A Cooperative Moving Relay Node System Deployment In A High Speed Train

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Abstract—In this paper we present system level simulation results for a cooperative moving relay node (MRN) system deployed on a high speed train (HST). Recently interest has grown in using MRNs to provide enhanced cellular coverage to users in public transport, particularly HSTs, of which the modern construction materials and techniques cause high vehicle penetration loss (VPL) when signals propagate into the train. MRNs utilising antenna arrays on the exterior and interior of the train are a promising solution to overcoming this VPL in order to provide onboard users with improved service. We show that a cooperative system of 8 MRNs onboard a HST is able to provide significant improvements to achievable throughput of onboard users when compared to direct transmission, as well as indirectly improving the throughput of other users located in cells the HST is passing through.

I. INTRODUCTION

Support for decode and forward (DF) type relay nodes (RN) in LTE is one of the key enhancements introduced in the 3GPP LTE release-10 standard, and along with femto and pico access points form the basis of a heterogenous network architecture. In LTE a relay node (RN) is essentially an enhanced NodeB (eNB) that is connected to the core network through a donor eNB (DeNB) with an in-band or out-of-band wireless backhaul link. An LTE RN operates its own cell and appears to user equipment (UE) as a normal eNB, maintaining backwards compatibility with release-8 LTE UE. Several recent studies have shown gains in capacity and coverage through deployment of static RNs, for example [1] shows significant gains for cell edge users when using relaying, and [2] shows the large gains in network coverage attainable through the use of RNs.

Recently the idea of using moving RNs (MRN) to provide enhanced cellular coverage to users onboard public transportation vehicles, for example trains, has attracted research interest [3], [4]. Currently only static or nomadic RNs are supported in the LTE release-10 standard, however support for mobility is being studied by the 3GPP for future LTE releases [5]. Modern HSTs present a particularly challenging environment for wireless communication between onboard UE and macro network infrastructure. The modern construction techniques and materials of HSTs cause high attenuation of radio signals when they propagate into a train, referred to as VPL. By utilising an antenna array on the exterior of a train carriage for backhaul link communication (MRN to DeNB), and an interior antenna array for access link communication (UE to MRN), it is possible to overcome the VPL that may be as high as 24dB in modern HSTs [6]. The use of DF type MRNs as opposed to basic repeaters will result in a large increase in received signal to interference (SIR) level at onboard UE as interfering signals are still subject to VPL.

In this paper we investigate a deployment of a half duplex cooperative MRN system on a HST. The system is based on the system model proposed in [3], where preliminary analytical results show potential capacity and coverage gains. We investigate the performance of the system using a modified LTE compliant system level simulator in order to investigate the gains in capacity and attainable throughput in a realistic cellular network. We consider the backhaul link to be the capacity bottleneck of the system, and therefore focus on the backhaul link assuming that the access link has sufficient capacity. The large spatial dimensions of the HST are exploited with the use of a large backhaul antenna array covering the entire length of the train, and the cooperative MRN system is able to form backhaul links with multiple DeNBs. We show that despite the half duplex loss, the cooperative MRN system significantly improves network capacity, and throughput attainable at vehicular UE (VUE) compared to direct eNB to VUE transmission.

II. COOPERATIVE MRN SYSTEM MODEL

We consider a HST consisting of 8 individual carriages illustrated in Figure 1, each equipped with a MRN. Each MRN has an external antenna array with \( N_{MRN} \) elements, evenly spaced along the length of the corresponding carriage. All MRNs are linked by an out of band link which may for example be used by the MRNs to share backhaul capacity amongst the VUE, and will be referred to as the crX2 interface. This crX2 interface is assumed to have zero latency and infinite capacity. The DeNBs serving the MRNs are aware that the group of 8 MRNs are cooperating as a group, and have full control over the backhaul link configuration. When multiple concurrent backhaul links are established between the HST and the donor network, transmissions to a VUE may be routed through any of them, and then forwarded internally through the crX2 link to the MRN serving the VUE. The backhaul link side of the MRN and access link side are considered two separate
entities, and will be referred to as MRN backhaul transceiver (MRNBT) and MRN access point (MRNAP) from here on. Both may operate entirely independently of each other for example a MRN may have its MRNBT completely disabled while still operating a cell on the MRNAP. A MRNBT is able to route received transmissions to any MRNAP on the HST over the crX2 interface.

