Alternative to Dynamic Rank Transmission for LTE Mobile Relay Node System

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Abstract—To obtain the appropriate number of layers for spatial multiplexing transmission on a high speed train equipped with moving relay nodes (MRN) cooperating with each other, the rank indicator (RI) is required. The conventional methods for calculating the RI have high levels of computational complexity and to dynamically obtain the RI based on the channel conditions require multiple times the computational complexity of a fixed rank transmission. We derive a method to reduce the computational complexity such that the RI is fixed, but the antenna positioning vary dynamically based on the channel conditions. Our simulation results show that our proposed method can achieve nearly the same throughput as with dynamic rank transmission schemes on the backhaul link with reduced complexity.

I. INTRODUCTION

The long term evolution (LTE) based mobile telecommunication system takes advantage of multiple input and multiple output (MIMO) schemes and orthogonal frequency division multiplexing (OFDM) techniques to attain higher data rates and achieve improved spectral efficiency. Additional technological components introduced by 3GPP (Third Generation Partnership project) such as carrier aggregation, coordinated multiple point transmission and advanced relay technology served as extensions in the fulfillment of International Mobile Telecommunications Advanced (IMT-Advanced) requirements specified by the International Telecommunication Union-Radiocommunication (ITU-R) [1].

Spatial multiplexing scheme can increase the capacity of the communication link in linear proportion to the number of possible spatial layers by exploiting the multipath characteristics of the wireless channel [2] but with increased constraints such as increased sensitivity to rank defects. In order to reduce the effect of rank defect and at the same time improve the SINR and limit the signaling overhead on the channel state information (CSI) feedback, the LTE/LTE-A standard adopted the use of codebook based precoding in its spatial multiplexing scheme [3].

With the increasing number of large high speed vehicles deployed such as the high speed train moving at velocities as high as 350 km/h, new challenges are faced in trying to ensure and maintain good quality services to mobile users onboard. The use of moving relay nodes (MRN) on the high speed vehicles to serve as backhaul links form a part of the solution as vehicular penetration losses can be eliminated, as well as large signalling overhead can be significantly reduced by performing group handover instead of individual mobile user handover. Combining the use of MRN and open loop spatial multiplexing, which adapts well to high mobility scenario, improves the throughput on the backhaul links. One of the key components of the open loop scheme is the rank indicator (RI) which forms part of the CSI, indicates the number of transmission layers that can maximize the throughput. Hence, to effectively maximize the downlink backhaul throughput, the rank indicator dynamically calculates the number of transmission layers according to the channel condition. However dynamic computation of the transmission rank in such high mobility scenario is difficult to achieve in reality due to feedback delay and signal processing hardware constraints.

In [4], computational burden was approached by not considering every subcarrier in the transmission rank calculation. Studies in [5] considers lowering computational complexity in RI calculation by sampling the reference signal (RS) channels. These two approaches are similar as they calculate the average capacity with a subset of the available subcarrier/RS channels and prior knowledge of the antenna correlation level is assumed.

This paper provides an alternative method to maximize the downlink backhaul throughput of a cooperative MRN system on a high speed train with eight carriages at a velocity of 300 km/h while using the open loop spatial multiplexing scheme. The proposed scheme aims at reducing the delayed feedback resulting from high speed. Our results show that the alternative method which exploits the transmit antenna position in selecting the transmitting antennas with low computational complexity can achieve nearly the same throughput as with dynamic rank transmission, that involves very high computational effort. The simulations were carried on the LTE-Advanced compliant system level simulator.

The paper is organized as follows. Section II describes the system and signal model of our implementation. Section III describes the computational effort involved in obtaining the rank for transmission. Section IV gives a detailed explanation of our proposed scheme and algorithm. Simulation scenarios and analysis are presented in Section V and Section VI draws conclusions.
II. SYSTEM MODEL

A. Cooperative MRN Description

The high speed train was modeled with eight carriages with each carriage having a MRN installed. The cooperation and coordination of the MRNs in the high speed train is based on [6]. The cooperation of the MRNs, which is achieved via a crX2 interface, ensures improved spectral efficiency for the multiple backhaul link connections.

