Extending Uplink Coverage of mmWave and Terahertz Systems Through Joint Phase-Time Arrays

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ABSTRACT In this paper, we establish the potential of joint phase-time arrays (JPTAs) for uplink coverage extension in cellular systems. JPTA allows the base station (BS) to create frequency-dependent wide-beams without sacrificing the array gain. In this work, we propose a novel use case of JPTA where the BS exploits the frequency-dependent beams to serve multiple users’ equipment (UEs) at different directions simultaneously with the full array gain and with no inter-UE interference. This is achieved by assigning each UE a corresponding bundle of sub-carriers that benefit from the full array-gain. A key feature of this scheme is the prolonged channel access for uplink communication for each user, due to the BS’s ability to serve multiple UEs at the same time. We focus on two performance metrics: uplink coverage and uplink throughput. Our results show that using JPTA can extend the uplink coverage range by 3× while boosting the uplink throughput by providing more flexibility for the BS in resource allocation. These results are based on both theoretical analysis and 3GPP spec-compliant simulations with a sub-terahertz transceiver prototype.

INDEX TERMS True time delay, 5G, 6G, millimeter wave, terahertz, sub-terahertz.

I. INTRODUCTION

Millimeter-wave (mmWave) has been a key technology in the fifth generation of cellular systems (5G), promising to provide high data rates due to the sizeable unutilized bandwidth at the mmWave band [1]. Following the same trend, terahertz (THz) communications is a promising technology in 6G that is intended to support even higher data rates thanks to larger bandwidth [2]. For example, the typical bandwidth in the mmWave band is a few GHz, while at THz bands, bandwidths of more than 10 GHz may be possible [3]. To this end, large antenna arrays with directional beamforming are an inevitable companion of any communication system operating at high-frequency bands [2].

A drawback to using large antenna arrays is the high power consumption if the same fully digital beamforming in lower bands was adopted [4]. To make it practically feasible, an analog beam-based architecture has been adopted in mmWave 5G [5]. To determine which beam to use, the BS relies on beam sweeping. The number of narrow beams (alternatively time slots) needed to sweep the whole-cell scales linearly with the number of antennas in the case of a simple beam sweeping procedure [6], or logarithmically at best if more sophisticated signal processing or machine learning techniques are used [7], [8], [9], [10]. This imposes scalability issues since the antenna arrays are expected to grow larger in 6G. In addition, phased antenna arrays (PAA)s are also adopted by 5G mmWave UE [11], [12], [13] and a best beam pair, instead a single best beam, has to be tracked. The challenge is further exacerbated by the UE rotation and movement [14], [15].

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In this paper, we consider an alternative beamforming architecture called the joint phase-time array (JPTA) [16]. In addition to phase shifters (PSs) (and switches) used in PAA, the JPTA architecture also incorporates true-time-delay (TTD) units. The significant difference between PAA and JPTA is the ability to create frequency-dependent phase shift in TTD, which provides the flexibility to designing beams that cannot be efficiently achieved using PAs. Despite the extra flexibility TTD provides, it has been overlooked in practice due to scalability issues in terms of power and area. Moreover, the limited delay range and resolution realizable in the delay units puts restrictions on the design of the frequency-dependent beams [17]. Recent advances improved the scalability and enabled the large delay range-to-resolution ratios [18], [19], [20], [21], which have made the implementation of JPTA feasible. Prior work has explored specific architecture and usage of JPTA, referring it as TD [22] or delay-phase precoding (DPP) [23]. In [16], we explored the full potential of JPTA by showing that JPTA can realize several beneficial frequency-dependent beamforming behaviors, which cannot be efficiently realized with PAs.

The main use cases of JPTA in the prior work are to combat beam squint and/or to achieve fast beam training [17], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35] as we explain in detail in Section II. Briefly, at high-frequency bands, the ratio between the bandwidth and the center frequency is relatively high, which causes beams at different frequencies to point to different physical directions, which results in losing some of the array gain [37]. By using frequency-dependent beamforming, the delays in the delay units can be set to mitigate this effect and restore a uniform array gain across the different frequencies [22], [23], [32], [33], [34], [35].

Fast beam training is another application for JPTA architectures. Contrary to beam squint compensation, this application further spreads the beams across the band in different directions. JPTA creates frequency-dependent beams such that the array gain at every spatial direction is near-optimal at a particular set of frequencies. Naturally, such beams are coupled with multi-carrier systems (e.g., OFDM), where the array gain is high at a specific bundle of sub-carriers in each spatial direction. Hence, instead of sweeping through many beams to cover the whole angular space, a single JPTA beam is sufficient, which reduces the beam training overhead to a single OFDM symbol independently from the array size [24]. It also allows multiple simultaneous transmissions to nodes in different spatial directions. This type of beams is sometimes referred to as a rainbow beam [38] or a prism beam [27], and can be realized by using only delay units [24].

In this paper, we answer the following question: What benefits does JPTA have in terms of the coverage and throughput? Current mmWave 5G deployments have limited coverage [39]. Because of the high penetration loss and blockage at the mmWave band, the cell radius of the mmWave 5G is much less than the sub-6 GHz mid-band 5G and low-band LTE. Nowadays, the mmWave 5G is mostly only available in downtown areas, stadiums, airports, etc. To increase the coverage, a straightforward solution is cell densification, which would substantially increase CAPEX/OPEX, but also has its limitations [40].

