Initial Beamforming for mmWave Communications

Vip Desai, Lukasz Krzymien, Philippe Sartori, Weimim Xia
Wireless Research and Standards,
Huawei R&D USA
3601 Algonquin Rd. Suite 1000
Rolling Meadows, IL 60008

Anthony Soong
Wireless Research and Standards,
Huawei R&D USA
5340 Legacy Drive, Suite 175
Plano Tx, 75024

Ahmed Alkhateeb
The University of Texas at Austin,
Texas, 78701
aalkhateeb@utexas.edu

Abstract—Cellular systems were designed for carrier frequencies in the microwave band (below 3 GHz) but will soon be operating in frequency bands up to 6 GHz. To meet the ever increasing demands for data, deployments in bands above 6 GHz, and as high as 75 GHz, are envisioned. However, as these systems migrate beyond the microwave band, certain channel characteristics can impact their deployment, especially the coverage range. To increase coverage, beamforming can be used but this role of beamforming is different than in current cellular systems, where its primary role is to improve data throughput. Because cellular procedures enable beamforming after a user establishes access with the system, new procedures are needed to enable beamforming during cell discovery and acquisition. This paper discusses several issues that must be resolved in order to use beamforming for access at millimeter wave (mmWave) frequencies, and presents solutions for initial access. Several approaches are verified by computer simulations, and it is shown that reliable network access and satisfactory coverage can be achieved in mmWave frequencies.

Keywords—millimeter wave, beamforming, initial access

I. INTRODUCTION

The amount of wireless data transmitted over the past few years is pushing the capacity of current cellular systems, including systems using the 3rd Generation Partnership Project (3GPP) long term evolution (LTE) standard. To increase capacity, these microwave frequency systems are employing small cells to densify heterogeneous network (HetNet) deployments [1]. While densification and also operating at higher bands (3 to 4.2 GHz) should alleviate this capacity crunch temporarily, spectrum in the millimeter wave (mmWave) frequency bands is attractive for future use with its vast amount of potential bandwidth. Many publications have begun examining channel characteristics and feasibility of several frequency bands (e.g., 28, 38, 60 and 73 GHz) for unlicensed operations, backhauls, and even 5G systems [2][4][5][6].

While operating at mmWave frequencies appears to be an extension of microwave frequencies, there are many technical, practical, and system-level challenges for cellular usage. In particular, because the pathloss is a function of the frequency, one challenge is how to mitigate the effects of increased pathloss, which manifests itself as reduced coverage area.

Further densification using more small cells operating at mmWave frequencies is feasible but it can be prohibitive in cost and introduce additional problems such as increased interference. Alternative methods that do not significantly alter network deployment but exploit signal processing techniques need consideration. A method often suggested in literature is to deploy systems with more antennas. With smaller sized antennas and with reduced antenna spacing, more antennas can be used in contrast to microwave implementations. By coupling beamforming strategies with more antennas, the resulting antenna gain can compensate for the reduction in coverage caused by operating at mmWave frequencies [5][6].

While beamforming can improve coverage, it introduces several issues that will be discussed in this paper including: how can a user equipment (UE) discover a beamformed signal when located anywhere within the improved coverage area; how to serve several UEs quickly; and how can this initial beamforming be applied to data transmission. To address these issues and discuss possible solutions, the paper is organized as follows. Section II provides a brief problem description while Section III discusses precoding options, and Section IV describes procedural changes. Section V presents some simulation results, followed by some conclusions.

II. PROBLEM DESCRIPTION

Microwave cellular systems are generally designed for wide area coverage so that UEs can receive synchronization signals and control signaling reliably anywhere within the cell. Once a control link is established, the base station can employ precoding to increase the throughput of data transmissions based on feedback from the UE. For typical microwave systems, initial access is based on broadcast signals with high levels of coding and redundancy. Such an approach may not be feasible in the mmWave frequencies due to higher pathloss: the pathloss can easily be 20 dB higher than at microwave frequencies for the same distance. Because compensating for this 20 dB is not realistically achievable with coding, a practical solution is to use beamforming.

