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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.
- 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.

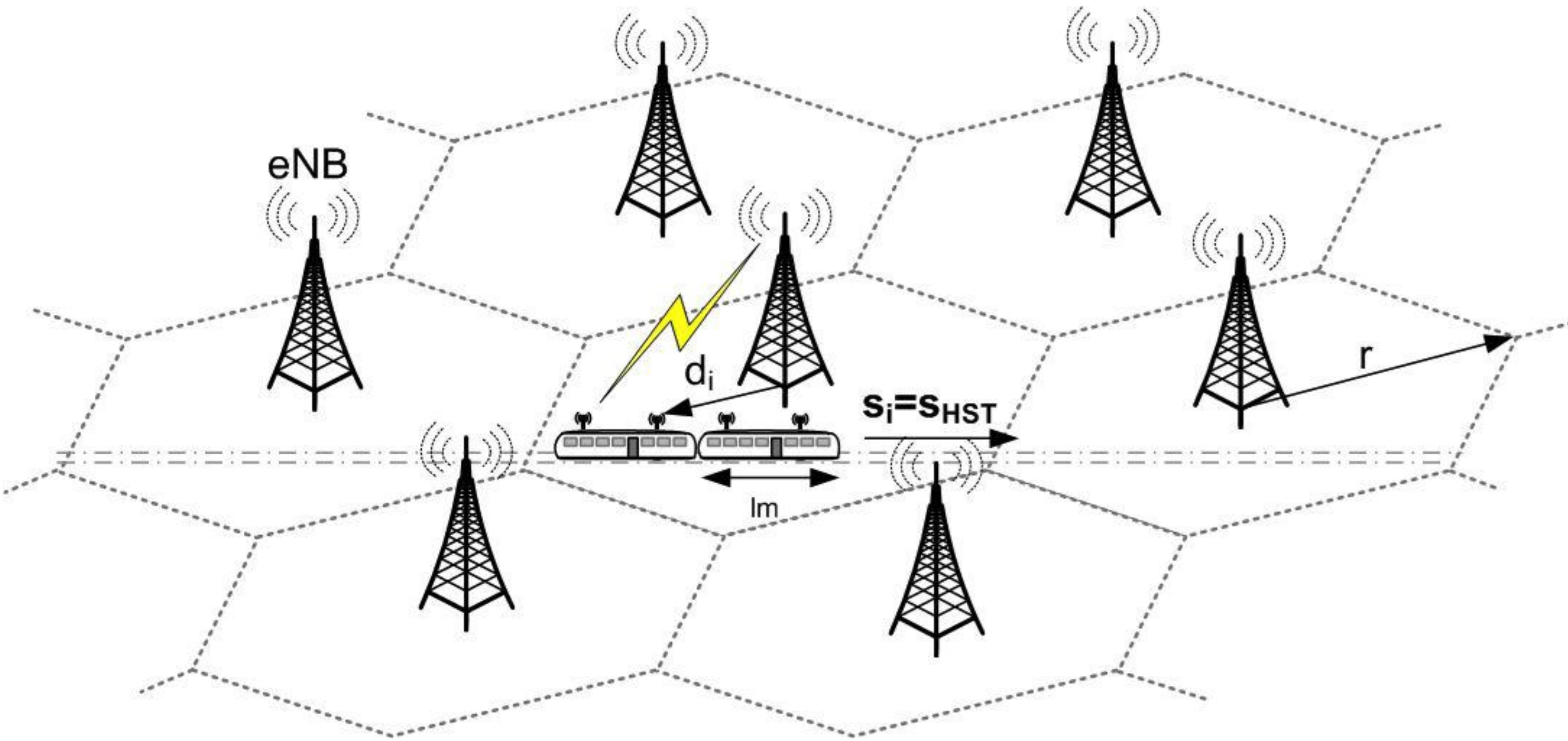
Introduction

- 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.
- 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.

Background and related work

- Satellite communications were traditionally used for wireless access over vehicles moving across vast geographical areas.The satellite service however would be disconnected in tunnels or at terminals.
- A recent proposal expands the use of heterogeneous wireless links to provide continuous slow connections and intermittent fast connections for high-speed vehicles.
- 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.
- Moving Extended Cell (MEC) is proposed as a solution to accommodate mobility in Radio over Fiber (RoF) networks.

System overview

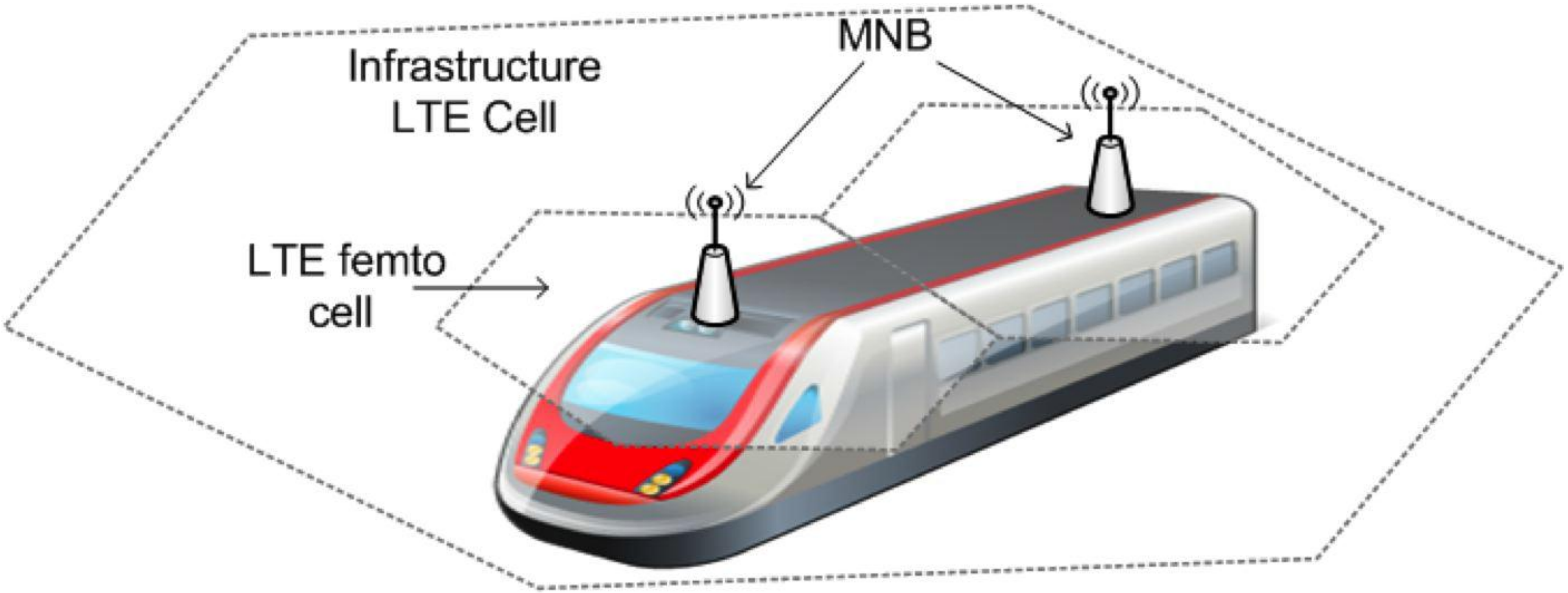


Seamless handover with cell array

- Our solution is completely based on LTE-Advanced networks to enhance the HST user connectivity and provides a novel vehicle-to-infrastructure communication solution to enhance the HST user connectivity.
  - A. moving LTE femto cell
  - B. cell array architecture
  - C. Predictive Handover Mechanisms

