Evaluation Of Different Transmission Modes In Coordinated Homogeneous And Heterogeneous Networks

Antony Onim, S. Musyoki, P. K. Kihato

Abstract: LTE supports different transmission modes such as: Single Input Single Output (SISO), Transmission diversity (TxD) and Multiple Input Multiple Output (MIMO). TxD aims at improving the signal strength at the receiver by using two or more transmit antennas while MIMO techniques are used to increase the throughput according to the number of antennas used. Coordinated Multipoint (CoMP) techniques reduce interference and improve signal strength. Homogeneous networks consist entirely of macrocells while heterogeneous networks (HetNets) have both macrocells and femtocells. HetNets are used to meet increased mobile traffic demands by providing low power nodes closer to the user equipment. This paper reviews popular transmission modes and investigates their performance in both homogeneous and heterogenous CoMP networks. Simulation of the different transmission modes is carried out and results show that CLSM is the best transmission mode to use in in homogeneous networks, and that CLSM and OLSM perform equally well in HetNets. Additionally, HetNets were found to provide significant throughput gains over homogeneous networks.

Index Terms: LTE, CoMP, HetNets, SISO, MIMO, throughput.

1. INTRODUCTION

The need for coordinated multipoint (CoMP) transmission and reception is driven by the rising demand for better quality services at the user equipment (UE) terminal and the limited frequency spectrum. CoMP transmission techniques make use of multiple transmit and receive antennas from different antenna site locations to reduce inter-cell interference and increase cell edge throughput [1]. Several base stations (BSs) work together in a manner that ensures the transmitted signals do not interfere with each other and can even be exploited as meaningful signals. Coordinating base stations are called a cooperating set. CoMP in LTE Release 11 exploits the low latency and high capacity backhaul between base stations in a cooperating set. Therefore, UE data may be available at multiple cooperating base stations. CoMP has been rigorously studied by 3GPP for the LTE-A standard development in [2,3]. In homogeneous networks, all the BSs are of the same type and class. The network deployment is based on macrocells only. In contrast, heterogeneous networks deploy low-power nodes called femtocells within macrocells, to meet increasing mobile traffic demands. Femtocells use low transmission power to deliver good quality indoor communications, hence improving the data rate at a low cost [4, 5]. Since the macrocells and femtocells utilize the same frequency spectrum, co-channel interference between them must be within acceptable limits [6]. Femtocells are a promising area for CoMP application [1]. CoMP would not be possible without LTE support for both SISO and MIMO transmission modes. The multi-antenna transmission modes are primarily used to improve diversity, data rate or both and include transmission diversity (TxD) and spatial multiplexing. How these transmission modes perform in different network environments i.e. in homogeneous coordinated networks versus in heterogeneous coordinated networks, is an interesting area of research.

2. RELATED WORK

In [1], D. Lee et al. discuss the different scenarios in which CoMP may be deployed in LTE-A transmission and reception, and their operational challenges. The authors conduct performance evaluations for CoMP based on simulation assumptions and modelling described in [7], and conclude that CoMP provides throughput gains over the single cell deployment for both homogeneous and heterogeneous networks. They also conclude that a greater number of UEs are likely to benefit from CoMP in heterogeneous networks. In [8], G. Nardini et al. develop a model for large scale coordinated scheduling through layering. In the first level, a cluster of three cells is coordinated. In the next, these clusters are then coordinated with other clusters. The authors treat both small scale and large-scale coordination as optimization problems and generate sub-optimal solutions using heuristic algorithms. However, their work focuses only on the coordinated scheduling aspect of CoMP and it is unclear whether their approach can be used for joint transmission or dynamic point selection CoMP.

In [9], M. Ammar et al. investigate transmission diversity and OLSM for LTE downlink transmission. After a thorough review of these transmission modes, they conclude, through their simulation results, that transmit diversity is suitable for channels with poor SINR while OLSM performs better in channels with good SINR conditions.

