

Multipath Division Multiple Access for 5G Cellular System based on Massive Antennas in Millimeter Wave Band

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Abstract—Mobile communications toward the fifth generation (5G) have been popularly discussed and investigated worldwide in academia and industry. 5G, as an evolution from the previous generations, demands both high system capacity and high data rate. A novel multiple access scheme based on millimeter wave transmission and massive antennas at a base station (BS), named multipath division multiple access (MDMA), is proposed in this paper to be a future 5G possible solution. MDMA is defined here as a method to use massive antennas at BS to achieve a processing gain to suppress multiple access interference (MAI) in cellular mobile radio system. The processing gain is obtained by implementing RAKE receivers at BS. The system concept is also demonstrated by computer simulations. Moreover, it has been shown through simple but crucial analysis that the system capacity and the aggregated data throughput could be boosted up to a considerable level.

Keywords— 5G communication, cellular system, millimeter wave, massive antennas, system capacity

I. INTRODUCTION

Over the past few decades, mobile communications have evolved rapidly and drastically to fulfil diverse demands through various international standards. Apart from voice transmission as the original and primary application for mobile communications, data transmission has gradually become more and more significant from short messaging service (SMS) in the second generation (2G) to video phone and web browsing in the third generation (3G) [1]. The required data rate is increasing exponentially year by year.

Around 2010, the 3rd Generation Partnership Project (3GPP) proposed a multi-carrier based solution known as Long Term Evolution (LTE) [2], which aimed to offer relatively high peak data rate, for example, 300 Mbps in the downlink (DL) and 75 Mbps in the uplink (UL). Moving forward to meet the International Mobile Telecommunications Advanced (IMT-Advanced) standard [5], 3GPP in 2011 proposed a refined version of LTE — LTE-Advanced (LTE-A) — that pushed the peak data rate up to 3 Gbps for DL and 1.5Gbps for UL [2]. In general, LTE-A is regarded formally as the fourth generation (4G) cellular mobile radio system nowadays.

Possible solutions toward the future 5G system are proposed by both academia and industry, based on heterogeneous networks, millimeter wave (mmWave) technology, and massive multiple-input multiple-output (massive MIMO) antennas [6]. The first approach allows different kinds of cells to co-exist and function simultaneously in the same area, which is popularly termed as small cells. The second approach resorts to utilizing the unexcavated spectrum of the millimeter wave frequency band, e.g., 20GHz-30GHz, since it not only avoids frequency spectrum congestion problem below 3GHz but also provides considerable bandwidth for high data rate transmission. However, it brings out the problem of much larger propagation loss at much higher frequency bands. Thus, the cell size must be reduced accordingly. The third approach considers employing a large amount of antennas at BS side [7]–[13], usually tens to hundreds of antennas. Reference [13] has stated that the massive number of antennas provides a substantial degree of freedom such that it can easily increase data rate 10 times or more, improve the radiated energy efficiency, be built with inexpensive and low-power components, enhance the robustness to interference etc.. However, some inherent problems need to be carefully handled such as pilot contamination [14]–[17] and various implementation related issues [13].

Contributions of this paper are capsuled as follows. A novel multiple access scheme for the 5G cellular systems based on millimeter wave transmission and massive antennas at BS, named multipath division multiple access (MDMA), is proposed in this paper. Different from the previous multiple access schemes (i.e., FDMA, TDMA, CDMA, and OFDMA), MDMA distinguishes its users by exploiting their distinct and rich multipath components through deploying massive antennas at BS. With MDMA as a means of implementing cellular systems, both system capacity and the aggregated data throughput could be boosted up to an appreciable extent, as we would explain in Section IV. A cellular system architecture built upon MDMA is presented, which could be served as a reference system architecture for future 5G cellular systems development.

The paper is organized as follows. Section II gives the radio system architecture, including the MDMA transceiver

architecture and a simplified analysis. Section III provides computer simulations as an auxiliary method to illustrate the system concept. Section IV offers a simple but crucial proof to verify the performance of the proposed system. And the paper completes with conclusions in Section V.

