicles

I. INTRODUCTION

THE PROLIFERATION of wireless accesses and the remarkably increased capability of mobile handheld devices have drastically changed the landscape of mobile networking, from once voice traffic dominated towards diverse data services enabled. Without a doubt, multimedia communications will become essential among them in the near future [1], and all of the next-generation wireless network standards have addressed this key service [2] [3]. In particular, the Long Term Evolution (LTE) of Third Generation Partnership Project (3GPP) for wireless access has enhanced the spectral and power efficiency, and improved the peak data rates in Release 8 and 9 proposals, so as to better accommodate multimedia traffic [4]. The expected finalization of LTE-advanced in 2011

[5] will further pave the road toward high-quality and cost-effective anywhere and anytime multimedia access.

Meanwhile, high speed trains are evolving and becoming popular as a new means of transportation. The Shinkansen in Japan (300 km/h), the Chinese high speed railway system (165km/h; expected to reach 350 km/h in the near future), and the Eurostar (175km/h to 334km/h) are extremely successful examples in use, with a number of others being under construction or preparation. Providing multimedia accesses for the passengers in these high speed trains thus becomes a critical demand when deploying wireless networks along the high speed railways [6].

Since a railway system usually covers a vast geographical area, it is economically expensive to build a special network only for the passengers, not to mention that most of the them do not always stay on the trains. As such, general-purpose networking should be adopted, particularly LTE, the *de facto* standard for the new generation of wireless cellular networks. The LTE physical layer can support high throughput data delivery at speeds up to 350km/h and even 500km/h in rural areas. State-of-the-art implementations of LTE [7] have the capability to support at least 200 active data users per 5MHz of bandwidth in a cell, which will further increase in LTE-Advanced. Yet a high speed train remains a challenge environment for LTE networks. First, the wireless channel condition changes drastically [8], thus disturbing the data rate; Second, handover across cells becomes much more frequent, thus interrupting connections. Both of them are highly undesirable for multimedia communications given the stringent demand on data bandwidth and continuity.

To address these challenges, we present a novel LTE-based solution to support high throughput and continuous multimedia services for high speed train passengers. Our solution is based on a *Cell Array* that smartly organizes the cells along a railway, together with a femto cell service that aggregates traffic demands within individual train cabins. Given that the movement direction and speed of a high-speed train are generally known, our Cell Array effectively predicts the upcoming LTE cells in service, and enables a seamless handover that will not interrupt multimedia streams. In this paper, we detail the signalling and actions in such a predictive handover. To accommodate the extreme channel variations, we further propose a scheduling and resource allocation mechanism to maximize the service rate for femto cell base stations, according to periodical signals quality changes. This ensures the multimedia service quality within each femto cell.

We have evaluated our proposed solution under diverse network and railway/train configurations. The simulation results

demonstrate that it achieves much lower handover latency and higher data throughput, as compared to existing solutions. It also well resist to network and traffic dynamics, thus enabling continuous high-throughput multimedia services for passengers in high speed trains.

This paper is organized as follows. In section II we review the related work, and discuss the strengths and shortcomings of state-of-the-art solutions. Section III offers an overview of the system. The Cell Array architecture is presented in IV, followed by the scheduling algorithm in V. We evaluate our proposal in VI and analyze the performance improvement. Section VII concludes the paper and outlines the future work.

II. BACKGROUND AND RELATED WORK

Satellite communications were traditionally used for wireless access over vehicles moving across vast geographical areas [9]. The satellite service however would be disconnected in tunnels or at terminals. Solutions that adaptively switch to Wireless Local Area Networks (WLANs) [10] or Distributed Antenna Systems (DAS) [11] [12] in None Line Of Sight (NLOS) places to enhance connectivity have been proposed. Nevertheless, the satellite communications remain expensive, not to mention the severely limited bandwidth, the high propagation delays, and the high overhead with the enhancements for NLOS.

A recent proposal expands the use of heterogenous wireless links to provide continuous slow connections and intermittent fast connections for high-speed vehicles [13]. Given the vast geographical coverage of the high speed train railway, deploying such a new network infrastructure can be costly.

The availability of wireless cellular network in both urban and rural areas, which eliminates the need for implementation of a new infrastructure for high speed trains, makes it a better alternative. Digital wireless broadcasting with Global System for Mobile Communications - Railway (GSM-R) for high speed train passengers has been demonstrated in [14], which complies the Chinese digital TV broadcasting standard [15]. For high-quality general purpose wireless accesses, a series of measurements have shown that, even with such new generation of standards as High Speed Packet Access (HSPA) [16], 3G, and 3.5G, remarkable performance degradation would still occur over high speed trains, particularly when the speed is over 250 km/h [17]. Including the user mobility information in link adaption for LTE to estimate the signal quality to choose the Modulation and Coding Scheme (MCS) and Multiple Input Multiple Output (MIMO) options have been studied [18]. The latest wireless standard, LTE-Advanced, could maintain quality links for speed up to 350-500 km/h. Yet, unlike a satellite that covers a huge area, an LTE cell is generally small. Highly frequent handovers and fast variations in signal quality thus become severe problems that must be addressed [19].

There are proposals to enhance the handover latency for high speed trains. A quick review of handover schemes in LTE-Advanced and WiMAX networks is presented in [19]. A three tier network topology based on heterogeneous wireless networks for seamless wireless connectivity has been proposed. They also propose a probabilistic fast handover procedure with reduced latency as compared to normal IPv6
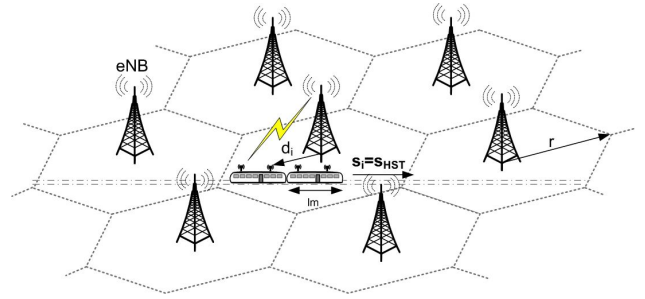

Fig. 1. System settings for LTE network access for high speed trains

handoff [20], but it still has higher average handoff latency compared to normal LTE seamless handover and WiMAX EBB handover mechanism.

