Impact of LTE Precoding for Fixed and Adaptive Rank Transmission in Moving Relay Node System

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Abstract—Improved capacity and reliability of wireless networks can be achieved by users onboard in a high speed train with the use of moving relay nodes (MRN) cooperating with each other. Further improvement in performance is achieved with codebook based precoders adopted by third generation partnership project (3GPP) for spatial multiplexed transmission mode. Open loop and closed loop precoded spatial multiplexing for fixed and adaptive rank transmissions were simulated and analyzed on the backhaul link of a cooperative MRN system in a high speed train. To obtain improved performance, channel information in the form of precoder matrix indicator (PMI) and rank indicator (RI) are required for the closed loop operation while the RI is only needed for the open loop operation.

The results show that throughput gain on the backhaul link of the cooperative MRN system can be achieved with the precoded transmission when compared to unprecoded spatial multiplexing transmission. Further improvement in throughput was achieved when the transmission rank changed dynamically according to the channel condition.

I. INTRODUCTION

The long term evolution (LTE) based mobile telecommunication system achieves higher data rate and improved spectral efficiency with the use of multiple input multiple output (MIMO) techniques, and variants of orthogonal frequency division multiplexing (OFDM) used for transmission mitigate against inter symbol interference (ISI). Additional features, such as relaying technologies, have been considered as vital elements in the fulfillment of International Mobile Telecommunications Advanced (IMT-Advanced) requirements specified by the International Telecommunication Union-Radiocommunication (ITU-R) [1]. Relays are low powered and low cost eNodeB devices that connect the core network through a donor eNodeB with wireless backhaul link.

Fixed relay nodes are deployed near the cell edge to increase system capacity and extend cell coverage area [2] at reduced cost without using cable or fiber [3]. The increasing pace at which large high speed transportation vehicles are being deployed, results in additional challenges to maintain good quality service for users onboard. Hence support for mobile relays on high speed vehicles has been considered by the 3GPP to solve challenging issues arising from speeds as high as 350 km/h and high penetration loss [4].

Recent studies have shown the practicability and potential of the use of moving relays on public transport vehicles. For example, studies in [5] show a significant reduction in call drops arising from group handover and reduced transmission power as a result of the short range link between the onboard users and the access point. The LTE/LTE-A standard has adopted the use of codebook based precoding in its spatial multiplexing transmission schemes in order to improve the SINR and at the same time limit the signaling overhead [6]. To examine the impact of codebooks on the throughput of our cooperative MRN implementation, the closed loop precoding scheme requiring feedback from the PMI and RI, was implemented in scenarios where the high speed train would be stationary or at low speed at certain places such as the train station. At high speed, the open loop precoding scheme was implemented on the train scenario with RI feedback.

This paper analyzes the impact of the use of LTE precoding spatial multiplexing transmission schemes on the backhaul link of a cooperative MRN system on a high speed train with eight carriages (e.g., the 8-car E Shinkansen). LTE codebook based precoders were derived for two and four transmit antennas and implemented on the backhaul link using the LTE-Advanced compliant system level simulator. Earlier studies in [7] have considered the backhaul link to be the capacity bottleneck of the system and, with the use of a large backhaul antenna array, the network capacity and throughput of onboard users improved significantly. Hence we focus on how to extensively improve the backhaul link throughput and limit the effect of delayed CSI feedback resulting from the high speed. We show that the backhaul throughput of the cooperative MRN system is further improved with the use of LTE precoders at certain instances on a realistic cellular network.

II. SYSTEM MODEL

A. Cooperative MRN Description

The moving relay deployment we address is based on dedicated moving relays in LTE/LTE-Advanced serving the train users in a high speed train that consists of eight carriages, illustrated in Fig. 1, where a moving relay node is installed in each of the eight carriages of the train. The eight MRNs connect to the donor cells in a coordinated and cooperative fashion to ensure sufficiently high data rates for the multiple backhaul link connections. The eight MRNs considered are
Each of the MRNs has multiple antennas on the exterior of the train and spans the length of each carriage. The donor cells connected to the MRNs have the knowledge that the MRNs are cooperating together. The cooperating MRNs are divided into groups based on their CSI information and the strongest MRN link in each group is used as the backhaul link for that group, while the other MRN links in each group are dropped. The choice of the optimal precoder from the codebook for each MRN is calculated from the current CSI.