A. Establishing control link

Initial access is used to establish a control link. Among the goals of initial access are allowing the UE to:

- Determine (discovery) the carrier frequency
- Synchronize both in timing and frequency
- Measure signal quality so that the base station with the best quality is chosen during initial access
- Determine preliminary operating information about the base station including bandwidth
The same procedure of initial access could be applied for mmWave frequencies but there would be coverage issues for both line-of-sight (LOS) and non-line-of-sight (NLOS) UEs. For NLOS UEs, there will be more coverage holes caused by blockages and limited diffraction, which is a characteristic of mmWave channels. Adding more base stations can reduce these coverage holes but is cost prohibitive. Beamforming techniques can improve the coverage distance for LOS UEs and reduce the coverage holes for many NLOS UEs. A byproduct of this increased coverage is a reduced beamwidth and hence limited coverage outside the reduced beamwidth.

Thus, the problem is how to maximize coverage of a cell during initial access using beamforming. This problem of initial beamforming was treated in [7], where the solution had the base station randomly transmitting synchronization signals in different directions for each time slot, eventually scanning the whole angular space. However, such an approach might entail excessive delays, and thus approaches with shorter completion times are needed for future cellular networks. The solution presented is a combination of architectural changes and procedural changes to refine beamforming.

III. IMPLEMENTING PRECODING

Precoding for cellular systems is based on a closed-loop procedure. At mmWave frequencies, this procedure is more difficult because the means for feedback have not been established. This section describes how a base station and an UE, each having an array of antenna elements but no beamforming knowledge, can establish beamforming. This section considers two architectures as well as two precoder strategies.

A. Precoder architecture

During initial access, open loop techniques, such as spacecraft block coding, ensure transmissions have sufficient diversity for reliable communications. After CSI is fed back, digital precoding is generally used for data transmission because it is the optimal strategy to achieve the capacity using a singular value decomposition of the MIMO channel. As the architecture in Fig. 1 shows, there is typically a one-to-one relationship between the number of antennas and RF chains.

B. Extending to mmWave frequencies

Even with the extended coverage from beamforming, the coverage range for mmWave frequencies is typically small. Hence, standalone mmWave cellular systems may not be appropriate when mobility is considered. One anticipated deployment is the HetNet scenario in Fig. 2 where the macrocell (operating at microwave frequencies) provides mobility support and fallback in case there is an mmWave link failure (e.g., blockage or out-of-coverage). The macrocell can also provide some initialization parameters for UEs to connect to base stations operating at mmWave frequencies. As a result, the goals for initial access at mmWave frequencies could be relaxed but can also include support for beamforming.
Analog beamforming (beamsteering). Many antennas per RF chain.

M \times \text{output streams. In addition, the phase shifters prevent the UE from identifying more scatterers, which can be performed.}

Fig. 3. Analog beamforming (beamsteering). Many antennas per RF chain.

Fig. 4. Hybrid precoding architecture.

Fig. 5. Exhaustive search strategy – one beam at a time.

To overcome the limitations of analog beamforming and digital precoding, hybrid precoding, which is a combination of both architectures, is being considered for mmWave implementations. The goal is to realize efficient transmission using less hardware (primarily RF chains) while retaining the performance of digital precoding [8]. The general architecture is presented in Fig. 4, where \( M_B \) is the number of streams transmitted, and \( M_R \) and \( M_A \) are the number of RF chains and antennas of the base station, respectively. For the UE, there are \( N_A \) antennas, \( N_R \) RF chains, and \( N_C \) output streams. In addition to the number of parameters that adjust the performance of the hybrid precoding architecture, there is question of how to select the baseband precoder \( \mathbf{F}_{BB} \) and the phase shifters \( \mathbf{F}_{RF} \). An example of a design procedure is presented in Section V.

B. Precoding strategies

Coupled with the architecture is how precoding is implemented. There are several assumptions in the scenario of Fig. 2: the UE and base station have no a priori information about the precoders; the macrocell provides the UE some configuration information about the mmWave base station including frequency and bandwidth.

A baseline strategy, shown in Fig. 5, has the base station transmitting a beam in a time division multiplexing fashion (e.g., each symbol) to \( N \) possible directions. On each symbol, the UE then combines its receive beams with the transmitted beam. This “exhaustive search” strategy can achieve good coverage and is feasible in hardware. Among the drawbacks are the time needed to examine \((M_B \times N_C)\) combinations; support for many UEs accessing simultaneously, and when using analog beamforming, limited beam pattern design.

