Comparison of Antenna Arrays in a 3-D Multiuser Multicell Network

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Abstract

A three-dimensional (3D) multi-cell multi-user system model along with spatial array processing are presented and studied in this paper. Most of the radio propagation in the literature has been studied and modeled in a two dimensional plane. The 3D propagation channel modeling has drawn attention recently. This is due to the fact that, in some scenarios, the assumption of small elevation domain angular spread does not hold. With multiple antenna elements displaced in a 3D space, e.g., uniform linear array (ULA) or uniform planar array (UPA), the base station (BS) is capable of forming beams in vertical domain. This is particularly interesting for interference limited systems, since the 3D array processing provides another degree of freedom to transmit signal and eliminate the interference. Using the 3D multicell channel model, the impact of elevation domain angular spread and antenna analog beam pattern on the base station antenna design, digital beamforming and power control are studied. Significant gains can be got due to the spatial array processing with the extra degree of freedom in vertical domain.

I. INTRODUCTION

The data rates as well as quality of service requirements for rich user experience in wireless communication services is growing. To achieve high spectral efficiency design targets in the wireless system, sophisticated antenna applications are implemented at the base station (BS). With multiple elements placed in a three-dimensional (3D) space, the BSs are able to form spatial beams to a desired direction. On the other hand, with multiple antenna technique, spatial richness of the channel can be exploited. Thus, with a proper antenna array designed for a certain scenario, the system capacity or receive signal quality can be expected to be improved.

Most of the multiple antenna research is based on the simplified two-dimensional (2D) channel model or on the assumption that the majority of the channel paths are concentrated in a 2D horizontal plane. The simplification and assumption make sense when the radio link is strong line-of-sight (LOS) or the clusters are only horizontally distributed. However, this assumption breaks down if the clusters are also vertically distributed or the incident power is rich in elevation domain. This is in fact the case and has been shown in the recent measurements. In [1], a measurement in Helsinki, Finland, shows that most of the power is concentrated from 0° to 16° above horizontal level. Measurement of urban scenario in [2] indicates that if the street is narrow and strong scatterers without LOS are around the mobile station (MS), 65% of the energy is incident with elevation angle larger than 10°. A 20° mean elevation arrival angle with standard deviation of 42° was found in [3]. The elevation dispersion is even larger than in the azimuth domain in the scenarios where the height of building is much larger than the width of the street.

The impacts of elevation propagation on the capacity or spatial correlation have been shown to be significant. In [4], a capacity expression as a function of 3D antenna elements spacing, angular spread and power spectrum is given. In [5], [6], elevation angular spread was shown to have a large impact on the capacity of a uniform planar arrays (UPA). Shafi [7] analyzed the capacity as a function of elevation angular spread and suggested a 3D channel model. A closed form upper bound of the multiple-input multiple-output (MIMO) was derived in [8], as a function of statistics of scatterers and antenna element displacement. Based on the these measurement results, the realistic 3D channel modeling is needed and has drawn attention recently [9]. The recent 3GPP spatial channel model (SCM) [10] considered a cross-polarized two-dimensional (2D) model and has been extended to a 3D model in the European WINNER II project [11].

The purpose of our paper are two-fold. First, we want to get an insight into the system level performance with a realistic 3D channel model and we extended our previous work in [12], where the 3GPP long term evolution (LTE) uplink open-loop power control and mechanical BS antenna down tilt were studied. Second, we study what type of spatial antenna array is the most suitable one with the extra vertical dimension of propagation. We mainly concentrate on uplink transmission in scenarios specified in LTE Release 9 (LTE-A) [13], where multiple BS coordination reception and power control are also included.

This paper is structured as follows. In Section II, the multicell uplink model, spatial channel model and antenna array model are presented. Section III gives a short introduction of the power control and BS cooperation. The simulation results will be given in Section IV, and, finally, in Section V, the paper is concluded.
II. SYSTEM AND CHANNEL MODEL

A. Multicell System

The considered cellular system consists of \( K \) MSs and \( B \) BSs in flat fading channels. Assuming that all MSs have one transmit antenna while BS \( i \) has \( N_i \) receive antennas, the received signal \( r_i \) at the \( i \)th BS is written as

\[
    r_i = \sum_{k=1}^{K} \sqrt{p_k} h_{k,i}s_k + n_i, \tag{1}
\]

where \( p_k \) is the transmit power of MS \( k \), \( h_{i,j} \in \mathbb{C}^{N_i \times 1} \) is the complex channel response from the \( k \)th MS to the \( i \)th BS, \( s_k \) is the transmitted symbol of MS \( k \) with average power normalized to 1, \( n_i \) is the additive white Gaussian noise (AWGN) vector at BS \( i \) with variance \( \sigma_i^2 \) for each receive antenna.