Each of the MRNs have multiple antennas on the interior and exterior of the train and span the length of each carriage with the internal and external antennas serving the access link and the backhaul link, respectively. The exterior antennas achieve better diversity gain on the backhaul link compared to direct connection while the interior antennas serve mobile users onboard and due to the relative positions of the mobile users w.r.t. the interior antennas, very high data rate can be achieved with reduced mobile user transmit power.

B. System Layout

The LTE-Advanced system level simulator used and the simulation parameters in this research has been calibrated following the guidelines established by the international telecommunications union radiocommunications sector (ITU-R) for IMT-A (international mobile telecommunications advanced) radio interface evaluation [1]. The length of a simulation is determined by the number of drops, where a drop is an instance of the network where the macro UEs/MRN are distributed randomly/systematically and fixed for the duration of the drop.

The LTE-Advanced system level simulator consists of a central hexagonal layout consisting of (19 sites × 3 sectors) cells with copies wrapped around the central layout to ensure uniform interference level across the central layout. A track with a radius of about 4 km with random origin is placed across the central layout such that it passes 50 m from the eNodeB at the start of a layout initialization and at the beginning of the drop, the high speed train is positioned on one end of the track inside the central layout and as the drop increases, the train moves along the track to the other end.

To model a realistic scenario, macro UEs are randomly distributed across the central layout in each drop during the simulation as illustrated in Fig. 1.

The simulator also utilizes the wireless world initiative new radio phase II (WINNER II) channel model which follows a geometry based stochastic channel modeling approach, allowing the creation of an arbitrary double direction radio channel independent of any antenna configuration [7].

So each of the eNBs and macro UEs/MRN in the layout is equipped with $N_T$ transmit and $N_R$ receive antennas, respectively.

C. Signal Description

Frequency Division Duplex (FDD) and Time Division Duplex (TDD) operating modes have been developed for LTE systems and can be implemented over a range of bandwidths. In this paper, the FDD orthogonal frequency division multiple access (OFDMA) configuration is considered with a channel bandwidth of 10 MHz according to the LTE standards [8].

For transmissions from the eNodeB to macro UEs, SU-MIMO with space frequency transmit diversity (SFTD) is applied following the LTE specifications [9] and for transmissions from the eNodeB to the cooperative MRN system, the open loop precoded SU-MIMO spatial multiplexing scheme is applied.

The received signal vector for the SU-MIMO transmission $y_{sc} \in \mathbb{C}^{N_R \times 1}$ for subcarrier $sc$ for each UE/MRN can be expressed as

$$y_{sc} = H_{sc} F_{i} x_{sc} + \sum_{i} H_{i} F_{i} x_{sc} + n_{sc}$$

where $H_{sc} \in \mathbb{C}^{N_R \times N_T}$ is the channel matrix for subcarrier $sc$ of the desired signal with $N_R \geq N_T$, $x_{sc} \in \mathbb{C}^{N_T \times 1}$ is the desired transmit signal vector per subcarrier, $F_{i} \in \mathbb{C}^{N_T \times N_L}$ is the open loop precoding matrix of index $i$ given by

$$F_{i} = F_{n[i]} * D_{sc} * U$$

where $F_{n[i]}$ 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 index of the subcarriers, $U$ is a fixed DFT matrix of size $N_L \times N_L$ and $N_L$ is the number of transmission layers, the superscript $i$ identifies the interfering components and $n_{sc} \sim \mathcal{C}\mathcal{N}(0, N_0)$ represents the additive noise vector.

The CDD $D_{sc}$ and the DFT $U$ matrix are defined for 2, 3, and 4 transmission layers in [10]. In our simulation, the matrices for two transmission layers were implemented since we restricted our transmission on two transmit antennas even though we have four transmit antennas. The RI indicates the number of transmission layers for spatial multiplexing [11] and the value which is ≤ min($N_T, N_R$) is defined by the level of linear dependency among the antennas in the channel.