### B. Signal Description

The LTE-Advanced system level simulator consists of a central hexagonal layout consisting of \((19\text{ sites} \times 3\text{ sectors})\) cells with copies wrapped around the central layout to ensure uniform interference level across the central layout. Each of the eNodeBs and macro UEs/MRNs in the layout are equipped with \(N_T\) transmit and \(N_R\) receive antennas, respectively. The received signal vector \(y_{sc} \in \mathbb{C}^{N_R}\) for subcarrier \(sc\) for each UE/MRN can be expressed as

\[
y_{sc} = H_{sc}F_{sc}x_{sc} + \sum_{l} H_{sc}^{l}F_{sc}^{l}x_{sc}^{l} + n_{sc}
\]  

where \(H_{sc} \in \mathbb{C}^{N_R \times N_T}\) is the channel matrix for subcarrier \(sc\) of the desired signal, \(x_{sc} \in \mathbb{C}^{N_T}\) is the desired transmit signal vector per subcarrier, \(F_{sc} \in \mathbb{C}^{N_T \times N_L}\) is the precoding matrix of index \(i\) chosen from the codebook for the desired channel, the superscript \(l\) identifies the interfering components and \(n_{sc} \sim \mathcal{CN}(0,N_0I_{N_R})\) represents the additive noise vector. The closed loop and open loop spatial multiplexing transmission schemes were implemented on the MRN backhaul link at a train speed of 1 km/h and 300 km/h, respectively. The RI indicates the number of transmission layers for spatial multiplexing [8] and the value which is \(\leq \min(N_T, N_R)\) is defined by the level of linear dependency among the antennas in the channel.

We considered the minimum mean square error (MMSE) receiver in our simulation with the effective channel matrix defined as

\[
H_{sc}^* = H_{sc}F_{sc}^*.
\]  

The MMSE filter decouples the transmitted data streams at the receiver with the decision variables generated as \(d_{sc}^* = W_{sc}H_{sc}^*y_{sc}\) and the filter weight matrix \(W_{sc} \in \mathbb{C}^{N_R \times N_T}\) is obtained by minimizing the mean square error defined as \(\mathbb{E}[||d_{sc} - W_{sc}H_{sc}^*y_{sc}||^2]\) and is given as

\[
W_{sc} = (H_{sc}^*H_{sc} + R_{sc})^{-1}H_{sc}^*.
\]  

The corresponding user’s SINR for subcarrier \(sc\) at the output of the MMSE receiver is given by

\[
\gamma_{sc} = \frac{P_t \cdot \text{diag}(\text{abs}(W_{sc}R_{sc}W_{sc}^*))}{\text{diag}(\text{abs}(W_{sc}^*R_{sc}W_{sc}))}
\]  

where \(P_t\) is the transmission power, \(R_{sc}\) is the interference plus noise covariance matrix and \(\text{diag}(\cdot)\) denotes the diagonal element of the argument.

### III. IMPLEMENTATION SCENARIO

In our simulation, the fast fading multipath channel model based on [9] was used. The channel was modeled to be realistic with a random LOS or NLOS propagation condition leading to random correlation scenarios. The application of precoding in our implementation improves system performance with signal isolation and/or beamforming (depending on the ratio between the number of transmit antennas and the number of spatial layers), when the multipath channel is unable to provide adequate SINR at one or more of the receive antennas by increasing or equalizing the received SINR across the receive antennas. The performance of the precoded spatial multiplexing scheme is directly related to the received SINR and the channel correlation properties which depend on the antenna spacing and configuration.

#### A. Closed Loop Precoded Operation on Cooperative MRN

The LTE codebook consists of a limited set of precoder matrices with each matrix corresponding to an index number. At each of the MRN receivers in each group formed, the PMI selects the appropriate index number based on the instantaneous channel condition and the MRN with the best channel quality signals its PMI back to the eNodeB with the remaining MRNs in the group becoming dormant. Then the eNodeB applies the precoder matrix corresponding to the index number received for its next transmission. The LTE codebook for four and two transmit antennas were implemented in our simulation. The precoder matrices for four transmit antenna were generated from the householder transformation to reduce computational complexity according to

\[
F_{n_4} = I_4 - \frac{2u_nu_n^H}{u_n^Hu_n}
\]  

where \(I_4\) is the \(4 \times 4\) identity matrix, the vector \(u_n\) is obtained from \(8PSK\) elements and the superscript \(H\) denotes conjugate complex transposition. The codebook indices and values can be found in [10].

#### B. PMI Selection for Closed Loop Operation

The PMI can be selected based on either capacity or SINR. The precoder selection presented in this paper is based on the capacity/mutual information selection criterion which obtains from the codebook, the appropriate precoder matrix by calculating the mutual information experienced by the channel for each subcarrier using the available precoding matrices in...
the LTE codebook. And then, choosing the precoder matrix that gives the maximum mutual information for each subband. The selection criterion can be expressed as

$$C_{sc}(F_i) = \log_2 \det \left( I_{N_L} + \frac{\varepsilon_s}{N_L N_0} P_i H_{sc}^H H_{sc} F_i \right)$$

where $I_{N_L}$ is the $N_L \times N_L$ identity matrix, $\varepsilon_s$ is the energy per bit to noise power spectral density ratio and $N_L$ is the number of transmission layers.