II. SYSTEM ARCHITECTURE

The proposed MDMA cellular system is exemplified in Figure 1. Every BS exploits massive antennas operating at the mmWave band, say 30 GHz, such that the size of each antenna (e.g., dipole antenna) is in the order of one centimeter, much smaller than the regular size (e.g., 30 centimeters for 1 GHz band). Thus, at BS, hundreds of antennas can be placed every other tens of wavelengths to make the received signals uncorrelated [4] across the BS antennas. For example, if we arrange 100 antennas in a two-dimensional square plane, then the total area occupied is about 10 m², which can be easily applied to real environments. In contrast, there is only one antenna at user terminal (UT). It is customary that any two users are separated by much more than a wavelength and their multipath fading profiles are different.

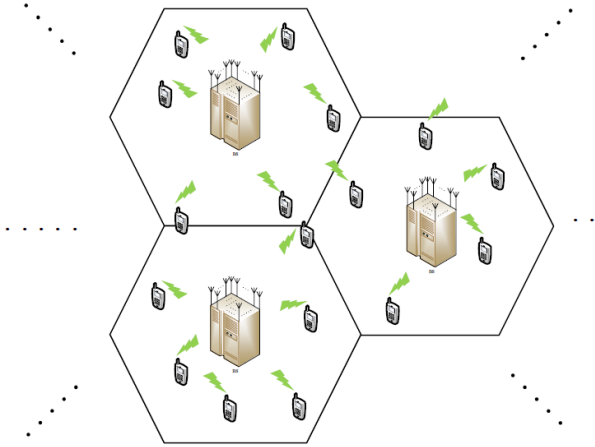


Figure 1. A cellular system with massive antennas at BS

In addition, a channel bandwidth of 200 MHz is assumed in our system at 30 GHz carrier frequency. For such a wide bandwidth used for transmission, the rich and distinct multipath components of each individual user can be resolved, which helps to distinguish all the users as compared to the traditional multiple access methods which separate users in frequency, time, and code domains.

Assume that the UL channel state information (CSI) is available at BS through channel estimation. Employing the Rake receiver [3] with massive antennas, we can equalize the received signal before data detection for desired users at BS. In brief, the equalization here is done in both *time* and *space* domains. This leads to a huge signal-to-interference plus noise ratio (SINR) gain for each user. The resultant spatial processing gain is analogous to a CDMA system's processing gain and is effective to suppress intersymbol interference (ISI), multiple access interference (MAI), and cochannel

interference.

A. Transceiver Architecture

Figure 2 shows the block diagram of the MDMA user terminal transmitter and the base station receiver. Consider a frequency-selective multi-user scenario with K single-antenna users and an M -antenna BS in each cell. Assume binary phase shift keying (BPSK) modulation is used and ideal power control is executed in the uplink. α_{lkm} and τ_{lkm} represent the complex gain and the path delay of the l -th resolvable path of the link between the k -th user and the m -th BS antenna, where $l = 1 \dots L$, $k = 1 \dots K$, and $m = 1 \dots M$. $P(t)$ denotes a transmit pulse-shaping filter, and T_b is the bit time (e.g., T_b equals to 5 ns with 200 Mbps BPSK data rate). CCI stands for the cochannel interference coming from other cells. Let $n_j(t)$ be the corresponding additive white Gaussian noise at the j -th BS antenna. $s_k(n)$ denotes the n -th data bit of the k -th user for transmission. $v_{kj}(t)$ is the received signal at the j -th BS antenna from the k -th user, and $u_{kj}(t)$ is the result of the k -th user's Rake receiver output at the j -th BS antenna. Accordingly, we have

$$v_{kj}(t) = \sum_{l=1}^L \sum_n \alpha_{lkj} P(t - \tau_{lkj} - nT_b) s_k(n), \quad (1)$$

and

$$u_{kj}(t) = \left(v_{kj}(t) + \sum_{\substack{q=1 \\ q \neq k}}^K v_{qj}(t) + \text{CCI} + n_j(t) \right) \otimes \sum_{l'=1}^L \alpha_{l'kj}^* P^*(T_b - t - \tau_{l'kj}), \quad (2)$$

for $k = 1 \dots K$ and $j = 1 \dots M$, where $\otimes$ and $*$ respectively denote the linear convolution operator and the conjugation.

