Performance Analysis of LTE-Advanced Mobile Relay Stations in Railway Environments

Bharat Pandey [1], Jaime Calle-Sanchez [2], Sharad Kumar Ghimire [3]

[1, 3] *Department of Electronics and Computer Engineering, IOE, Central Campus, Pulchowk, Tribhuvan University, Nepal*

[2] *Department of Signal, Systems and Radiocommunications, ETSIT, Technical University of Madrid, Spain*

Corresponding Email: [1] bpaans.elx@gmail.com, [2] jcalle@gmr.srr.upm.es, [3] skghimire@ioe.edu.np

---

Abstract: Nowadays interest has grown in using Mobile Relay Station (MRS) system to provide cellular coverage to the onboard users in public transport, particularly in High Speed Trains (HSTs) due to high penetration rate of portable electronic devices such as smart phones, tablets and laptops. In the railway scenarios, when the signal propagates into the train, it suffers through the high order of Vehicle Penetration Loss (VPL) due to modern construction materials and techniques used for the train. Beside that rapid temporal variations in the radio channel and Inter-Carrier Interference (ICI) issues due to Doppler shift effects produce a quick battery drain or increased call drop rates indeed. Therefore users inside train will suffer worse channel propagation conditions, similar to cell-edge users. Thus the coverage and capacity at railway scenario remain relatively small due to low Signal-to-Noise Ratio (SNR).

The deployment of MRS system to transmit data between the Donor eNB (DeNB) and the User Equipments (UEs) through multi hop communication significantly improves the achievable throughput of onboard users as compared to direct transmission. Besides that, it also improves the throughput of the macro users located in cells that the train is passing through. This paper presents system level simulation results on improving performance throughput of macro pedestrian users and onboard train users by deploying Long Term Evolution – Advanced (LTE-Advanced) MRS system in railway scenarios.

Keywords: LTE-Advanced; High Speed Train; Donor eNB; Mobile Relay Station; Performance Throughput

---

1. Introduction

LTE-Advanced is considered to be the next big dive in the broadband mobile communications world, aims to reach and go beyond the International Telecommunications Union (ITU) requirements for International Mobile Telecommunications-Advanced (IMT-Advanced) [1]. LTE-Advanced should be backward compatible and should share the frequency bands with the previous releases of LTE. The most important LTE-Advanced benefits is the ability to take advantage of advanced topology networks; optimized heterogeneous networks with a mix of macros with low power nodes such as picocells, femtocells and new relay nodes. This new paradigm of network architecture brings the network closer to the user by adding many of these low power nodes, which improves the capacity and coverage, and ensures user fairness.

Broadband mobile cellular communication in High Speed Train (HST) has been gaining momentum in the recent years. To provide broadband data access to the onboard users, it is necessary to extend network coverage area to the railway tracks. However, extending coverage areas to railway tracks by merely increasing transmitted power may not be the most suitable solution for providing high speed broadband internet access to onboard users. The group mobility environment presents several specificities and challenges related to the high speed, which severely degrade the Quality of Service (QoS) of onboard users. Under this scope, the 3GPP working group for LTE standardization is paying more attention on high speed railways needs [2]. This organization has proposed a new radio access architecture paradigm for group mobility scenario, the Mobile Relay Station (MRS) [3].

Regarding LTE standard specification, the significant improvement in data rates and QoS assurances, matches with the potential to meet passenger and operational services requirements. However, the specificity of HST scenario poses a major challenge for satisfying the required communications QoS levels. The main challenges in high speed mobility scenarios are related with large Doppler shift and rapid Doppler transitions in the radio link, which affects to both the receiver and scheduler performance for channel estimation, equalization and radio resource management. Moreover, the railway environments present a major challenge that must be addressed is high penetration losses of the signal through the shielded train carriages [4].

The deployment of MRS system is focused on the enhancement of the coverage and capacities of the onboard users in the train. The MRS architecture is currently under study in the Release 11 of LTE standard [2]. The MRS acts as a dedicated network node equipped on the top of the vehicles to provide a fixed access link to the passengers riding on vehicles. The network node is an LTE node, while the access link to indoor passengers can be provided by means of Wi-Fi devices or LTE small cells ones. The proposed solutions are focused on enhancing performance of the onboard users and the cell network by deploying LTE-Advanced MRS in the railway environments.

