Directional Antennas for Point-to-Multipoint Millimetre Wave Communications

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***Abstract* — In this paper, we investigate the feasibility and potential performance of applying an antenna array of directional elements such as horn antennas for mmWave point-to-multipoint communications. We propose a conceptual design of the array, and review options for antenna elements and mechanical steering devices. We then estimate the achievable performance with respect to link data rate and distance, and show that pointing to users exactly does not always achieve system capacity, but the gap is typically small. We also provide comparison for two types of multiple access schemes.**

1 INTRODUCTION

Millimetre wave (mmWave) bands such as those at 38 GHz, 70 GHz and 80 GHz provide enormous bandwidth and can potentially enable very high data rate wireless communications over a short to medium range. Recently, there are strong needs for short-range high speed point-to-multipoint (PTMP) links as fronthaul/backhaul for connecting multiple small cell base-stations to a local micro-station. These small cell base-stations can be static/permanant, or temporally set and fixed, or even moving slowly to adapt to hotspot traffic requirement. The mmWave technologies have been considered for such scenarios, but candidate options being studied have been limited to massive mmWave antenna arrays, which can generate steerable high-gain beams. However, the cost of a massive mmWave antenna array is still very high. It will remain very costly until COMS technologies become efficient for mmWave frequencies.

Directional antennas such as high-gain horn and dish antennas are typically considered only for fixed PTP connections. For mmWave such as E-band 60 to 90 GHz, these antennas can have 20 to 40 dB gains with physical aperture only ranging from tens to hundreds cm^2. This is equivalent to the gain achievable by a phased-array with 100 to 10000 antenna elements. Therefore, there could be significant cost savings if we can use directional antennas to form an array for this purpose.

There is little work on PTMP antenna arrays of directional elements in the literature. A sectorised horn antenna array using a rotary switch based on RF MEMS technology is reported in [2]. But beam direction is only changed via selecting different antennas, and only one user can be served at a time. Nevertheless, the testing results in [2] show that mutual coupling is acceptable and it is feasible to use horn antenna arrays even when they are very close to each other.

In this paper, we investigate the feasibility and the approach of using directional antenna arrays for PTMP mmWave communications. We will first develop a conceptual system setup and investigate the feasibility based on mechanical steering. We will then study the performance of such a system and the pointing direction optimization problem.

2 Feasibility Study

2.1 System Setup

Fig. 1 shows the top view of two conceptual cylinder layouts of antenna arrays using, e.g., horn directional antennas. Horn antennas can be placed in either one or multiple layers. One-layer setup may lead to a simpler mechanical design but will contain denser antenna elements. Multiple-layer setup provides increased space for (larger) antennas and allows wider scanning range. These horn antennas will be steered mechanically to serve nodes with changed locations.

The horn antennas can be placed in various layouts, depending on requirements for coverage, wind load and scanning range. A cylinder configuration allows uniform coverage and large scanning range. But it allows less antennas to point to the same area and hence will be less efficient in providing higher data rate for hot areas.

Each horn antenna will have its own radio components and digital-to-analog and analog-to-digital converters. Their digital (baseband) signal will be processed jointly. Spatial division multiple access (SDMA) techniques [3] will be applied to remove potential multiuser interference, and hence many users, up to the number of antennas, may be served at the same time using the same frequency channel.

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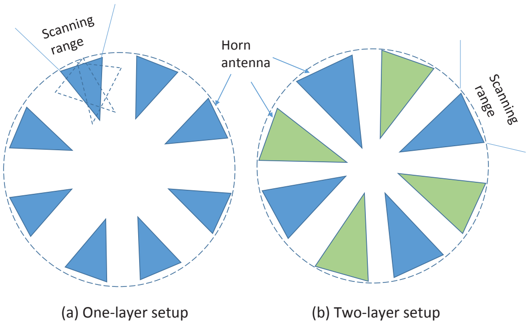

(a) One-layer setup

(b) Two-layer setup

Figure 1: Conceptual layout of the array using Horn antenna elements: (a) One-layer and (b) Two-layer setups. Green and Blue triangles represent horn antennas at different layers.