3. CONTRIBUTIONS OF THE PAPER

This paper reviews selected transmission modes and investigates their performance in CoMP enabled homogeneous and heterogeneous networks. Simulation and analysis of the different transmission modes is done using the Vienna LTE-A Downlink System Level simulator. The following modes of transmission are investigated:

- Single antenna (SISO)
- Transmit diversity (TxD)
- Open loop spatial multiplexing (OLSM)
- Closed loop spatial multiplexing (CLSM)
- Rank 1 CLSM

Metrics used for the evaluation of the transmission modes include throughput (mean, edge, and peak), spectral efficiency and SINR. Results show that CLSM is the best performing transmission mode in both network environments. Results also show that heterogeneous
networks do provide significant throughput gains over homogeneous ones.

4. Overview of General CoMP Techniques
The backhaul characteristics of the X2 interface greatly determine how CoMP can be applied in the network. Such characteristics include latency and capacity (data rate). These attributes determine what kind of CoMP technique can be used and its performance. Considering the various possible network topologies and backhaul characteristics in LTE-A, research into CoMP has focused on the following cases [1]:

- Coordination between sectors of the same BS. In this case, a backhaul connection is not necessary.
- Coordination between cells that are controlled by different base stations.
- Coordination between a base station and several low power nodes within its coverage area. Each transmission node controls its own cell and has an independent cell identity. Similar to 3, with the difference that the low power nodes form scattered antennas of the base station and have a similar identity as the base station.
- Cases 1 and 2 are encountered in homogeneous networks while cases 3 and 4 are encountered in heterogeneous networks.

CoMP can be implemented in one of three ways:
- Coordinated Scheduling and Beamforming (CS/CB). The data for the UE can only be found at one base station within the cooperating set. Data is therefore sent from one base station. Information from the other base stations in the cooperating set is used to coordinate scheduling, link adaptation and beamforming tasks so as to reduce inter-cell interference. Dynamic Point Selection (DPS). The serving base station, also called the transmission point (TP), can be altered at every transmission period (1 ms), in order to transmit optimally to a UE that is experiencing changing channel conditions. The UE data is required to be readily accessible at several base stations in the cooperating set. DPS is mostly applied at the edges of cells, where long-standing channel conditions favour the primary TP, but current conditions favour other BSs in the cooperating set. Joint Transmission (JT). This involves the simultaneous transmission of UE data from several BSs in the cooperating set. The transmissions may be coherent or non-coherent. Coherent JT enables the receiver to achieve coherent combining of the transmissions by jointly precoding the transmissions from multiple TPs. Non-coherent JT, on the other hand, involves independent precoding of the transmissions by each TP, hence only a gain in power can be achieved at the receiver. The UEs feedback the channel state information (CSI), which the network uses to make CoMP transmission decisions. Each UE feedback report corresponds to different postulates about the transmission decisions made by coordinating BSs. To generate feedback reports, each UE can be equipped with a maximum of four CSI processes. For each CSI process, the UE calculates and reports the CSI indicators required by the network. These indicators include the:
  - Channel Quality Indicator (CQI),
  - Rank Indicator (RI),
  - Precoding Matrix Indicator (PMI),
  - MIMO Transmission Modes