2. System Model

2.1 LTE Radio Access Architecture in HST

The eNB of the LTE networks without MRS system treats train onboard users as normal macro users. Since the railway environments present high order of penetration losses in the shielded carriages, rapid temporal variations in the radio channel and Inter Carrier Interference (ICI) issues due to Doppler shift effects, which produce a quick battery drain and/or increased call drop rates for the onboard users inside train. Therefore, onboard users face worse channel propagation condition as that of cell-edge users.

On the other hand, handover frequency for high speed mobility condition is really high. The more frequent handover leads to shorten the battery life due to increment of the channel state measurements carried out both in idle and connected mode. It also causes greater number of connection losses. In addition, as the number of onboard user increases, users will not be able to achieve their QoS levels or may not be able to be scheduled for transmission due to excessive usage of Physical Downlink Control Channel (PDCCH) resources. The fact is that, onboard users will require more PDCCH resources per scheduling assignment/ Downlink Control Information (DCI) message due to adverse radio channel condition experienced by them.

The key usage of MRS in railway environment is to provide high saving in terms of signaling traffic and increasing handover efficiency through the aggregation of multiple user connections to a single access point. Moreover, the relay antenna gain on the top of carriage will lead to increase network efficiency for the onboard train users [5].

2.2 Mobile Relay System for LTE-Advanced

Relays are a key new feature of LTE-Advanced, introduced in Release 10 of the LTE specifications. Relaying being one of the promising deployment scenarios deploy low-power base stations known as Relay Node (RN) within the macro-overlaid network. The primary objective of the RN was for coverage extension in cell-edge, rural area, urban hot-spots, dead zones, indoor hot-spots, events and exhibitions, etc. In these days, the group mobility as a new scenario where the RN deployed on the top of the vehicle; buses, trams or trains to provide fixed access link to onboard passengers is gaining momentum. Mobile relaying as a solution for improving LTE network performance on high speed scenario is being investigated on 3GPP Release 11 [2].

The MRS is connected to a Donor eNB (DeNB) via wireless link called backhaul link and the link between MRS and onboard User Equipments (UEs) is referred to as access link. The backhaul link will have to cope with all the challenges of railway scenarios as described in the previous section: Doppler shift effects, synchronization problems, fast fading and temporal fading channel, etc.

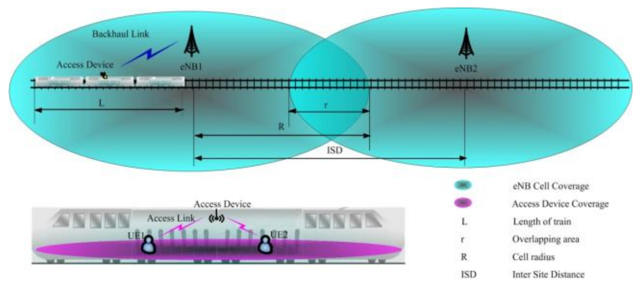

Figure 1: MRS Deployment in Railway Scenario

According to transmission mechanism, relays can be characterized as Type 1 or Type 2 relay [6].

2.2.1 Type 1 Relay

It is an inband, half duplex, non-transparent relay and appears to users as a separate cell. This relay is a layer 3 relay with all the necessary Radio Resource Management (RRM) functionalities to support the handover and the mobility management, specifically; this relay has its own scheduler to serve on board users. Besides, it transmits its own Cell Identity (ID), synchronization channel, reference signal and control channels to UEs as well as support of Hybrid Automatic Repeat Request (HARQ) processes. The only difference with eNB is wireless relay link to connect with core network via DeNB. Type 1 relay is further classified into Type 1a and Type 1b relays. Both have the Type 1 characteristics with a difference that Type 1a is outband relay while the Type 1b relay is inband and has sufficient isolation between the received and transmitted signals to enable full-duplex operation – i.e. the backhaul and access links can be active simultaneously without the need for time-division multiplexing. Although three classes of Type 1 relays were studied by 3GPP, only inband half duplex relay is standardized in 3GPP LTE Release 10 [7].

2.2.2 *Type 2 Relay*

Type 2 relays, are in-band relays, which are transparent to users i.e. LTE Release 8 UEs are unaware of type 2 relay in the cell and assume centralized resource scheduling by DeNB, thus, exploiting the cooperative nature of relay [7]. Normally, its deployment means to enhance the eNB signal in the donor cell. Some examples are the smart repeaters, Decode and Forward (DF) relays and L2 relays. This relays have not been standardized yet.

