Effect of Joint Detection on System Throughput in Distributed Antenna Network

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SUMMARY This paper evaluates the throughput of a distributed antenna network (DAN) with multiple mobile terminal scheduling and the usage of joint maximum-likelihood detection (MLD). Mobile terminals are closer to the desired antennas in the DAN which leads to higher throughput and better frequency utilization efficiency. However, when multiple mobile terminal scheduling is applied to the DAN, interference can occur between transmitted signals from antennas. Therefore, in this research, mobile terminal scheduling along with joint MLD is applied to reduce the effects of interference. A system level simulation shows that the usage of joint MLD in a densely packed DAN provides better system throughput regardless of the numbers of mobile terminals and fading channels.

key words: Distributed Antenna Network, Joint Detection, User Scheduling, Small Cell

1. Introduction

With the on-going popularity of mobile devices such as smartphones and tablet PCs, there are increasing demands for high-speed and large capacity wireless communications \([?, ?]\). To accommodate this explosive traffic growth, the fifth generation mobile communication system (5G) is currently being developed. One solution to improve spectrum efficiency is the distributed antenna network (DAN) \([?]\). DANs were originally introduced for indoor radio communications simply as a mean of extending coverage to dead spots \([?]\). However, the DAN’s advantages in reducing power consumption and increasing system capacity were quickly exploited for use in broadband multi-cell environments \([?]\). In the DAN, several antennas, known as distributed antennas (DAs), are dispersed in a cell. The DAs are physically connected to a centralized baseband unit (BBU) via highspeed optical fronthaul links \([?]\). Mobile user terminals (MT) are connected to DAs depending on BBU’s configuration such as scheduling criteria. Since low-power DAs are geographically placed throughout the cell to reduce access distances, the DAN mitigates channel impacts such as shadowing and fading, which deteriorates transmission capacity and coverage \([?]\). It has been shown that a conventional cell model, such as a centralized antenna network (CAN), does not allow as much, if not any, frequency reuse, resulting in the DAN providing better spectrum efficiency \([?]\).

With cell models that deploy multiple antennas near each other, such as the DAN, frequency and channel reuse is a common technique for improving spectral efficiency. However, reusing the same frequency in mobile wireless systems often leads to a degraded link and service quality due to co-channel interference (CCI) at cell coverage boundaries. In order to suppress interference from adjacent antennas, interference rejection combining has been specified in the 4G Long-Term-Evolution (LTE) standard as a part of coordinated multi-point transmission, which consequently increases fronthaul traffic \([?]\). The amount of fronthaul traffic may be a significant problem if the same technologies are applied to the DAN. In this research, the DAN with joint maximum likelihood detection (MLD) is proposed for suppressing interference. Joint MLD treats the received signals as the superposition of the desired and the interference signals and regards them as a signal with a larger number of constellation points \([?, ?, ?]\). Since the total number of constellation points increases to the multiplication of modulation orders of signal streams, the performance benefit obtained by joint MLD leads to increased complexity.

Scheduling the frequency resources to provide fairness and maintain better network throughput becomes a problem when there are more MTs in a network. In \([?]\), the authors discuss three MT scheduling schemes, proportional-fair (PF), round-robin (RR), and max-carrier-to-interference (C/I), and their effects on downlink (DL) transmission in the DAN. It was concluded that RR scheduling achieves high fairness and throughput with a simple algorithm. MT scheduling in the DAN is also discussed in \([?]\), where combining multiple scheduling algorithms to create a scheduling criteria achieved a fair and high throughput system.

The DAN with DAs that transmit on the DL to multiple MTs is assumed in this research. In the as-
sumed DAN, it is proposed that each MT demodulates signals for its own and the other via joint MLD and multi-MT scheduling is applied. For the multi-MT scheduling, RR scheduling is used with max-(C/N) as a selection algorithm for DAs. The proposed scheme is compared against the conventional scheme as well as a scheme without the use of joint MLD, where the throughput evaluation is based on the numerical analysis of multi-cell simulation using constellation constrained capacity (CCC).

This paper is organized as follows. Section 2 describes the system model and the conventional and proposed schemes. Section 3 presents numerical results obtained through computer simulation. Section 4 concludes this research.