A hierarchical search strategy is presented in this paper. This search is based on observed channel characteristics for mmWave frequencies: it is poorer in scattering in comparison to microwave frequencies. Such a scattering channel can be modeled with few (usually 3–4) paths that are characterized by their angle of departure (AoD) and angle of arrival (AoA). Due to geometrical properties of the mmWave channel, these angles are expected to be highly correlated in the frequency domain, i.e., the 10 MHz channel has very similar characteristics to the 100 MHz on a 30 GHz carrier [3][8][9].

In the hierarchical search, the UE can simultaneously process several narrow bandwidth transmissions from the base station. In each stage of transmissions, the UE can process narrower beamwidth signals. This procedure also can allow the UE to resolve the AoA of many scatterers.

IV. PROCEDURE

The evaluated initial access procedure of mmWave frequencies is based on the hybrid architecture and hierarchical search described previously. The analog architecture with exhaustive search will be simulated for comparison purposes.

Since the base station and the UE do not know which precoder to use, there are two options: use high gain, narrow beamwidth signals (such as used for the exhaustive search) or use low gain, wide beamwidth signals. When using low gain beams, some symbol design is needed to boost coverage. Assuming OFDMA is used on the downlink, several periodic symbols can be dedicated for discovery. Unlike the symbols used for the control channel for LTE where power is generally distributed equally across the subcarriers in the entire downlink bandwidth, these dedicated symbols have fewer occupied subcarriers, and blocks of adjacent subcarriers are grouped to form sub-channels. By using fewer subcarriers in the downlink, the total power can be allocated to those subcarriers. Secondly, by forming sub-channels, each sub-channel can be associated with a beam, as shown in Fig. 6.

A base station periodically broadcasts frequency multiplexed beams that cover the whole angular range to maximize the coverage area. For example, there can be 16 beams each covering 11° of angular range (symmetry of the uniform linear array (ULA) causes the remaining 180° to be covered). A UE has a set of combining vectors that also cover the whole angular angle. Each combining vector combines all sub-channels the base station transmitted on. Thus, the UE can detect the best beam from the base station by detecting them in frequency. By examining the power levels for each sub-channel, the UE can determine the best transmit and combining beams. This process can be performed repetitively using smaller beamwidth precoders and combiners. Once the best beams are determined, the index of the sub-channel is fed back to the base station. After a control link has been established, further refinements, such as setting the precoder for larger bandwidths and identifying more scatterers, can be performed.
With the hierarchical search, the procedure requires 2 or more dedicated symbols. The UE first starts by several wide beamwidth combiners, as shown in Fig. 7(a). On a subsequent symbol, several narrower beamwidth combiners are used, where the angular span of these combiners corresponds to the best combiner in the first symbol, as shown in Fig. 7(b). The process of selecting narrower beamwidth combiners can continue on additional symbols. However, based on factors such as supporting limited mobility and accounting for the quality of channel estimation, the smallest beamwidth of the combiners should be in the range of $5^\circ$ to $10^\circ$.

At the base station, several choices are possible for the precoders depending on the number of available RF chains. With 16 chains, the base station can use $11^\circ$ beamwidth signals for each dedicated symbol. For fewer chains, such as 4, the beamwidth may change each symbol, with the first being $45^\circ$ wide and subsequent symbols being $11^\circ$. For the purposes of comparisons, 16 RF chains are assumed.

V. SIMULATION RESULTS

Simulation studies were performed to compare digital precoding, analog architecture with exhaustive search, and hybrid architecture with both exhaustive and hierarchical search. The simulation parameters are presented in Table I.

A. Hierarchical search and hybrid precoding details

For the simulation, the base station used $M_A=16$ antenna elements and $N_{RF}=8$ RF chains. On the first symbol, the UE made measurements using 4 combining beams ($45^\circ$ beamwidth) using 8 antennas. The UE decided the best combining direction (e.g., the one associated with the combining vector maximizing the received power). On the second symbol, the UE designed its combining weights for 16 antennas and with $11^\circ$ beamwidth. The received signals are then processed to select the best narrow ($11^\circ$ beamwidth) beamforming and combining pair. The UE fed back the index of the best sub-channel to the base station. The procedure for constructing a combiner follows the procedure for generating the hybrid precoder.