![Diagram](image)

**Fig. 1.** Cooperative MRN system on HST

We consider a backhaul link management scheme referred to as group formed backhaul (GFB) where joint detection is performed over groups of MRNBTs managing a single backhaul link. In the GFB scheme one MRNBT is designated train master and the rest designated slaves under control of this train master. All slave MRNBTs signal their channel state information (CSI) to the train master through the crX2 interface. The train master MRNBT then uses this CSI information to form groups of MRNBTs with each group being responsible for one backhaul link. In each group one of the slave MRNBTs acts as the group master with the rest of the the group under its control. All slave MRNBTs including the group masters remain under full control of the train master MRNBT and any instruction from the train master is prioritised over instruction from a group master. Joint detection is performed over a MRNBT group, which may potentially have an antenna array spanning the length of the train, with all information exchange occurring over the crX2 interface. The group configuration remains under the control of the train master MRNBT and may be changed at any time. Since the backhaul configuration remains under control of the donor network, the GFB scheme may influence the backhaul link configuration by manipulating channel state information (CSI) feedback to the DeNBs serving the train. All MRNBTs report CSI to the DeNB serving their group, but the master DeNB may force them to report deceptive CSI to force the network to schedule transmissions through other links. The groups may jointly detect reference symbols to calculate CSI, with the group master transmitting the CSI as calculated, and the rest of the group transmitting deceptive CSI in order that they are not assigned resources. It is assumed that the donor network needs no knowledge of the group configuration.

**III. SYSTEM LEVEL SIMULATOR**

The LTE release-10 compliant downlink system level simulator is based on the Winner II [7] fast-fading channel model, and simulation parameters follow the guidelines established by the international telecommunications union radiocommunications sector (ITU-R) for international mobile telecommunications advanced (IMT-A) radio interface evaluation [8].

**A. System Layout**

The system layout consists of a central layout, consisting of 19 eNB sites each serving 3 sectors for a total of 57 sectors. In addition 6 copies of the central layout are wrapped around the edge of the central layout to form a layout with a total of 399 sectors. The wraparound layout ensures that interference levels are uniform across the entire central layout. At the start of a drop macro UEs (MUEs) are evenly distributed throughout the 57 sectors in the central layout, and paired with the 57 sectors providing the strongest received signal strength calculated by distance based path loss and angle based antenna gain. The sector providing the strongest received signal strength is selected as the serving sector, the remaining 56 paired sectors are interference, and unpaired sectors are considered to have no influence on the MUE. The pairings remain constant throughout a drop, and therefore handover is not considered by the simulator. A track with a random radius of greater than 4km, with random origin such that it passes 50m from the central eNB is created at the beginning of a layout initialisation as illustrated in Figure 2. The track runs from one edge of the central layout to the other and is made up of of discrete points 10m apart, with the HST advancing along the track by a defined number of points between drops. At the first drop after a layout initialization the train is positioned on one end of the track such that the entire train is inside the central layout, once the train has reached the opposite end of the track and cannot be advanced without leaving the central layout, a layout initialisation is triggered. VUE and MRNs are paired to eNBs in the same way as MUE, with all 57 links considered interference when VUE are connected to MRNAPs. VUE are paired with all MRNAPs on the train, the serving link is with the MRNAP located in the same carriage, all other links are considered interference.