2.3 *Resource Allocation for Backhaul Link*

Taking into consideration of Type 1 relay, which has been proposed for LTE-Advanced, the MRS cannot transmit and receive simultaneously as it operates on half duplex mode. Since it is an inband relay, the backhaul link (DeNB-MRS) and access link (MRS-UE) operate in same frequency band. As a consequence, the backhaul link and access link of a MRS never activate at the same time. To achieve orthogonality, the links are multiplexed in time domain on subframe basis. In LTE system the backhaul subframe allocation is restricted to the Multimedia Broadcast over Single Frequency Network (MBSFN) subframes [8].

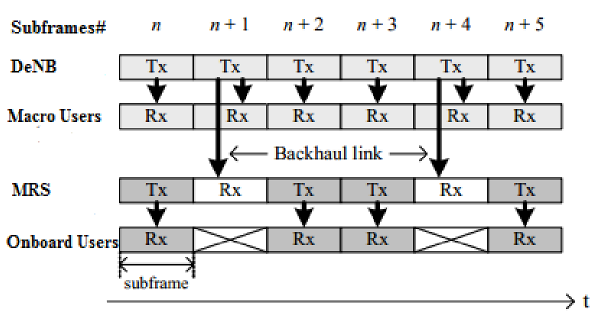

Figure 2: Subframe Structure in Relay System

When the backhaul link shares a frequency band with the access link, it usually causes self-interference, where transmitted signals interfere with received signals in a MRS. To avoid this self-interference, simultaneous transmission and reception are forbidden; the backhaul and access links at the MRS are separated into different subframes in the LTE-Advanced relay system. The LTE subframe, which has 1 ms of duration, is defined as the minimum unit of the physical resource allocation in the time domain to UEs and MRS in LTE and LTE-Advanced systems. Here, the subframes n+1 and n+4 are configured as backhaul subframes. In these subframes, DeNB transmits downlink data to MRS and macro users, and the MRS and macro users receive this transmitted data. In other subframes, the DeNB transmits downlink data to the macro users, and the MRS transmits downlink data to the onboard users. Although the macro users receive downlink data from the DeNB in all subframes, the onboard users receive downlink data from the MRS in subframes except for n+1 and n+4.

The main advantage of this mode is that the MRS operates in a single carrier without requiring additional spectrum but it requires transmission of control data to the MRS as well as relay needs time gaps for switching between reception and transmission, as a result onboard users suffer delay. Moreover, there are additional constraints related to the timing of PDCCH transmission. As a consequence, 3GPP define a new relay backhaul control channel, the Relay - Physical Downlink Control Channel (R-PDCCH). Taking into account that the MRS cannot receive control data when transmitting data to onboard users, R-PDCCH information must be transmitted on user data resources, and therefore, there will be a reduction in the backhaul link data transmission efficiency [9]. Apart from these drawbacks, the ratio between MBSFN subframes and access subframes in the LTE radio frame have a key impact on relay performance. The actual number of MBSFN subframes within each period depends on the current load on backhaul link and on the desired link fairness, when no QoS requirements are defined [8].

2.4 *Resource Scheduling Algorithm*

The scheduler introduces a new approach to opportunistic allocation of Resource Blocks (RBs). The main idea behind this proposal is based on the unbiased sharing of resources and respect for the QoS requirements of each user independently, trying not to prioritize users for their channel state if they do not have real needs.

Table 1: Scheduler Parameters

Parameters	Description
N	Number of users in the eNB
N_a	Number of active users
S	Available RBs in the eNB
$n_i(t)$	Number of RBs allocated to user 'i' in the TTI 't'
r_i	Average traffic of user 'i'
$\mu_{ij}(t)$	Maximum transmission rate on RB 'j' assigned to user 'i'
$\mu_i(t)$	Average rate of user 'i' if it is assigned all RBs
$e_i(t)$	Time to expiry of the HoL (Head of Line) packet of user 'i'
$d_i(t)$	Number of discarded packets of user 'i'

It is modeled as a decoupled Time Domain (TD) and Frequency Domain (FD) scheduler which can take advantage of each user channel status. It follows an approach to allocate opportunistically the set of available RBs in a time-frequency grid. First of all, HARQ users are introduced into the resource sharing process, then users are priority sorted according to its time of packets expiration deadline. The frequency domain scheduler assigns the best quality RBs to the users, according to their priorities.