B. Simplified Analysis

As already mentioned, the received signal at BS would be equalized for each user using the Rake receiver and then combine the results of Rake receiver outputs in a coherent manner, where a spatial processing gain is achieved for every user. This can also be verified from the above equations. If we consider user k being the desired user, then (1) corresponds to the desired signal through the channel that needs to be further processed. Inserting (1) into (2) and neglecting interference and noise terms lead to

$$u_{kj}(t) = \int_{-\infty}^{\infty} \left(\sum_{l=1}^L \sum_m \alpha_{lkj} P(\xi - \tau_{lkj} - mT_b) s_k(m) \right) \times \left(\sum_{l'=1}^L \alpha_{l'kj}^* P^*(T_b - t + \xi - \tau_{l'kj}) \right) d\xi. \quad (3)$$

Suppose the combination of the transmit and receive filters satisfies the Nyquist criterion for ISI-free transmission, i.e., $P_{\text{eff}}(iT_b) = \delta[i]$, $i \in \mathbb{Z}$, where $P_{\text{eff}}(t) \equiv P(t) \otimes P^*(-t)$ and $\delta[n]$ is equal to one for $n = 0$ and zero otherwise. Thus, sampling $u_{kj}(t)$ in (3) at $t = (n+1)T_b$, we have

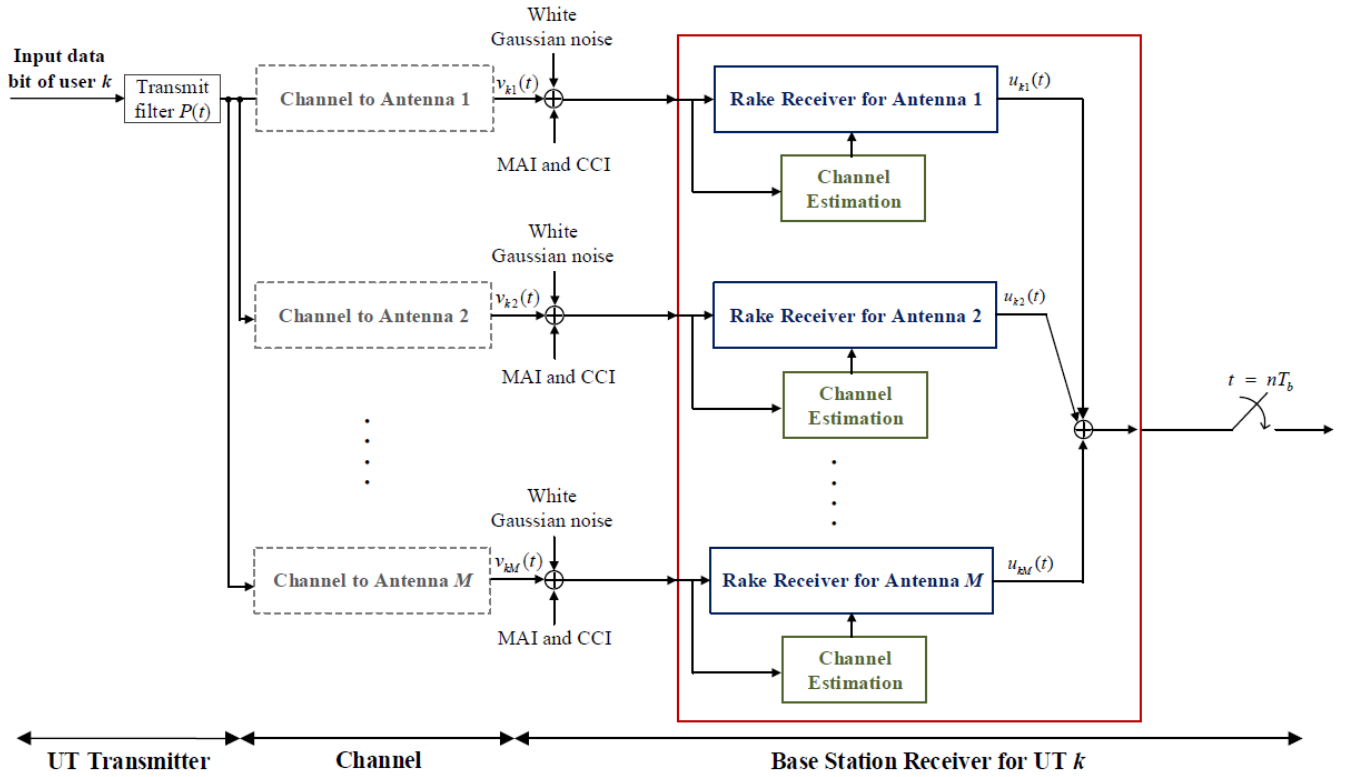


Figure 2. MDMA UT transmitter and BS receiver block diagram

$$\begin{aligned}
 u_{kj}((n+1)T_b) &= \int_{-\infty}^{\infty} \left(\sum_{l=1}^L \sum_m \alpha_{lkj} P(\xi - \tau_{lkj} - mT_b) s_k(m) \right) \\
 &\quad \times \left(\sum_{l'=1}^L \alpha_{l'kj}^* P^*(-nT_b + \xi - \tau_{l'kj}) \right) d\xi \\
 &= \int_{-\infty}^{\infty} \left(\sum_{l=1}^L |\alpha_{lkj}|^2 P^2(\xi - \tau_{lkj} - nT_b) s_k(n) \right) d\xi + \text{ISI} \\
 &= s_k(n) + \text{ISI}, \tag{4}
 \end{aligned}$$

where the last equality holds assuming that $\int_{-\infty}^{\infty} P^2(t) dt = 1$