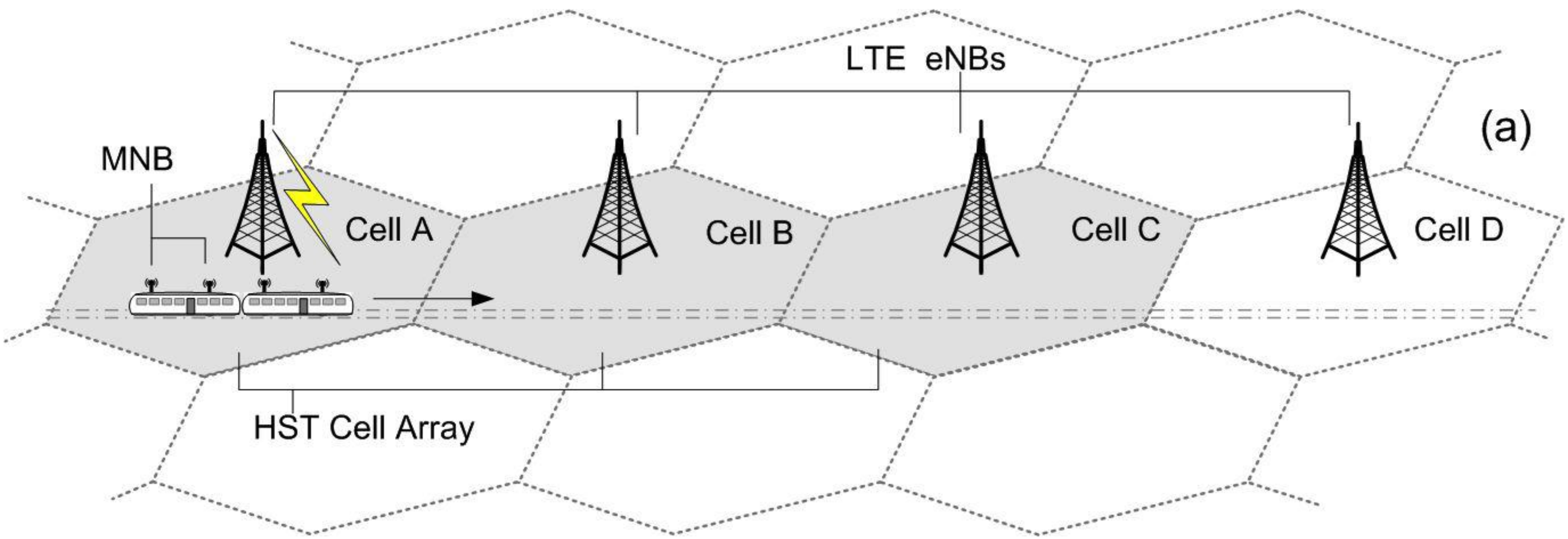
Moving Femtocell

- A femtocell is a small cellular base station, designed for limited coverage of 10 to 40 meters.
- The typical length l = 25m of an HST cabin fits well within the coverage range of an LTE femto cell.



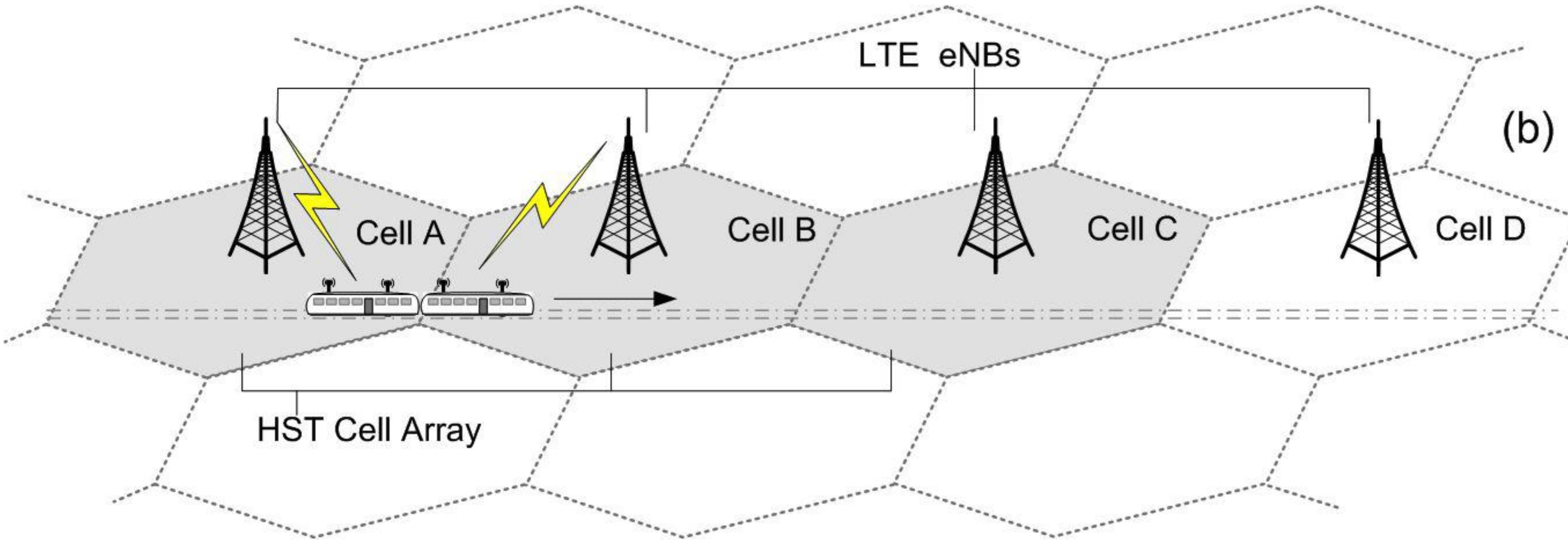
Cell Array

- 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.



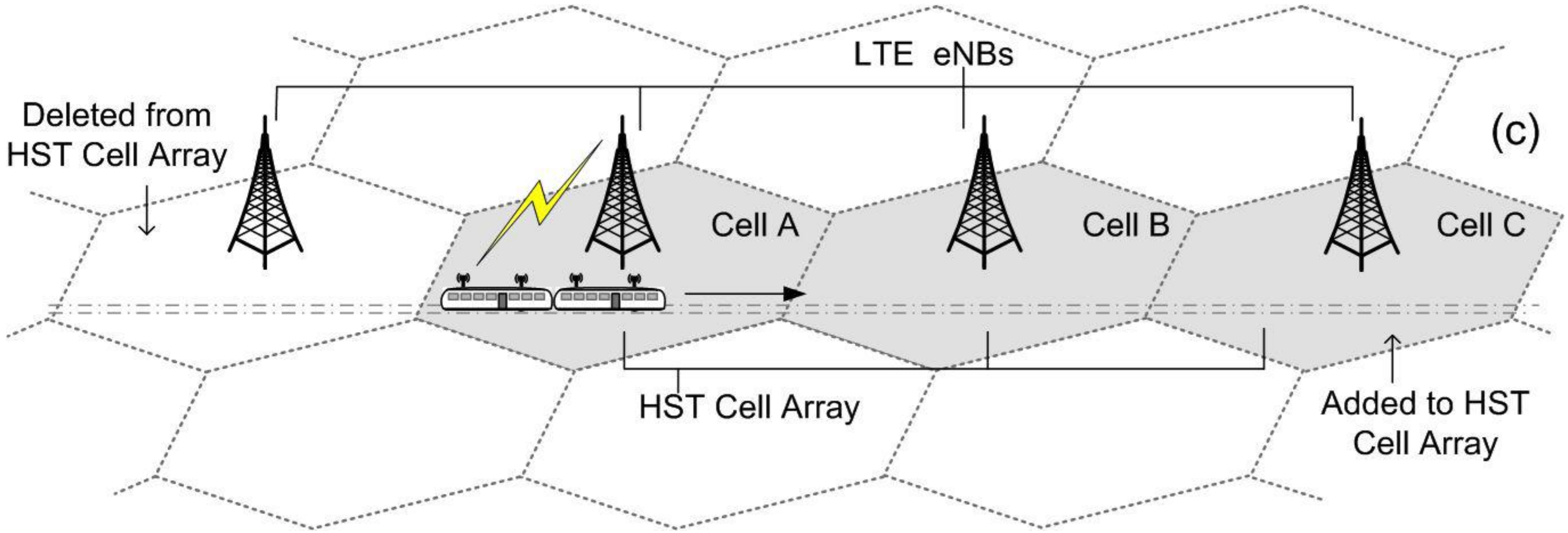
Cont.

- Train can be partially in cell A and partially in cell B in any given time.



Cont.

- As soon as the whole train is in cell B, cell A is no longer in the extended cell configuration.