2.4.1 *RB Sharing Algorithm*

Number of RBs to be assign for each active user based on three factors [11]:

- The quality of the user channel.
- The average rate of user traffic.
- The remaining time to discard its HoL packet.

Firstly, RBs are assigned by using the following equation:

$$n_i(t) = \left\lceil \frac{r_i}{\left|\frac{1}{N_a}\right| \sum_{j\in N_t} r_j} \frac{\mu_i(t)}{\left|\frac{1}{N_a}\right| \sum_{j\in N_t} \mu_j} \right\rceil \qquad \text{........ (1)}$$

After the first deal, extra RBs shall be divided among users who are in a more dangerous situation (i.e. users whose time to discard the HoL packet is less and have a higher percentage of dropped packets). Now leftover RBs can be calculated as follows:

$$S' = S - \sum_{N_a} n_i(t) \qquad \text{........ (2)}$$

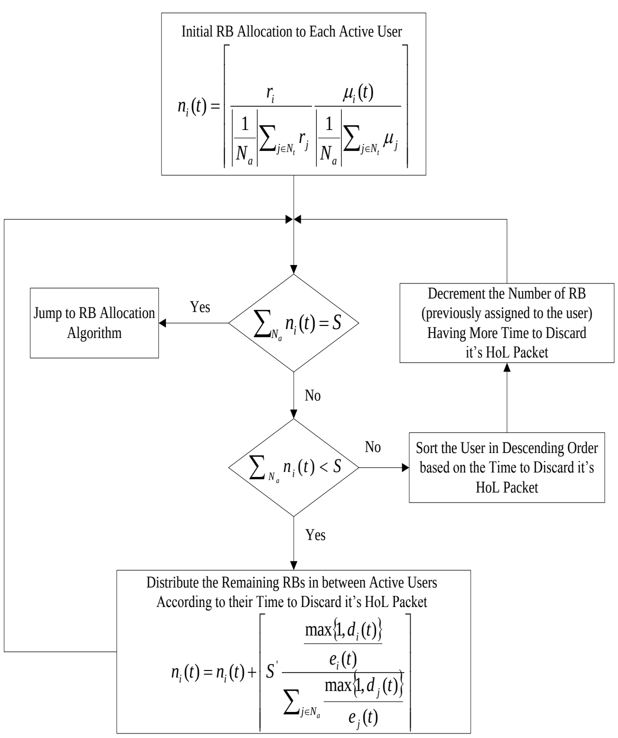

Figure 3 : Flowchart of the Distribution of RBs to Each User

The new division is calculated at this time as given by the following equation:

$$n_i(t) = n_i(t) + \left\lceil S' \frac{\frac{\max\{1, d_i(t)\}}{e_i(t)}}{\sum_{j\in N_a} \frac{\max\{1, d_j(t)\}}{e_j(t)}} \right\rceil \qquad \text{......... (3)}$$

At this point, we could have allocate more resource than available ones, and therefore, we should reduce the number of RB allocated to a user. In this case, the chosen approach is based on iteratively reduce the number of RB allocated to users who have more time to transmit it's HoL packet, until the number of assigned RB matches with available RB in the eNB.

2.4.2 *RB Allocation Algorithm*

The objective of this allocation algorithm is to accommodate those users for which each RB has best available channel, thereby maximizing the total transmission rate provided by the eNB. For the priority, each user is associated based on the number of packets that the eNB has discarded to that user. If multiple users match in number of packets, higher priority is given to the users having best channel. Once active users are prioritized then we can proceed to assign the RB in that order.