![Diagram](image)

**Fig. 2.** HST in system layout, showing MRNs (black diamonds), VUE (red dots), MUE (blue dots), donor eNB (black triangle)
B. Signal model

We consider frequency-division duplexing (FDD) orthogonal frequency division multiple access (OFDMA) following the LTE standard [9]. In the case of transmission to VUE through the cooperative MRN system, an un-precoded single user multiple input multiple output (SU-MIMO) spatial multiplexing transmission scheme is used for backhaul link transmissions. For direct transmission from eNB to VUE, SU-MIMO with space frequency transmit diversity (SFTD) transmissions. For direct transmission from eNB to VUE, multiplexing transmission scheme is used for backhaul link through the cooperative MRN system, an un-precoded signal. The LTE standard [9]. In the case of transmission to VUE and MRNs) at the eNB. Scheduling relies on CSI feedback, in this case in the form of channel quality indicator (CQI) which is created by users and is available after a delay to the scheduler as there is no simulation of the uplink channel. After scheduling, based on the resource allocations and CQI, a modulation and coding scheme is set for each user. As previously mentioned no data symbols are used in the simulator, instead the MCS value determines the FEP at the MIESM link to system level interface and the transport block size, i.e. number of bits transmitted, for throughput calculations.

At user $k$ LMMSE filtering is applied, and SINR is calculated using (2). The SINR values are used in the link to system level interface to calculate a MIESM value for each user, which is then used with the MCS value in determining frame error probabilities. Hybrid automatic repeat request (HARQ) acknowledgements for each user are determined in the system level interface and fed back to the eNBs after a delay. CSI is calculated periodically for each user every 6ms and fed back to the eNBs with a delay. For users with successful transmissions/retransmission the number of correctly received bits is calculated and used in throughput calculations.

D. Resource Scheduling

The resource scheduler is designed to make as fair as possible a comparison between the performance of VUE when directly connected to an eNB and through the cooperative MRN system. The scheduling process is based on the assumption that the eNB is aware of which users are VUE and which are normal MUE only when VUE are connected through the MRN system. When VUE are connected through the MRN system the scheduler splits resources between MUE and MRNs) at the eNB. Scheduling relies on CSI feedback, in this case in the form of channel quality indicator (CQI) which is created by users and is available after a delay to the scheduler as there is no simulation of the uplink channel. After scheduling, based on the resource allocations and CQI, a modulation and coding scheme is set for each user. As previously mentioned no data symbols are used in the simulator, instead the MCS value determines the FEP at the MIESM link to system level interface and the transport block size, i.e. number of bits transmitted, for throughput calculations.

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C. Link Model

Figure 3 shows a simplified block diagram of the link model which starts with the scheduling of users (MUE, VUE, and MRNs) at the eNB. Scheduling relies on CSI feedback, in this case in the form of channel quality indicator (CQI) which is created by users and is available after a delay to the scheduler as there is no simulation of the uplink channel. After scheduling, based on the resource allocations and CQI, a modulation and coding scheme is set for each user. As previously mentioned no data symbols are used in the simulator, instead the MCS value determines the FEP at the MIESM link to system level interface and the transport block size, i.e. number of bits transmitted, for throughput calculations.

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to be supporting more VUE than lower quality links for the purpose of the resource splitting. Obviously due to the half duplex operation, the maximum amount of resources available to a backhaul link is 50%. After the resources are split, they are allocated to MUE and VUE (if connected directly to an eNB) using a proportional fair (PF) scheduling algorithm. In the MRN system the same PF scheduling algorithm is used to schedule resources to VUE, with backhaul link resources shared between the MRNAPs for serving VUEs on the access link based on the number of users they are serving. If an access link becomes a bottleneck, the backhaul capacity assigned to the corresponding MRNAP is accordingly reduced and assigned to other MRNAPs. Sub-band CQI is used for scheduling MUE, however only wideband CQI is used for scheduling VUE, it is assumed that the fast fading of the channel at high speed renders the sub-band CQI too inaccurate for use in the resource scheduling.