With sub-THz or THz communications being proposed for 6G, the coverage is becoming more severe. Hence, showing that JPTA can also extend the coverage area and enhance the throughput for the cell-center user certainly makes it more appealing. Compared to the downlink, the uplink is more likely to be the bottleneck of the cell coverage, because of the smaller UE transmission power than that of BSs. Furthermore, the uplink coverage is becoming more and more important because the new 5G/6G use case, for example, video surveillance and sharing, AR/VR/XR, need more uplink bandwidth. To this end, we study the uplink performance of a BS deploying JPTA with many traditional UEs equipped with traditional PAs. We focus on two aspects: coverage extension and UE throughput, and provide theoretical analysis in addition to simulation results based on the 5G specifications. Our results show that using JPTA increases the coverage range of the BS by a factor of three in an urban-micro environment while boosting the overall cell throughput, depending on the users’ locations. We also discuss some challenges that might affect the adoption of JPTA in practice and our future work plan.

Summary of Contributions:

- We proposed a novel JPTA beamforming scheme where the cell is divided into spatial zones and every spatial zone is served by a JPTA beam. In this scheme, UE can access the uplink channel for a prolonged duration compared to simple round-robin scheduling used in traditional PAA beamforming.
- We compare the coverage distance of a BS employing JPTA beamforming with a BS employing traditional PAA beamforming. We show that under the power-law path loss model with a path loss exponent of β, JPTA can extend the coverage up to \( K^{\frac{1}{\beta}} \), where \( K \) is the ratio of uplink transmission opportunities of JPTA beamforming. The transmission opportunity is defined as the number of time-slots a UE can access the channel relative to the simple round-robin scheduling used in traditional PAA beamforming. Hence, \( K \) is related to the number of JPTA beams used to cover the whole cell and the max number of UEs in the cell that can be served simultaneously. We follow this analysis by a link-budget analysis and 5G-compliant link-level and system level simulators. Our results confirm the potential gains of JPTA in coverage extension where the maximum coverage distance can be extended by up to \( K^{\frac{1}{\beta}} \).
- We also utilize our simulators to show that the benefits of using JPTA are not limited to coverage extension, i.e., improving the performance of cell-edge users, but also results in a throughput boost for all users in the cell. Similar to the coverage extension results, the cell
throughput enhancement is directly proportional to the parameter $K$.

The rest of the paper is organized as follows: In Section II we discuss the previous works in detail and point out how they are related to our work in this paper. In Section III we discuss the JPTA architecture and define key parameters that determine the performance of the system and different trade-offs. Theoretical analysis for the coverage extension is presented in Section III. The simulation setup and the simulation results are discussed in Section V before concluding in Section VII.

The notation used in this paper is summarized in Table 1.

II. DETAILED REVIEW OF PRIOR WORK

In this section, we review relevant prior works on frequency dependent beam design. Note that frequency-dependent beams can be realized by using leaky-wave antennas. However, these antennas are bulky and inefficient, especially at mmWave bands [20]. Hence, we focus the discussion of frequency-dependent beams using JPTA.

JPTA can be used to reduce the overheads in beam training [17], [22], [24], [25], [26], [27], [28], [41] which can be realized by a pure TTD network [24], [29], [30]. JPTA [25], [26], [27], [28], or hybrid (multiple RF-chains) JPTA [17]. All of these works assume a uniform delay model, where the delay difference between any two consecutive antennas ($\Delta t$) is uniform, and it is sufficient to set $\Delta t$ proportional to the inverse of the bandwidth to achieve the near-optimal gain across the whole 180° angular region under the narrowband assumption. The conclusion of these works focuses on the beam training overhead reduction, where a single OFDM symbol is enough to accurately estimate the AoD regardless of the number of antennas in arrays. Another important outcome out of all these works is the feasibility of JPTA beamforming in practice and that it can be realized through the current state-of-the-art technology as demonstrated in [20].

JPTA can also be used to combat beam squint by setting the delays to be inversely proportional to the center frequency [23], [34], [35]. Such delays ensure a uniform array gain across different frequencies and angles and enable efficient wideband beamforming. Other related interesting works include [31], where mapping frequencies and spatial directions in TTD systems is discussed, [21] where the authors proposed using fixed delay units instead of adjustable ones to reduce the energy consumption. Another interesting work is [20], where the authors showed that JPTA could be realized using CMOS technology as an alternative to bulky Rotman lenses.

In [22], using JPTA to mitigate beam squinting in the data communications phase and to create rainbow beams in the initial access phase. In our work, we look at the potential of using JPTA with rainbow beams in the data communications phase since the algorithm we use takes care of the beam squint effect while designing the delays [16]. Note that the previous works we discussed so far do not address the potential of JPTA in the data communications phase and stop at the initial access phase. In [38], the authors propose a multiple-access scheme using TTD arrays, aiming at reducing the overall latency. The latency reduction is a result of the fact that we do not need explicit beam training or grant requests in this case. In [42] the authors considered a broadband THz downlink network and focused on how to design beams in the case of non-uniform UE distribution and resource allocation optimization, which is different from what we study in this paper. Another interesting application of the JPTA is beam tracking as in [36], where the beam split effect is exploited to track the UE movement within a certain angular range.