For multi-BS cooperation reception and beamforming, MS \( k \) is simultaneously received and processed by a set of chosen BSs \( \pi_k \), a set of linear beamformers can be utilized to extract its signal from those BSs, i.e.,

\[
    \hat{s}_k = \sum_{i \in \pi_k} w_{k,i}^H r_i = \sum_{i \in \pi_k} \sqrt{p_k} w_{k,i}^H h_{k,i}s_k + \sum_{i \in \pi_k} \sum_{k' \neq k} \sqrt{p_{k'}} w_{k',i}^H h_{k',i}s_{k'} + w_{k,i}^H n_i \tag{2}
\]

where \((\cdot)^H\) means Hermitian of the matrix and \( w_{k,i} \in \mathbb{C}^{N_{Rx} \times 1} \) is the receiver beamformer gain vector for MS \( k \)'s received signal at BS \( i \) and \( \pi_k \) is the multi-BS set serving MS \( k \). Its elements are the indices of BSs jointly providing service to MS \( k \) which are denoted by \( \pi_k(\cdot) \).

B. 3D Spatial Channel

The 3D channel model is based on the WIM II channel model which is a geometry based stochastic model [14]. A more general form of MIMO channel matrix than (2) is given by

\[
    H(t, \tau) = \sum_{n=1}^{N} H_n(t; \tau), \tag{3}
\]

where \( n \) is the path index, \( N \) is the total number of paths \( \tau \) is the delay time, \( t \) is the time index. \( H_n(t, \tau) \) is the channel matrix for cluster \( n \) which is expressed as [14]

\[
    H_n(t, \tau) = \int F_{Rx}(\phi)H(t; \tau, \phi, \varphi)F_{Tx}^T(\varphi) d\phi d\varphi, \tag{4}
\]

where \( F_{Rx}(\phi) \) and \( F_{Tx}(\varphi) \) are the beam gain matrix for received antenna (Rx) and transmit antenna (Tx) on direction \( \phi \) and \( \varphi \) respectively. \( H(t; \tau, \phi, \varphi) \) is the dual-polarized channel response matrix. The channel coefficient from Tx element \( s \)

to Rx element \( u \) for cluster \( n \) is given as follows [14]

\[
    h_{u,s,n}(t; \tau) = \sum_{m=1}^{M} \left[ \begin{array}{c} F_{Rx,u,V}(\varphi_{n,m}) \\ F_{Rx,u,H}(\varphi_{n,m}) \end{array} \right] \left[ \begin{array}{c} \alpha_{V,n,m} \alpha_{H,n,m} \end{array} \right] \left[ \begin{array}{c} F_{Rx,v,m,V}(\phi_{n,m}) \\ F_{Rx,v,m,H}(\phi_{n,m}) \end{array} \right] \exp(j2\pi \lambda_0^{-1}(\varphi_{n,m} \cdot r_{Rx,u})) \exp(j2\pi \lambda_0^{-1}(\phi_{n,m} \cdot r_{Tx,u})) \exp(j2\pi v_{n,m} t) \delta(\tau - \tau_{n,m}), \tag{5}
\]

where \( F_{Rx,u,V} \) and \( F_{Rx,u,H} \) are the field patterns for vertical and horizontal polarizations of antenna element \( u \) respectively, \( \alpha_{V,n,m} \) and \( \alpha_{H,n,m} \) are the complex gains of vertical-to-vertical and horizontal-to-vertical polarizations of ray \( n, m \) respectively. Parameter \( \lambda_0 \) is the wave length of the carrier frequency, \( \varphi_{n,m} \) is the angle of arrival (AoA) unit vector, \( \phi_{n,m} \) is the angle of departure (AoD) unit vector, \( r_{Rx,u} \) and \( r_{Tx,u} \) are the location vectors of elements \( s \) and \( u \) respectively, and \( v_{n,m} \) is the Doppler frequency of ray \( n, m \). If polarization is not considered, the central matrix in the second line of (3) is replaced by a scalar \( \alpha_{n,m} \) and only vertically polarized field pattern is considered. More detailed description of the channel model can be found in [14].