3.1 Transmit Diversity
Transmit diversity utilizes two or more antennas at the transmitter to reduce fading. Since only one receive antenna is used, there is a chance of destructive interference occurring when the two signals add up at the receiver’s antenna [10]. This problem can be solved in either of two ways: In closed loop transmit diversity, a phase shift is applied to either or both signals prior to transmitting them, ensuring that they get to the receiver in phase, with no possibility of destructive interference. The receiver calculates a PMI that is sent back to the transmitter and used to determine the amount of phase shifts to be applied. The PMI is chosen to be a function of frequency because the phase shifts produced by the physical layer are determined by the frequency of the carrier wave. This is convenient for an OFDMA system such as 4G LTE, since the receiver is able to calculate different values of PMI for different sets of subcarriers. For rapidly moving mobiles, however, the PMI could be obsolete when it is received. This is because of the time delays in the feedback loop. Hence, closed loop transmit diversity can be used accurately only for UEs which are moving slowly enough. For rapidly moving UEs, open loop transmit diversity is preferred. Open loop transmit diversity can be implemented using Alamouti’s technique. In this technique, the transmitter sends two symbols, \( s_1 \) and \( s_2 \), in two consecutive time steps, using two antennas. During the first time-step, the transmitter sends \( s_1 \) from antenna 1 and \( s_2 \) from antenna 2. During the second time step, it sends \( s_1^* \) from antenna 1 and \( s_2^* \) from antenna 2. \(*\) represents the complex conjugate). The receiver is then able to make two consecutive measurements of the signal and solves the resulting equations to retrieve the transmitted symbols. Alamouti’s technique works only when the fading patterns remain approximately the same between the two successive time-steps, and when the two signals do not experience fading simultaneously. Both conditions are easily met [10].

Spatial Multiplexing
MIMO spatial multiplexing involves transmitting independent data streams at the same time and frequency. Combined with OFDMA, MIMO spatial multiplexing is extensively used to improve the data transfer rate according to the number of antennas used. The highest data rate which can be achieved is proportional to \( \min(N_T,N_R) \), where \( N_T \) and \( N_R \) are the number of antennas used in the transmitter and the receiver, respectively. Spatial multiplexing techniques include OLSM and CLSM. OLSM only uses the rank indicator, fed back from the UE, to change the number of independent data streams transmitted, while CLSM uses both the rank indicator and a precoding matrix indicator for optimum precoding of the symbols before transmission.

Open loop spatial multiplexing (OLSM)
OLSM uses spatial multiplexing adaptively. It sends multiple symbols simultaneously if the channel behaves well, and reverts to diversity processing otherwise. Figure 1 shows a 2×2 OLSM system. The receiver works out the elements of the channel and calculates a rank indicator (RI) which shows how many symbols it can receive successfully. The
receiver then sends the RI back to the transmitter via a feedback channel [10].

If the RI is two, the transmitter sends two symbols simultaneously. It maps the two symbols $s_1$ and $s_2$, from its transmit buffer, to two independent data streams called layers using its layer mapper. The antenna mapper then uses a straightforward mapping operation to send a symbol to each antenna:

$$x_1 = s_1, \quad x_2 = s_2.$$  \hspace{1cm} (1)

At the receiver, the incoming signals are measured, and the transmitted symbols recovered as:

$$y_1 = H_{11} x_1 + H_{12} x_2 + n_1,$$
$$y_2 = H_{21} x_1 + H_{22} x_2 + n_2.$$  \hspace{1cm} (2)

where $H_{ij}$ represents the channel elements which attenuate and phase-shift the transmitted symbols as they travel from the $j$th transmit antenna to the $i$th receive antenna, $x_1$ and $x_2$ are the transmitted signals, $n_1$ and $n_2$ are the noise and interference at each antenna, and $y_1$ and $y_2$ are the signals received at each antenna. Writing (2) in matrix notation,

$$[\begin{bmatrix} y_1 \\ y_2 \end{bmatrix}] = [\begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix}] [\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}] + [\begin{bmatrix} n_1 \\ n_2 \end{bmatrix}]$$
\hspace{1cm} (3)

where $H$ is an $N_R \times N_T$ matrix of the channel elements, $N_R$ is the number of receiver antennas, $N_T$ is the number of transmit antennas, $x$ is an $N_T \times 1$ matrix of the transmitted signals, and $n$ and $y$ are $N_T \times 1$ matrices of the noise and resultant signals at the receiver, respectively. Assuming the number of transmit and receive antennas are equal, such that $N_T = N_R = N$ and that a zero-forcing detector is used at the receiver AND that the channel matrix $H$ is non-singular, the transmitted symbols may be estimated as

$$x = H^{-1} y.$$  \hspace{1cm} (4)

where $H^{-1}$ is the inverse of the matrix of channel elements, $H$ as estimated by the receiver and $x$ is the receiver’s estimate of the transmitted signals. If the noise and interference is too great, the detector fails to function correctly and a minimum mean square error (MMSE) detector must be used instead.