B. Hybrid precoding

Among the ways to select the analog precoders $F_{RF}$ and baseband precoders $F_{BB}$ for hybrid precoding is to choose the beamforming vectors that minimize the distance between the desired optimal digital precoder $F$ and the cascade $F_{BB}F_{RF}$ according to [8]

$$
\begin{align*}
\begin{bmatrix} F_{RF}^*, F_{BB}^* \end{bmatrix} &= \arg \min_{F_{RF}, F_{BB}} \|F_{RF}F_{BB}\|_F^2 \\
& \text{s.t. } F_{RF} \in A_{can} \\
& \quad |F_{RF}F_{BB}|_F^2 = 1,
\end{align*}
$$

where $\| \cdot \|_F$ is the Frobenius norm of a vector/matrix. Vector $F_{RF}$ contains a set of candidate precoders in analog domain. The constraint in (2) states that the vectors of the RF precoding matrix should be chosen from a finite set of vectors in the matrix $A_{can}$, which captures the constraints of the analog phase shifters. The digital precoder $F$ is selected using

$$
F^*a(\theta) = \begin{cases} C, & \text{if } \theta \in I \\ 0, & \text{otherwise} \end{cases},
$$

where $a(\theta)$ is the steering vector in direction $\theta$, $C$ is a gain for certain directions in angular interval $I$.

C. Results

In Fig. 8, the access error probability for several access procedures as a function of distance is shown. This probability counts the number of times the highest signal-to-noise ratio (SNR) in a set of measured SNRs is below a threshold. The SNR is measured at the output of each combiner for each sub-channel. For Fig. 8, the threshold is set to $-4$ dB. For large distances, a high error rate is expected because the pathloss will keep the SNR low. The exhaustive search uses 256 symbols while the hierarchical search uses 2 symbols.
Since the results show almost no difference in performance between the digital and hybrid architectures, the hybrid architecture is viable for mmWave frequencies. With the analog architecture, the performance of beamsteering varies with the search procedure. An analysis showed that wide beams (e.g., 45° beamwidth) had more power in the sidelobes than narrow beams (e.g., 11°). As a result, a UE would more likely select an incorrect beam in the first stage of the hierarchical search and then fail to find a beam with sufficient SNR in the second stage. For the exhaustive search results, we noticed that the main beam for beamsteering had more power than for digital precoding, leading to better performance for beamsteering.

The figure also shows that hierarchical search performs worse than exhaustive search. Our analysis determined that an incorrect combiner was selected in the first symbol, mostly when the AoA was on the boundary of two combiners. Improving the steps of the hierarchical search to account for boundary conditions should improve performance.

We also examined how to refine hybrid precoding vectors and combiners after completing initial access. We sought to design precoders for 64 antennas to realize beams of 2.8° resolution from the base station, and for the UE to design the weights of 32 antennas to have combining vectors of 5.6° beamwidth. After initial access, the base station used 64 antennas and 16 RF chains, and the UE used 32 antennas and 8 RF chains. The base station transmitted 4 beams of 2.8° beamwidth covering the 11° range of the best beamforming vector decided in initial access, and the UE used 4 beams that cover the angular range of the combining vector. The results in Fig. 9 show several interesting results. The performance for thresholds of -4dB and 16dB for initial and post-initial access, respectively, are equivalent. This result indicates a refined precoder and combiner can provide 20dB improvement in SNR. Another observation is when the same threshold is used (16 dB), a refined precoder will increase the Tx-Rx distance.

VI. CONCLUSION

An initial access procedure for cellular operation can be implemented at mmWave frequencies using base stations with relatively large coverage distances provided that beamforming is coupled with a search strategy. The hierarchical search strategy can provide fast discovery but refinements are needed to improve its performance. The results show hybrid precoding approaches the performance of digital precoding.

As we continue examining discovery, we need to evaluate the performance with NLOS UEs. We also should evaluate coverage as a function of the parameters of hybrid architecture (how many RF chains, how many antennas, how many streams). We are also exploring whether different metrics of access error probabilities can be used to distinguish architectures. Investigating coverage with intra-cell interference and multi-user hybrid precoding is also an interesting direction.

REFERENCES