On the other hand, Moving Extended Cell (MEC) [21] is proposed as a solution to accommodate mobility in Radio over Fiber (RoF) networks. RoF is a new paradigm for high speed wireless access at 60GHz [21]. The line of sight requirement of 60GHz signal and air propagation losses limit the cell coverage in these networks, which complicates the access at high speeds. Our solution is initially inspired by the MEC concept, though ours is based on LTE femto-cell [22]. Our solution also works in the wide frequency band of LTE networks and it combines hard and soft handovers, as well as known information about high speed trains to improve the handover experience for high speed train passengers.

III. SYSTEM OVERVIEW

We investigate the problem of seamless high-throughput wireless access for High Speed Train (HST) passengers in an area covered by LTE cells and provide a seamless handover solution. Each LTE cell [23] has an outer radius of r, and a frequency reuse distance of D meters. In practical implementations of LTE networks, r is typically 250-500 m for urban cells, and 1-10 km for rural cells. A base station is the user access point of a cell, referred to as eNodeB or eNB in short. A user, connected to an eNB by its User Equipment (UE), can move freely across the cells, and a handover takes place when a UE changes the serving base station (eNB). The procedure of a hard handover includes the registration of the user to the new cell, deletion of its information from the previous eNB, and changing its routing path to the new eNB.

An HST H is a cascade of M cabins. Each cabin is l meters long and can accommodate up to n passengers. For ease of exposition, we assume that all HST passengers are LTE users and are using Mobile User Equipments (MUEs). The train H is moving at speed $0 \leq s \leq S_{Max}$, where S_{Max} is up to 500 $kmph$, which has yet to be achieved in today's systems. The users in an LTE cell, particularly the MUEs in the HST, are moving in the multi-cell arrangement. Therefore, d_i, the distance of each MUE i to its currently serving eNB is changing over time. Figure 1 shows the settings and the key system parameters for the HST wireless access.

IV. SEAMLESS HANDOVER WITH CELL ARRAY

Our solution is completely based on LTE-Advanced networks and provides a novel vehicle-to-infrastructure communication solution to enhance the HST user connectivity. We
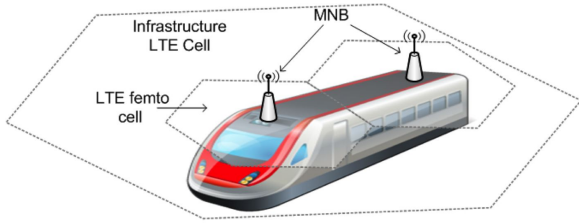
Fig. 2. A number of LTE femtocells can be used to cover each train cabin

introduce the concept of a moving LTE femto cell. Then we design a cell array architecture that ensures seamless handovers when the femto cell moves across the LTE cells.

A. Moving Femtocell

A femtocell is a small cellular base station, designed for limited coverage of 10 to 40 meters. The femtocells are traditionally used for extending wireless service coverage to the indoor spaces or for office or home usage. The typical length $l = 25m$ of an HST cabin fits well within the coverage range of an LTE femto cell. We propose using two LTE femto cells to provide vehicle-to-user communication within an HST cabin as illustrated in Figure 2. A femtocell base station is referred to as Moving eNB (MNB) throughout this paper. Using femtocells, the HST users can access LTE wireless services through their local MNB.

An LTE femto cell uses the same frequency bands as an LTE macro cell. The number of allocated frequency subcarriers [24] can be decided based on the number of the wireless users within the femtocell. In our design, each femto cell covers half of an HST cabin and up to 50 users. A frequency band of 5MHz supports wireless access for the users in each femtocell. To accommodate the mobility of femtocells along the railway, the frequency band of the MNBs and their frequency reuse distance D have to be considered in frequency band selection.

On the other hand, an MNB should also receive the aggregate traffic for all MUEs through the LTE air interface. Therefore, each MNB includes two interfaces that work within two different frequency bands. One for cabin-to-infrastructure communications, i.e. receive the aggregate download traffic from the infrastructure LTE network, and send the requests and feedbacks. In this part of the communication, the MNB is an MUE for the infrastructure LTE cells. The other interface is used to communicate with the MUEs within the cabin, where the MNB functions as an LTE femtocell base station.

B. Cell Array

We define a Cell Array as an extended cell architecture composed of three cells in a row along the path of the high speed train railway. We call them cells A, B, and C. Cell A is the cell that train is partially or completely in at the current time. Cell B is the adjacent cell that is ahead of cell A along the railway path. Train can be partially in cell A and partially in cell B in any given time. As soon as the whole train is in cell B, cell A is no longer in the extended cell configuration. The cell array reconfigures when the train completely leaves cells A and enters cell B. Figure 3 shows the cell array reconfiguration process as the train moves along the path. When
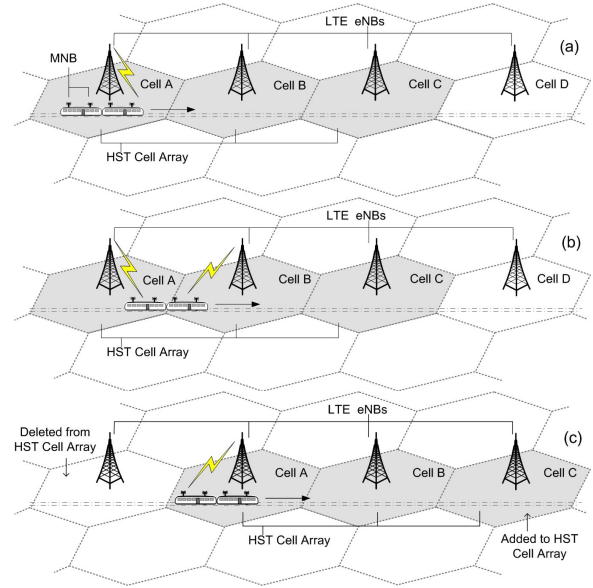

Fig. 3. Cell Array (CA) reconfiguration along the railway path

cell D joins the extended cell, the original cell A is deleted and we rename the cells to A, B and C again.

We use the cell array structure to include the known railway path and the speed of train in the scheduling and handover mechanisms. It facilitates fast handover and helps us minimize the amount of data to be transferred among the eNBs in case of a handover. We always have the information of the MNBs registered in all of the three cells in the cell array. Only cell A and sometimes cell B are transmitting to the MNBs. Therefore, there is no need to transfer the whole downlink data to all of the eNBs in the cell array. Only the eNBs of the transmitting cell will receive the downlink data.

Inclusion of cell C in the cell array is to facilitate frequency spectrum assignment for MNBs of the HST without service degradation in an LTE cell. We call it a *soft handover*. It also provides scheduling and predictive buffering chances for non real-time traffic. It is worth noting that the reason we extend the cell array in three cells along the path is to smoothly clear the spectrum for vehicle to user communication without disturbing the currently active users in the cell, as well as to buffer non-real time data in case of delayed scheduling.