If the rank indication is one, only one symbol, $s_1$, is mapped and sent to both transmit antennas as:

$$x_1 = s_1, \quad x_2 = s_1.$$  \hspace{1cm} (5)

Equation (2) thus becomes

$$y_1 = (H_{11} + H_{12}) s_1 + n_1,$$
$$y_2 = (H_{21} + H_{22}) s_1 + n_2.$$  \hspace{1cm} (6)

Therefore, the receiver makes two measurements of the transmitted symbol $s_1$, and combines them to recover the transmitted data.

Closed loop spatial multiplexing (CLSM)

In closed loop spatial multiplexing, another antenna mapping for rank one indication is defined as:

$$x_1 = s_1, \quad x_2 = -s_1.$$  \hspace{1cm} (7)

After measuring the channel elements, the receiver sends the RI and the PMI back to the transmitter. Figure 2 depicts the operation of a 2×2 CLSM system.

If the RIs are zero, diversity processing is performed and only one symbol is transmitted using either the antenna mapping of (5) or (7), depending on the PMI.

The post-coding stage in the receiver undoes the precoding effect and performs soft decision estimation. In practice, the channel matrix $H$ may be singular, meaning it does not have an inverse, or it may be badly conditioned, so that its inverse is corrupted by noise. In such cases, the transmitted symbols cannot be recovered using (4). The channel matrix is then written as

$$H = \Lambda^{1/2} \cdot \Lambda P^{-1} A P^{-1},$$
\hspace{1cm} (8)

where $P$ is a matrix of the eigenvectors of $H$ and $\Lambda$ is a diagonal matrix of the eigenvalues of $H$. For a case of two antennas, as is considered, $\Lambda$ can be written as:

$$\Lambda = [\begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix}],$$
\hspace{1cm} (9)

where $\lambda_1$ and $\lambda_2$ are the eigenvalues.

The received symbol vector at the output of the post-coding stage shown in Fig. 5 is

$$r = G H F s + G n,$$  \hspace{1cm} (10)

where $s$ is the matrix of the symbols to be transmitted at the beginning of the precoding stage, $F$ is the matrix used for
precoding. H is the channel matrix and G is the matrix used for post-coding. Choosing F and G as reasonable estimates of the matrices of the eigenvectors,
\[
F = P^{(-1)}, \quad G = P
\]
The vector of received symbols in (10) becomes
\[
r = P \cdot H \cdot P^{(-1)} \cdot s + P \cdot n \Rightarrow s = P \cdot n - P \cdot r
\]
Ignoring the noise, the received symbols can be written as,
\[
[\mathbf{s}(r_1 \& r_2)] = \lambda \cdot (\lambda_1 \& \lambda_2)[\mathbf{s}(r_1 \& r_2)]
\]
and hence the receiver can easily recover the symbols that were sent, as
\[
s_i = r_i \lambda_i \quad (14)
\]
If H is singular, then some of its eigenvalues, \(\lambda_i\), are zero. If it is not well setup, some of the eigenvalues are exceedingly small and the recovered symbols are heavily distorted by noise. The RI equals the number of functional eigenvalues in H (called the rank of H). For instance, the received symbol vector for a system with two antennas and a rank indication of 1 would be
\[
[\mathbf{s}(r_1 \& r_2)] = \lambda \cdot (\lambda_1 \& \lambda_2)[\mathbf{s}(r_1 \& r_2)]
\]
(13)
In practical systems, the receiver does not send a complete report of F back to the transmitter since this would involve excessive feedback. The receiver only chooses the most accurate estimate of \(P^{(-1)}\) from a codebook and uses the PMI to indicate its choice [10].

Rank 1 CLSM

In a 2 × 2 rank 1 CLSM system, transmission and reception is governed by (15) and the system reverts to diversity processing.