2. System Model

2.1 Cell Model

A hexagonal-cell concept is assumed for the DAN cell model [7]. Each macro cell has uniformly distributed \( N_{DA} \) DAs. In this research, \( N_{DA} \) is set to seven. Each DA is placed in a smaller hexagonal-cell with a radius of \( R' \), as shown in Fig. 2. Surrounding the center cell, there are six other outer macro cells with the same configuration. Also, the center cell is assumed to be the cell of interest.

In the assumed DAN, the same channel is shared by the DAs in the cell. Also, the same frequency channel can be assigned to two DAs in each macro cell. In the receiver of a MT, joint MLD is applied to mitigate the CCI in the macro cell. The MT receives the signals transmitted from two DAs in the same macro cell. With the joint MLD, the receiver extracts its desired signal even though the signal for the other MT is transmitted from one of the other DAs on the same channel.

2.2 Scheduling

For the multiple MT scheduling, the RR scheduling of the MTs and the max-C/N scheduling (or selection) of the DAs are applied at the same time. For comparison, a single MT scheduling scheme is also considered in this research where each MT is chosen one at a time and the DA with the best C/I is chosen via the max-C/N scheduling. In the DAN, using all of the DAs in a dense cell can lead to CCI and, as researched in [7], turning off some of the DAs in a multi-MT environment could increase transmission throughput. This is also the reason to reduce the number of receiving MTs to two per resource block (RB). Limiting the number of MTs lead to low CCI and improves system throughput with joint MLD.

Algorithm 1: Multi-MT scheduling algorithm.

\[
\begin{align*}
\text{Data: } & P, N_{perm}, N_{frames}, N_{RB}, H_{fa}, H_{fb} \\
\text{begin} & \\
& i = 1 \\
& \text{for } f = 1 \rightarrow N_{frames} \text{ do} \\
& \quad \quad H_{fa} = \sum_{i \in \{i_r\}} H_{fa}^i \\
& \quad \quad H_{fb} = \sum_{i \in \{i_r\}} H_{fb}^i \\
& \quad \text{for } r = 1 \rightarrow N_{RB} \text{ do} \\
& \quad \quad k_\alpha, k_\beta \leftarrow P(i) \\
& \quad \quad l_\alpha, l_\beta \leftarrow \arg \max \{H_{fa}^l(k_\alpha, l_\alpha) + H_{fb}^l(k_\beta, l_\beta)\} \\
& \quad \quad i = i + 1 \\
& \quad \text{if } i > N_{perm} \text{ then } \\
& \quad \quad i = 1 \\
& \text{end} \\
\text{end} \\
\text{end}
\end{align*}
\]

In detail, the proposed multi-MT scheduling algorithm is shown in Algorithm 1. The \( k_\alpha \)-th and \( k_\beta \)-th MTs are chosen, and each MT receives its desired signal from the \( l_\alpha \)-th and \( l_\beta \)-th DAs, respectively. \( N_{MT} \) represents the number of the MTs. \( N_{frame} \) and \( N_{RB} \) are the two resource factors, where \( N_{frame} \) represents the total number of frames and \( N_{RB} \) represents the total number of RBs. \( P \) defines all of the permutations of selecting two MTs out of the total \( N_{MT} \), and the total number of permutations is given by \( N_{perm} = N_{MT}! / 2 \). For example, the \( i \)-th index \( P(i) \) contains the scheduled MT pair, MT \( k_\alpha \) and MT \( k_\beta \), which means \( (k_\alpha, k_\beta) \in P \). Two MTs are selected per RB at each time index. \( H_{fa}^i \) and
\( \mathbf{H}_f^i \) are the channel matrix on the \( i \)-th subcarrier with a size of \( N_{MT} \times N_{DA} \) and they are also assumed to be constant over \( N_{frames} \). \( \mathbf{H}_f^i(k_\alpha, l_\alpha) = h_{k_\alpha, l_\alpha} \) and \( \mathbf{H}_f^i(k_\beta, l_\beta) = h_{k_\beta, l_\beta} \) are the channel responses from the \( l_\alpha \)-th and \( l_\beta \)-th DAs to the \( k_\alpha \)-th and \( k_\beta \)-th MTs on the \( i \)-th subcarrier, respectively. In this algorithm, the DAs for each MT is chosen for the scheduled MTs, \( k_\alpha \) and \( k_\beta \), by finding the maximum sum of the channel responses, \( \mathbf{H}_f^i(k_\alpha, l_\alpha) + \mathbf{H}_f^i(k_\beta, l_\beta) \). As shown in line 1, the scheduled DAs are represented by \( l_\alpha^{\text{max}} \) and \( l_\beta^{\text{max}} \), and the total channel response for these pairs is \( h_f^{\text{max}} = \mathbf{H}_f^i(k_\alpha, l_\alpha^{\text{max}}) + \mathbf{H}_f^i(k_\beta, l_\beta^{\text{max}}) \).