Cont.

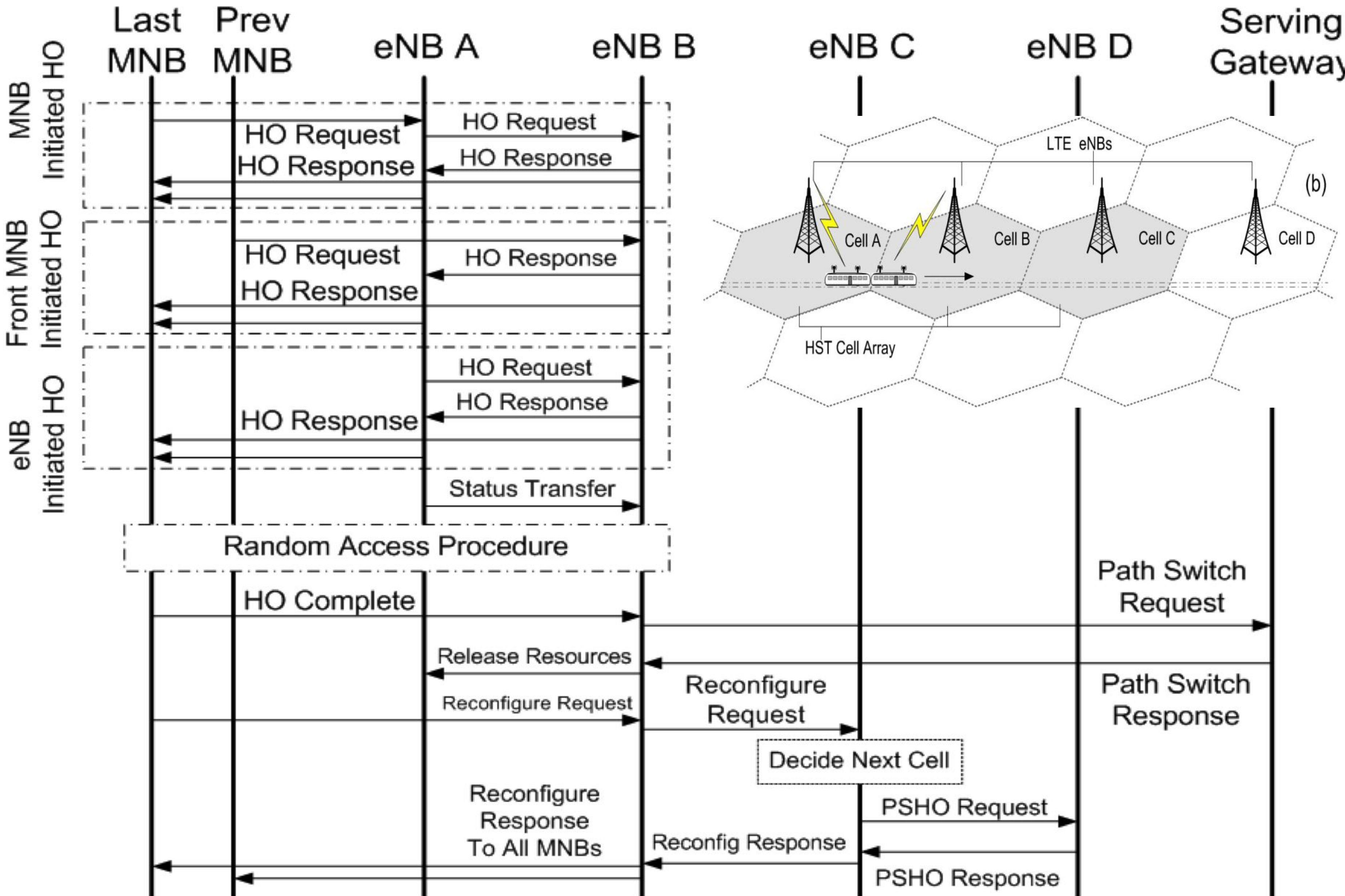
- Only cell A and sometimes cell B are transmitting to the MNBs. Therefore, there is no need to transfer the whole downlink data to all of the eNBs in the cell array.
- Inclusion of cell C in the cell array is to facilitate frequency spectrum assignment for MNBs of the HST without service degradation in an LTE cell.

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
  2. Predictive Soft Handover

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.
- Our hard handover mechanism is predictive because we predict two cells ahead by adding them to the cell array.
- Three different network elements can initiate a PHHO:
  1. the MNB crossing the cell boundaries
  2. the front neighboring MNB
  3. the current eNB (cell A)

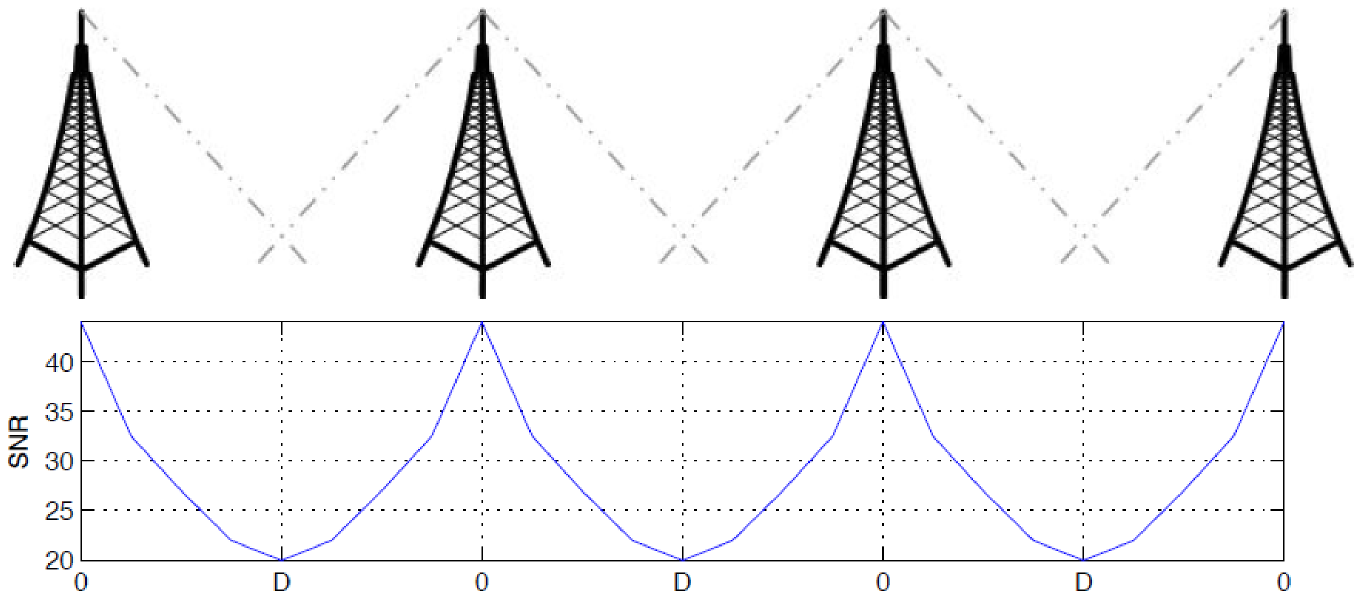

Last MNB
Prev MNB
eNB A
eNB B
eNB C
eNB D
Serving Gateway
MNB Initiated HO
Front MNB Initiated HO
eNB Initiated HO
HO Request
HO Response
HO Request
HO Response
HO Request
HO Response
HO Response
HO Request
HO Response
HO Response
Status Transfer
Random Access Procedure
HO Complete
Path Switch Request
Release Resources
Path Switch Response
Reconfigure Request
Reconfigure Request
Decide Next Cell
Reconfigure Response To All MNBs
PSHO Request
Reconfig Response
PSHO Response
LTE eNBs
(b)
Cell A
Cell B
Cell C
Cell D
HST Cell Array

Predictive Soft Handover (PSHO)

- PSHO provides a predictive mechanism to register user information in a cell array.
- 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.
- 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.

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 continuous high throughput connectivity for seamless multimedia services.



Optimal Scheduling

- We allocate K = T × F Resource Blocks (RB) to the LTE cell users.
  - T be the scheduling period in which we target the maximum rate(10 ms)
  - *F* is the number of available frequency subcarriers.
- The Modulation and Coding Scheme (MCS) decides the number of bits to be transmitted in each RB.