The minimum mean square error (MMSE) receiver was implemented in our simulation with the effective channel matrix defined as

$$H_{sc} = H_{sc} F_{i}$$

with the omission of $F_{i}$ for macro UEs. The MMSE filter can be achieved by the filter weight matrix $W_{ac} \in \mathbb{C}^{N_R \times N_T}$ and
it decouples the transmitted data streams at the receiver. The MMSE filter is obtained by minimizing the mean square error defined as $E\left[\|x_{sc} - W_{sc}^H y_{sc}\|^2\right]$, where

$$W_{sc} = (H_{sc}^* H_{sc}^H + R_{sc})^{-1} H_{sc}^* .$$

(4)

The corresponding UE’s SINR for subcarrier $sc$ at the output of the MMSE receiver is given by

$$\gamma_{M,sc} = \frac{P_t \times \text{diag}(W_{sc}^H H_{sc}^*)^2}{\text{diag}(W_{sc}^H R_{sc} W_{sc})}$$

(5)

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

$$R_{sc} = \sum_i P_t^i H_i^H H_i^H + n_{sc}$$

(6)

with $I$ representing the interfering components.

D. Link to System Level Mapping

Link to system level mapping is designed to model the physical layer for system level simulation. The huge computational complexity resulting from link level simulations of large number of links that are present in system level simulations, necessitates a simplified model of the link layer to estimate the frame error probability (FEP) based on the instantaneous channel realization, known as link layer abstraction [12]. The link layer abstraction algorithm used in our simulator utilizes the mutual information effective SINR metric (MIESM) in which each SINR value per subcarrier calculated, is mapped to a mutual information curve according to the selected modulation schemes. Then the average mutual information is exploited to obtain the average effective SINR for each user from the curve, which is in turn mapped using a lookup table to a FEP corresponding to the coding rate of the transmission. This FEP is then inputted in a random frame error process to determine whether a frame error has occurred or not.

E. Resource Scheduling

The resource scheduler deployed at the eNodeB distributes available resources among the active users in order to maximize the overall throughput and at the same time be as fair as possible. The resources are shared based on the proportional fair scheduling algorithm and the scheduling process is done such that the eNodeB is aware of the users that are macro UEs and the onboard users served by the cooperative MRN system. Hence, the scheduler splits resources between the macro UE and the MRN backhaul links based on the number of active macro UEs and onboard users. A maximum of 50 percent of the resources are made available to the backhaul link due to its half duplex operation. Once the resources are split and allocated, the reported CQI value for each user and the reported RI are used to select the appropriate modulation and coding scheme (MCS) for transmission.

III. COMPUTATIONAL COMPLEXITY OF DYNAMIC RANK SCHEMES

The use of codebook precoders and dynamic rank transmissions achieved through RI selection in LTE systems provides robust link connections and enhanced capacity. The RI feeds back the selected rank along with the CQI report and/or PMI to the eNodeB and is only applicable for open loop and closed loop spatial multiplexing when $RI \geq 2$. If $RI = 1$, transmission mode switches to transmit diversity in case of open loop spatial multiplexing transmissions. Different RI selection schemes have been proposed, most of which have a very high level of computational complexity when trying to implement dynamic rank selection, as the RI schemes are repeated as many times as the possible number of transmission layers.

A. Capacity Based Rank Adaptation

One of the RI schemes used with the closed loop transmission is the capacity based rank adaptation [13], which involves the selection of the RI based on maximizing the capacity such that the average capacity over all subcarriers for each possible transmission layer along with all the possible codebook precoders is calculated for every user according to

$$C(F_i) = \sum_{sc=1}^{N_{sc}} \log_2 \det \left( I_{N_{sc}} + \frac{\varepsilon_{sc}}{N_{sc} N_0} P_i H_{sc}^H H_{sc} F_i \right).$$

(7)