### 2.3 Throughput Calculation

![System model for proposed scheme.

In this research, each MT is equipped with a single antenna and DL transmission is assumed. The system model for the proposed scheme is shown in Fig. ???. In the assumed DAN, at most two DAs transmit at once on the same channel in the multi-MT scheduling. Each MT receives the desired signal as well as the interference signal from the other DA. Each MT also receives interference from the surrounding macro cells.

Suppose that \( x_i^l(s_{i_\beta}^l) \) is treated as an interference signal from the other \( l_\beta \)-th DA in the same cell and \( s_{i_\beta}^l \) is the index for the constellation points of the interference signal on the \( i \)-th subcarrier. Also assume that \( E[|x_i^l(s_{i_\beta}^l)|^2] = E[|s_{i_\beta}^l|^2] = 1 \) and the number of constellation points of the interference signal is \( N_{i_\beta}^l \) (\( 0 \leq s_{i_\beta}^l \leq N_{i_\beta}^l - 1 \)). The received signal at the \( k_\alpha \)-th MT, \( y_{k_\alpha} \), on the \( i \)-th subcarrier is given as

\[
y_{k_\alpha} = h_{k_\alpha, l_\alpha} x_i^l(s_{i_\alpha}^l) + h_{k_\alpha, l_\alpha} x_i^l(s_{i_\beta}^l) + n_{k_\alpha}^i
\]

and similarly, the \( k_\beta \)-th MT's received signal, \( y_{k_\beta} \), is given as

\[
y_{k_\beta} = h_{k_\beta, l_\alpha} x_i^l(s_{i_\alpha}^l) + h_{k_\beta, l_\alpha} x_i^l(s_{i_\beta}^l) + n_{k_\beta}^i,
\]

where \( h_{k,l}^i \) is the channel response from the \( l \)-th DA to the concerning \( k \)-th MT.

For throughput evaluation, the inter-cell interference is regarded as a Gaussian noise and is subject to Gaussian distribution. Therefore, Eqs. (??) and (??) can be rewritten as

\[
y_{k_\alpha} = h_{k_\alpha, l_\alpha} x_i^l(s_{i_\alpha}^l) + h_{k_\alpha, l_\alpha} x_i^l(s_{i_\beta}^l) + z_{k_\alpha},
\]

\[
y_{k_\beta} = h_{k_\beta, l_\alpha} x_i^l(s_{i_\alpha}^l) + h_{k_\beta, l_\alpha} x_i^l(s_{i_\beta}^l) + z_{k_\beta},
\]

where \( z_{k} \) is the sum of the additive white Gaussian noise (AWGN) and the inter-cell interference and its total variance is given as \( \sigma^2 \).

Two demodulation schemes for MLD are researched in this paper. In the first scheme, system throughput when the MT applies MLD for the desired signal only is calculated. In this case, the signal for the other MT in the same cell is treated as CCI. From Eqs. (??) and (??), the CCC with the MLD is given as Eqs. (??) and (??) where \( \sigma^2 \) includes interference power that is subject to a distance [?, ?]. The system throughput is then calculated by the sum of the entire RB given by,

\[
T_m = \sum_i \left[ \sum_{r=1}^{N_{RB}} T_m^{r, k_\alpha} + \sum_{r=1}^{N_{RB}} T_m^{r, k_\beta} \right].
\]