- Variable X_{ift} is the scheduling variable, indicating the final scheduling decision.
  - user I
  - frequency block f
  - time slot t

Rate maximization

- The rate maximization problem in an LTE cell, containing an HST, can be formulated as follows:

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

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

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

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

Cont.

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

$$a_{ift} = p_{ift} \times c_{ift} \times h_{it}$$

- 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.

$$CQI \in \{0, \ldots, CQI_{max}\}$$

$$(\text{in LTE } CQI_{max} = 15)$$

Cont.

$$p_{ift} = CQI_{ift} \times q_i^s$$

- where q_i^s is the set by the quality of service parameters

$$a_{ift} = p_{ift} \times c_{ift} \times h_{it}$$

- *Cift* shows the potential capacity of an RB if assigned to user *i*. *Cift* is the MCS value which will be acquired based on the CQI feedback of the user. **C**ift ∈ {0, ..., 64}.
- hit provides the handover probability of the user I in time t.

(0 ≤ *hit* ≤ 1)

Real-time Scheduling

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

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

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

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

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

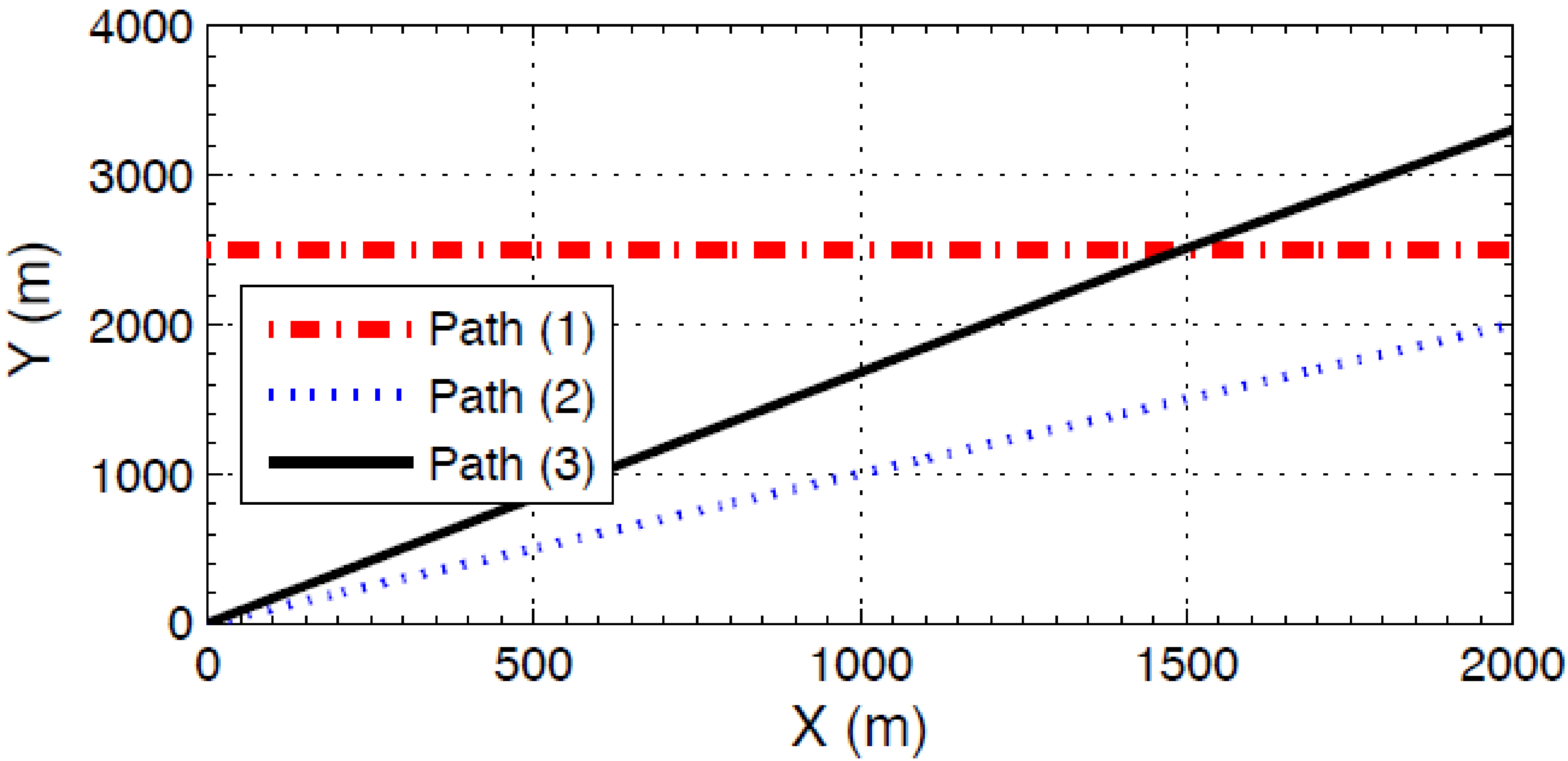
Cont.

- 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 Wi 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.
- 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 × K RBs already allocated to users, we finish the
- scheduling cycle and start a new one.

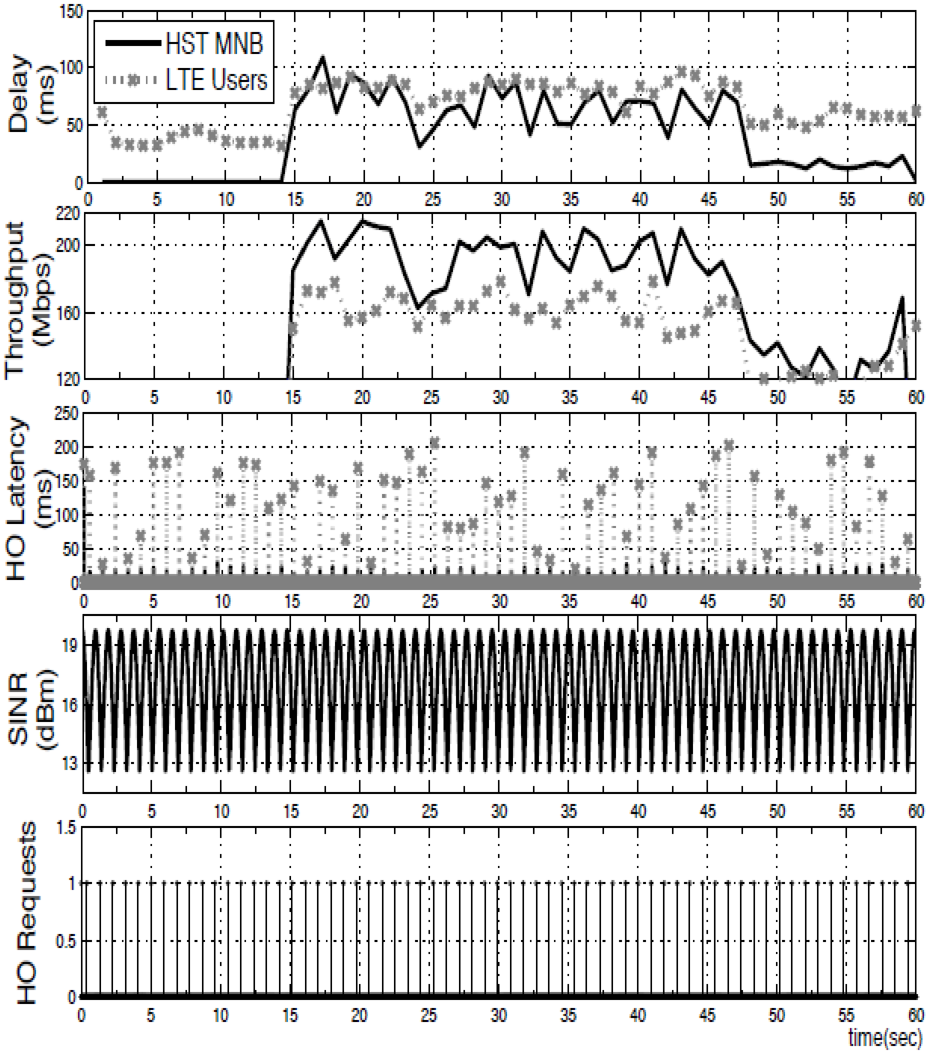
Performance evaluation-Simulation Settings