C. Predictive Handover Mechanisms

We now detail the two different types of predictive handovers for successfully reconfiguring the cell array as well as performing the hard handover for the MNB along the railway path. Our predictive handover mechanisms benefit from the cell array architecture to shorten the handover time and keep the service uninterrupted in high mobility conditions.

1) Predictive Hard Handover (PHHO): A hard handover is the procedure of registering a UE, which is the MNB of the moving femtocell in our solution, in a cell and switching its data forwarding path to the new eNB. After a hard handover, the MNB will no longer be registered in the previous cell. Our hard handover mechanism is *predictive* because we predict two cells ahead by adding them to the cell array. Therefore, during the hard handover, there is no need for the current eNB
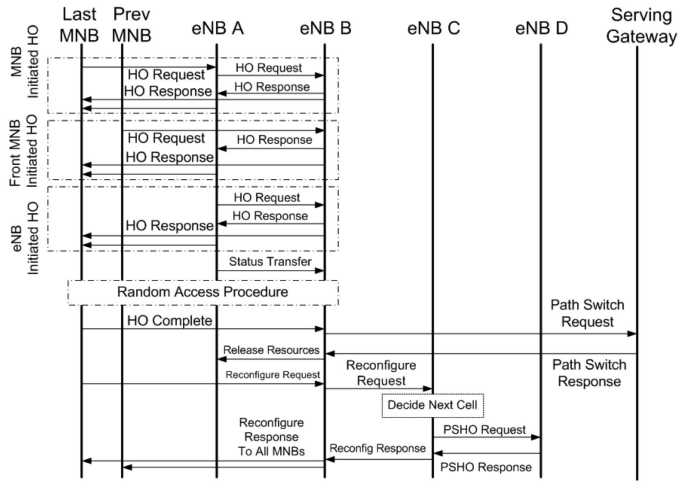
Fig. 4. PHHO and PSSO handover mechanisms for high speed trains with different initiation requests

to negotiate the registration of the MNB to the neighbouring eNBs, neither the MNB has to find the target cell by signal quality. This is because they both have the information of the target cell, which is reported by the MNB to the eNB, or the MNB initiates the handover as discussed in detail below.

Three different network elements can initiate a PHHO: the MNB crossing the cell boundaries, the front neighbouring MNB, or the current eNB (cell A). All these three elements are able to initiate a handover request so if any of them fails, others will be able to do the handover and initiate the cell array re-configuration. The first PHHO request is initiated by the MNB crossing the cell boundaries. When an MNB crosses the borders of cell A and enters the cell B, it sends a handover request to the eNB of cell A. The eNB of cell A informs eNB of cell B of the handover.

The second PHHO request mechanism is provided by the front neighbouring MNBs. Since the speed of the train is known for each MNB, when sending a handover request for itself, an MNB can send the handover request for the MNB following it. A high speed train moves in speeds of 50-100m/s. Therefore, the next MNB in the train will be reaching the handover point in fraction of a second. It will still be connected in cell A, but as soon as it can receive signal form target cell, handover is confirmed and its connection is established with cell B. Now, this MNB can request handover for its next in row MNB on the train. During the time it is registered in cell A and the handover request is initiated, new non real-time download traffic to this MNB is forwarded to cell B. The third PHHO request mechanism is initiated by the eNB of cell A. In case any of the previous two handover initiation mechanisms are not started before signal degradation for the MNB, the eNB of cell A can start it. The eNB of cell A knows the next cell in the cell array, therefore it can start the handover process without negotiating with neighbours. The MNB will remain connected to cell A, but as soon as it can receive signal form cell B, the handover is confirmed and its new connection will be established. All these handover mechanisms and their associated signalling are illustrated in Figure 4. Note that the handover responses are sent both to the current cell eNB and

to the MNB itself. This is because the MNB may move during the handover and might already have entered the new cell. As such, sending the handover response along with the random access code directly to the MNB will speed up the handover process. When the eNB of the cell A receives the handover response, it tries to inform the eNB of the handover response. It sets a timer and sends the handover response to the MNB. After the timer expires, the eNB deletes the information of the MNB. Therefore, during the handover the MNB is still registered in cell A. The handover response sent through the eNB A is useful for the MNB if the reception of the MNB is still better through the eNB A. Otherwise, it can receive the handover response directly. This is possible, because other needed information are exchanged among the eNBs A and B before the hard handover, when arranging the cell array

In all the three handover initiation mechanisms, both cells B and C already have the registration information of the train MNBs. Buffering of traffic to cell B starts as soon as the handover request is initiated. As soon as all the train MNBs are transferred to cell B, cell A is deleted from the cell array configuration. The next cell along the railway path will be selected to be added to the cell array. This selection will be made in the Predictive Soft Handover Mechanism (PSHO).

2) Predictive Soft Handover (PSHO): While in PHHO the cell array has the registration information of the train MNBs and the active cell change takes place, PSHO provides a predictive mechanism to register user information in a cell array. The MNB femto cells use the same frequency bands as the infrastructure LTE cells. If not chosen properly, the femto cell frequency bands will interfere the infrastructure LTE cells. To prevent this, and also to facilitate using the known path and speed information in the cell array architecture, we now propose a soft handover mechanism.

We register cell C in the cell array to announce the femto cell frequency band. This is to prepare cell C for probable allocation of a large chunk of its frequency spectrum to an MNB femto cell traffic. Since the railway is on a known path, it could be considered in initial frequency band selection of LTE cells so that the frequency used by HST femto cells will not be used by the Infrastructure LTE cells. In the rare case of sharing the same spectrum, cell C should be aware not to use that frequency spectrum in the next scheduling and RB allocation cycle and send the scheduled UEs to their next preferred band with the highest Channel Quality Index (CQI) value. The eNB for cell C will be informed by the previous cell C's (before reconfiguration) eNB. Cell C's eNB approximates the time it can still use the spectrum according to the speed of the train and diameter of its region:

$$T_{AHO_1} = \frac{2 \times D_{CellC}}{Speed} \tag{1}$$

After frequency band selection, and registration of HST MNBs in the cells B and C, cell A receives the cell B and C's information for the hard handover cell selection and handover response process. We call this procedure a Predictive Soft Handover (PSHO). The PSHO signalling will be done across the MNBs and the newly added cell to the CA, when the last MNB enters cell B. The signalling for this procedure in shown in Figure 4. Our PSHO only performs user registration and

frequency spectrum allocation for the MNB femto cells. The MNBs will be registered in cell C after the PSHO. However, there will be no path switching or data forwarding to cell C.