III. JPTA BEAMFORMING

The JPTA architecture we consider is shown in Fig. 1. Each antenna is connected through an adjustable delay unit and an adjustable PS, then all the antenna branches are connected through a single RF-chain. The delay values in the delay units are set to create a beam as shown in Fig. 2, where at each spatial direction between $\theta_{\text{min}}$ and $\theta_{\text{max}}$, there are a set of sub-carriers that can be used to receive the full array gain.

The algorithm we use to determine these values is discussed in detail in [16]. Note that it is sufficient only to use delay units to create the beam shown in Fig. 2, but this limits the BS to use a single JPTA beam to cover the whole cell. Instead, we use a combination of PSs and delay units, where the delay units are used to create a beam pointing towards the boresight direction with the desired angular width, then the PSs are used to rotate the beam to cover the whole cell. Furthermore, this setup reduces the maximum delay required in the delay units, which is a bottle-neck for JPTA beamforming, since the angular width of each beam is less than the whole cell.

Hence, the PSs are used to rotate the beam towards a different spatial directions, i.e., $[\theta_{\text{min}}^{(j)}, \theta_{\text{max}}^{(j)}] \cap [\theta_{\text{min}}^{(j)}, \theta_{\text{max}}^{(j)}] = \emptyset \ \forall i \neq j$, where $\emptyset$ is the empty set and $[\theta_{\text{min}}^{(j)}, \theta_{\text{max}}^{(j)}]$ define the spatial zone covered by the $j^{th}$ beam. In this work, we assume uniform JPTA beams, where the area of the spatial zones covered by the different beams is the same, i.e., $[\theta_{\text{min}}^{(j)} - \theta_{\text{min}}^{(j)}] = \Delta \theta$. $\forall j \in \{1, \ldots, N_{\text{SZ}}\}$, where $N_{\text{SZ}}$ is the total number of spatial zones (JPTA beams) which is given by $N_{\text{SZ}} = \frac{120}{\Delta \theta}$ assuming that the BS covers a sector with 120° angular span.

Hence, there are $N_{\text{SZ}}$ spatial zones (JPTA beams) covering the whole angular span of the BSs. Multiple users can be served simultaneously in each spatial zone by allocating a distinct set of sub-carriers to each UE with no interference. For the example shown in Fig. 2, if there are 4 UEs with
uniform angular spacing (over the 120° sector) in the cell, i.e., $N_{UE} = 4$, then if $N_{SZ} = 1$, all the UEs can be served simultaneously by the BS with each UE using a different set of sub-carriers, and if $N_{SZ} = 2$, then only two UEs can be served simultaneously. Hence, the fewer the spatial zones, the larger the number of UEs whose data can be multiplexed together. However, the fewer the spatial zones, the smaller number of sub-carriers (denoted as $N_{SC}$) that can be allocated to each UE while having an interference-free communication and a decent array gain. Note that a smaller number of $N_{SZ}$ means a larger angular span covered by each JPTA beam, which leads to a smaller number of sub-carriers that have the full array gain, as we shall see in Section V-A.

Another important factor that is determined by $N_{SZ}$ is the number of time slots needed by the BS to serve all its UEs. Following the same example in Fig. 2, if $N_{SZ} = 1$, then the BS can serve all UEs in a single time slot and if $N_{SZ} = 2$, then it needs at least two time slots, and so on. Hence, the number of time slots allocated to each UE is doubled if $N_{SZ} = 1$ compared to $N_{SZ} = 2$. We call this gain in time slots transmission opportunity and denote it by $K$, where $K = \lceil \frac{N_{UE}}{N_{SZ}} \rceil$. Formally, the transmission opportunity $K$ is defined as the number of time-slots a UE can access the channel relative to the simple round-robin scheduling used in traditional PAA beamforming. If the number of spatial zones is equal to the number of UEs, then $K = 1$, i.e., a UE in JPTA has the same access to the channel as a UE in PAA. If the number of spatial zones is 1, then all the UEs will have a continuous access to the channel and $K = N_{UE}$.

To sum up, $N_{SZ}$ affects the other parameters as follows: $N_{SZ} \propto N_{SC} \propto K^{-1}$. Note that changing $N_{SZ}$ does not have an effect on the time-frequency resources for each UE. However, having more transmission opportunities is very valuable in the uplink communications, due to the limited transmit power of the UEs as we discuss in the following section.

IV. A THEORETICAL ANALYSIS: JPTA VS PAA

In the conventional PAAs, the BS switches among the narrow beams to receive the uplink signal from the UEs. Therefore, each UE can only transmit over a fraction of time, but potentially over the whole bandwidth as determined by the uplink grant. Considering a simple setup where $N_{UE}$ UEs are dropped in the cell with same distance to the BS and uniform angular spacing. When the UE is transmitting with power $P_{UE}$, the uplink power received at the BS is

$$P = P_{UE}G_{UE}G_{BS}G_h,$$  

where $G_{UE}$ ($G_{BS}$) and $G_h$ stand for the beamforming gain at the UE (BS), and the path gain, respectively. The uplink throughput of each UE is

$$R_{PAA} = \frac{W}{N_{UE}} \log \left( 1 + \frac{P}{W N_0} \right),$$

where $N_{UE}$ is the number of active UEs, $W$ is the bandwidth, and $N_0$ represents the power spectrum density of AWGN. Note that we ignore the beam squint effect in (2) for simplicity.