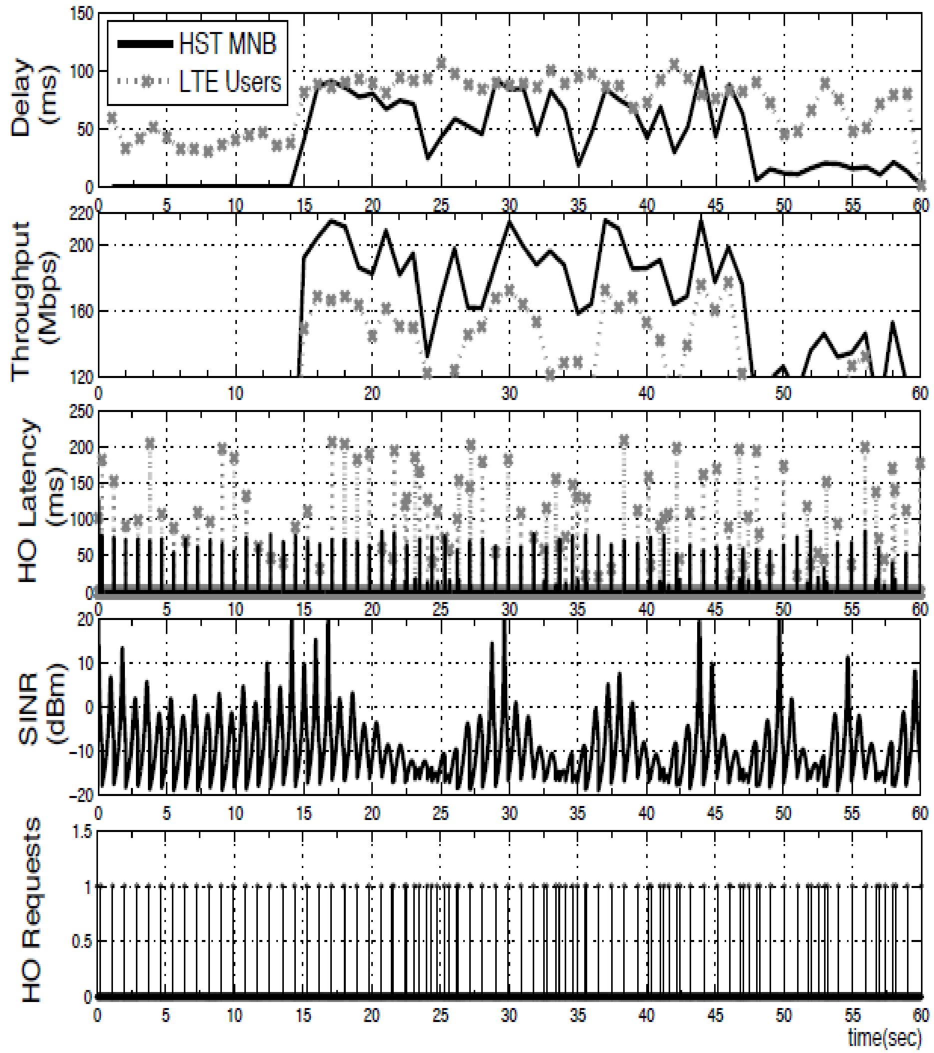
- Each high speed train cabin is 25 meters.
- Accommodating 100 users.
- Equipped with two LTE femtocell MNBs.
- In both urban and rural settings.
- Size of an urban cell is 500 meters, and that of a rural cell is 10km.