Implementation of railway systems and an infrastructure network to provide connectivity to high speed train passengers are costly projects. Therefore, it is possible to consider an infrastructure cell alignment implementation next to the railway. However, if the railway crosses edges of multiple cells, the eNB C starts to negotiate selection of the eNB D during the PSHO process. The selection is reconsidered each time reconfiguring the cell array and will be available for the MNB before a PHHO. Therefore, cell A never has to negotiate cell selection, or wait for MNB cell selection during the PHHO. This allows more aggressive settings handover failure and re-entry timer which leads to faster handovers.

V. SCHEDULING

Although the moving femto cells and the cell array architecture along with the predictive handover mechanisms enable fast handover for seamless wireless connectivity, HST multimedia service users need continuos high throughput connectivity for seamless multimedia services. This is provided with a scheduling mechanism tuned with high speed movement and handover information. The wireless coverage along the railway path is not uniformly distributed: as illustrated in Figure 5 [15] the signal is stronger near the eNBs and weaker as the HST gets further away towards cell edges. As such, when the MNBs handover to a new cell in the cell array, they send their speed and path information in the first communication to the target eNB. We assume the speed of the train in one cell is relatively constant. Each time the MNB sends a Channel Quality Index (CQI) feedback of the received signal quality, the eNB receives the position of the MNB as well. We now present a scheduling algorithm that uses the information of the HST provided in the cell array architecture for high throughput scheduling within an LTE infrastructure cell.

A. Optimal Scheduling

Let N be the number of users in a cell, and T be the scheduling period in which we target the maximum rate. A scheduling period is a duration T, during which we allocate $K = T \times F$ Resource Blocks (RB) to the LTE cell users. F is the number of available frequency subcarriers. In the 3GPP LTE standard, a Resource Block (RB) is the smallest allocation unit in the LTE OFDM radio resource scheduling. Each RB can be independently modulated and assigned to a user. Each RB contains 6 or 7 symbols, with 12 adjacent sub-carriers of 15KHz (=180 kHz) in the frequency domain. Two resource blocks form one time slots (1ms) in the time domain. The Modulation and Coding Scheme (MCS) decides the number of bits to be transmitted in each RB. The scheduling period is 10 ms in an LTE network. Variable x_{ift} is the scheduling variable, indicating the final scheduling decision. Value of the scheduling variable x_{ift} is 1 if the RB on the frequency block f, and time slot t is assigned to the user i, and 0 otherwise. The rate maximization problem in an LTE cell, containing an HST, can be formulated as follows:

$$\text{Maximize} \quad \sum_{i=1}^{N}\sum_{f=1}^{F}\sum_{t=1}^{T} a_{ift} \times x_{ift} \qquad (2)$$

$$\text{Subject to} \quad \sum_{i=1}^{N}\sum_{f=1}^{F}\sum_{t=1}^{T} x_{ift} \leq F \times T$$

$$\sum_{f=1}^{F}\sum_{t=1}^{T} x_{ift} \geq 1, \forall i \in \{0, ..., n_m\}$$

$$x_{ift} \in \{0 , 1\}$$

where n_m is the number of passengers in cabin m of the HST. a_{ift} is the scheduling coefficient, which indicates the importance of each RB on time t and frequency subcarrier f to the user i. a_{ift} can be defined as:

$$a_{ift} = p_{ift} \times c_{ift} \times h_{it} \qquad (3)$$

where p_{ift} is the scheduling preference coefficient. The scheduling preference coefficient indicates the user feedback element in the scheduling coefficient. We use Channel Quality Index (CQI), speed and direction of mobile users to estimate the p_{ift} during the scheduling period T. Every user i sends a $\overrightarrow{CQI_i} = \{CQI_{ift}\}^{F \times T}$ feedback vector containing supported $CQI \in \{0, ..., CQI_{max}\}$ values for $F \times T$ RBs to the eNB after receiving a scheduled RB (in LTE $CQI_{max} = 15$). The CQI value is an integer that represents effective Signal to Interference and Noise Ratio (SINR) as observed by UEs (the MUEs or the MBNs for the HST). The UE can provide the CQI values for the whole frequency band or a number for each selected frequency subcarrier. We assume frequency selective CQI, where the CQI values is reported for each frequency subcarrier. We also assume that an eNB is capable of calculating speed and direction of the movement of a user based on its previous and current position in the cell, which is available to the eNB. A user provides its speed information during the registration to a cell. We define speed vector $\overrightarrow{S} = \{s_i\}^{1 \times N}$. Speed values can be up to the maximum speed a cell can provide connectivity to : $0 \leq s_i \leq S_{max}$. We define the direction vector with $\overrightarrow{E} = \{e_i\}^{1 \times N}$. $e_i \in \{-1, 0, 1\}$ shows if a user is moving toward or away from high signal area, or there is no change in its signal region.

$$e_i = \left\lceil \frac{Avg(\overrightarrow{CQI_i}) - Avg(\overrightarrow{CQI_i'})}{avg(\overrightarrow{CQI_i})} \right\rceil \qquad (4)$$

In normal mobiility patterns, the changes in the channel conditions is not fast enough to change the channel and signal quality from the last CQI report to the transmission time. Therefore, scheduling is based on the last reported CQI of the user. This CQI value which is based on the user's last received data is quite accurate for scheduling purposes in normal mobility patterns. In fast mobility scenarios, although physical layer is able to combat Doppler effect and provide connection, but the fact that the CQI might be changed due to fast movement can reduce throughput. To address this problem, we try to predict the values of CQI on the transmission time:

$$\overrightarrow{CQI_i} = (1- \mid \alpha_i \mid) \times \overrightarrow{CQI_i} + \alpha_i \times \overrightarrow{CQI_i^2}/\overrightarrow{CQI_i'} \qquad (5)$$
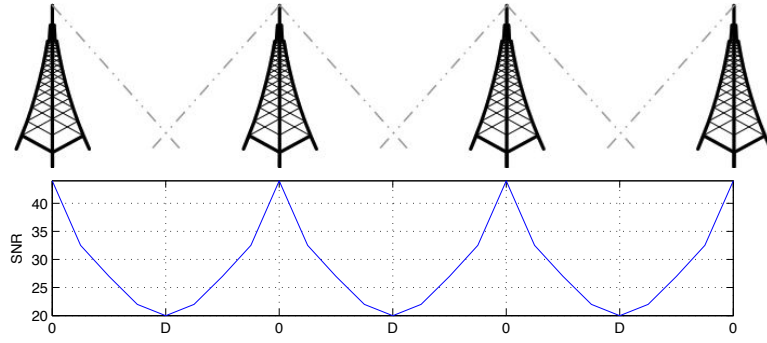
Fig. 5.   Signal To Noise Ratio Throughout Cells