and $\sum_{l=1}^L |\alpha_{lkj}|^2 = 1$ for normalization purposes. Summing over all M BS antennas, we can get the desired signal as $Ms_k(n)$ after sampling at time $(n+1)T_b$, whereas the interference and noise terms add *noncoherently*. In other words, the end-to-end equivalent channel of each user tends to be an ideal channel as M increases, i.e., an impulse-like channel, which is shown in Section III. Assume that data power of every user equals unity. Then, one can easily derive the average signal-to-interference power ratio (SIR) to be M/K (note that the noise is ignored for an interference-limited cellular system). Since the massive antennas are used at BS (i.e., $M \gg K$), the average SIR could be boosted up to a great amount. Thus, M is the (spatial) processing gain offered by the MDMA based cellular system with massive BS antennas.

III. COMPUTER SIMULATIONS

As the proposed 5G system operates in the millimeter-wave band, the channel model used for the 5G system performance

simulation should be reasonably accurate and match with the real situations. Rappaport *et al.* has conducted several real-world channel measurements for millimeter-wave frequencies [18]–[23], especially at 28 GHz. Reference [23] presented spatial channel characteristics for the 28 GHz band, including path loss statistics, cluster distributions etc. The results of [23] can be used for system-level simulations, e.g., cellular system capacity evaluation, yet improper for link-level simulations since it did not show the temporal channel characteristics such as power delay profile and the associated statistical distributions.

For computer simulations in this paper, we modified the S-V channel model with the spatial parameters according to [23]. First, we set the number of clusters by the Poisson law. The arrival time of the clusters is uniformly distributed within the maximum delay spread, e.g., 404.1 ns [20]. Then, we calculate the power of each cluster using the model of [23]. Afterwards, we generate the relative arrival time of each ray within individual cluster according to the exponential distribution. Finally, we compute the power of each ray.