**Methods**

Simulation of the transmission modes is carried out in different network environments. In one network environment, CoMP is used together with an additional layer of femtocells (heterogeneous network) while in the other, CoMP is applied in a homogeneous network. In both network environments, the CoMP functionality is coordinated scheduling and beamforming, using a round robin scheduler. The transmission modes investigated are listed in Table I [11].

**Table I**

<table>
<thead>
<tr>
<th>Transmission modes investigated</th>
<th>Transmission scheme of PDSCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Single antenna</td>
<td>2 Transmit diversity</td>
</tr>
<tr>
<td>3 OLSM</td>
<td>4 CLSM</td>
</tr>
<tr>
<td>6 Rank 1 CLSM</td>
<td></td>
</tr>
</tbody>
</table>

The simulations are carried out using Vienna LTE-A Downlink System Level Simulator v2.0_Q3_2018. The MATLAB-based simulator analyses the performance of an entire network made up of multiple eNodeBs and UEs. The simulator is made up of a link measurement model (LMM), and a link performance model (LPM). The LMM uses UE feedback reports to evaluate the quality of the link. It is needed for adapting the link and allocating resources. The quality of each link is determined for all the subcarriers. Using the SINR, the UE calculates the CSI which is sent back to the eNodeB and used for adapting the link. Using this feedback, the scheduler allocates resources to the UEs in a manner that optimizes the system’s performance [12]. The LPM then predicts the link’s BLER using the SINR of the receiver and the parameters of the transmission.

The network topology consists of multiple eNodeBs each with a scheduler. Depending on which scheduling algorithm is used, and the feedback provided by the UE, the schedulers allocate appropriate MCSs, precoding matrices and PHY resources to their UEs. The UE then calculates the received subcarrier post-equalization symbol SINR using the LMM and generates a CQI feedback report through SINR-to-CQI mapping. This report is transmitted back to the eNodeB using a feedback channel which has variable delay.

The LPM obtains an AWGN-equivalent SINR (\(\gamma_{AWGN}\)) through Mutual Information Effective SINR Mapping (MIESM) (see [12], and the references therein). Link performance curves are then used to map \(\gamma_{AWGN}\) to BLER [13,14]. The BLER values are used in conjunction with the magnitude of the Transport Block (TB) to calculate the capacity of the link. Outputs of the simulations include traces of the link data rate and error ratios for each UE, cell aggregates such as the mean, peak and edge throughput and ECDF curves of the average throughput and spectral efficiency [12]. Figure 3 summarizes the working of the simulator.
heterogeneous networks, the parameters in Table III were used for the femtocells.

**Table II**
Parameters used for each of the transmission mode simulations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network geometry</td>
<td>Regular hexagonal grid</td>
</tr>
<tr>
<td>Inter-eNodeB distance</td>
<td>500 [16]</td>
</tr>
<tr>
<td>Number of eNodeBs</td>
<td>21</td>
</tr>
<tr>
<td>UEs per eNodeB</td>
<td>24</td>
</tr>
<tr>
<td>Considered UEs</td>
<td>All (504)</td>
</tr>
<tr>
<td>Transmission bandwidth</td>
<td>20 MHz (100 resource blocks)</td>
</tr>
<tr>
<td>Antennas (N_TX×N_RX)</td>
<td>2×2</td>
</tr>
<tr>
<td>UE speed</td>
<td>5 km/h</td>
</tr>
<tr>
<td>Pathloss model</td>
<td>TS 36.942 ¬¬¬¬ Urban area, 70 dB MCL ¬ [17]</td>
</tr>
<tr>
<td>Channel model</td>
<td>Typical urban (TU) [17]</td>
</tr>
<tr>
<td>Feedback</td>
<td>AMC: CQI, MIMO: RI and PMI</td>
</tr>
<tr>
<td>Feedback delay</td>
<td>3ms</td>
</tr>
<tr>
<td>Shadow fading</td>
<td>Claussen</td>
</tr>
<tr>
<td>Noise spectral density</td>
<td>-174 dBm/Hz</td>
</tr>
<tr>
<td>Minimum coupling loss</td>
<td>70 dB [17]</td>
</tr>
<tr>
<td>Receiver model</td>
<td>Zero forcing [13]</td>
</tr>
<tr>
<td>Antenna pattern</td>
<td>TS 36.942</td>
</tr>
<tr>
<td>Transmit power (Macrocell eNodeB)</td>
<td>40 W</td>
</tr>
<tr>
<td>Simulation length</td>
<td>50 subframes (TTIs)</td>
</tr>
<tr>
<td>Scheduling algorithm</td>
<td>Round robin CS/CB</td>
</tr>
</tbody>
</table>