TABLE I
SUMMARY OF THE VARIABLES

Var	Description	Var	Description
r	Outer Cell Radius	D	Frequency reuse distance
i	User	N	Number of users in the cell
M	Number of Cabins	l_m	Length of Cabin
m	Cabin	s	Speed
f	Frequency	F	Frequency Band
t	time slot	T	Scheduling Time Block
p_{ift}	Preference Coefficient	c_{ift}	Capacity Coefficient
h_{ift}	Handover Coefficient	q_i^s	Criticality of source s for user i
E	Direction Vector	e_i	Direction of user i

where CQI_i' are old CQI_i values. $0 \leq \alpha \leq 1$ brings the speed and direction into account. It is computed as follows:

$$\alpha_i = 1/2 \times \frac{s_i}{S_{max}} \times e_i \qquad (6)$$

We do not want to completely ignore the new CQI values. Therefore, we use $1/2$ coefficient in calculating the α. At the fastest speed of the train, the newly received CQI values will weight for the half of the forward CQI value. We use these CQI values as well as Quality of Service (QoS) parameters of each user to calculate p_{ift} values:

$$p_{ift} = CQI_{ift} \times q_i^s \qquad (7)$$

where q_i^s is the set by the quality of service parameters. c_{ift} shows the potential capacity of an RB if assigned to user i. c_{ift} is the MCS value which will be acquired based on the CQI feedback of the user. $c_{ift} \in \{0, ..., 64\}$.

Finally, h_{it} provides the handover probability of the user i in time t. $0 \leq h_{it} \leq 1$ shows if user i is currently in the cell or performing a handover to or from the cell. If it is completely in the cell at time t, the probability should be 1 (or higher than a preset threshold).

The presented scheduling formulation for high speed trains is a 0-1 integer programming problem, therefore, NP-hard. It can hardly be implemented in realtime because scheduling decisions must be carried out in every subframe, that is, every $10ms$ of LTE scheduling time. Therefore, it is necessary to further simplify the formulation model.

B. Real-time Scheduling

We convert the scheduling problem presented in equation (2) to a Linear Programming (LP) formulation presented in

equation (8).

$$\text{Maximize} \qquad \sum_{i=1}^{N} \sum_{f=1}^{F} \sum_{t=1}^{T} a_{ift \times} x_{ift} \qquad (8)$$

$$\text{Subject to} \qquad \sum_{i=1}^{N} \sum_{f=1}^{F} \sum_{t=1}^{T} x_{ift} \leq F \times T$$

$$\sum_{f=1}^{F} \sum_{t=1}^{T} x_{ift} \geq 1, \forall i \in \{0, ..., n_m\}$$

$$0 \leq x_{ift} \leq 1$$

This formulation does not exactly specify the download RB allocated to each. Since x_{ift}s can take values between 0 and 1, each block may be assigned to more than one user with fractional values. To avoid this, in algorithm 1, we run a Weighted Round Robin (WRR) on users to select the user to be scheduled next. The LP-based scheduling is then solved for each user W_i times and the highest values of variables found for user i are selected as the RBs assigned to that user. If the highest x_{ift} is on the RB already assigned, the next best values f the x_{ift} for that user is used. The decided variables are omitted from the LP and their x_{ift} values is assumed as 1. The LP is solved again for the remaining variables and the same process continues. Since the scheduling in the LTE-based systems takes place every $10ms$ and the subcarrier placing is $15KHz$, all LTE users in the cell may not be allocated an RB in one scheduling duration. That is why if we have all the $F \times K$ RBs already allocated to users, we finish the scheduling cycle and start a new one. To have even a better time complexity, we can select all W_i variables for user i in one run of the LP.

Note that we use the same algorithm to schedule both HST passengers in the cell and the normal LTE users. The only difference is in how we compute the a_{ift} values for these two types of users. For the normal users, a_{ift} can simply be a CQI report without update with speed and direction information.

VI. PERFORMANCE EVALUATION

In this section we evaluate our solution and also compare it with the state-of-the-art LTE solutions. There are a number of open source simulation software available for LTE networks in the link and system levels. However, to our knowledge, none of them is capable of simulating LTE networks for the high mobility patterns, that is, higher than $120kmph$. The high

Algorithm 1: Scheduling Algorithm

Inputs: M = Number of MNBs = Number of Cabins;
N = Number of users in the cell, including M;
W_i= Aggregate weight of user i;
$\overrightarrow{CQI}$ values for N users;
for *each scheduling duration* **do**
    Reset Counter;
    Sort users based on their CQI_{avg} values;
    for *i=0 to N* **do**
        for *w=1 to W_i* **do**
            Solve updated scheduling LP 8 ;
            Choose highest x_{ift} value for user i with available RB;
            Assign $x_{ift} = 1$ to the selected value;
            Select that RB for user i;
            Mark RB_{ft} as used;
            Counter++;
        Omit that x_{ift} from LP and user i from sorted list;
        if *Counter=$F \times K$* **then**
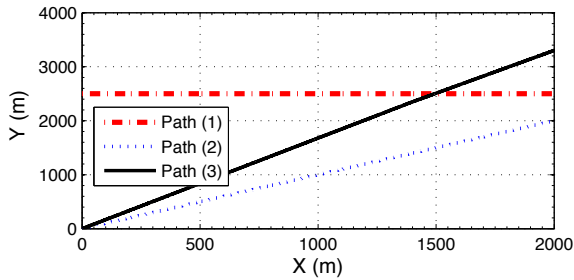   Break;

Fig. 6.   High Speed Train Movement Path

speed mobility patterns need simulation of a large number of cells to examine the effect of frequent handovers. A detailed implementation of the handover process and an accurate yet abstract system-level simulation of the cellular environment for HST is therefore expected.