The single-element field pattern is adopted from [15] as

\[
    A_A(\theta) = -\min \left[ 12\left( \frac{\theta}{\theta_{3dB}} \right), A_m \right], -180^0 \leq \theta \leq 180^0, \tag{6}
\]

where \( \theta_{3dB} \) is the 3dB beamwidth which is 70° for 3-sector cell and \( A_m = 20 \)dB is the maximum attenuation.

C. Antenna Array

The spatial displacement of the receive and transmit antenna elements and phase shifts among them is included in \( \exp(j2\pi \lambda_0^{-1}(\varphi_{n,m} \cdot r_{Rx,u})) \) and \( \exp(j2\pi \lambda_0^{-1}(\phi_{n,m} \cdot r_{Tx,u})) \) in (5), where \( r_{Rx,u} = [x_u, y_u, z_u]^T \) is the location of the \( u \)th receive antenna element and AoA unit vector is

\[
    \varphi_{n,m} = [\cos \theta_{n,m} \cos \gamma_{n,m}, \sin \theta_{n,m} \cos \gamma_{n,m}, \sin \gamma_{n,m}]^T, \tag{7}
\]

where \( \theta_{n,m} \) is the arrival azimuth angle and \( \gamma_{n,m} \) is the arrival elevation angle of subpath \( n, m \). The phase offset of element \( u \) can be calculated as

\[
    \Delta \psi_{u,n,m} = 2\pi \lambda_0^{-1} \varphi_{n,m} \cdot r_{Rx,u} = 2\pi \lambda_0^{-1} (x_u \cos \theta_{n,m} \cos \gamma_{n,m} + y_u \sin \theta_{n,m} \cos \gamma_{n,m} + z_u \sin \gamma_{n,m}). \tag{8}
\]

The transmit antenna array and AoD are similar. An illustration of the antenna coordination system and incident wave is shown in Fig. 1.

For a UPA with \( N_{Rx} = N_{RxV}N_{RxH} \) elements, the channel vector is \( h_{k,i,u}^{UPA} \in \mathbb{C}^{N_{Rx} \times 1} \), where \( N_{RxV} \) and \( N_{RxH} \) is the number of vertical and horizontal elements, respectively. For a uniform linear array (ULA) with same amount of elements, the channel vector is \( h_{k,i,u}^{ULA} \in \mathbb{C}^{N_{RxV} \times 1} \), where the output of the \( u \)th port is the sum of the vertical co-phased signals as

\[
    h_{k,i,u}^{ULA} = \sum_{j=(u-1) \times N_{RxV} + 1}^{u \times N_{RxV}} h_{k,i,j}, 1 \leq u \leq N_{RxH}. \tag{9}
\]
With smaller size of beamforming vector, the noise power of ULA in (2), \( \|w_{k,i}\|^2 \sigma_i^2 \), is \( N_{\text{RxV}} \) times smaller than UPA.

Since the signal power of ULA can be at best the same as that of UPA after co-phased combining, for \( N_{\text{RxV}} = 4 \), the post processing SNR of ULA is at best 6 dB larger than UPA. For interference limited case, the spatial distributed interference plays a bigger role than noise. Because UPA has a better freedom in vertical domain to form the beams, the SINR would benefit from vertical beamforming and interference avoidance. The UPA/ULA performance under noise and interference limited cases are to be evaluated in Section IV.

III. UPLINK POWER CONTROL AND BS COOPERATION

Multiple BS joint reception is interesting in 3D channel models. Even two BS antennas are in the same horizontal plane, as long as they are horizontally separated, the two BSs are able of forming the beams in vertical domain. The UL power control, multi-BS cooperation and receive beamforming with per MS signal-to-interference-plus-noise ratio (SINR) can be formulated as a minimum transmit power problem [16], [17].