In the JPTA system, the BS can simultaneously serve multiple UEs on different directions at different frequencies. Assume that there are $N_{SZ}$ spatial zones and each UE can access $\frac{W N_{SZ}}{N_{UE}}$ frequency band over $\frac{1}{N_{SZ}}$ uplink duration, the uplink throughput of each UE is,

$$R_{JPTA} = \frac{W N_{SZ}}{N_{UE} N_{SZ}} \log \left( 1 + \frac{P}{W N_0} \right) \times K,$$  

where $K = \lceil \frac{N_{UE}}{N_{SZ}} \rceil$. Comparing (2) and (4), there is a power boosting with a factor of $K$ for the JPTA system due to smaller bandwidth.
and more uplink transmission opportunities in the temporal domain per UE.

A simple example of uplink transmission in PAA and JPTA system is provided in Fig. 3. There are 4 narrow beams for the PAA case and 1 beam for JPTA. In the PAA case, the UE can only transmit in a single timeslot (the 2nd timeslot in the figure). In contrast, the UE in the JPTA case can transmit over 4 timeslots, but only over a quarter of the frequency band. The total radio resource assigned to that UE is the same, however, the UE in the JPTA case delivers $4 \times$ more energy to BS than that for PAA, assuming there is an instantaneous power constraint for UE due to power amplifier and/or RF exposure limits [43], [44].

The uplink coverage can be defined as the maximum distance where the UE can attain a minimum uplink throughput $R_{\text{min}}$, which translates to the minimum received power requirement as,

$$P_{\text{PAA}} \geq \left( \frac{2K R_{\text{min}}}{\beta} - 1 \right) W N_{0}$$

$$P_{\text{JPTA}} \geq \left( \frac{2K R_{\text{min}}}{\beta} - 1 \right) W N_{0} \frac{K}{K}.$$  

To estimate the uplink coverage, we assume that the large-scale path gain is $G_h = \alpha d^{-\beta}$, where $\beta$ is the path loss exponent, and $\alpha$ is the path gain at 1m distance. The received uplink power at BS from UE at distance $d$ is

$$P = \frac{P_{\text{UE}} G_{\text{UE}} G_{\text{BS}} \alpha}{d^{\beta}}.$$  

And the uplink coverage of PAA and JPTA is,

$$d_{\text{PAA}} = \left( \frac{P_{\text{UE}} G_{\text{UE}} G_{\text{BS}} \alpha}{W N_{0} \left( \frac{2K R_{\text{min}}}{\beta} - 1 \right)} \right)^{1/\beta},$$  

$$d_{\text{JPTA}} = \left( \frac{K P_{\text{UE}} G_{\text{UE}} G_{\text{BS}} \alpha}{W N_{0} \left( \frac{2K R_{\text{min}}}{\beta} - 1 \right)} \right)^{1/\beta} = K^{1/\beta} d_{\text{PAA}}.$$  

As shown in (9), the JPTA system increases the uplink coverage radius by a factor $K^{1/\beta}$. The coverage area is then extended by a factor $K^{2/\beta}$, implying the BS deployment density could be reduced by the same factor. The coverage radius and area extension with $K$ is illustrated in Fig. 4. It is seen that the $K$-times uplink SNR gain is translated to the coverage radius and area extension. For example, when there are 32 UEs in the cell, and $\beta = 3$, the coverage radius increases by a factor $32^{1/3} \approx 3.17$; the coverage area increases by a factor $32^{2/3} \approx 10.08$; and the BS density can decrease to about 10%, which means a network
installation cost saving of 90%! Although this is an idealized example, the advantage in uplink coverage extension is clearly significant. Note that this analysis is independent of the operating frequency bands; hence it applies to both mmWave and THz bands. However, the JPTA is more suitable for THz bands since the maximum delay required in the delay units is inversely proportional to the BS, as we discussed. Hence, the larger BW at THz makes it more attractive to JPTA beamforming.

For the downlink transmission, the JPTA throughput is the same as the phased antenna array throughput,

\[
R^\text{DL}_{\text{JPTA}} = R^\text{DL}_{\text{PAA}} = \frac{W}{N^\text{UE}} \log \left(1 + \frac{P^\text{BS}G^\text{UE}G^\text{BS}h}{W\eta} \right). \tag{10}
\]

Hence, there is no clear gain the downlink following the simple calculation we presented. Note that, we ignore the beam squint effect of PAA, which will only degrade the throughput of PAA.

In the next section, we describe the simulation setup that we use to verify the gains we derived in this section using more realistic assumptions and to draw further insights on the network performance.

V. SIMULATION SETUP

The goal of the simulator is to find the block-error-rate (BLER) and throughput given a certain array architecture (JPTA vs PAA), physical layer parameters (FFT size, MCS level, number of sub-carriers, sub-carrier spacing (SCS), number of antennas, HARQ, etc.), radio channel assumptions (pathloss, LOS, SNR, etc.), and a network topology. To simplify such intensive simulations, researchers tend to separate the simulation into a link-level simulation (LLS) and a system level simulations (SLS) with an interface between them to reduce the complexity and execution time [45].

The LLS abstracts the physical layer according to the 5G NR standard [47], similar to the simulator described in [45]. There are a lot of features and details in the specifications, hence, we refer the reader to [45] for the details and we just briefly describe the relevant parts in this section. The parameter values for the LLS are summarized in Table 2.