To this end, we developed our own simulator for HST in LTE in C++ and MATLAB, providing system-level simulation of HST wireless access in the LTE networks with speeds up to $500kmph$. The first part of our simulator consists of a detailed yet simplified model of the LTE physical layer. This part simulates train movement, and geographical placement of cells. It computes physical layer SINR, path loss, and frequency selective CQI feedback values. Programmed in C++, at a higher layer, it also provides detailed implementation of the LTE handover mechanism that monitors handover request times and granted times. We use the time and frequency selective CQI feedback values for HST and individual LTE users from the C++ code output and run the scheduling part with MATLAB. This way, scheduling is not always performed in real-time during the simulation, but generally finished in an acceptable timeframe. Therefore, our simulation is composed of two steps: running the C++ code and getting LTE parameters on each part of the map, and then providing

TABLE II
SIMULATION SETTINGS

Parameter	Value
Size of an Urban Cell	500m
Size of a Rural Cell	10km
Number of eNBs	500-2500
Number of active HST users	100
Number of non-HST users in a cell	500
Number of active cell users	400

the output file from the C++ simulation to the scheduling provided in MATLAB where the scheduling for the video trace file is done using the LTE information and trace file data using the proposed algorithm. The movement paths across the LTE cell map is defined with a line or a curve that crosses multiple cells along a railway. This path can be input using the parametric representation of the line or the curve. Both the MATLAB and C++ parts of our simulation codes are publicly available on *http://www.sfu.ca/~oba2/dls*.

We used Variable Bit Rate (VBR) High Definition (HD) video streams as the source traffic, which are randomly chosen for each user and downloaded for each user in unicast. Our video sources is the single layer Sony Demo coarse grained SVC trace file in HD, 30 frames/sec from the Video Trace Library [25] [26].

A. Simulation Settings

Throughout our simulation, each high speed train cabin is 25 meters, accommodating 100 users, and is equipped with two LTE femto cell MNBs. We run simulations for 1 to 10 cabin combinations, and in both urban and rural settings, where size of an urban cell is 500 meters, and that of a rural cell is 10km. Table II shows these simulation settings, which are based on practical values available in the current HST implementations. Figure 6 shows the geographical map of three typical paths we used for simulation of HST movement to cover different cell crossing scenarios. We also run simulations for other random movement patterns to find out the average latency, delay and throughput and their relation to movement patterns. All of the simulations are carried our during a 5 min simulation time, within which 10-200 handovers takes place in different scenarios.

B. Simulation Results

1) Handover Latency: Our solution provides significantly lower handover latency compared to the normal LTE with seamless re-entry. Figures 9 - 12 show a detailed comparison of the handover latency values in six different simulation settings, which cover speeds of 200-500, paths 1, 2, and 3 in both urban and rural cells. The throughput and delay values are shown for transmission of the video trace file that simulates a video with high transmission volume at times 15-47. We can see that parameter variations have less impact on latency value in our solution. This is because the cell array architecture ensures the selection of the target cell well ahead of the hard handover time, eliminating the need for searching for the target cell in the MNB, and that for negotiating the hard handover time in the eNB.
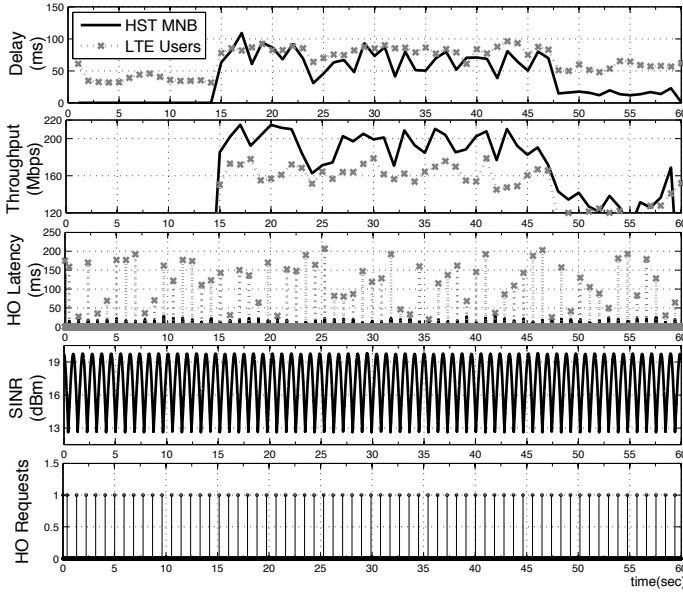
Fig. 7. Urban Cell, Speed: 350kmph, Path:1. (a) Delay (ms) (b) Throughput (Mbps) (c) Handover Latency (ms) (d) SINR (dBm) (e) Handover Requests
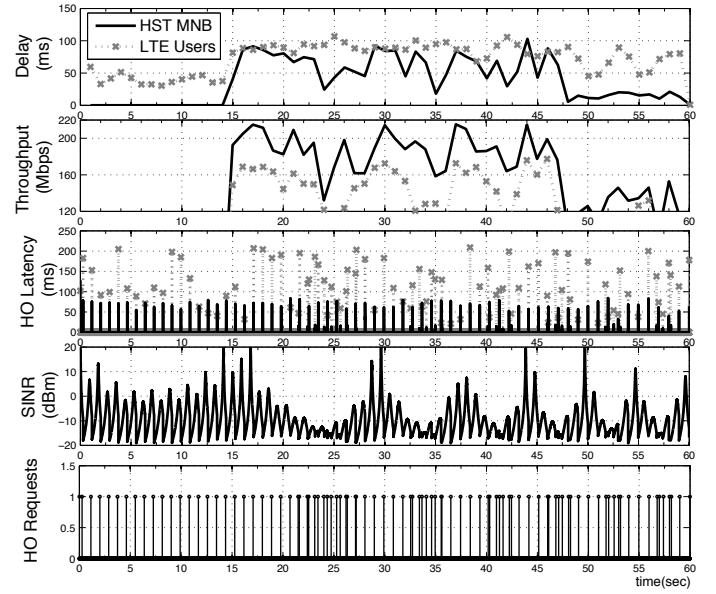

Fig. 8. Urban Cell, Speed: 350kmph, Path:3. (a) Delay (ms) (b) Throughput (Mbps) (c) Handover Latency (ms) (d) SINR (dBm) (e) Handover Requests
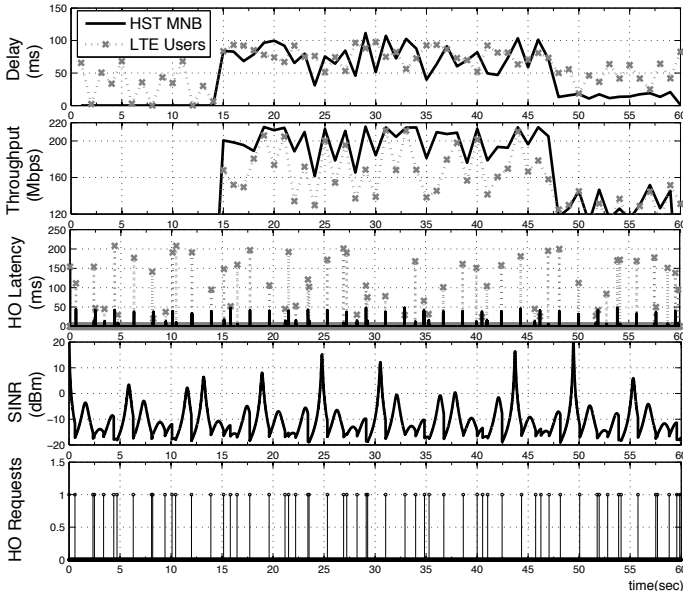