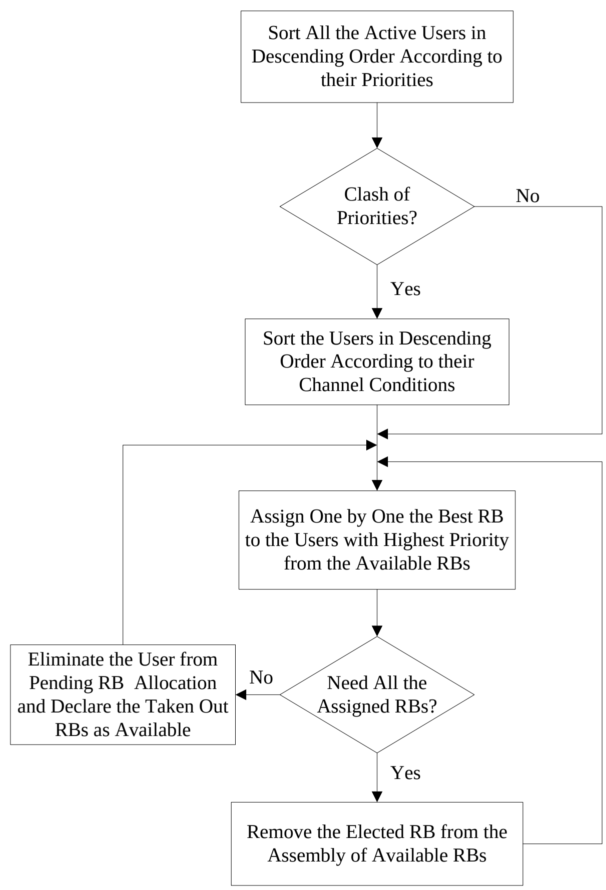

Figure 4: Flowchart for the Assignment of RBs to Each User

4. Simulation

The proposed simulation results are evaluated by using LTE system level simulator developed by Polytechnic University of Madrid (UPM) researchers.

4.1 Simulation Assumptions

For the simulation of the system, a single simulator approach would be better, but complexity of such a simulator is too high for the required simulation resolution; since it includes all the system parameters from link level processing to multi-cell network. Thus, for the simplicity of operation this simulator considers the link to system model, which is based on look up tables obtained from link level simulations. For each Modulation and Coding Scheme (MCS), look-up tables with Block Error Rate (BLER) values for different code block sizes allow knowing the success probability of decoding and receiving the transmitted information.

Table 2: Simulation Parameters

Bandwidth	5 MHz
Carrier Frequency	2.6 GHz
Simulation Time	3000 TTI
CQI Reporting	Wideband, 120 ms
OLLA Increment	0.5 dB
Channel Model for Onboard Train Users	Winner II (D2a), 120 Km/hr
Channel Model for Pedestrian users	EPA, 3 Km/hr
Transmission Scheme	SISO
MRS Antenna Gain and Height	4 dB, 3 m
MBSFN Subframes	3
VPL	20 dB
DeNB PIRE and Height	58 dB, 30 m
Noise Figure	7 dB
Number of Pedestrian Users	10, 30 and 50
Number of Onboard Train Users	10
Number of Iteration	500
Traffic	Video-Streaming 384 kbps

Moreover, the simulation environments consider one train carriage with 10 UEs and two eNBs. The train carriage having 10 UEs are connected to the DeNB or aggregated in MRS depending upon whether there is MRS or not. The macro cell users are considered pedestrian ones and randomly distributed in each cells with a velocity of 3km/h. As a result, two cells may contain a different number of users. The serving eNB for the macro users will be selected according to the lowest total path-loss including distance dependent path-loss, shadowing, and effective antenna gains. The total number of pedestrian users is taken as 10, 30 and 50. In addition, the railway tracks are located on two different positions depending on simulation scenarios. In the first scenario the tracks are located at 1 km away from DeNB and that of second one at 2 km. The pathloss model for onboard train users and MRS is the WINNER II rural channel model (D2a) [12] whereas for pedestrian macro users, Extended Pedestrian-A (EPA) channel model is employed.

4.2 Simulation Results

The cell network performance in terms of obtained and required throughput for pedestrian users of both eNBs for two different railway environments and different cell traffic loads is shown in figures 5 and 6 below. The first scenario shows the pedestrian user's performance for different traffic loads; 10, 30 and 50 users and railway tracks at 2 km away from DeNB. In the figure 6, tracks are located at 1 km away from DeNB. Throughput results for both scenarios are compared for different numbers of pedestrian users with and without deploying MRS.