Then the RI is selected according to

$$RI = \arg \max_{N_L \in [1.. \min N_R, N_R]} 1 \sum_{F_i \in \text{codebook}} \left( \max_{C(F_i)} \right).$$

(8)

Hence for dynamic rank transmissions, in one TTI with four transmit antennas and 16 codebook based precoders for each transmission layer at a bandwidth of 10 MHz, the number of computations involved to select the appropriate RI includes 38,400 capacity calculations resulting from 50 RBs × 12 subcarriers/RB × 4 transmission layers × 16 precoders/layer. The capacity calculation involves 115,200 matrix multiplications and 38,400 determinant calculations. However, if we assume that a range of successive subcarriers is correlated, the number of capacity calculations can be reduced by a factor corresponding to the number of successive subcarriers that are correlated.

B. MMSE-post Capacity Based Rank Adaptation

A RI selection scheme used with the open loop transmission is the MMSE-post capacity based rank adaptation in which the SINRs obtained for different layered transmissions at the MMSE receiver are used to calculate the capacity and the RI is selected based on maximizing the capacity. The capacity calculation is influenced by the SINR according to

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

(9)

where $\gamma_{M,sc}^r$ is the MMSE post processed SINR for each layer in the transmission per subcarrier obtained from (5), and $R$ represents the different possible number of transmission layers.
where the maximum value of $R$ is $\min(N_T, N_R)$. The RI is selected according to

$$\text{RI} = \arg\max_{N_L \in [1, \ldots, \min(N_T, N_R)]} \left( \frac{1}{N_L} \right) C_R(\gamma_{max}). \quad (10)$$

The computational effort in obtaining the RI selection for dynamic transmissions involves 2,400 capacity calculations resulting from 50 RBs \times 12 subcarriers/RB \times 4 transmission layers. From (4), (5) and (9), we can observe that there are five times matrix multiplication with one matrix inversion for every capacity calculation yielding a total of 12,000 matrix multiplications.

With this high computational effort, implementing on real systems will require high complexity and increased operational cost. However, an alternative to rank adaptation is proposed such that the RI is fixed and the positions of the transmit antennas are exploited with less computational effort and achieving almost equal throughput.

IV. ALTERNATIVE METHOD TO DYNAMIC RI CALCULATION

We propose an alternative method derived from [14] to maximize the downlink backhaul link throughput of our cooperative MRN system with considerably less computational complexity than with the conventional methods of calculating the RI. For $N_T \times N_R$ antenna configuration with $N_T = 4$, instead of trying to calculate the suitable number of transmission layers ranging between 1 and $\min(N_T, N_R)$, the RI sets the number of transmission layers equal two and an algorithm is put into place to select the appropriate two transmit antennas at the eNodeB that will maximize the throughput. With four transmit antennas, there are six possible antenna positions that can be obtained as illustrated in Fig. 2.

Algorithm 1 Alternative algorithm

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>procedure API($H_{sc}$, RI)</td>
</tr>
<tr>
<td>2</td>
<td>Estimate $H_{sc}$</td>
</tr>
<tr>
<td>3</td>
<td>$RI = 2 \quad \triangleright$ Set rank indicator equal 2 for $N_T = 4$</td>
</tr>
<tr>
<td>4</td>
<td>for $i = 1 : N_T$ do</td>
</tr>
<tr>
<td>5</td>
<td>$w(i) = \frac{1}{N_T} \sum_{sc=1}^{N_T}</td>
</tr>
<tr>
<td>6</td>
<td>$c(:, i) = \frac{1}{N_T} \sum_{sc=1}^{N_T}</td>
</tr>
<tr>
<td>7</td>
<td>end for</td>
</tr>
<tr>
<td>8</td>
<td>for $i = 1 : N_T$ do</td>
</tr>
<tr>
<td>9</td>
<td>$\text{met}(i) = \frac{1}{\text{rowsum}} (c(:, i) \times w(i^*))$</td>
</tr>
<tr>
<td>10</td>
<td>end for</td>
</tr>
<tr>
<td>11</td>
<td>Select the two minimum elements of $\text{met}$ which represents the position of transmit antenna elements that will be used for transmission</td>
</tr>
<tr>
<td>12</td>
<td>Enhance transmission of two data streams on two transmit antennas with the application of $2 \times 2$ open loop codebook whose structure is given in (2)</td>
</tr>
<tr>
<td>13</td>
<td>end procedure</td>
</tr>
</tbody>
</table>

The algorithm which involves series of vector multiplications and avoids capacity calculations and matrix multiplications is described in Algorithm 1.