Fig. 9. Urban Cell, Speed: 200kmph, Path:2. (a) Delay (ms) (b) Throughput (Mbps) (c) Handover Latency (ms) (d) SINR (dBm) (e) Handover Requests
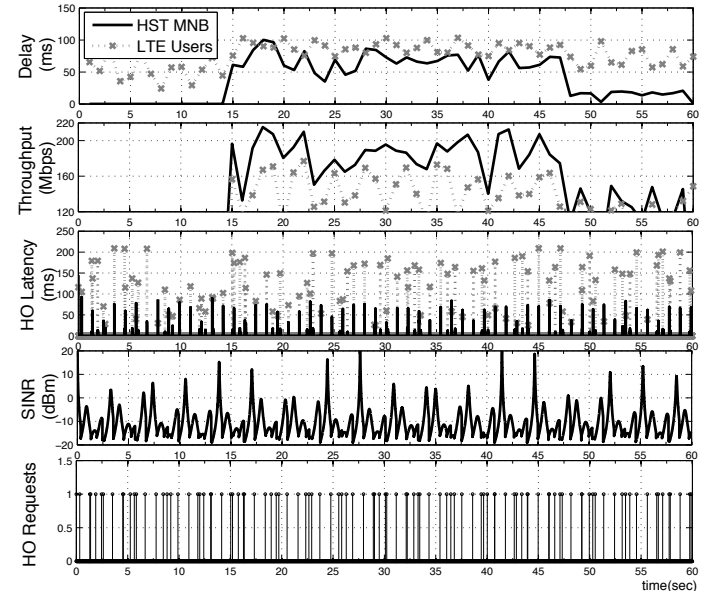

Fig. 10. Urban Cell, Speed: 350kmph, Path:2. (a) Delay (ms) (b) Throughput (Mbps) (c) Handover Latency (ms) (d) SINR (dBm) (e) Handover Requests

A handover latency is a summation of different delays in the process of registering to a new cell:

$$T_{HOLatency} = T_{HO} + T_{re-entry} + T_{re-establish} \qquad (9)$$

T_{HO} is the handover time which is the sum of the cell search and negotiation, registration and random access times. If the handover fails, the user should go through a re-entry process. $T_{re-entry}$ is the time it takes for the re-entry. $T_{re-establish}$ is the time it takes to re-establish a connection if it was dropped because of a long handover latency. Since the handover process in our cell array simplifies the search for a new target cell, all of these times are considerably shorter. This also increases the probability of success in each step, and hence possibility of our HST to successfully register to a cell

within the T_{HO} deadline. Although the handover latency is not highly variable in different speed patterns, users with higher mobility experience longer handovers. Figure 13 illustrates the handover latency changes with increasing the HST speed. The handover latency noticeably increases in the normal LTE access. This is because of the need for frequency handovers and the need for the eNBs to provide random access to a large number of users entering a cell in a short period of time. The handover latency in our solution is lower and increases more smoothly as the speed increases. Besides the better prediction, the MNB acting as a single user also contributes to this.

2) Handover Failure Rate: Figure 14 illustrates the handover failure rate in different movement speeds. Without surprise, the failure rate increases in higher speeds. This is
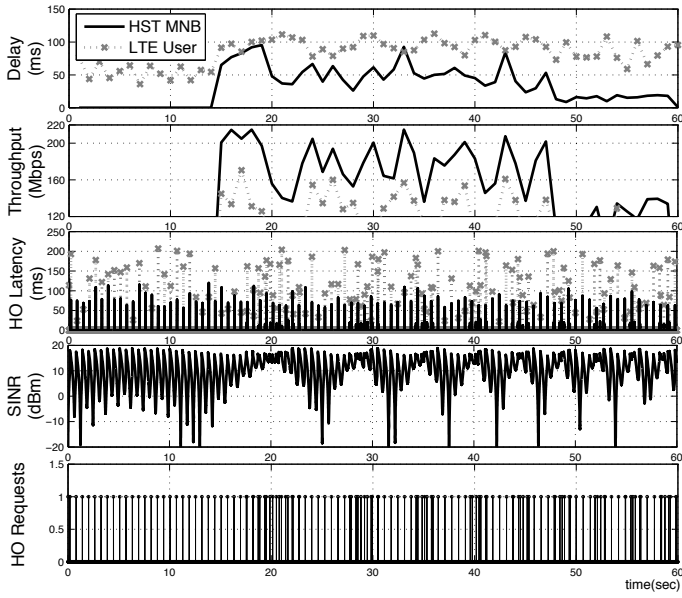
Fig. 11. Urban Cell, Speed: 500kmph, Path:3. (a) Delay (ms) (b) Throughput (Mbps) (c) Handover Latency (ms) (d) SINR (dBm) (e) Handover Requests
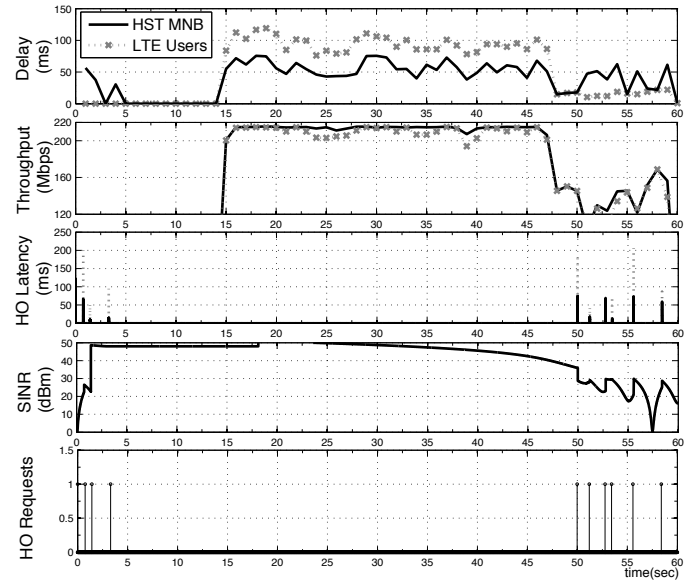