For the MCS levels, the table we use is [47, Table 5.2.2.3], which we provide in Table 3 and the EESM parameter (\(\eta\)) is taken from [45]. In the simulator, different re-transmissions of the same message are combined using hybrid automatic repeat request (HARQ). More specifically, we use incremental redundancy HARQ (HARQ-IR), where every re-transmission contains different coded bits than the previous one [48]. The maximum number of transmissions of the same packet is denoted by \(N^\text{TR}\). Hence, if the message has not been successfully decoded after \(N^\text{TR}\) transmissions, then the whole block is discarded and if the message was decoded successfully using fewer transmissions than \(N^\text{TR}\), then the UE starts transmitting a new message.

After running the simulation for all the different values of \(N^\text{TR}\), MCS levels, and SNR values, we end up with different curves mapping the SNR to the BLER and spectral efficiency. For example, for MCS 0, we get the BLER and spectral efficiency shown in Fig. 5 and Fig. 6. Note that for a fixed MCS level, doubling \(N^\text{TR}\) reduces the SNR required to maintain the same BLER by 3 dB at MCS 0. This is simply due to aggregating the energy of the different transmissions before decoding. In other words, HARQ-IR does not yield additional gain compared to a simple chase combining (HARQ-CC) where every transmission contains the same coded bits [48].

In Fig. 6, the spectral efficiency of \(N^\text{TR} = 32\) is the best, and it converges to \(N^\text{TR} = 16, 8, \ldots, 1\) as the SNR increases.

\[\text{TABLE 2. Link level simulation configuration.}\]

| Parameter          | Value   |
|--------------------|---------|
| Num of frames      | 80      |
| SCS                | 960 kHz |
| # of RBs           | 4       |
| Delay spread       | 0       |
| UE speed           | 0       |
| Channel estimation | perfect |
| Synchronization   | perfect |
| Carrier frequency  | 140 GHz |
| FFT size           | 4096    |
| MCS Table          | Table 3 |
| LDPC Decoding Algo | min-sum |
| # of TX antenna    | 1       |
| # of RX antenna    | 1       |

\[\text{TABLE 3. 5G NR PUSCH setup.}\]

\[\begin{align*}
\text{PUSCH} & = \text{DL} = \text{UL} = \text{PCH}, \\
\text{MCS} & = \text{MCS} = \text{MCS} = \text{MCS}, \\
\text{SCS} & = \text{SCS} = \text{SCS} = \text{SCS}. \\
\text{FFT size} & = 4096, \\
\text{MCS Table} & = \text{Table 3}, \\
\text{LDPC Decoding Algo} & = \text{min-sum}, \\
\text{# of TX antenna} & = 1, \\
\text{# of RX antenna} & = 1.
\end{align*}\]

\[\text{TABLE 4. 5G NR PUSCH setup.}\]

\[\begin{align*}
\text{PUSCH} & = \text{DL} = \text{UL} = \text{PCH}, \\
\text{MCS} & = \text{MCS} = \text{MCS} = \text{MCS}, \\
\text{SCS} & = \text{SCS} = \text{SCS} = \text{SCS}, \\
\text{FFT size} & = 4096, \\
\text{MCS Table} & = \text{Table 3}, \\
\text{LDPC Decoding Algo} & = \text{min-sum}, \\
\text{# of TX antenna} & = 1, \\
\text{# of RX antenna} & = 1.
\end{align*}\]

\[\text{TABLE 5. 5G NR PUSCH setup.}\]

\[\begin{align*}
\text{PUSCH} & = \text{DL} = \text{UL} = \text{PCH}, \\
\text{MCS} & = \text{MCS} = \text{MCS} = \text{MCS}, \\
\text{SCS} & = \text{SCS} = \text{SCS} = \text{SCS}, \\
\text{FFT size} & = 4096, \\
\text{MCS Table} & = \text{Table 3}, \\
\text{LDPC Decoding Algo} & = \text{min-sum}, \\
\text{# of TX antenna} & = 1, \\
\text{# of RX antenna} & = 1.
\end{align*}\]

\[\text{TABLE 6. 5G NR PUSCH setup.}\]

\[\begin{align*}
\text{PUSCH} & = \text{DL} = \text{UL} = \text{PCH}, \\
\text{MCS} & = \text{MCS} = \text{MCS} = \text{MCS}, \\
\text{SCS} & = \text{SCS} = \text{SCS} = \text{SCS}, \\
\text{FFT size} & = 4096, \\
\text{MCS Table} & = \text{Table 3}, \\
\text{LDPC Decoding Algo} & = \text{min-sum}, \\
\text{# of TX antenna} & = 1, \\
\text{# of RX antenna} & = 1.
\end{align*}\]

1However, at high MCS levels, one should expect additional coding gain (on top of the 3 dB) once HARQ-IR is implemented as discussed in [48].
FIGURE 5. BLER vs SNR assuming MCS index 0 for different maximum numbers of transmissions of each packet.

FIGURE 6. Spectral efficiency vs SNR assuming MCS index 0 for different maximum numbers of transmissions of each packet.

FIGURE 7. 8V X 16H BS array and 8V X 2H UE array assumed in this paper.

It is because $N_{TR}$ is the maximum number of transmissions, and as SNR increases, the actual number of transmissions needed to successfully decode the messages is reduced to a smaller number than $N_{TR}$ (at minimum $N_{TR} = 1$). The maximum spectral efficiency is around 0.044 bps/Hz. It is lower than 0.058 bps/Hz (QPSK, 0.029 coding rate) because the signalling overhead (e.g., demodulation reference signal (DMRS), cyclic prefix) has been taken into account in the simulation.

