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Beamspace Multiplexing for Wireless Millimeter-Wave Backhaul Link

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Abstract—This paper studies the beamspace multiplexing for free-space wireless millimeter-wave (mm-wave) backhaul applications, which has never been investigated before. A system architecture of a dual-beam mm-wave link is established, and the synthesis approach for the system key parameters that enable the beamspace multiplexing is presented. Extensive simulations are performed and the obtained results show a higher spectrum efficiency in the proposed beamspace multiplexing backhaul link than that could be achieved in the single beam system under the constraint of the same transmitted power.

Index Terms—Backhaul, beamspace multiplexing, millimeter-wave (mm-wave) communication, spectrum efficiency.

I. INTRODUCTION

The new generation of mobile communication system, i.e., 5G, is expected to support a thousand times more capacity than the current cellular networks [1]. Heterogeneous network (HetNet), which could provide efficient spatial reuse, together with the disruptive technologies, such as massive-MIMO and millimeter-wave (mm-wave) communication, are considered as a promising solution [2]. In current cellular networks, backhaul data traffics between cell base-stations (BSs) and the central macro-cell BS are normally fulfilled using high capacity fiber connections. However, in future HetNets the cost of fiber infrastructures between macro-cell BS and small-cell BSs, which provide high capacity within a small spatial coverage, would be prohibitively high, simply due to the fact of a huge number of small-cells and their high flexibility, e.g., the site of a small-cell can be moved according to the change of user distributions. As a consequence, great efforts have been devoted to the wireless backhaul, especially in mm-wave band [2] [3] because the larger available frequency bandwidth is able to provide higher spectrum efficiency [4].

In order to combat high propagation path loss in mm-wave communications, directional high gain antennas are equipped at both ends of the backhaul link [5] [6]. In previous work in free-space line-of-sight (LoS) mm-wave backhaul links, which can be satisfied by carefully choosing BS antenna sites, only a single high gain beam that was formed by either a dish antenna or an antenna array was considered, while multiplexing was taken place at other domains, such as time, frequency, or polarization. A great amount of available frequency resource may justify the use of a single beam to achieve more than 10 Gbps capacity.

However, this imposes a demanding requirement on mm-wave radio frequency (RF) frontend components, such as wideband flat-gain power amplifiers and up/down-converters. Instead in this paper, we investigate the feasibility of beamspace multiplexing in the free-space mm-wave backhaul links.

This paper is organized as follows. In Section II the backhaul mm-wave communication system architecture under investigation is described, followed by the details of the synthesis approach of the phase delay networks that are utilized to achieve beamspace multiplexing in Section III. Section IV presents the simulation results, showing a higher achievable spectrum efficiency in the proposed beamspace multiplexing backhaul link than that in the single beam system under the same transmitted power constraint. Conclusions are drawn in Section V.

Throughout the paper, boldface capital letters denote matrices, and boldface small letters refer to vectors.

II. SYSTEM MODEL

The model of the backhaul link under investigation in this paper is now illustrated in Fig. 1. Since in mm-wave communications LoS propagation is dominant and both BS nodes are static in space and in time, the free-space static wireless link is considered in this paper. In the case of the presence of the multipath, the analysis below can still be applicable when the transmit BS acquires the knowledge of channel state information.

In Fig. 1, it is assumed that both transmit and receive BSs are equipped with a uniform linear antenna array with one half wavelength ($\lambda/2$) spacing, and they are positioned along boresight ($\theta = 90^\circ$) of each other with a distance R . The system operation frequency is chosen as 30 GHz, and the sizes of the both antenna array apertures are set to 0.5 m, so that it can be calculated that at each end $N = 100$ antenna

Fig. 1. Simplified model of free-space mm-wave backhaul link.

elements are accommodated. At transmitter side a Fourier beamforming lens is used to create orthogonal beams [7]. Only two beams around boresight are selected, seen in Fig. 2 for far-field radiation patterns, for beamspace multiplexing when two data streams are superimposed onto each of them respectively. More beams could have been selected, but the wider angular spread and the unbalanced power illuminated on the receive antenna array make them inefficient. It should be pointed out that the generated radiation beams are only orthogonal, i.e., no cross-talk, along some discrete spatial directions. However, when signals detected on more receive antenna elements (with a number of $2N_r \leq N$) are intended to be used for data recovery, the cross-talk between two data streams is inevitable. In order to minimize the cross-talk, $2N_r$ receive antenna elements are symmetrically selected at each edge of the array, where the intended data beams are strong while the other interference data beams are relatively weak. Before being combined to recover the corresponding data streams two identical N_r -path phase delay networks, seen in Fig. 1, are exploited to further minimize the interference leaked from the other data streams. The synthesis approach of the required phase delay networks is elaborated in the following section.