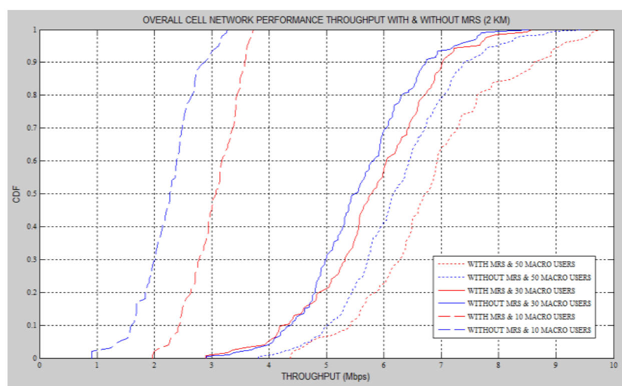

Figure 5: Overall Cell Network Performance of Pedestrain Users with (Red) and without (Blue) MRS for Railway Tracks Located 2 Km away from DeNB

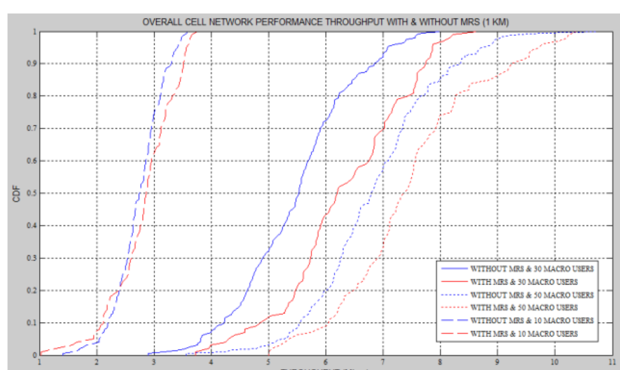

Figure 6: Overall Cell Network Performance of Pedestrain Users with (Red) and without (Blue) MRS for Railway Tracks Located 1 Km away from DeNB

It shall be noticed that the demanded data rate is 3.75 Mbps for 10 users, taking into account the video-streaming traffic data rate of 384 Kbps. Regarding the Cumulative Distribution Function (CDF) of the obtained data rate from macro users in figure 5 and figure 6, it can be concluded that the tracks location has a dramatic impact on the overall network performance. Moreover, this effect increases as the number of macro user increases.

Bad propagation conditions of onboard users plays a key role in this results since 10 onboard users consume many network resources leading to a dramatic lowering for macro users even though 10 macro pedestrian users, as seen in figure 5. The results are slightly better in figure 6 as tracks are near from DeNB. It is clear that railway radio propagation channel losses are the key element to take into account when deploying LTE networks in railway environments.

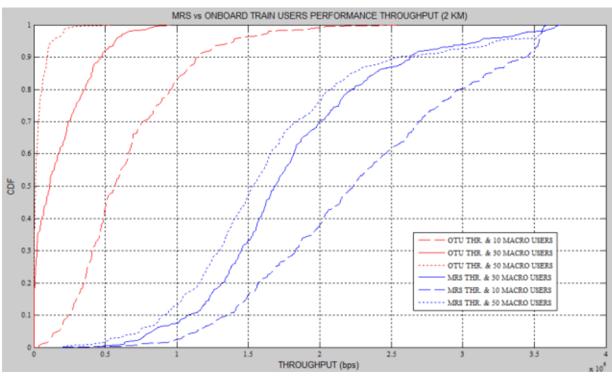

Figure 7: MRS (Blue) vs Onboard Train Users (Red) Performance for Railway Tracks Located 2 Km away from DeNB

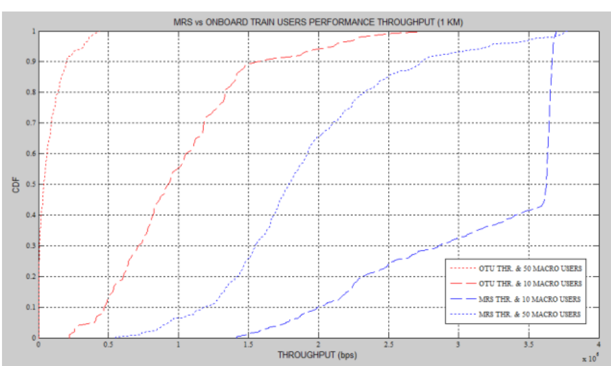

Figure 8: MRS (Blue) vs Onboard Train Users (Red) Performance for Railway Tracks Located 1 Km away from DeNB

The performance of MRS and onboard train users are also compared for the same scenarios as before. For both scenarios, the MRS performance is far better than that of onboard users as they connect directly to the DeNB. It can be marked that the deployment of MRS can improve the train user's capacity more than a 50% compared to that of without MRS.