On the other hand, the throughput of the joint MLD scheme is also calculated. In this case, the receiver of the MT jointly demodulates the signals for the concerning MT and another one in the same cell. Compared to the MLD, the joint MLD requires the modulation orders and the channel responses of the interference signal as well as the desired signal and the complexity of the joint MLD increases since the received signal point is chosen by finding the maximum of the channel responses of the interference signal, \( \mathbf{H}_f^i(k_\alpha, l_\alpha) + \mathbf{H}_f^i(k_\beta, l_\beta) \), and the desired signal and the complexity of the joint MLD increases since the received signal point is chosen by finding the maximum of the channel responses of the interference signal, \( \mathbf{H}_f^i(k_\alpha, l_\alpha) + \mathbf{H}_f^i(k_\beta, l_\beta) \), and the desired signal.

The system throughput is then calculated by

\[
T_j = \sum_i \sum_{r=1}^{N_{RB}} T_k^{r, k_\alpha}.
\]

Multi-cell system-level simulation is conducted.
for each trial. The number of transmit symbols for each MT drop is 5. The channel response is renewed
per MT drop is 200 and the number of trials

\[
T_{m_{k_t}} = \log_2(N_{s_t}) - \frac{1}{N_{t_s}N_{t_p}} \sum_{s_t=0}^{N_{s_t}-1} \sum_{t_p=0}^{N_{t_p}-1} \sum_{s_s=0}^{E} \left[ \log_2 \frac{\sum_{j_s=0}^{N_{s_s}-1} \exp(-|h_{s_t,j_s}(x_t(s_s) - x_t(t_p)) + h_{s_s,j_s}(x_s(s_s) - z_s)^2/\sigma^2)\]}{\exp(-|h_{s_t,j_s}(x_t(s_s) - x_t(t_p)) + z_s^2/\sigma^2)\]} \right]
\]

\[
T_{m_{k_p}} = \log_2(N_{s_t}) - \frac{1}{N_{t_s}N_{t_p}} \sum_{s_t=0}^{N_{s_t}-1} \sum_{t_p=0}^{N_{t_p}-1} \sum_{s_s=0}^{E} \left[ \log_2 \frac{\sum_{j_s=0}^{N_{s_s}-1} \exp(-|h_{s_t,j_s}(x_t(s_s) - x_t(t_p)) + h_{s_s,j_s}(x_s(s_s) - z_s)^2/\sigma^2)\]}{\exp(-|h_{s_t,j_s}(x_t(s_s) - x_t(t_p)) + z_s^2/\sigma^2)\]} \right]
\]

\[
T_{j_{s_p}} = \log_2(N_{s_t}) - \frac{1}{N_{t_s}N_{t_p}} \sum_{s_t=0}^{N_{s_t}-1} \sum_{t_p=0}^{N_{t_p}-1} \sum_{s_s=0}^{E} \left[ \log_2 \frac{\sum_{j_s=0}^{N_{s_s}-1} \exp(-|h_{s_t,j_s}(x_t(s_s) - x_t(t_p)) + h_{s_s,j_s}(x_s(s_s) - z_s)^2/\sigma^2)\]}{\exp(-|h_{s_t,j_s}(x_t(s_s) - x_t(t_p)) + z_s^2/\sigma^2)\]} \right]
\]

to compare the system throughputs of the conventional schemes, the single-MT scheduling, the multi-
MT scheduling with MLD, and the proposed multi-MT scheduling with joint MLD scheme. Simulation con-
ditions are presented in Table 1. A seven hexago-
nal macro-cell model with a seven hexagonal DA cell in each macro-cell is assumed as shown in Fig. 1.
The inter-antenna distance between adjacent DAs is changed from 25 m to 250 m. N_MT MTs are dropped
randomly with an uniform distribution and they are dropped further than 5 m from DAs. Distance de-
dpendent path loss with a decay factor of 36.7 and log-
normal shadowing with standard deviation of 8 dB is
used for the propagation model. The shadowing corre-
lation between the antennas are set to 0.5. A one-path
Rician fading channel model with a $K$-factor of 10 is
assumed for the cell of interest and a six-path Rayleigh
fading channel model is assumed for the macro-cells
surrounding the cell of interest. For comparison of
different channels, a six-path Rayleigh fading channel
model is also used for the cell of interest. The total
power of interference from the other cells is required for
the calculation of $\sigma^2$ and it is derived based on the
distances between the DAs and the MTs with the assumed
distance dependent path loss model. The system band-
width is set to 4.32 MHz. The number of RBs, $N_{RB}$, is
24 and the number of subcarriers for each RB is 12. The
symbols are modulated with QPSK, 16QAM, 64QAM,
or 256QAM on each subcarrier. Each DA has a height
of 10 m and the transmit power is 30 dB. Each MT is
set at a height of 1.5 m and the receiver noise density is
-174 dBm/Hz. The throughputs in Eqs. (5), (6), and (7)
of the conventional and proposed schemes are simu-
lated through Monte Carlo simulation [7]. The
number of MT drops is 200 and the number of trials
per MT drop is five. The channel response is renewed
for each trial. The number of transmit symbols for each