III. SYNTHESIS OF PHASE DELAY NETWORKS

Using the model of the backhaul link described in Section II, we can write the mn^{th} entry of the N -by- N channel matrix $\mathbf{H}$ as

$$h_{mn} = \frac{1}{\sqrt{N}} \exp \left(j \frac{2\pi}{\lambda} \sqrt{R^2 + [(m-n)\lambda/2]^2} \right). \quad (1)$$

The detected signal vector $\mathbf{p}_x$ ($x = 1, 2$) of *Data_x* on the receive antenna array, then, can be expressed as

$$\mathbf{p}_x = D_x \mathbf{b}_x \mathbf{H}, \quad (2)$$

where D_x refers to the stream *Data_x*, and the 1-by- N vector $\mathbf{b}_x$ takes Fourier transformation with the n^{th} entry of

Fig. 2. Normalized magnitude patterns of two central beams generated by the transmit array with a Fourier beamforming lens in Fig. 1.

$$b_{xn} = \frac{1}{\sqrt{N}} \exp \left[-j \frac{2\pi}{N} \left(\frac{N}{2} + (x-1) - \frac{N+1}{2} \right) \left(n - \frac{N+1}{2} \right) \right]. \quad (3)$$

The terms ' $1/\sqrt{N}$ ' are added in (1) and (3) for the purpose of power normalization.

Two examples of the vector $\mathbf{p}_x$ are plotted against receive antenna index in Fig. 3 and Fig. 4 for the distances R of 26 m and 100 m, respectively. Here the magnitudes are normalized such that each of the two main beams at the corresponding distance has a power of 0 dBm. From Fig. 3 it can be seen that when $R = 26$ m, two beams generated with the Fourier lens are pointing to each edge of the receive antenna aperture. Since here no far-field approximation is made, unlike that in Fig. 2, the orthogonality between two beams does not exist along main beam pointing directions. As the increase of the distance R , the power of the normalized beams illuminated on the receive antenna array is reduced and the phases of two beams begin to converge, see evidence in Fig. 4.

At the receive BS end, the following phase delay networks in Fig. 1 are utilized to 'filter' out the useful signal conveyed by one beam while with the minimum interference caused by the other beam. Thus the synthesis of the phase delay networks is an optimization process, with the cost function CF in (4), i.e., the inverse of the signal to interference and noise ratio (SINR), to be minimized.

$$CF = \frac{1}{SINR} = \frac{\frac{1}{N_r} \left(\sum_{n=1}^{N_r} p_{1n} g_n \right)^2 + P_{noise}}{\frac{1}{N_r} \left(\sum_{n=1}^{N_r} p_{2n} g_n \right)^2} \quad (4)$$

In (4) p_{xn} denotes the n^{th} entry of the vector $\mathbf{p}_x$, and g_n is the phase delay connected to the n^{th} receive antenna, expressing as

Fig. 3. Normalized magnitudes and phases of the received signal vector $\mathbf{p}_x$ on the receive antenna array when $R = 26$ m.

Fig. 4. Normalized magnitudes and phases of the received signal vector $\mathbf{p}_s$ on the receive antenna array when $R = 100$ m.

$$g_n = \exp(jk_n), \quad (5)$$

where k_n is the value of phase delay in radian. P_{noise} in (4) refers to the power of the additive white Gaussian noise (AWGN). Due to the symmetry property of the two beams and the receive antenna along the axis of $\theta = 90^\circ$, only the upper half of the receive antenna and the associated phase delay network are discussed here. Thus in this case data stream D_2 embedded in the Beam2 are useful signals, while data stream D_1 in the Beam1 are treated as interference.

Population-based particle swarm optimization (PSO) algorithm, [8], [9], is selected to minimize CF in (4) and eventually the required phase delay networks can be obtained. In the PSO setup, 1000 particles are used and the search region is an N_r -dimensional space with each dimension ranging from 0° to 360° . The resolution of the dimension, i.e., the resolution of the phase delay k_n in degree, is set to Δk . 1000 times of iteration is used. Other parameter details, e.g., particle velocity, acceleration constants, and boundary condition, can be found in [10].

IV. SIMULATION RESULTS

In this section the system performance is obtained by simulations for various system parameters and is compared with that of their counterparts for single beam backhaul communication links. The single radiation beam is generated to point exact boresight. In order to make fair comparison, transmitters in both systems are assumed to radiate the same amount of power for each pair of comparison. Different to the proposed dual-beam multiplexing links where the $2N_r$ antenna elements are selected at the both edges of the receive array, the same amount of receive antenna elements involved in the single beam backhaul links are located in the center of the receive array where the energy of the single radiation beam concentrates.

Firstly, we study the impact of the resolution Δk of the synthesized phase delay networks on the achieved system performance. Some examples are provided in Table I and

Table II for the cases when $R = 50$ m, $N_r = 49$ (and 15), and $P_{noise} = -40$ dBm. Five resolutions are chosen, namely, 1° , 22.5° , 45° , 90° , and 180° . Clearly it can be concluded from Table I and Table II that the resolution Δk does not need to be fine, e.g., 90° (2-bit phase shifters) when $N_r = 49$ and 45° (3-bit phase shifters) when $N_r = 15$ are sufficient, in order to maintain the high system performance, i.e., SINR and the sum spectrum efficiency. This permits a great reduction with regard to the complexity and the cost of the phase delay networks.