It is supposed that for the fixed number of MBSFN subframe allocation, MRS should obtain same data rates. However, both the figures 7 and 8 show MRS capacity is decreased as the number of macro pedestrian user increases. This is because of the co-channel interference from eNB2. The location of tracks has also great impact on MRS and onboard user's capacity. For both 10 and 50 users in the macro cell, the MRS can nearly fulfill all the required capacity (3.75 Mbps for 10 users) in the last scenario. Undoubtedly, railway tracks shall be located as near as possible to DeNB considering the results presented in figure 6 and figure 8.

5. Conclusion

In this work, the onboard train users performance and overall cell network performance throughput are evaluated with and without MRS deployment on two different railway scenarios. The performance of onboard train users is enhanced by deploying MRS system. The results show that the MRS performance greatly depends on the distance of railway tracks to the DeNB. The obtained results clearly show that the deployment of MRS in railway scenario is highly beneficial, since the LTE system in railway scenario with MRS outperforms the results than that of without MRS; when the onboard users directly connected to the DeNB. Result shows, the MRS can also improve the overall cell network performance in the railway environments.

In the above results, the impact of macro pedestrian users on MRS performance is also analyzed. It shows, the MRS capacity is decreased when the number of macro pedestrian user increases. This is because of the macro pedestrian user increases. This is because of the co-channel interference from eNB2. As the number of pedestrian user increases in the network, the interference is also increases. That's why it is necessary to implement proper interference avoidance mechanisms for improving the MRS and the cell network performance.

References

[1] ITU-R REPORT, M.2134, "Requirements related to technical performance for IMT-Advanced radio interface(s)", 2008.

[2] 3GPP TR 36.836 V2.0.2, "Technical Specification Group Radio Access Network; Mobile Relay for Evolved Universal Terrestrial Radio Access (E-UTRA)," tech. rep., http://www.3gpp.org/.

[3] Yang Yang, Honglin Hu, Jing Xu and Guoqiang Mao, "Relay technologies for WiMax and LTE-advanced mobile systems", IEEE Communications Magazine, Vol:47 ,Issue: 10, pp.: 100-105.

[4] E. Tanghe, XV. Joseph, L. Verloock, and L. Martens, “Evaluation of vehicle penetration loss at wireless communication frequencies,” IEEE Trans. Veh. Technol.. vol. 57, no. 4, pp. 2036—2041, Jul. 2008.

[5] W. Li et al., “Performance Evaluation and Analysis on Group Mobility of Mobile Relay for LTE-Advanced System,” Proc. IEEE VTC 20 12-Fall.

[6] Ahmed Hamdi, Mohamed Gaafar and Omar Abdallah, “Exploitation of Relaying and Network Coding in LTE-Advanced for Enhanced Capacity and Coverage”, 4G++ Project, D5.1, Work Package 5, Rev 1.0

[7] Y. Yuan, “LTE-Advanced Relay Technology and Standardization”, Signals and Communication Technology, Springer-Verlag, Berlin Heidelberg, 2013.

[8] Liebl G., de Moraes T. M., Soysal A., and Seidel E., "Fair resource allocation for inband relaying in LTE-Advanced," Multi-Carrier Systems & Solutions (MC-SS), 2011 8th International Workshop on, vol., no., pp.1, 5, 3-4 May 2011.

[9] Gora J., and Redana S., "In-band and out-band relaying configurations for dual-carrier LTE-advanced system," Personal Indoor and Mobile Radio Communications (PIMRC), 2011 IEEE 22nd International Symposium on, vol., no., pp.1820,1824, 11-14 Sept. 2011.

[10] Harri Holma and Antti Toskala, “LTE for UMTS: Evolution to LTE-Advanced”, Nokia Siemens Networks, Finland, 2011.

[11] David D. Antonio Monte, “Study and simulation of self-organizing architectures for LTE networks in high speed railway environments”, ETSIT, UPM.

[12] Pekka Kyösti, Juha Meinilä, Lassi Hentilä, Xiongwen Zhao, Tommi Jämsä, Christian Schneider, Milan Narandzić, Marko Milojević, Aihua Hong, Juha Ylitalo, Veli-Matti Holappa, Mikko Alatossava, Robert Bultitude, Yvo de Jong, and Terhi Rautiainen, “Part I Channel Models”, IST-4-027756, WINNER II D1.1.2 V1.2, WINNER II Channel Models, 2007.