High Speed Train Movement Path

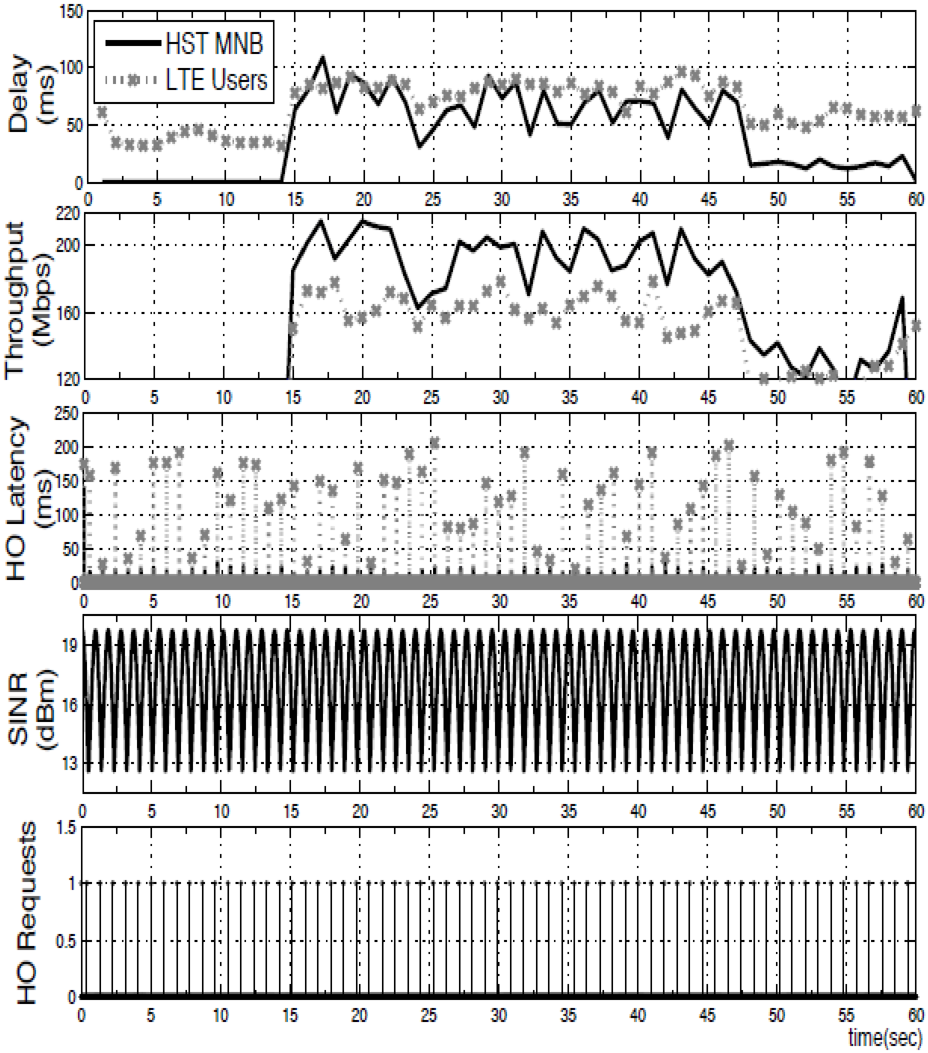


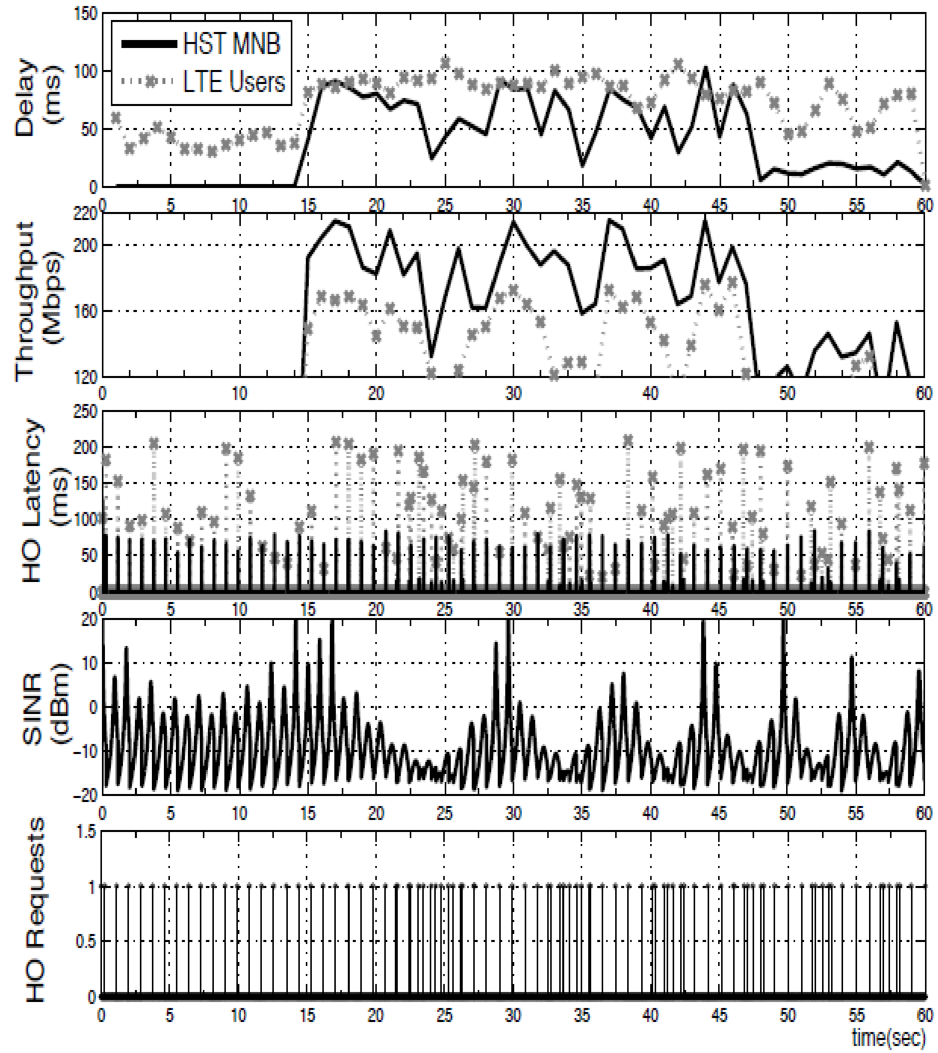
Urban Cell, Speed: 350kmph, Path:1 V.S. Path:3



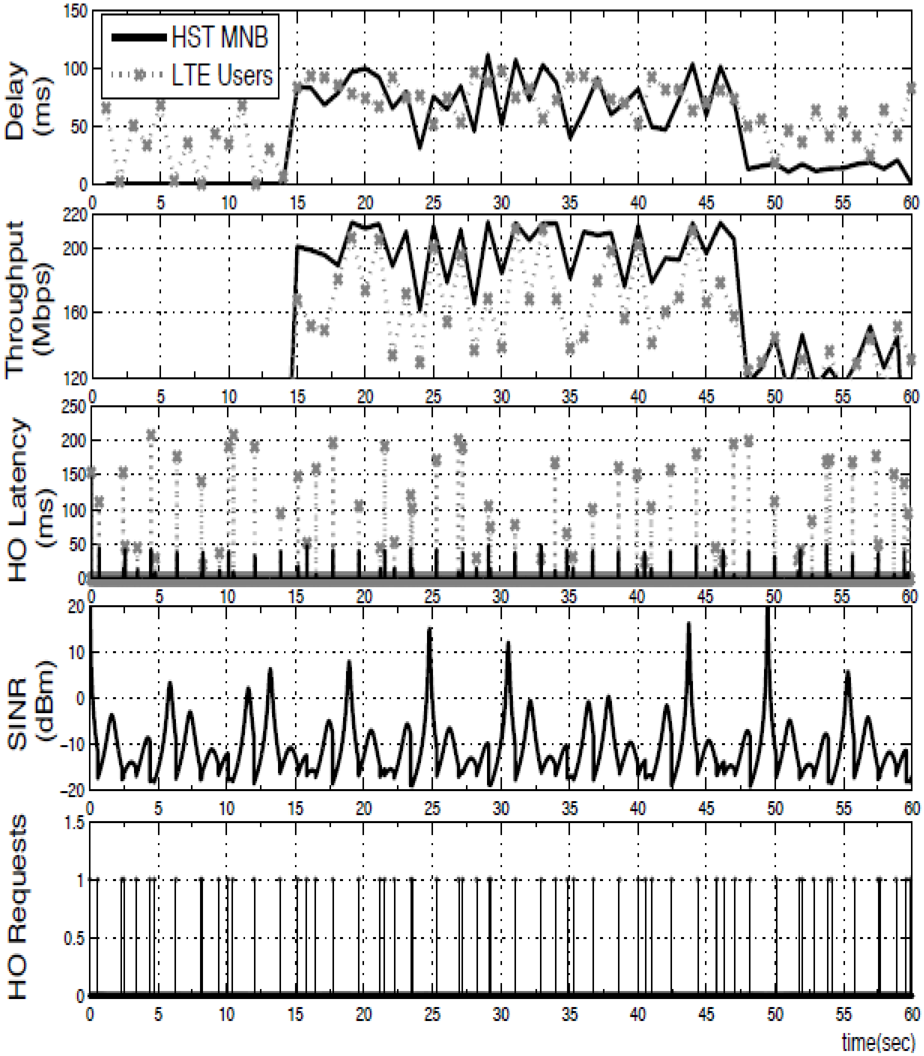


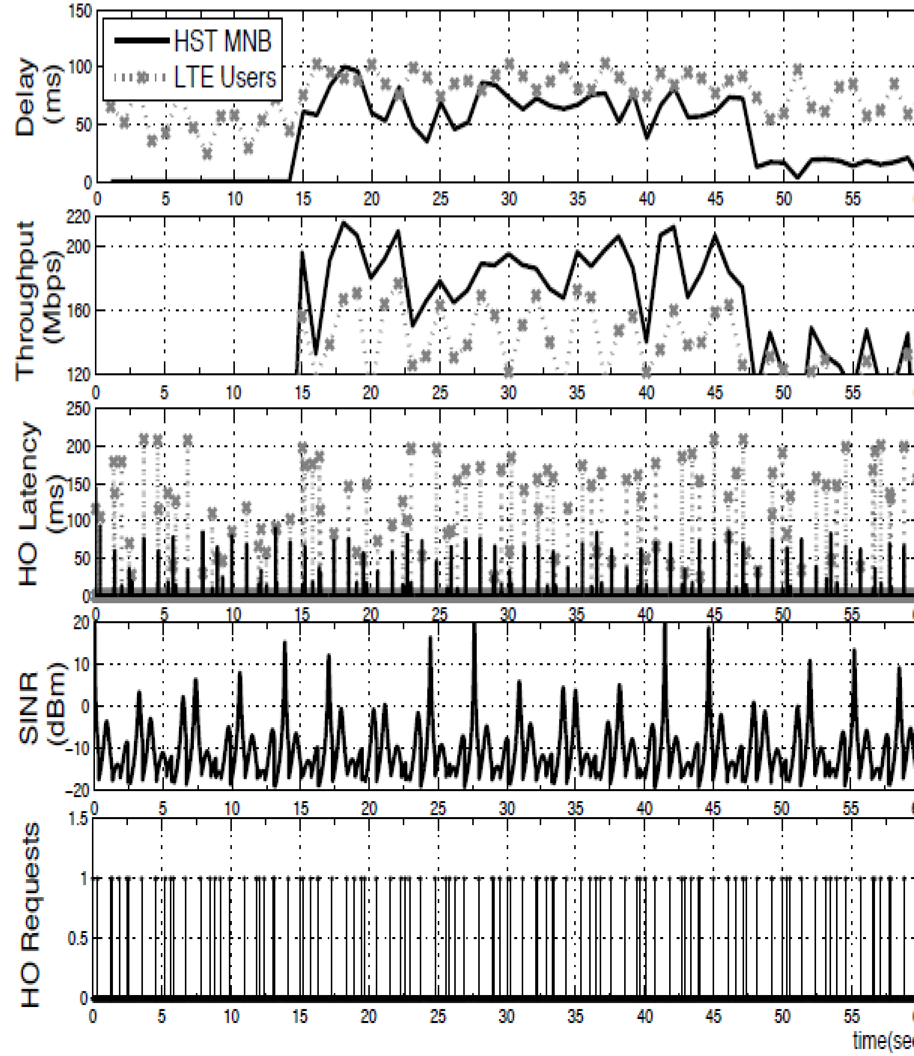
Urban Cell, Speed: 350kmph, Path:1 V.S. Path:3