Figure 3 shows an effective impulse response of a desired user in a single cell scenario under ideal power control in a full loading cell which serves 25 users simultaneously (The effective impulse response of a user is plotted including interference (both MAI and ISI) observed before the sampler in Figure 2 at the receiver for the user.). It is clear that as the number of BS antennas grows, the effective impulse response becomes more impulse like, i.e., the interference effect is mitigated when more antennas are deployed at BS, which agrees with the simplified analysis in section II B. Besides, Figure 4 depicts the desired user's PDF of the receive SIR

before the sampler. It can be seen that the mean values are around -14 dB, -4 dB, and 6 dB, respectively for 1, 10 and 100 antennas. Again the results match well with the simplified analysis that the average SIR is the number of BS antennas (M) divided by that of total users (K) in a cell. In addition, the PDF curve turns out to be more concentrated around the mean when the number of antennas at BS increases. Therefore, the receive SIR tends to be more deterministic for each user that guarantees better system performances, which is due to the rich and distinct multipath components in the mmWave band and the law of large numbers provided by massive antennas at BS. Figure 5 plots the cumulative distribution of the receive SIR with 100 BS antennas and different number of users in a *multi-cell* scenario. The cellular system layout is composed of 127 hexagonal cells corresponding to 6 tiers of cochannel cells. First, it can be seen that the average SIR is also the function of M / K which coincides with the simplified analysis in the previous section. Similarly, the performance gets improved as the ratio of M over K increases. Second, the average SIR is less than M / K by about 1.7 dB which accounts for the other cell interference described in the next section. Third, variations around the mean of the receive SIR diminish as the number of users increases due to the law of large numbers of MAI. That is, the receive SIR converges to its mean as more users are served in the system.

IV. SYSTEM CAPACITY EVALUATION

From the preceding analysis and simulation results, a simple but crucial system capacity evaluation for the proposed MDMA cellular system is presented as follows. We set the system at the outset to operate at the carrier frequency of 30 GHz with the channel bandwidth of 200 MHz, and it works under cell reuse factor of one (i.e., a universal frequency reuse plan is adopted). Assume that the cellular system considered is interference-limited. Recall that BPSK modulation is used and the ideal power control is executed in the uplink. Additionally, the system is under full load, i.e., K users are always transmitting concurrently. Under these assumptions, the average receive SIR at each user's demodulator output is thus

$$\frac{E_b}{I_0} \cong \frac{S}{I} = \frac{M^2}{M(K-1) + M} \times \frac{1}{1+f} = \frac{M}{K} \times \frac{1}{1+f}, \quad (5)$$

where E_b and I_0 represent the received energy per bit and the interference power spectrum density. S and I are the average signal and interference power, respectively. $\frac{M^2}{M(K-1) + M}$

derives from the fact that the desired signal of each BS antenna adds coherently while the interference (which contains MAI and ISI) sums up noncoherently. f denotes the other-cell relative interference factor defined as the ratio of the interference power from other cell to the interference power from the home cell. It is found in [3] that f is approximately 0.5 due to the dominant 1st-tier and 2nd-tier co-channel interference, which can also be inferred from Figure 5. Rearranging (5) leads to

$$K \cong \frac{M}{E_b/I_0} \times \frac{1}{1+f}, \quad (6)$$

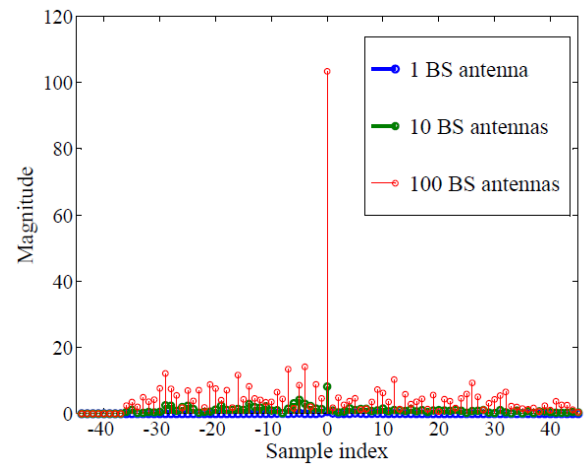


Figure 3. An effective impulse response of a desired user in a single cell scenario under ideal power control in a full loading cell with 25 active users