Given the receiver beamformers \( w_{k,i} \) and the cooperation BS set \( \pi_k \), the effective SINR of MS \( k \) can be written as

\[
\Gamma_{k,\pi_k} = \frac{\left|\sum_{i \in \pi_k} w_{k,i}^H h_{k,i}\right|^2 p_k}{\sum_{k' \neq k} \left|\sum_{i \in \pi_k} w_{k,i}^H h_{k',i}\right|^2 p_{k'} + \sum_{i \in \pi_k} \left\|w_{k,i}\right\|^2 \sigma_i^2},
\]

(10)

where \( |\cdot| \) denotes the absolute value and \( \|\cdot\| \) the standard Euclidean vector norm. The power control, BS cooperation, reception and beamforming problem can be reformulated as

\[
\begin{align*}
\text{minimize}_{\pi_k, p_k} & \quad \sum_{k=1}^{K} p_k \\
\text{subject to} & \quad \sum_{k' \neq k} \left|\sum_{i \in \pi_k} w_{k,i}^H h_{k',i}\right|^2 p_{k'} + \sum_{i \in \pi_k} \left\|w_{k,i}\right\|^2 \sigma_i^2 \geq \gamma_k, \\
& \quad p_k \leq P_k
\end{align*}
\]

(11)
where $\gamma_k$ is MS $k$’s SINR requirement and $P_k$ is the maximum transmit power of MS $k$ and optimal beamforming vector is given by

$$\arg \max \{ w_{k,1}, w_{k,2}, \cdots, w_{k,|\pi_k|} \} \quad w_{k,i} = \frac{1}{p_k} \sum_{k' \neq k} \sum_{i \in \pi_k} \left| \sum_{i \in \pi_k} w_{k,i}^H h_{k',i} \right|^2 \cdot \frac{1}{p_k} + \sum_{i \in \pi_k} \left| w_{k,i} \right|^2 \sigma_i^2$$

(12)

Though the optimization problem (12) is a non-convex problem in general, the minimum total transmit power solution, the optimal receiving BSs set and the optimal beamforming vector can be found after iterative search, as long as the power vectors of the MSs are feasible. A more detailed description of the algorithm can be found in [18].

IV. SIMULATION RESULTS

In the simulation, we consider a cellular system containing 19 BSs with 3 sectors per BS, so 57 sectors in total. As shown in Fig. 4, the central 57 sectors are the original sectors while the outer sectors are the copies of the central sectors. The blue circles indicate MSs and the black bars indicate the antenna board directions of selected sectors. Multiple BSs can jointly processing the received signals from one MS. The units of x and y axis are meters. The edge effect is eliminated by wrapping around the network [19]. Other simulation parameters can be found in Table I.

![An illustration of the wrap-around multicell multiuser network layout.](image)

Table I: Simulation Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layout</td>
<td>19 cells, 3 sectors/cell</td>
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<tr>
<td>Propagation scenario</td>
<td>Base coverage urban</td>
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<tr>
<td>Cell radius</td>
<td>1000 m</td>
</tr>
<tr>
<td>Maximum MS transmit power</td>
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<tr>
<td>Maximum antenna gain</td>
<td>17 dBi</td>
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<tr>
<td>Thermal noise density</td>
<td>$-174$ dBm/Hz</td>
</tr>
<tr>
<td>Number of users</td>
<td>30, 160 in 19 cells</td>
</tr>
<tr>
<td>BS receiver antenna array</td>
<td>ULA UPA</td>
</tr>
<tr>
<td>BS receiver antenna elements</td>
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</tr>
<tr>
<td>MS antenna</td>
<td>1</td>
</tr>
<tr>
<td>Number of BSs for coordinate reception</td>
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<tr>
<td>SINR constraint per MS</td>
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<tr>
<td>MS speed</td>
<td>3 km/h</td>
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<tr>
<td>Shadowing correlation</td>
<td>Log-Normal, 8 dB standard deviation</td>
</tr>
<tr>
<td>Down tilt angle</td>
<td>independent</td>
</tr>
</tbody>
</table>

The system of UPA/ULA with multiple BS joint reception and beamforming are to be simulated. The performance will be evaluated in terms of average transmit power, number of feasible links can be supported by the network. The performance of the 4 x 4 ULA and UPA are studied in two scenarios, i.e., noise limited scenario and interference limited scenario.