**C. Open Loop Precoded Operation on Cooperative MRN**

The open loop precoded spatial multiplexing operation is suitable for high mobility scenarios because it provides an increased level of diversity by transmitting delayed versions of the time domain signal simultaneously from the multiple antennas of the active MRN in each group formed. The PMI is not required, only the RI feedback is used to determine the size of the precoding matrices that will be applied cyclically across the subcarriers. A subset of the LTE codebook is used in combination with DFT matrices and large cyclic delay diversity matrices and expressed in this form

$$F_{sc} = F_n[i_{sc}] \ast D_{sc} \ast U$$

where $F_n[i_{sc}]$ is a $N_T \times N_L$ precoding matrix from the LTE codebook, $D_{sc}$ is a cyclic delay diversity (CDD) matrix of size $N_L \times N_L$ that changes with the subcarriers, $U$ is a fixed DFT matrix of size $N_L \times N_L$ and $N_T$ is the number of transmit antennas. The CDD $D_{sc}$ and the DFT $U$ matrix are defined for $2$, $3$, and $4$ transmission layers in [10]. In our implementation for two transmit antennas, $F_n[i_{sc}]$ was fixed while for four transmit antennas, $F_n[i_{sc}]$ varied among four precoding matrices obtained from the LTE codebook with respect to a cyclic increase of the index $i_{sc}$ according to

$$i_{sc} = \text{mod}(\text{floor}(sc/N_L), 4) + 1,$$

where $sc$ is the index of the subcarrier and $\text{floor}(X)$ rounds the expression in brackets to the nearest integer less than or equal to $X$.

**D. Dynamic Rank Selection**

In this paper, the transmission rank was estimated at the terminal (MRN) and a single rank was applied across the whole bandwidth for each active MRN in the cell. In our implementation, the RI feeds back the selected rank alongside with the channel quality indicator (CQI) and/or PMI to the eNodeB. In the closed loop transmission, dynamic rank selection was achieved with the different set of precoders for different number of antennas using (6), while for the open loop transmission, rank adaptation was achieved by maximizing the obtained capacities through the SINRs at the MMSE receiver for different number of possible transmission layers in such a way that the number of parallel transmission streams $N_L$ over the channels are assumed to be decorrelated at the MMSE receiver with the total SINR spread among the layers. Based on the SINR values, rank adaptation was achieved by evaluating the channel capacity for each layer at the MMSE receiver. The total channel capacity for the number of layers used for transmission is given as

$$C_R(\gamma_{M,sc}) = \sum_{r=1}^{R} \sum_{sc=1}^{N_L} \left\{ \log_2 \left( 1 + \frac{N_{MRN} R}{\gamma_{M,sc}} \right) \right\}$$

where $\gamma_{M,sc}$ is the MMSE post processed SINR for each layer in the transmission per subcarrier obtained from (4), $N_{MRN}$ is the number of receive MRN antennas, and the maximum value of $R$ is min($N_T, N_{MRN}$). The adaptation process is illustrated in Fig. 2.

**Fig. 2. Flow diagram of the closed and open loop rank adaptation processes.**

**IV. PERFORMANCE EVALUATION**

The impact of applying closed loop codebook based precoding on the backhaul throughput of the cooperative MRN is evaluated when the train is assumed stationary.

**TABLE I. SIMULATION PARAMETERS.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>System bandwidth</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Number of macro UEs</td>
<td>570</td>
</tr>
<tr>
<td>Number of MRNs</td>
<td>8 (1 in each carriage)</td>
</tr>
<tr>
<td>Propagation scenario</td>
<td>suburban macro</td>
</tr>
<tr>
<td>MRN duplex mode</td>
<td>half duplex FDD</td>
</tr>
<tr>
<td>eNodeB → MRN antenna config</td>
<td>2x2, 2x4, 4x4, 4x8</td>
</tr>
<tr>
<td>MRN transmission scheme</td>
<td>SU-MIMO spatial multiplexing</td>
</tr>
<tr>
<td>MRN transmission mode</td>
<td>open loop and closed loop precoding</td>
</tr>
<tr>
<td>HARQ</td>
<td>chase combining</td>
</tr>
<tr>
<td>Receiver type</td>
<td>MMSE</td>
</tr>
<tr>
<td>L2S interface metric</td>
<td>MIESM [11]</td>
</tr>
<tr>
<td>Train carriage wall attenuation</td>
<td>20 dB</td>
</tr>
<tr>
<td>Train speed</td>
<td>1 km/h and 300 km/h</td>
</tr>
</tbody>
</table>

The throughput for four different antenna configurations were considered with the different possible precoding sets applied from the LTE codebook. The application of the open loop precoding was also considered at a train speed of 300 km/h and was implemented with large cyclic delay diversity alongside a subsection of the LTE codebook. The main parameters for the simulation are given in Table I and the antenna configurations with the corresponding precoder set applied are listed in Table II.