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<td>7 DA network</td>
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<tr>
<td>Inter-antenna distance</td>
<td>25, 50, 100, 150, 200, 250 m</td>
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<tr>
<td>Minimum distance between MT and DA</td>
<td>5 m</td>
</tr>
<tr>
<td>Path loss</td>
<td>$140.7 + 36.7 \log_{10}(R)$ dB, $R$: Distance [km]</td>
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<tr>
<td>Height of antennas</td>
<td>10 m</td>
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<tr>
<td>Height of MTs</td>
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<tr>
<td>Shadowing deviation</td>
<td>8 dB</td>
</tr>
<tr>
<td>Shadowing correlation</td>
<td>0.5</td>
</tr>
<tr>
<td>Channel model (inner)</td>
<td>One-path Rician ($K = 10$)</td>
</tr>
<tr>
<td>Channel model (outer)</td>
<td>Six-path Rayleigh</td>
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<tr>
<td>Number of MTs</td>
<td>5, 7, 10, 15, 20, 25</td>
</tr>
<tr>
<td>Transmit power</td>
<td>30 dBm</td>
</tr>
<tr>
<td>Receiver noise density</td>
<td>-174 dBm/Hz</td>
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<tr>
<td>System bandwidth</td>
<td>4.32 MHz</td>
</tr>
<tr>
<td>RB bandwidth</td>
<td>180 kHz</td>
</tr>
<tr>
<td>Number of RBs</td>
<td>24</td>
</tr>
<tr>
<td>Modulation scheme</td>
<td>QPSK, 16QAM, 64QAM, 256QAM</td>
</tr>
<tr>
<td>MT drops</td>
<td>200</td>
</tr>
<tr>
<td>Trials per MT drop</td>
<td>5</td>
</tr>
<tr>
<td>Number of symbols per trial</td>
<td>100</td>
</tr>
</tbody>
</table>

trial is 100. The same RR scheduling is applied over all
of the cells and this implies that only one or two DAs
in each surrounding cell cause interference to the cell on interest.
3.2 Effect of MT Numbers

The average throughput versus the number of MTs are presented in Fig. ??.. This figure is simulated with an inter-antenna distance of 25 m. For the first characteristic, as shown in Fig. ??, the number of MTs ($N_{MT}$) does not affect on the overall average throughput of the system. This is due to the employment of the RR scheduling. Unlike the PF scheduling, even if the ratio of unfavorable conditioned MTs increases, the DA assigns the same amount of RBs to each MT. The average throughputs for the multi-MT with joint MLD, the multi-MT without joint MLD, and the single-MT scheduling are almost constant throughout the different numbers of MTs. This is due to the fact that for each RB at a specific time frame, only one or at most two MTs are scheduled for transmission depending on the single or multi-MT scheduling. This means that in the multi-MT scheduling, the best throughput can be achieved if two MTs could transmit 256QAM symbols to their desired DAs. In Fig. ??, the effect of joint MLD is clear since the average throughput goes up around 15% as compared to that without joint MLD and 40% as compared to that of the single-MT scheduling.