Each element in the obtained vector $\text{met}$ represents the position of each transmit antenna at the eNodeB and determines which antennas will be active during transmission. The division in Algorithm 1 is element by element division and $i^*$ represents the columns of the channel matrix $H_{sc}$/signal strength vector $w$ excluding the $ith$ column in question. Index 5 and 6 from the algorithm, obtains the signal strength and correlation level from the $ith$ transmit antenna w.r.t. the receive antennas from the channel matrix respectively. Index 9 obtains the two antenna positions that will maximize the signal power and at the same time minimize the correlation between the two selected antennas. An additional indicator will be reported back to the eNodeB. We call this the antenna position indicator (API) which indicates a number between 1 and 6 according to Fig. 2. The eNodeB selects the two transmit antennas to use for transmission based on the API and the transmission is enhanced with the application of the $2 \times 2$ open loop codebook.

![Table I: Simulation parameters.](image_url)
V. SIMULATION SCENARIOS AND RESULTS

A. Simulation Scenarios

We consider the impact on the backhaul throughput of the cooperative MRN system, when two transmit antennas are selected using API from a total of four transmit antennas as compared to having only two transmit antennas at the eNodeB at a train speed of 300 km/h. The main parameters for the simulations are given in Table I.

We also compared the backhaul throughput of the API selection method to the case where all the four transmit antennas are used with full rank transmission. And finally the transmission from the eNodeB was enhanced with open loop codebook implementation and the throughput was compared to dynamic rank transmission. Simulations were done with 1000 drops with 50 channel samples in each drop.

B. Simulation Results

The performance evaluation of our proposed scheme is based on the backhaul link throughput that can be achieved. Fig. 3, shows the cumulative distribution function (CDF) of the backhaul link throughput for transmissions with antenna configurations $4 \times 4$ and $2 \times 4$ without openloop implementation.

According to Fig. 3, at the 50% mark on the CDF curve, a throughput gain of about 13% was achieved with $2 \times 4$ API antenna configuration when compared with $4 \times 4$ fixed antenna configuration. Also shown in Fig. 3 is a comparison of $2 \times 4$ fixed antenna configuration with $4 \times 4$ fixed antenna configuration in which a throughput gain of 1 Mbps was achieved in the later case. The result shows that transmitting on two antennas with API implementation achieves throughput improvement when compared with transmission on four transmit antennas. The CDF of the backhaul link throughput for the case of dynamic rank transmission and API implementation with openloop precoding is shown in Fig. 4. The result shows similar throughput response between the dynamic ranking transmission and the API transmission with openloop precoding until the 60% mark. A maximum throughput loss of 2 Mbps was observed at 90% mark. Also shown in Fig. 4 is a comparison of fixed $4 \times 2$ openloop precoding on $4 \times 4$ antenna configuration with the dynamic transmission and a throughput gain of about 7 Mbps was achieved in the later case at the 50% mark.

VI. CONCLUSION

In this paper, we introduced an alternative scheme to dynamic rank spatial multiplexing transmission in a high speed train incorporated with cooperative MRN system with the aim of reducing computational complexity and reduce the impact of feedback delay in terms of the rank selection while till maintaining a lower feedback overhead. An additional indicator, API was introduced which forms part of the CSI report. About 13% increase in throughput was achieved with API when compared to the use of all four transmit antennas. Simulation results show that we can achieve almost same backhaul throughput with the alternative scheme when compared to dynamic rank transmissions for open loop operation with number of transmit antennas equal to four.

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