**Table III**
Femtocell parameters used for the heterogeneous network simulations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Femtocells per cell</td>
<td>2</td>
</tr>
<tr>
<td>UEs per femtocell</td>
<td>2</td>
</tr>
<tr>
<td>Femtocell transmit power</td>
<td>0.1 W</td>
</tr>
<tr>
<td>Operating mode</td>
<td>CSG</td>
</tr>
<tr>
<td>Macroscopic pathloss model</td>
<td>Dual slope [17]</td>
</tr>
<tr>
<td>Minimum coupling loss</td>
<td>45 dB [17]</td>
</tr>
<tr>
<td>Indoor area radius</td>
<td>20 m</td>
</tr>
<tr>
<td>Wall loss</td>
<td>20 dB</td>
</tr>
<tr>
<td>Penetration loss</td>
<td>B</td>
</tr>
</tbody>
</table>

**5 Results and Discussions**

In this section, results of the simulations are presented. Each of the transmission modes listed in Table 1 has been simulated in both homogeneous and heterogeneous network scenarios. The transmission modes are compared on the basis of throughput, spectral efficiency and achieved UE wideband SINR.

**Homogeneous network**

The average UE throughput ECDF and spectral efficiency ECDF are graphed in Fig. 4 and Fig. 5, respectively. As can be seen from the graphs, the best performing transmission modes are the 2×2 CLSM and the 2×2 Rank 1 CLSM. These transmission modes exhibit almost identical performance, with their throughput ECDF and spectral efficiency ECDF curves mapping almost exactly onto each other.

![Fig. 4. Average UE throughput ECDF (homogeneous network)](image1)

![Fig. 5. Average UE spectral efficiency ECDF (homogeneous network)](image2)

Figure 6 compares the transmission modes using mean, edge, and peak throughput. The peak data rate obtained using these transmission modes was 2.993 Mbps for 2×2 CLSM and 3.0184 Mbps for Rank 1 CLSM. The poorest performing transmission mode was the SISO mode, which is presented for comparison purposes. The other transmission modes perform well, with 2×2 TxD slightly outperforming 2×2 OLSM, with a peak data rate of 2.728 Mbps to OLSM's 2.4383.

**Heterogeneous network**

In the heterogeneous network, significant throughput gains were attained from the addition of femtocells. CLSM and OLSM emerged as the best transmission modes in this network setup, as can be seen in Fig. 7 and Fig. 8, where the throughput ECDF and spectral efficiency ECDF have been plotted, respectively. CLSM and OLSM perform equally well, with their ECDF curves mapping exactly onto each other.
Conclusion

In this paper, the performance of SISO, 2×2 OLSM, CLSM, Rank 1 CLSM and TxD is evaluated in terms of throughput and spectral efficiency for both heterogeneous and homogeneous networks that employ coordinated scheduling and beamforming. Simulation results show that CLSM and Rank 1 CLSM are the best choice of transmission mode in homogeneous networks while either CLSM or OLSM is a good choice in heterogeneous networks. Results also show that significant throughput gains can be attained in heterogeneous networks, for all the transmission modes. We therefore conclude that the use of either CLSM or OLSM in a heterogeneous network would offer the best throughput gains.

References