Fig. 12. Rural Cell, Speed: 500kmph, Path:3. (a) Delay (ms) (b) Throughput (Mbps) (c) Handover Latency (ms) (d) SINR (dBm) (e) Handover Requests
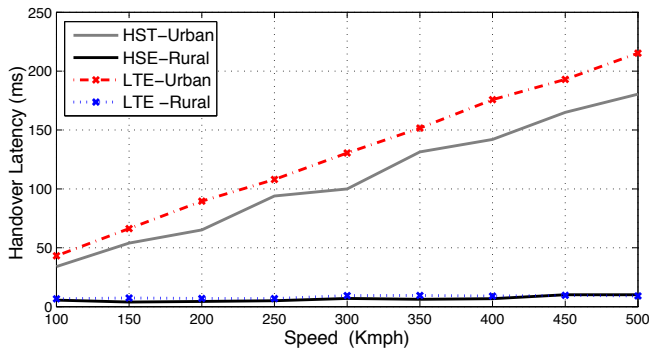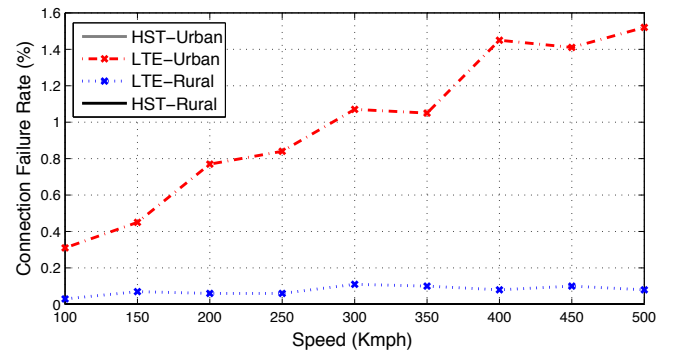

Fig. 13. Handover Latency

Fig. 14. Handover Failure Rate

Fig. 15. Average Throughput

because of the short duration a user is residing in a certain cell area. In the normal LTE, this usually happens when a handover initiated by the eNB fails and the UE has to start a re-entry process. While a user have to search and find a new eNB during a re-entry process, it might reach the cell edges already. In this case, the user may not be able to establish the connection to the found cell before it enters the new cell, thus breaking the connection.

As we discussed before, the predictive handover mechanism in the cell array eliminates the need for the search for a new eNB when the HST is in the cell. Thus, the handover latency is considerably shorter and the probability that the handover is successful in the target cell increases.

3) Throughput: Figure 15 shows the throughput of our proposed solution, as compared to those of the individual HST passengers. With increasing the speed, the enhancement of the proposed algorithm experiences an improvement of 10% to 35%. This is because of two main reasons: (1) the decreased latency (as discussed above), and (2) the handover process does not take place for each user. The latter, decreases the registration overhead that affects the RB allocation for a new user in a cell. For the HST in our algorithm, the handover
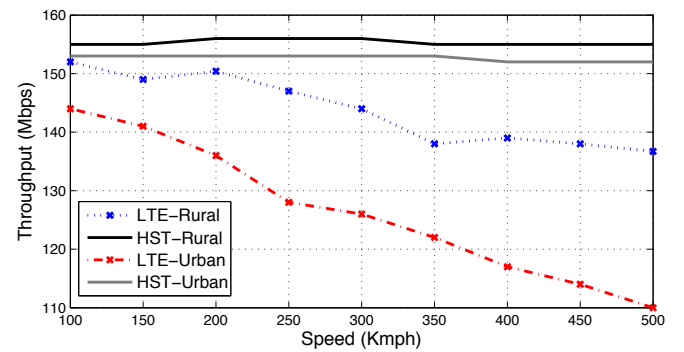
only happens once for each MNB and an aggregate traffic is requested for the RB allocation.

Figures 7 - 12 also provide a detailed comparison of the throughput in our six simulation settings. The throughput of the proposed solution experiences lower fluctuations with changing path and speed. There is an obvious drop in throughput in the normal LTE performance in the urban area compared to that of the rural cells. Our solution only experiences a
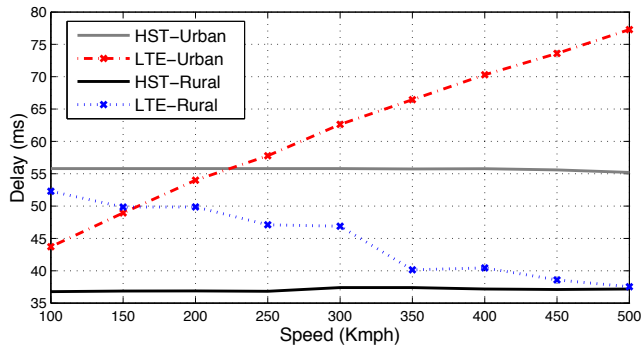
Fig. 16.   Average Delay

slight drop only. This is due to the more frequent handovers while moving across smaller urban cells. This minor drop in throughput in our solution is largely caused by the lower SINR values in the urban areas due to higher interferences.

4) Delay: Figure 16 compares the delays of the proposed solution. It experiences 5%-18% lower delays mainly due to the lower handover latency for each user. However, we see some sudden increases in delay when a handover takes place. These delays are for data forwarding to the new cell. Since the delay is mostly on the non-delay sensitive data, it is negligible.

More detailed delay values for different simulation settings are also provided in figures 9 - 12.

VII. Conclusion

This paper proposed a novel infrastructure and scheduling algorithms for high-throughput wireless access for high speed train passengers. Our solution, based on a Cell Array organization, effectively utilizes the railway trajectory to predict upcoming LTE cells in service, enabling seamless handover that will not interrupt multimedia streaming. We also modelled the rate-maximized scheduling problem and demonstrated its complexity. We further provided effective near-optimal approximations.

We evaluated the performance of proposed solution through extensive simulations. The results suggest that it achieves high throughput, low handover latency, and lower delay compared to state-of-the-art solutions. There are a number of possible future avenues toward improving our design including energy aware scheduling, and predictive buffering. In particular, we are currently working on further improvement on the approximation algorithm for scheduling, and customized organization for irregular cells in certain geographical areas.

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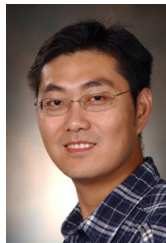
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