IV. SIMULATION SCENARIOS

We consider two main simulation scenarios, where all VUE are connected directly to the network through an eNB, and where all VUE are connected through the cooperative MRN system. The main simulation parameters are listed in Table I. We consider 3 different antenna configurations for the backhaul link, with 2 transmit antennas at the eNBs and 4 (2x4) or 8 (2x8) receive antennas at the MRNs, as well as 4 transmit antennas and 8 (4x8) receive antennas. We also consider a comparison of performance with different number of VUEs onboard the HST, comparing the case that there are 20, 30, 40 and 50 active users onboard.

V. RESULTS

Figure 4 shows the cumulative distribution function (CDF) of VUE throughput for the case of direct connection to eNB and through the MRN system with 3 different backhaul configurations when 20 active VUE are onboard the HST. The throughput performance of VUE is dramatically improved when connected through the MRN system for all 3 backhaul configurations. At the 50% point on the CDF curves throughput is increased from 200 kb/s in the case of direct connection to 800 kb/s in the case of connection through the MRN system with 2x4 backhaul. Figure 5 shows how increasing the number of onboard VUE affects throughput performance when connected through the MRN system. The throughput of VUE remains significantly improved even when there are 50 VUE compared to the case of 20 VUE directly connected to eNBs. At the 50% point on the CDF curves, there is only a 150 kb/s reduction to throughput performance compared to the case of 50 VUE over 20 VUE, however the throughput achieved by VUE with the most favorable conditions is significantly reduced, at the 80% point there is a reduction of 1.75 Mb/s. The results indicate that the access links in more congested carriages are becoming the bottleneck of the system, and resources are being directed to access points with lower congestion resulting in some users achieving very high throughput. This is again highlighted in Figure 4 where there is little improvement to VUE throughput when comparing the 4x8 backhaul case to the 2x8 case, however there is a significant improvement to the backhaul link throughput shown in Figure 6.

The backhaul link throughput shown in Figure 6 shows a clear improvement to throughput when increasing the number of receive antennas to 8 per MRN (64 total) from 4 (32 total). The CDF curve of the 2x4 case shows only a slight increase in throughput between the 50% and 80% points, with similar behavior for the other antenna configurations. This behavior is caused by the MRN system only forming one backhaul link for large sections of the track where the whole train is inside one cell area, and receiving 50% of the cells resources. The increase in throughput above the 80% point of the CDF curve clearly points to a significant gain where the MRN system is able to form backhaul links with multiple eNBs, in this case

![Table I: Simulation parameters for system level evaluation](image)
where the train is crossing over cell boundaries.

![Graph 1](image1.png)

**Fig. 5.** CDF plot of VUE throughput for the case of 20, 30, 40 and 50 active VUE in HST connected through MRN system with 2x4 antenna configuration. 20 VUE case when directly connected to eNB included for comparison.

![Graph 2](image2.png)

**Fig. 6.** CDF plot of MRN backhaul link throughput for three antenna configurations (2x4, 2x8 and 4x8).

Figure 7 shows the throughput performance of MUE located in cells serving VUE, and in cells not serving VUE. Compared to the case of direct connection for VUE, the MRN system results in a slight improvement in throughput for MUE located in the cells serving trains. With 2 antenna transmission there is a 50% reduction in throughput of MUE compared to cells not serving VUE, corresponding to the 50% maximum resources available to MRNs due to the half duplex backhaul link operation. In the case of 4 antenna transmission, MUE located in cells serving VUE achieve similar throughput to MUE in cells not serving VUE with 2 antenna transmission.

**VI. CONCLUSION**

We have shown that the cooperative MRN system is able to provide significant gains to VUE throughput when compared with the case of direct transmission. We have also shown that MUE located in the same cells as VUE also achieve improved throughput as a result of the cooperative MRN system deployment, when compared to the case of direct transmission to VUE.

**REFERENCES**