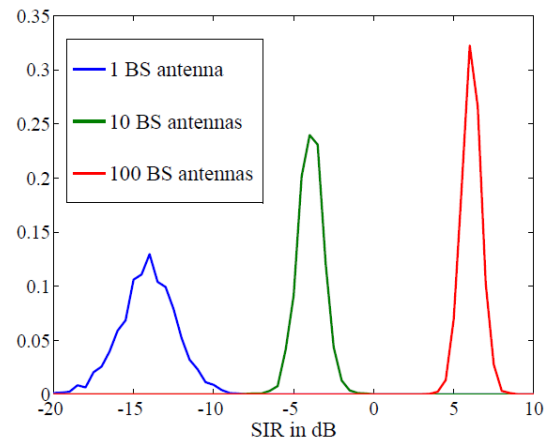


Figure 4. A desired user's PDF of the receive SIR in a single cell scenario under ideal power control in a full loading cell with 25 active users

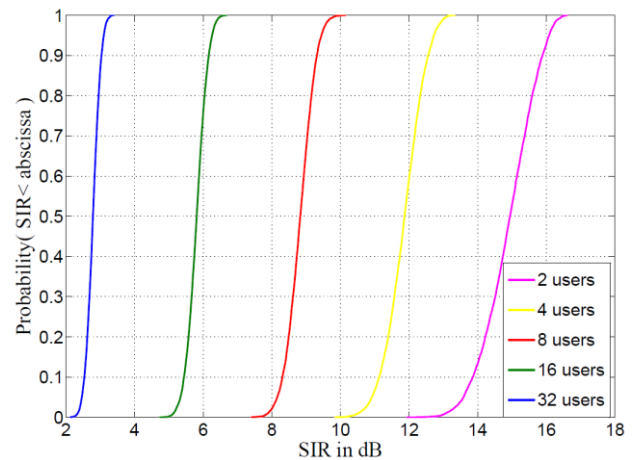


Figure 5. The cumulative distribution of the receive SIR with 100 BS antennas and different number of active users in a multi-cell scenario

which gives an elegant formula for the number of users the BS can serve under the required E_b / I_0 at each user's demodulator output.

Under the minimum required E_b / I_0 of 6 dB ($= 4$ in linear scale) for data detection with the acceptable performance [3], 150 BS antennas can afford 25 full loaded users in every cell

simultaneously since $\frac{150}{4} \times \frac{1}{1+0.5} = 25$. In practice, the number of users can be greatly increased if they are not full loaded.

Note that the system capacity can be further increased using sector antennas. Moreover, multi-user detection techniques (e.g., successive interference cancellation or parallel interference cancellation) are capable of eliminating intra-cell interference such that the system capacity can be boosted up three times more for $f = 0.5$ since $1/(1+f)$ in (6) could be replaced by $1/f$.

Due to the fact that each user in the cell shares the whole 200 MHz bandwidth, the proposed cellular system can thus achieve the total throughput of 5Gbps (200 Mbps $\times$ 25) using BPSK signaling, even without using multi-user detection and sector antennas.

V. CONCLUSIONS

Evolving from the 3G and the 4G communication systems, the 5G system demands both high system capacity and high data rate. Multipath division multiple access (MDMA), a novel multiple access scheme based on millimeter wave transmission and massive antennas at BS, is proposed in this paper to be a future 5G possible solution. MDMA is defined here as a method to use massive antennas at BS to achieve a processing gain to suppress multiple access interference in a cellular mobile radio system. The processing gain is obtained by implementing RAKE receiver at BS. The associated UT transmitter and BS receiver block diagram is presented for practical concerns. Operating at millimeter wave bands provides a relatively large channel bandwidth, which benefits the high data rate transmission. On the other hand, making use of massive antennas offers excess degrees of freedom, which is helpful to suppress interference so as to increase the system capacity. With MDMA as a means of implementing cellular systems, it has been shown in this paper that both system capacity and the aggregated data throughput can be boosted up to a considerable level. Users in a cellular system built upon MDMA are separated by their distinct multipath structures through deploying massive antennas at BS. Thus, a cellular system of frequency reuse factor of one can be established. In brief, MDMA could be served as an alternative to implement a 5G cellular mobile radio system.

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