B. SYSTEM LEVEL SIMULATIONS

The system level simulation setup is based on an antenna array developed for sub-THz communication [49]. The BS array consists of 2 8V X 1H sub-arrays as shown in Fig. 7. Each sub-array has one InP power amplifier and one phase shifter. Each sub-array has an array gain of 12 dB at the boresight direction, and total array gain is $12 + 10 \log_{10}(16) = 24$ dB. The antenna element spacing is half-wavelength in both the horizontal and vertical directions. The UE array consists of 2 8V X 1H sub-arrays. The total transmission power from 2 InP power amplifiers is 18 dBm, and the total array gain is $12 + 10 \log_{10}(2) = 15$ dB.

We drop the UE uniformly in a 120° sector. Fig. 8 shows the UE distance to the BS and the path gain. The current prototype supports horizontal beam steering but not vertical beam steering. Thus, we simply assume that the BS and UE are on the same height.

For PAA, we assume that 32 analog beams are adopted to receive the uplink signal from UE. The beam patterns are illustrated in Fig. 9. We choose 32 beams, since a smooth angular coverage is achieved where the maximum beam gain is 24 dB and the minimum gain is 23.3 dB. Note that the beam pattern is plotted at the carrier frequency 140 GHz. In our simulation, since the relative bandwidth is small (2 GHz bandwidth at 140 GHz band), the beam squint effect is minor. Nevertheless, we have modeled the beam squint in our simulation. The PAA sweeps the 32 beams in the time domain, each beam occupying 1/32 of the total uplink duration. As for JPTA, we assume that 16 delay units are connected to the 16 sub-arrays. The JPTA arrays can adopt beam codebooks consisting of $N_{SZ} = 1, 2, 4, 8$, or 16 beams, each beam covering a spatial zone. The radiation pattern of the 2-beam codebook is illustrated in Fig. 10. Note that in Fig. 9 and Fig. 10, the maximum beam gain of PAA and JPTA is the same at 24 dBm. Thus, JPTA does not degrade the peak beam gain.

We only consider the large scale fading in this paper. Let $G_h$ denote the distance-dependent path gain (in dB), then we can find it as,

$$G_h = 20 \log_{10} \left( \frac{c}{4\pi f_c} \right) - 10\beta \log_{10}(d),$$

where $c$ is the speed of light, $f_c$ is the carrier frequency, $d$ is the distance between UE and BS, and $\beta$ is the path loss exponent.

We assume the UE can transmit with the maximum power during the assigned uplink time-slot. As for UE orientation,
TABLE 3. Used MCS levels with the corresponding EESM parameter ($\eta$), modulation order, and coding rate.

| MCS index | $\eta$ | Modulation order | Coding rate | MCS index | $\eta$ | Modulation order | Coding rate |
|-----------|--------|------------------|-------------|-----------|--------|------------------|-------------|
| 0         | 1.54   | QPSK             | 0.029       | 15        | 3.97   | 16QAM           | 0.332       |
| 1         | 1.55   | QPSK             | 0.039       | 16        | 4.27   | 16QAM           | 0.369       |
| 2         | 1.56   | QPSK             | 0.049       | 17        | 4.71   | 16QAM           | 0.424       |
| 3         | 1.57   | QPSK             | 0.063       | 18        | 5.16   | 16QAM           | 0.479       |
| 4         | 1.58   | QPSK             | 0.076       | 19        | 5.66   | 16QAM           | 0.540       |
| 5         | 1.59   | QPSK             | 0.097       | 20        | 6.30   | 16QAM           | 0.602       |
| 6         | 1.60   | QPSK             | 0.117       | 21        | 9.95   | 64QAM           | 0.428       |
| 7         | 1.61   | QPSK             | 0.133       | 22        | 10.97  | 64QAM           | 0.455       |
| 8         | 1.63   | QPSK             | 0.188       | 23        | 12.92  | 64QAM           | 0.505       |
| 9         | 1.65   | QPSK             | 0.235       | 24        | 14.96  | 64QAM           | 0.534       |
| 10        | 1.67   | QPSK             | 0.301       | 25        | 17.06  | 64QAM           | 0.602       |
| 11        | 1.70   | QPSK             | 0.370       | 26        | 19.33  | 64QAM           | 0.650       |
| 12        | 1.73   | QPSK             | 0.438       | 27        | 21.85  | 64QAM           | 0.702       |
| 13        | 1.76   | QPSK             | 0.514       | 28        | 24.51  | 64QAM           | 0.754       |

TABLE 4. System level simulation setup.

| Parameter                           | Default Value |
|-------------------------------------|---------------|
| Bandwidth                           | 2 GHz         |
| Carrier frequency                   | 140 GHz       |
| FFT size                            | 4096          |
| Subcarrier spacing                  | 960 kHz       |
| number of analog beams in PAA       | 32            |

FIGURE 9. Phased antenna array adopts a 32-beam codebook to serve a 120° sector. Different beams are plotted with different colors. The figure plots the beam patterns at the carrier frequency $f_c$.

FIGURE 10. Example of JPTA beam patterns where 2 beams are serving 2 spatial zones, [−60°, 0°], and [0°, 60°], where the bright blue region represents the high array gain region.