In Fig. 5, a noise limited case is studied, where 30 MSs are uniformly distributed in 57 sectors. Single BS, two and three BSs joint reception are simulated. It is clear that despite of how many BSs are involved in reception, ULA always performs better than UPA. It is not surprising, since UPA has 6dB larger noise power than ULA. With a larger beamforming gain, UPA is only 1.8 dB worse than ULA for single BS reception case.

The performances of interference limited case are plotted in Fig. 6, where 160 MSs are generated. As we can see from the figure, no matter how many BS are receiving, UPA performs better than ULA. When single BS is receiving, the beamforming gain of UPA is larger compared with ULA. As much as 5 dB gain can be get from UPA when cumulative distribution function (CDF) of transmit power is 0.5, bearing in mind that UPA has 6 dB larger noise power at the combiner than ULA. If more BSs are involved in the reception, the vertical beamforming gain is smaller, because two separated cooperating ULA antennas can also form the beam in vertical domain. More BSs are involved in cooperation, better/narrower vertical beams can be shaped. When three BSs are used for joint reception, the UPA is slightly better than ULA.

The performance of noise limited case with SINR of 8 dB are plotted in Fig. 7, as the SINR constraint getting higher, the performance gap between the ULA and UPA reduces. In interference limited scenario, 160 MSs with SINR constraint of 8 dB per MS is plotted in Fig. 8. The single BS and two BSs joint reception curves are not plotted, because with high SINR constraint and small size of cooperation BS cluster, the feasibility of the link can not be guaranteed, i.e., the maximum transmit power constraint is exceeded. Compared with the 0 dB constraint in Fig. 6, the three BSs UPA beamforming gain is huge.

The feasibility performance of the two antenna arrays and BS cooperations are plotted in Fig. 9 and Fig. 10. In interference limited scenario, for single BS reception, the supported number of MSs nearly doubles. For interference limited case, the UPA can support more MSs than ULA with the same
amount of receiving BSs. With single BS reception, UPA supports about 3 times amount of MSs as ULA at feasibility of 90%.

In Fig. 11, we examine the performance of UPA and ULA in different elevation angular spread (EAS) cases with single BS reception. The small, medium and large EAS corresponds to the rural, urban macro and suburban scenarios, respectively. As we can see, UPA always performs better than ULA. In small EAS case, UPA has the largest gain. If EAS becomes larger, there are more diversity gains coming from elevation domain and beamforming gains becomes less.

V. CONCLUSION

A 3D multicell channel model and spatial antenna array models including ULA and UPA were presented. The UL system level simulation were carried out with multiple BS joint reception, power control and beamforming. Under noise limited scenario, ULA was observed to outperform the UPA, because the latter has more amplifiers than the former. This fact increases the noise power. With the help of vertical coherent combining in UPA, the loss due to the noise is partly compensated. In interference limited scenario, the UPA is better than ULA due to the large vertical beamforming gain and elevation domain interference avoidance. However, the performance gap between the UPA and ULA becomes small as the number of cooperating BSs increases. We also compared the performance of UPA and ULA in different scenarios with different elevation angular spread, from where a conclusion is that UPA performs significantly better than ULA in rural scenarios.

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Fig. 5. Transmit power of ULA vs. UPA with the SINR constraint of 0 dB in a noise limited scenario (30 MSs in 57 sectors).

Fig. 6. Comparison of transmit power of ULA and UPA with the SINR constraint of 0 dB in an interference limited scenario (160 MSs in 57 sectors).

Fig. 7. Comparison of transmit power of ULA and UPA with the SINR constraint of 8 dB in a noise limited scenario (30 MSs in 57 sectors).

REFERENCES

Fig. 8. Comparison of transmit power of ULA and UPA with the SINR constraint of 8 dB in an interference limited scenario (160 MSs in 57 sectors).

Fig. 9. Probability of feasible connections of ULA vs. UPA with the SINR constraint of 0 dB.

Fig. 10. Probability of feasible connections of ULA vs. UPA with the SINR constraint of 8 dB.

Fig. 11. Transmit power of ULA vs. UPA with the SINR constraint of 0 dB with different elevation angular spread in an interference limited scenario (160 MSs in 57 sectors).