	QuinStar	Mi-Wave
Model number	QGH-EPRR00	261E
Gain (dB)	23	25
Dimension (LxWxH, mm)	59x31x24	81x37x30

Table 1: Examples of mmWave Horn antennas

2.2 Directional Antenna Elements

Typical small high-gain directional antennas suitable for mmWave applications include parabolic, horn and lens antennas. These antennas can generally provide more than 20 dB gain with dimension of tens of cubic centimetres. Achieving a good balance between gain and ease of operation, horn antennas are the best option for the setup considered in this paper. In Table 1, we list some examples of pyramidal horn antennas working in the frequency range of $60-90$ GHz. Such a horn antenna typically has a 3dB beamwidth of about 10 degrees. State-of-the-art automatic positioning system such as GPS-assisted tracking can work efficiently in this case. The cost of this type of horn antenna ranges from \$500 to \$1000. Parabolic antennas are slightly larger and have higher gains. For example, the MTi wireless's $71-86$ GHz 20cm dish antenna has a gain of 44 dB with a 3dB beamwidth of 1 degree. However, the narrow beamwidth makes re-positioning challenging and requires more advanced tracking systems such as those used in [1].

2.3 Steering Mechanism

A lot of techniques have been developed for steering an antenna,with a survey for mmWave applications available from [4]. When selecting a beam steering technique, the following properties need to be considered: insertion loss, steering range and resolution, steering speed, complexity, size and cost. The system setup in this paper has the following essential requirements for steering: Being able to steer multiple medium size antennas, but not simultaneously; Support static or slow moving targets; Steering range is medium to large, and fine steering resolution is preferred due to narrow beam width of directional antennas. Based on these requirements, mechanical steering is a reasonable option. Mechanical steering introduces no insertion loss and offers flexibility in steering range and resolution. Its limitation on steering speed is not a problem for applications where nodes are mostly static. Hence a mechanical steering system with reasonable size and cost is desired.

A mechanical steering device typically consists of a controller, stepper motors, and antenna fixings. These individual components are widely available as off-the-shelf commercial products. However, the whole steering device generally needs to be customer-built, adapting to specific antenna arrays. Examples of automatic 3D mechanical steering systems for mmWave directional antennas are reported in [5] for a dielectric lens antenna and in [6] for horn antennas. As shown in Fig. 2 the hypocycloidic steering system in [5] uses two parallel levels and a rotating stick across the two levels. The gear level contains planetary gears driven by a uniaxial stepping motor, and the joint level provides a universal joint in center position that allows for two dimensional slanting movements. The rotating stick connects the antenna through the joint to a ball joint at the gear level. Between the two levels either a waveguide or a whole transceiver may be attached to the stick. The system has a maximal steering angle of 50 degrees. This mechanism is simple but requires a certain distance between the two levels to achieve wide scanning range. In [6], the horn antenna is housed in a 3D-printed platform, and a controller and stepper motors of 3.6 degree resolution are used to automatically step through receiver orientations. The receiver is separate to the housing. A housing, however, may have significant impact on the radiation pattern of a horn antenna.

The most common steering system today rotates the entire horn antenna assembly. Typically the transceiver coupled to the horn antenna remains fixed while the antenna is rotated. This requires flexible cables or rotary joints between the moving antenna and the transceiver, which often cause signal loss, unwanted noise and system failure mechanisms. In patent [US20160056537], a new idea is proposed to shift outer horn plates only instead of the whole antenna for beam steering, as shown in Fig. 2 (b). This in principle maintains fixed connec-

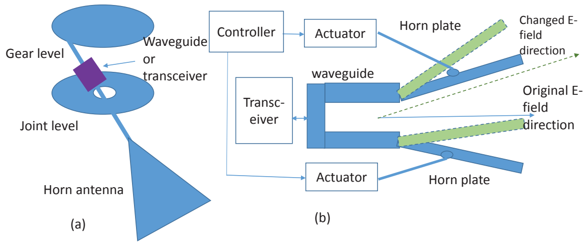

Figure 2: Examples of mechanical steering: (a) a hypocycloidic steering system; and (b) Steering horn plates instead of the whole antenna.

tion between radio and antennas, and reduces the weight of the antenna to be rotated. For practical implementations, however, controlling the rotation of the two outer plates synchronously is challenging. The possible loss in antenna gain due to the rotation also needs a careful assessment.