Other points that we can make from Table I and Table II are that the proposed dual-beam multiplexing backhaul links with the phase delay networks of coarse resolutions (as little as 2-bit and 3-bit for each case) are able to a) provide excellent isolation between two data streams, i.e., higher than 49.6 dB and 45.1 dB, respectively; b) achieve higher sum spectrum efficiencies than those can be achieved in the corresponding single beam backhaul links under the same transmitted power constraint, indicating the acquirement of the beamspace multiplexing gain.

In order to provide a whole and clear picture of the proposed system performance and its comparison with that in the single beam backhaul links, the calculated spectrum efficiencies in both systems for different distances R between transmit and receive BSs, and for different numbers of

TABLE I. EXAMPLES OF SIMULATED SYSTEM PERFORMANCE ^a

Dual-beam multiplexing	Phase delay network resolution Δk				
	1°	22.5°	45°	90°	180°
Signal (dBm)	-1.8	-2.0	-1.8	-1.8	-11.2
Interference (dBm)	-53.5	-51.4	-52.4	-53.2	-48.4
SINR (dB)	38.0	37.6	38.0	38.0	28.2
Sum spectrum efficiency (bps/Hz)	25.2	25.0	25.2	25.2	18.8
Single beam spectrum efficiency(bps/Hz)	19.8	19.8	19.8	19.8	19.8

^a $P_{noise} = -40$ dBm, $N_r = 49$, $R = 50$ m.

TABLE II. EXAMPLES OF SIMULATED SYSTEM PERFORMANCE ^b

Dual-beam multiplexing	Phase delay network resolution Δk				
	1°	22.5°	45°	90°	180°
Signal (dBm)	-10.9	-11.3	-11.6	-11.6	-10.8
Interference (dBm)	-59.6	-56.4	-60.7	-38.8	-36.8
SINR (dB)	29.1	28.6	28.4	24.7	24.2
Sum spectrum efficiency (bps/Hz)	19.3	19.1	18.9	16.4	16.1
Single beam spectrum efficiency(bps/Hz)	18.2	18.2	18.2	18.2	18.2

^b $P_{noise} = -40$ dBm, $N_r = 15$, $R = 50$ m.

receive antenna elements selected for signal extraction, i.e., $2N_r$, are plotted in Fig. 5 and Fig. 6 respectively. The transmit power in both systems is identical and is normalized such that the delivered power along each of the two main beam directions in the dual-beam multiplexing system at the corresponding distance is 0 dBm.

It can be seen in Fig. 5 that the proposed dual-beam multiplexing backhaul link achieves higher spectrum efficiency than the single beam link with the transmit and receive BS distance up to 100 m when $N_r = 49$ and $P_{noise} = -40$ dBm, or up to 80 m when $N_r = 30$ and $P_{noise} = -40$ dBm. These distances can be further extended to 160 m and 120 m, respectively, when 20 dB more transmit power is used, which is equivalent to 20 dB less P_{noise} under the transmit power normalization. The spectrum efficiencies in the dual-beam multiplexing backhaul links reach their maximum when R is around 15 m or 20 m for each case which is the distance at which each of the two beams is pointed towards the center of the upper and lower N_r antenna elements. The spectrum efficiency in the single beam link keeps fairly constant when R is greater than 30 m under the power normalization condition.

As shown in Fig. 6, when the distance R and the noise power are small, e.g., $R = 50$ m and $P_{noise} = -60$ dBm, the achieved spectrum efficiency in the proposed dual-beam multiplexing system even with a small number of receive antennas, i.e., $2N_r = 20$, is higher than the single beam system with almost entire available antenna elements, i.e., $2N_r = 98$. As for the larger distance R , the required number of receive antenna elements needs to be increased in order to maintain the multiplexing gain. When the noise power increases which is equivalent to the decrease of the transmitted power, the multiplexing gain in the proposed dual-beam system diminishes for the larger transmit and receive distance.

V. CONCLUSION

In this paper the beamspace multiplexing was

Fig. 5. Simulated spectrum efficiencies of the proposed dual-beam multiplexing and the traditional single beam wireless backhaul links for various distances R between transmit and receive BSs. $N_r = 49$ or 30 , $P_{noise} = -60$ dBm or -40 dBm, and $\Delta k = 22.5^\circ$.

Fig. 6. Simulated spectrum efficiencies of the proposed dual-beam multiplexing and the traditional single beam wireless backhaul links against the number of selected receive antennas, i.e., $2N_r$, that are used for signal recovery. $R = 50$ m or 100 m, $P_{noise} = -60$ dBm or -40 dBm, and $\Delta k = 22.5^\circ$.

investigated for the free-space mm-wave backhaul applications. The Fourier beamforming lens at transmit side was used to generate narrow beams that could be exploited to transmit multiplexing data in beamspace. The phase delay networks at the receive side, with the synthesis approach described in this paper, were able to provide high isolation between different data streams. It has been shown with the simulation results that the higher spectrum efficiency could be achieved in the proposed beamspace multiplexing backhaul link even with coarse phase shifter resolutions, when compared with the single beam link, especially when the transmit and receive distance is small and medium, the hardware noise is small, and more receive antennas were activated.

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