V. SIMULATION RESULTS AND DISCUSSION

In this section, we show the link level and system level simulation results. The default path loss exponent $\beta$ is set as 3, which is close to the 3GPP urban-micro close-in model whose path loss exponent is ($\beta = 3.19$) and the weighted average

we assume that the UE is pointing to the BS perfectly for simplicity. In the transmission, the UE adjusts the modulation and coding scheme and the bandwidth based on the SNR level to maximize the throughput with a BLER is less than 10%. The minimum bandwidth is four resource blocks, which is equal to 46 MHz in our case. The simulation parameters are summarized in Table 4.

In the system level simulation, the angle-of-arrival (AoA) and angle-of-departure (AoD) are first identified in the uplink transmission. Then we find the beam gain for each beam and SC. The beam providing the largest gain is identified as the serving beam. We then select a subset of the sub-carriers, whose gain is within 3 dB of the maximum gain. Then we combine the SNRs into the effective SNR by a EESM as we explained earlier in this section. In the last step, the effective SNR is mapped to the BLER and spectral efficiency using the tables we got from the LLS.

Lastly, to maintain the same maximum delay per message for the different beamforming cases, we set the maximum number of transmissions ($N_{TR}$) of the message to the number of transmission opportunities $K$ provided by the beamforming scenario. For example, for PAA with 32 UEs, the UE can transmit each message once, but for JPTA with $N_{SZ} = 16$, each UE gets two transmission opportunities, i.e., $K = 2$, and hence, can afford setting $N_{ST} = 2$ without adding more maximum delay for the message.

VI. RESULTS AND DISCUSSION

In this section, we show the link level and system level simulation results. The default path loss exponent $\beta$ is set as 3, which is close to the 3GPP urban-micro close-in model whose path loss exponent is ($\beta = 3.19$) and the weighted average
NLOS path loss exponent ($\beta = 2.96$) from the measurement done in 28, 38, 73, 142 GHz [50]. Note that although we do not show the LOS results here, there are more coverage extension benefits brought by JPTA when $\beta = 2$ since $K^{1/2} > K^{1/3}$.

### A. LINK-BUDGET ANALYSIS

We first discuss the potential of JPTA using simple link-budget calculations, similar to the analysis done in [51]. The calculations are shown in Table 5. The values in (a) and (b) are fixed for the different schemes and set based on what we discussed in the previous section. (c) is the sum of (a) and (b). (e) is the BW, which is assumed to be 4 RBs with SCS of 960 kHz. (f) is (d) times (e). (h) is from the LLS and Fig. 5. (i) is the sum of (f) and (h). (l) is equal to (c)-(i)+(j)-(k). (l) is the same as (m) since we do not consider shadowing or penetration losses.

From the table, we can see that to maintain a 10% BLER at max, the path loss has to be at maximum 155.04, 160.96, and 170.44, in dB for the three cases presented in the table (PAA, JPTA with 8 spatial zones ($N_{SZ} = 8$), JPTA with 1 spatial zone ($N_{SZ} = 1$)). This can be directly translated into the maximum distance range once a specific path loss model is considered. Following the model in (12) with $\beta = 3$, the corresponding distances in meters are 454, 715, and 1481, for the three cases, respectively. Hence, relative to the PAA, JPTA with 8 spatial zones provides 1.59 distance gain and JPTA with a single spatial zone provides 3.26 distance gain. These gains match the ones predicted by the theoretical analysis in Section IV and shows the superiority of JPTA from the coverage perspective. In the next section, we show the potential of JPTA not only in terms of the coverage extension, but also in terms of the cell throughput. To this end, we utilize the more sophisticated SLS.

### B. SIMULATION RESULTS

We first show the MCS index versus distance for PAA in Fig. 12. At each distance, we average over the MCS of UEs on the 120° arc. The best MCS index is the one with maximum throughput and less than 10% BLER. As seen in the figure, the best MCS index starts at 28 at the cell center ($< 60$ m) and decreases to 0 at the cell edge ($> 400$ m).

The throughput per UE is illustrated in Fig. 13. In this figure, we assume that there are 32 active UEs at the same time in the sector, each falling in the coverage of a PAA analog beam. The per-UE throughput is obtained by averaging over different realizations of the UE drops. The minimum rate for coverage is 57 kbps, which is decided by the minimum MCS level, the maximum re-transmission of the HARQ scheme and 10% BLER. The UE is out of the coverage if the minimum rate cannot be obtained. We can find that JPTA of 1 spatial zone has the largest coverage radius of 1500 m, while the PAA has the minimum coverage radius of 418 m.

In addition, we can see that besides the coverage extension, the JPTA also enhances the throughput in the cell-middle region from a few tens of meters to the cell edge. In the cell center, UEs in all the cases have the same throughput, 225 Mbps per UE, because the maximum MCS limits the spectral efficiency and all the messages are decoded successfully from the first try due to the high SNR. Hence, having the full bandwidth for PAA with 1 time slot out of each 32 per UE is equivalent to having $\frac{1}{32}$ of the BW but continuous transmission (32 time slots out of each 32 time slots per UE) in JPTA with $N_{NZ}$. However, as we see from the figure, the UE benefits more from having more time slots, compared to having more BW, in the medium and low SNR regimes due
TABLE 6. Maximum delay in nano seconds required in the delay units for different schemes and different frequency bands.

| Scheme | THz setup | mmWave setup |
|--------|-----------|--------------|
| $N_{SZ} = 1$ | 3.52 | 8.82 |
| $N_{SZ} = 2$ | 1.67 | 4.2 |
| $N_{SZ} = 4$ | 0.71 | 1.8 |
| $N_{SZ} = 8$ | 0.32 | 0.86 |
| $N_{SZ} = 16$ | 0.16 | 0.46 |

FIGURE 13. Throughput per UE versus the UE-BS distance for different cases assuming the THz setup. The dashed line represents the minimum throughput required for coverage.