2.4 Dimension

Based on the dimensions in Table 1, we may get a reasonable estimate for the size of such an antenna array. For example, for 8 horn antennas as shown in Fig. 1, the diameter of the cylinder can be well below 1 meter , when a steering device can be less than 30 cm in one dimension. This represents an acceptable profile for easy installation.

3 Performance Study

3.1 Link Performance

The link performance including data rate and link range depends on many factors, such as bandwidth, equivalent isotropically radiated power (EIRP), receiver sensitivity, and pathloss. EM solution and CSIRO demonstrated a low-latency E-band PTP system achieving 5 Gbps over a range of more than 15 km [1], where two 1.2m-diameter dish antennas of about 55 dB gain is used. For the PTMP system considered in this paper, potential interference between users can reduce the receiver sensitivity, which we assume causes a 3 dB implementation loss. We also assume that the horn antenna has a gain of 25 dB and the remote nodes being connected use a 60cm dish antenna of 50 dB gain (such as MT-799001/W/A). Assume that we have similar system specifications with those in [1] including maximal transmission power, and a reduced receiver sensitivity of 3 dB due to multiuser interference. With the reduction of a total of $30 + 5 + 3 = 38$ dB link budget, the achievable link distance of this PTMP system is approximately 260m for a data rate of 5 Gbps.

3.2 Capacity Optimization

In a PTP system, it is desired to point the directional antenna exactly to a user to maximize the antenna gain. In PTMP, system capacity is not always maximized in this way, but the difference is generally small for typical radiation patterns. Larger capacity can generally be achieved by using SDMA techniques, except that users are close in both direction and distance when techniques such as time division multiple access (TDMA) could be a better option. We validate these statements using a simple example with a two-antenna array and two users below. Note that we do not consider line-of-sight (LOS) MIMO techniques here directly because it is very challenging to realize between multiple users. But adding phase into channel modeling below achieves similar effect with LOS-MIMO.

We use the bound of the sum rate region as a metric for performance evaluation, which is the maximal achievable sum rates of all users and can be achieved through dirty paper coding [3]. For a 2-user SDMA scheme, following (4) in [3] this bound for multi-access channel is given by

$$R_{\mathrm{SDMA}} = \log\det\left(\mathbf{I}_2 + \gamma\sum_{k=1}^{2}\mathbf{H}_k\mathbf{H}_k^H\right), \qquad (1)$$

where $\mathbf{I}_2$ is a 2×2 identity matrix, $\mathbf{H}_k = (h_{1,k}, h_{2,k})^T$ and $h_{i,k}$ is the channel between antenna i and user k, γ is the signal to noise ratio (SNR) and is assumed to be the same for all users. Note that each user's rate cannot exceed its single user capacity, which is not presented here.

Consider LOS propagations. Assuming parallel incoming waveforms, we can represent $h_{i,k}$ as

$$h_{i,k} = g(\theta_{i,k})\,\varepsilon_k e^{j2\pi d(i-1)\sin(\phi_k)}e^{j\alpha_k},$$

where $g(\theta_{i,k})$ is the beamforming gain as a function of the difference between the pointing direction of the i-th antenna and the angle of arrival (AoA) ϕ_k of the k-th user's signal, ε_k is the pathloss for user k, and d is the separation of the two horn antennas normalized to the wavelength, $e^{j\alpha_k}$ is the initial phase difference between users. Here we have assumed that the pathloss terms from all the antennas to one user are the same, and all antennas have the same radiation pattern.