With 2 transmit antennas at the eNBs and transmission rank 2, three precoding choices are available in the LTE codebook,
while for 4 transmit antennas at the eNBs, 16 precoders were derived for each transmission layer to choose from. The PMI selection for the closed loop operation was based on maximizing the channel mutual information. Simulations were done with 1000 drops with 50 channel samples in each drop. The backhaul throughputs were obtained and compared with the unprecoded spatial multiplexing transmissions of the same antenna configuration.

### A. Closed Loop

Fig. 3 shows the cumulative distribution function (CDF) of the backhaul link throughput for $2 \times 2$ and $2 \times 4$ antenna configurations with $2 \times 2$ LTE precoder set at a train velocity of 1 km/h. The throughput performance of the backhaul link is degraded slightly with the application of the $2 \times 2$ LTE precoder set.

Fig. 4. CDF plot of $4 \times 4$ MRN backhaul throughput with $4 \times 2$ closed loop precoding at 1 km/h.

The 50% point on the CDF curve of Fig. 4 shows an increase of 3 Mbps in the precoded throughput as compared to the unprecoded throughput. The gain in throughput is achieved by the $4 \times 2$ precoding which provides a combination of improved orthogonalized layer transmission and beamforming. Since the number of layers ($N_L$) is less than the number of transmit antennas ($N_T$), the precoding provides a mapping of $N_T \rightarrow N_L$ achieving beamforming and with the number of receive antennas ($N_{MRN}$) equal to the number of transmit antennas, the 2 spatial layers constructed achieve improved isolation at the receiver side which yields the improved performance in Fig. 4. Since the MRN receive antennas are widely spaced and span the length of the train, it results in highly uncorrelated channels between the cooperative MRN antennas and the eNBs and the effects of the precoders applied are minimal.

### B. Open Loop

Spatial multiplexing for $4 \times 4$ and $4 \times 8$ antenna configuration with the application of $4 \times 4$ and $4 \times 2$ LTE precoding set are presented in Figs. 5 and 6.

Fig. 5. CDF plot of $4 \times 4$ MRN backhaul throughput with $4 \times 4$ and $4 \times 2$ open loop precoding at 300 km/h.

The increase in speed causes the four spatial layers constructed to loose a certain degree of orthogonality. In both

<table>
<thead>
<tr>
<th>Antenna configuration ($N_T \times N_{MRN}$)</th>
<th>LTE precoder ($N_T \times N_L$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2 \times 2$</td>
<td>$2 \times 2, 2 \times 1$</td>
</tr>
<tr>
<td>$2 \times 4$</td>
<td>$2 \times 2$</td>
</tr>
<tr>
<td>$4 \times 4$</td>
<td>$4 \times 4, 4 \times 2$</td>
</tr>
<tr>
<td>$4 \times 8$</td>
<td>$4 \times 4, 4 \times 2$</td>
</tr>
</tbody>
</table>
Throughput [Mbps]
CDF

throughput and a 8 Mbps increase is achieved with the precoded throughput at 300 km/h. When comparing the unprecoded with the 4 × 2 precoder set, the gain in throughput is as a result of increased frequency diversity which improves the resilience of the spatial multiplexed transmissions.

C. Rank Adaptation

Fig. 7 presents a comparison of the throughput for open loop adaptive ranking at a train speed of 300 km/h with fixed rank transmission for unprecoded, 4 × 4 and 4 × 2 precoding set.

There is a significant increase in the adaptive ranking throughput between the 1% point and 100% point on the CDF curve. At the 60% point on the CDF curve, the increase in throughput compared to the unprecoded is 14 Mbps, while the increases in throughput compared to 4 × 4 and 4 × 2 open loop precoding implementation are 11 Mbps and 6 Mbps, respectively.

V. CONCLUSION

In this paper, we analyzed the throughput gains that can be achieved with the implementation of closed loop and open loop precoding on a cooperative MRN system deployed on a high speed train. Adaptive transmission ranking was also considered in our implementation. Our simulation results with full rank for closed loop operation show that throughput gain cannot be achieved at relatively low speed when compared with the unprecoded spatial multiplexing scheme. But with less than full rank transmission, throughput gain is achieved. Simulation results obtained for open loop operation show performance improvement in the throughput gain at high speed both for full and less than full rank transmission. Further throughput gain is achieved with adaptive ranking.

ACKNOWLEDGMENT

This research was supported by the Finnish Funding Agency for Technology and Innovation (TEKES), Nokia Siemens Networks (NSN), Renesas Mobile Europe, Elektrobit and Anite Telecoms.

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