FIGURE 14. Throughput per UE versus the UE-BS distance for different cases assuming the mmWave setup. The dashed line represents the minimum throughput required for coverage.

to the energy aggregation provided by HARQ and the limited transmit power of the UEs.

Note that we have focused so far on the THz band with a high bandwidth. However, the intuition behind JPTA gains can also be extended to other frequency bands like mmWave. In Fig. 14 we show the per-UE throughput for the mmWave case assuming a center frequency of 28GHz, 800MHz bandwidth, and SCS of 240kHz. The other setups are the same as the THz case. The curves in Fig. 14 have the same trend as in Fig. 13. In principle, JPTA can be applied to mmWave bands which possibly can be attractive in the beyond-5G (B5G). However, the cost of applying JPTA at lower frequency bands is related to the maximum delay needed in the delay units to create a beam as in Fig. 2, since the maximum delay is inversely proportional to the BW. The maximum delay required to create JPTA beams with different $N_{SZ}$ is given in Table 6.

The maximum delay required for a single spatial zone is the highest and may not be realizable using the current state-of-the-art TTD designs. JPTA with two spatial zones can actually be realized with the current technology ( [52] for the THz setup and [53] for the mmWave setup). Hence, JPTA is not only attractive for the THz bands in 6G, but for the mmWave in B5G as well. Also, note that the flexibility added by using PSs in addition to the delay units allows the designer to increase the number of spatial zones up to the point that the maximum delay required in the delay units can be physically feasible using the desired technology.

C. CHALLENGES AND FUTURE WORK

In general, JPTA of 1 spatial zone attains the best coverage and throughput performance. It also has the least latency in the uplink since UE can transmit in the whole uplink duration. However, it needs the largest delay range for the delay units as we showed in Table 6, which implies more difficulties in the hardware implementation, for example, big form factor and high cost. In addition, JPTA of 1 spatial zone is more prone to cause overheating at UE since UE is transmitting for the whole uplink duration. The JPTA with more than 1 spatial zone provides different trade-offs between the delay unit requirement, BS deployment cost, and UE temperature control, etc. Also, note that to achieve the coverage extension promised by JPTA, UE has to transmit over a longer duration in the uplink. This could cause UE overheating, which in turn forces UE to stop uplink transmission early or reduce the transmission power. In addition, the maximum permissible exposure (MPE) requirement of the handheld phone by regulators, e.g., FCC, could also limit the uplink transmission power or duty cycle [44]. Our analysis ignores these effects by assuming that the overheating can be resolved by better cooling technology or better power saving method in the future, and the uplink power is not too high to exceed the MPE limit.

Considering the hardware complexity and cost, the horizontal array size of the BS is chosen to be 16 in this paper, which is relatively small especially for the sub-terahertz or terahertz bands. With larger horizontal array size, the number of PAA analog beams is expected to be larger than 32, and JPTA will provide more uplink transmission opportunities, and thus a larger factor of coverage extension.

Moreover, we have assumed in this paper that the power consumption and insertion loss of different components required in JPTA is similar to the simple phase shifters in PAA. In practice, this is not necessarily true since adding the delay elements causes additional insertion loss, reducing the potential gains we observed for JPTA. A detailed analysis of...
the power consumption and insertion depends on the architecture and technology used to build the hardware for JPTA, and the amount of delay needed [16, Table 2] [20]. Since we do not consider a specific design for the delay units and focused on the systems aspects of JPTA, modelling all the losses due to the hardware design is beyond the scope of this paper, and one can look at the presented results in this work as an upper bound of the performance we will see in practice.

A future direction is to consider the 3D beamforming of JPTA where the BS height is different from UEs. Another direction is to consider a system with non-full-buffer traffic, rather than the full-buffer traffic considered in this paper. The UE scheduling over the frequency-dependent JPTA beams could be an interesting problem. Moreover, we assume a simplified channel model in the system level simulation, where only the large scale path loss is considered. A future direction is to take into account other factors in the channel, including the blockage, multi-path, penetration loss, etc. The simulation with ray-tracing data is a viable option.

Last but not least, the JPTA architecture in the paper only has one RF chain. Extending to multiple RF chains is an interesting direction.

VII. CONCLUSION

In this paper, we proposed a new array setup called joint phase-time array (JPTA). The limited coverage, especially the uplink coverage, is a bottleneck of the mmWave network deployment and terahertz network in the future. A simplified information-theoretical analysis shows that compared to the phased analog array (PAA), JPTA can extend the cell coverage by $K^{1/β}$ where $K$ is the ratio of uplink transmission opportunities of JPTA beamforming over that of PAA beamforming, and $β$ is the large scale path loss exponent. We then did a practical simulation by following the transmission schemes defined in the 5G specifications, and modelling the antenna array based on a sub-terahertz transceiver prototyping. The uplink coverage radius can extend significantly by a factor of three in an urban-micro environment. Moreover, the JPTA also improves the throughput of the cell-middle region UEs, thus boosting the overall cell throughput.

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