3.3 Effect of Inter-DA Distance

Figure ?? presents the average throughput per area versus the inter-DA distance of the DAs. The number of MTs are set to seven. The effect of joint MLD can be seen greatly according to the inter-antenna distance of the DAs. As shown in Fig. ??, when the distance between the DAs are longer, such as from 150 to 250 m, the throughput differences among those schemes diminish. On the other hand, if the distances between adjacent DAs is shorter, such as from 25 to 50 m, the throughput differences are greater. By comparing the single and multi-MT schemes, in the shorter inter-DA distance DAN, the multi-MT schemes provide better system throughput. In the multi-MT schemes, when the inter-antenna distance is 25 m, the throughput with joint MLD is higher than the one without joint MLD, whereas in the other distances, the multi-MT scheduling with and without joint MLD achieves the same improvements. This is due to the fact that in the shorter inter-DA distance DAN, the channel is more likely to be interfered by the signals from the surrounding DAs than that when the cells were more widely spread out. Joint MLD provides better throughput since this scheme mitigates the effect of the interference.

Throughput curves shown in Fig. 5 also imply that the DAN can achieve better spectrum efficiency as compared to the CAN. From Fig. 2, the average distance between the MT and the antenna in the CAN is about three times larger than that of the DAN. With a distance of 75 m, even though the number of transmit MTs is two, the average throughput is less than 1/4 of the single MT with a distance of 25 m. This means that the number of transmit MTs increases to seven, which is equivalent to the CAN with a distance of 75 m, the average throughput of the DAN with a distance of 25 m is better than that of the CAN with a distance of 75 m.

In Fig. ??, the cumulative distribution function (CDF) curves of the system throughput for inter-DA distance of 25 m is presented. In the figure, single-MT scheme only transmits around 8 bits / RB / sec since only one MT is allowed to transmit at a specific resource slot. At a particular resource slot, the assigned MT is not affected by CCI since interference will come only from the outer macro cells, which is assumed to be farther than the connected antenna. This means that these MTs can transmit symbols with higher order modulation, such as 256QAM. For the single-MT scheduling, the main source of the interference is the signal from the closest DA in the adjacent outer cell.
If only one DA in each of the surrounding outer cell is activated due to the RR scheduling, sever interference occurs only when the scheduled MT is located at the cell edge and the closest DA in the adjacent outer cell is transmitting. On the other hand, in the multi-MT schemes, at most two MTs can transmit for each resource slot. If two MTs can transmit at 256QAM, the throughput will be 16 bits / RB / sec. As clearly shown in the figure, around half of the resource slots in the multi-MT scheme without joint MLD can transmit at 8 bits / RB / sec, whereas the scheme with joint MLD provides the MTs that transmit at greater throughput which means that those resource slots can now transmit two MTs at once. For the multi-MT scheduling, the main source of the interference is the signal from the other MTs within the cell of interest. In this case, both of the MTs achieve throughput of 4.0 bits / RB / sec in most cases since the inferences from the adjacent DAs limit the throughput without joint MLD. It also shows how joint MLD can provide better system throughput when the DAs are closer to one another. In Fig. ??, around 87% of the MTs are able to transmit at throughput of 9.7 bits / RB / sec without joint MLD, whereas 87% of the MTs are able to transmit at throughput of 11.6 bits / RB / sec. Joint MLD enables the simultaneous transmission of all of the MTs in each resource slot.

3.4 Effect of Rayleigh Fading Channel

Figure ?? presents the average throughput per area versus varying inter-DA distances on the six-path Rayleigh fading channel. Compared to the curves on the one-path Rician fading channel used in Fig. ??, the overall throughput curves with six-path Rayleigh fading channel are higher while the tendencies of the curves are similar. This is because more interference occurs on the Rician fading channel with a K-factor of 10. It is similar in the manner that as the inter-DA distance becomes shorter, the throughput becomes larger, and vice versa. Also, the multi-MT schemes are deemed superior than the single-MT scheme and, in the multi-MT schemes, the use of joint MLD provides better throughput performance.

4. Conclusions

In this research, the DAN with joint MLD has been proposed by taking into consideration the scheduling of multiple MTs. The system throughput for the proposed scheme was compared with those of the conventional single-MT scheduling and the multi-MT scheduling without joint MLD in a system level simulation. The results show that using joint MLD in the multi-MT scheduling scheme increases system throughput. In particular, when the inter-DA distance is 25 m, the system throughput improves around 15%. The same throughput is maintained when the number of MTs changes and similar trends are seen in the Rician and Rayleigh fading channels.

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References

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