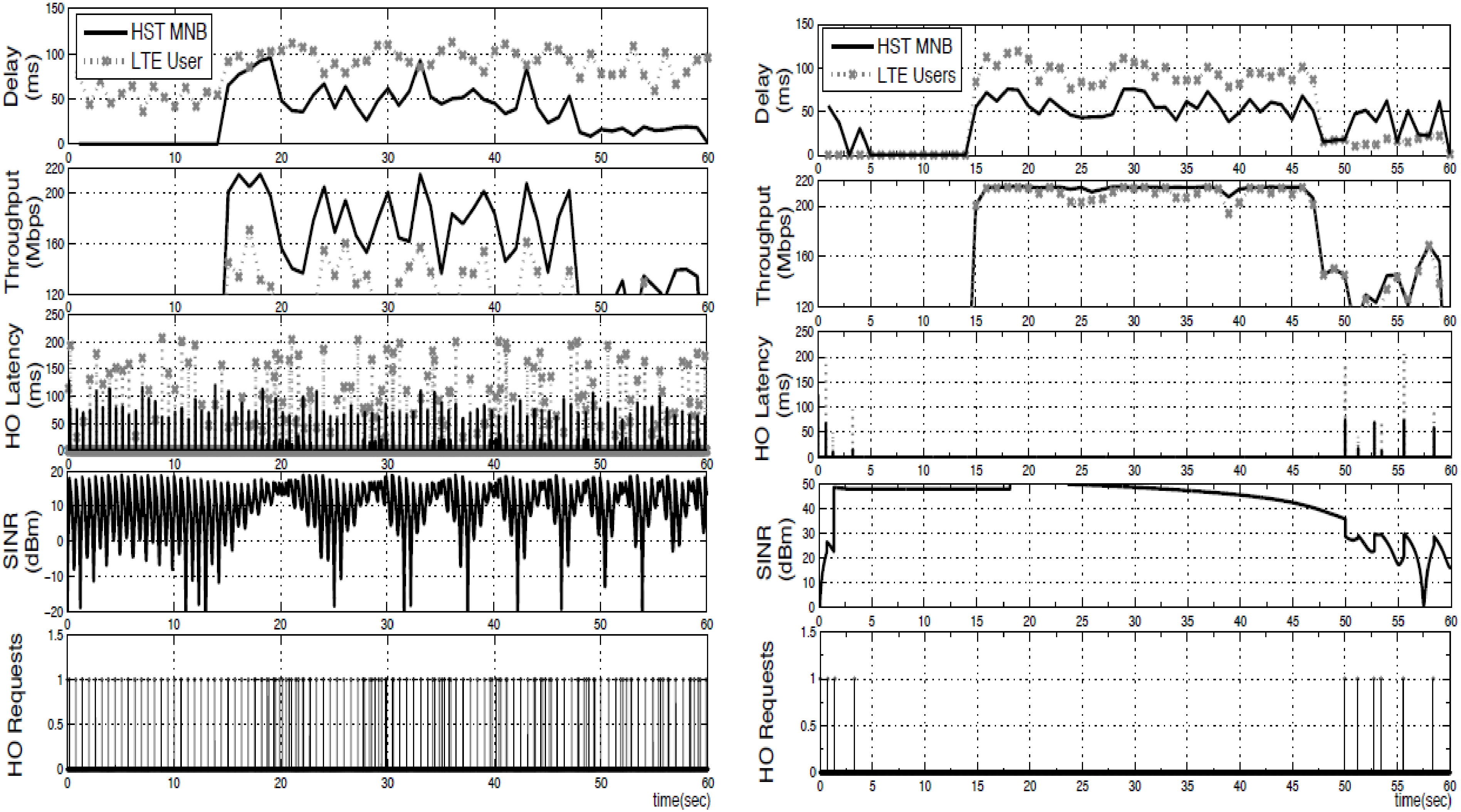


Urban Cell, Path:2, Speed:200kmph V.S. 350kmph

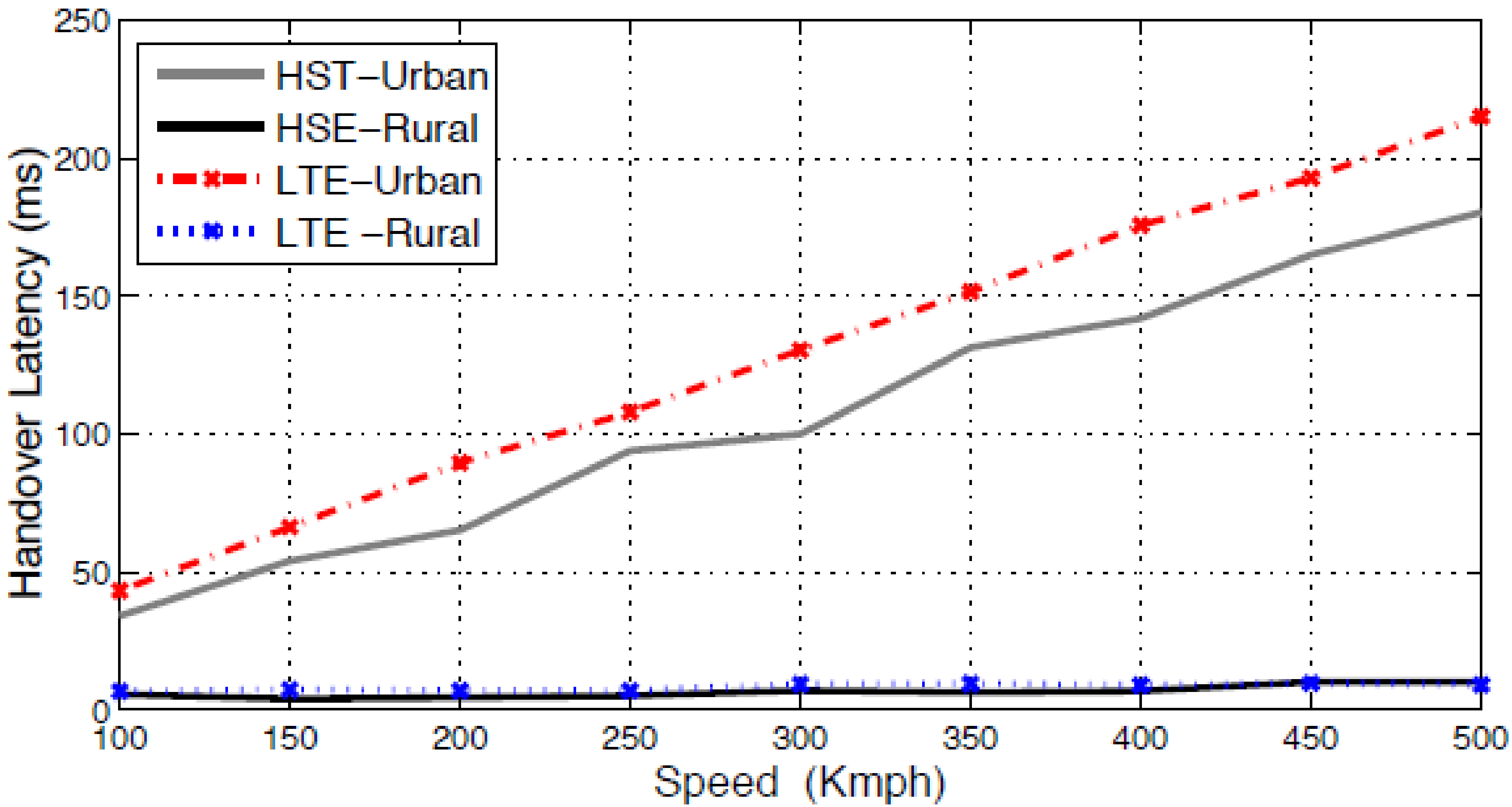




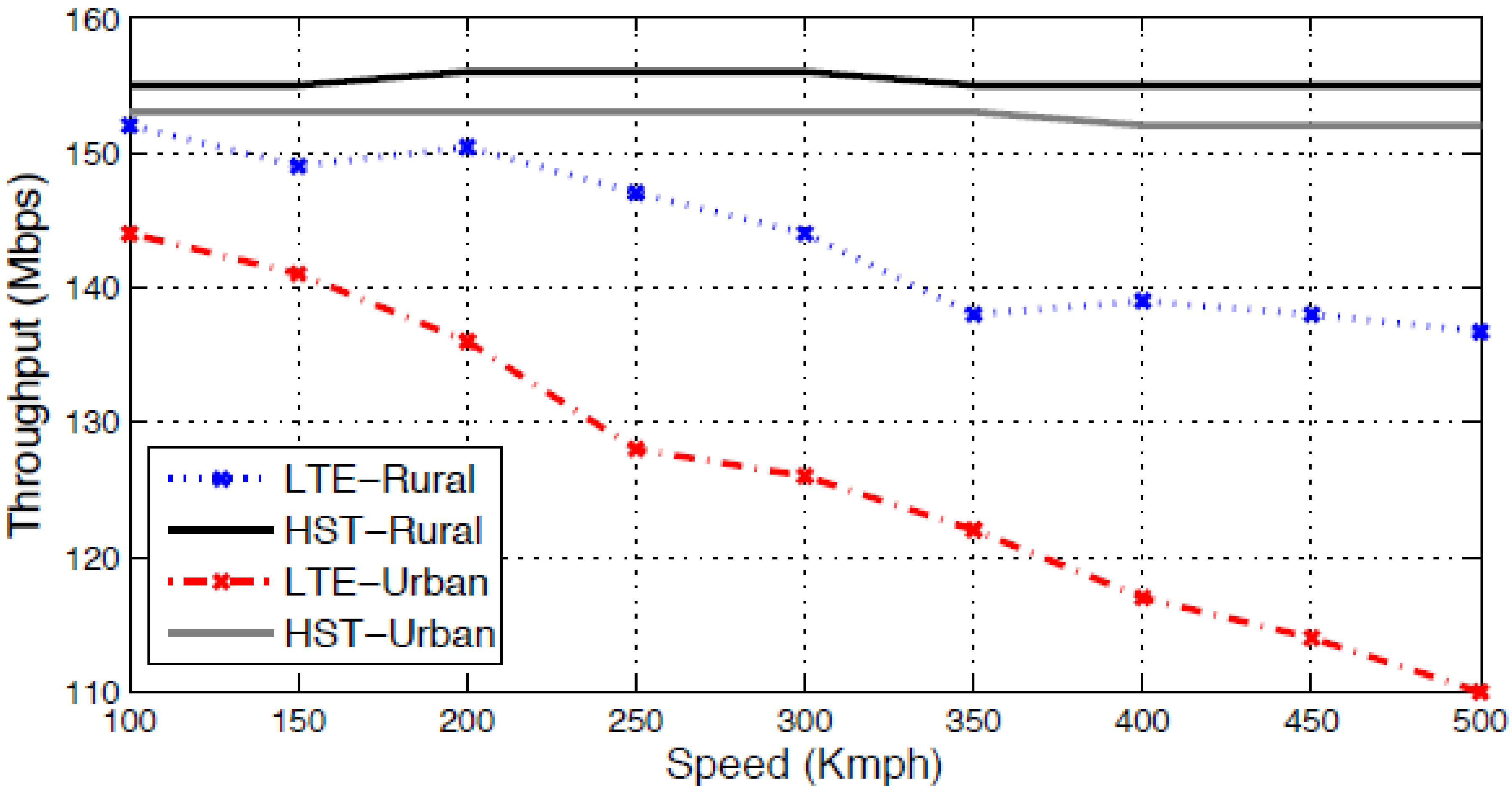
Speed: 500kmph, Path:3. Urban Cell V.S. Rural Cell



Handover Latency

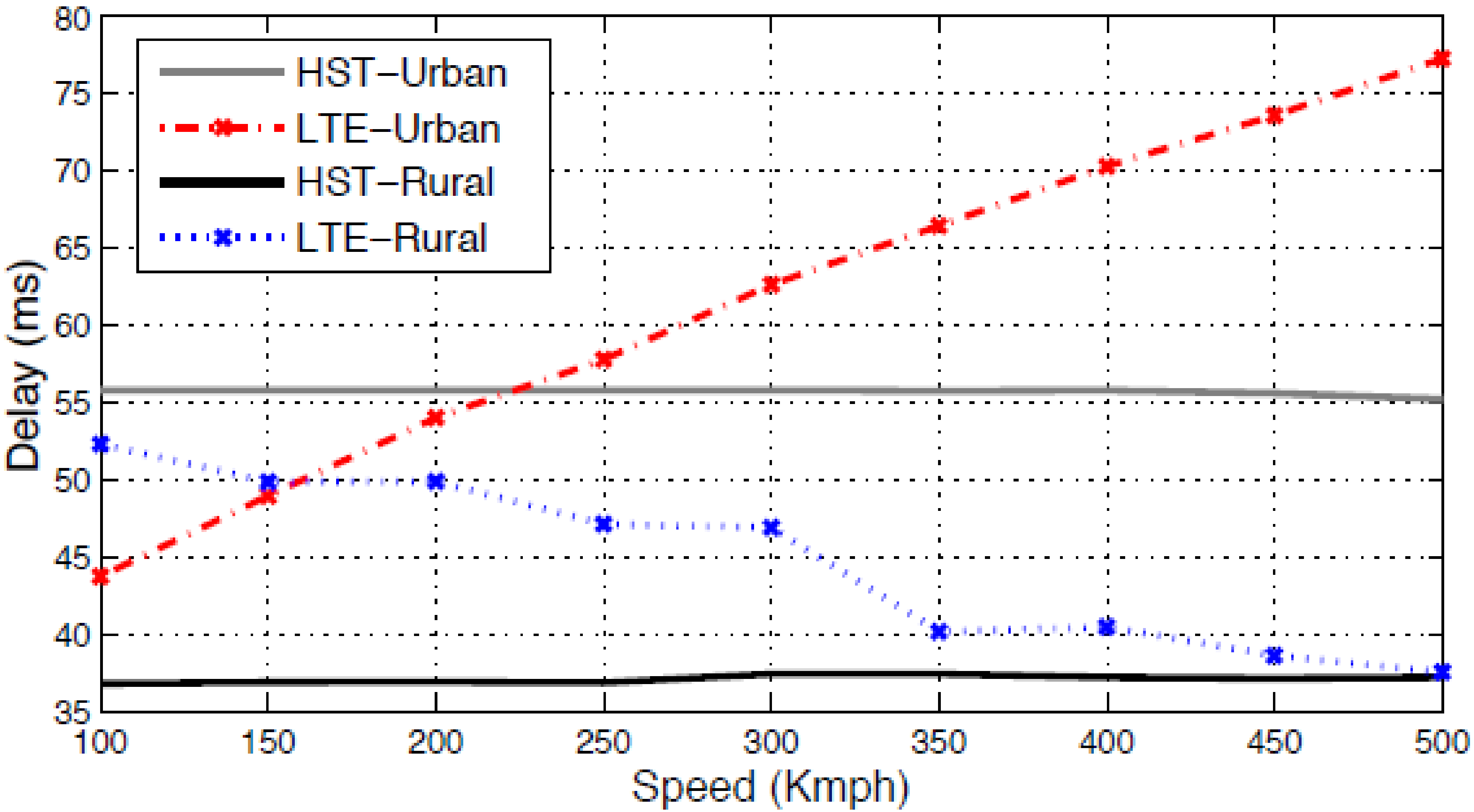


Throughput



160
150
140
130
120
110
100
150
200
250
300
350
400
450
500
Throughput (Mbps)
Speed (Kmph)
LTE–Rural
HST–Rural
LTE–Urban
HST–Urban

Delay


HST−Urban
LTE−Urban
HST−Rural
LTE−Rural
Delay (ms)
Speed (Kmph)
80
75
70
65
60
55
50
45
40
35
100
150
200
250
300
350
400
450
500

Conclusion

- This paper proposed a novel infrastructure and scheduling algorithms for high-throughput wireless access for high speed train passengers.
- 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.
- 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.