When $h_{i,i}, i = 1, 2$ are dominating and γ is large, we can ignore I_2 and approximate the determinant in (1) as

$$\beta \triangleq \gamma\varepsilon_1^2\varepsilon_2^2\cdot \left|g(\theta_{1,1})g(\theta_{2,2}) - g(\theta_{1,2})g(\theta_{2,1})e^{j2\pi d(\sin(\phi_1)-\sin(\phi_2))}\right|^2.$$

Since $\theta_{i,1}-\theta_{i,2}$ is fixed, $g(\theta_{i,1})$ and $g(\theta_{i,2})$ depend on each other. Thus β is not always maximized when $g(\theta_{1,1})$ and $g(\theta_{2,2})$ are set to the maximum (pointing to users exactly). The optimal pointing direction mainly depends on the radiation pattern. But the difference could be quite small for typical radiation pattern with narrow mainlobe.

There is a similar optimization problem on pointing direction in TDMA. To maintain user fairness and simplify the analysis, we assume that each user shares the transmission time equally. Then based on the TDMA sum rate expressions (5) and (6) in [3], the two-user sum rate bound in this case is given by

$$\begin{aligned}R_{\text{TDMA}} &= 0.5\sum_{k=1}^{2}\log\left(1+\gamma\mathbf{H}_k^H\mathbf{H}_k\right)\\ &= 0.5\sum_{k=1}^{2}\log\left(1+\gamma\varepsilon_k^2(g^2(\theta_{1,k})+g^2(\theta_{2,k}))\right)\end{aligned}$$

Ignoring 1 in the above equation, we can see that maximization of R_{TDMA} is equivalent to maximizing $\prod_{k=1}^{2}(g^2(\theta_{1,k})+g^2(\theta_{2,k}))$. Obviously the optimal pointing direction also mainly depends on the radiation pattern.

For a particular channel realization, comparing R_{SDMA} and R_{TDMA} will tell us which access scheme can achieve higher sum rate capacity.

In Fig. 3, we show the sum rate capacity for both optimal pointing and exact pointing to users (i.e. $\theta_{k,k}=0$ for any k), in both SDMA and TDMA modes. The antenna radiation pattern is approximated as a Gaussian function with parameters $(0, 0.009)$, which corresponds to a 3 dB beamwidth of 12 degrees. The two horn antennas are separated by 8 cm and central frequency of the band is 72.5 GHz. Users' directions are generated following a uniform distribution between $[-r, r]$. Free space path loss model is used, with users uniformly distributed over a range of 100 to 250 meters. The averaged SNR is 15 dB. Each user's rate is required not to be smaller than 30% of their single user capacity when each antenna is pointed to one user exactly. The optimal values are determined using exhaustive search.

The figure shows that the sum rates achieved by the two types of pointing directions are very close, and SDMA achieves higher sum rates than TDMA. The sum rate of TDMA decreases with r, which is consistent with the shape of the Gaussian waveform. Interestingly, the sum rate of SDMA first increases and then decreases with r increasing. This is primarily attributed to the channel phase. The phase difference between the channels can make channels less correlated and even orthogonal; such an effect, together with reduced magnitude correlation with r increasing, leads to the maximum sum rate at some r, and then phase becomes having almost no impact on sum rates when two users are largely separated and each antenna almost serves each user independently.

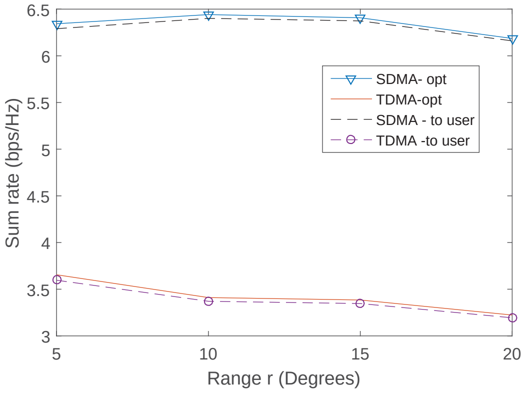

Figure 3: Sum Rate versus range r for optimal and exact pointing directions.

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