Reducing Subcarriers Beam-Squinting of Ultra-Wideband Mobile Communication Systems using Phased Array Antennas

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Abstract: There has been increasing demand for accessible radio spectrum with the rapid development of mobile wireless devices and applications. For example, a GHz of spectrum is needed for fifth-generation (5G) cellular communication, but the available spectrum below 6 GHz cannot meet such requirements. Fortunately, spectrum at higher frequencies, in particular, millimeter-wave bands, can be utilized through phased-array analog beamforming to provide access to large amounts of spectrum. However, the gain provided by a phased array is frequency dependent in the wideband system, an effect called beam squint. We examine the nature of beam squint and develop convenient models with a uniform linear array. To further simplify the evaluation of the system performance, an approximated closed-form expression for the array gain is derived. Furthermore, to evaluate the performance of the proposed design, rigorous numerical results concerning different system parameters are provided in this paper.

I. INTRODUCTION

Applications of wireless technologies and the number of wireless devices have been growing significantly in the past decade. For example, the global mobile data traffic grew 63 percent in 2016, and it is expected to grow at a compound annual growth rate of 47 percent over the next five years. There are increasing demands for radio spectrum to meet the requirements of higher data rates for an increasing number of mobile devices. As noted in a report from the President’s Council of Advisors on Science and Technology (PCAST), access to spectrum will be an increasingly important foundation for economic growth and technological leadership in the coming years. However, the current process of long-term, static frequency allocation below 6 GHz cannot meet these demands for mobile spectrum. Two major directions are being explored for enhancing spectrum access, namely, reusing currently under-utilized spectrum through dynamic spectrum access (DSA), or spectrum sharing, and enabling access to spectrum at higher frequencies, e.g., millimeter-wave (millimeter-wave) bands.

Although both directions require progress on interesting technical issues, this dissertation focuses on enabling spectrum access in millimeter-wave bands based upon, on the one hand, its potential for wide bandwidths and less congested airwaves and, on the other hand, DSA’s on going regulatory and market uncertainties despite over a decade of significant research effort. There are several key features of millimeter wave bands that make them very attractive as the next frontier in wireless technology development. First, the millimeter-wave band ranges from 30 GHz to 300 GHz, with spectrum opportunities on the order of tens of GHz wide. In a loose sense, the 20-30 GHz band is also considered part of the millimeter wave band, further increasing the amount of available spectrum. By contrast, the total amount of spectrum available for sharing below 6 GHz is limited, on the order of hundreds of MHz. Second, signals at millimeter wave frequencies experience higher path loss and atmospheric absorption, typically 20 dB or more attention, than those below 6 GHz. Therefore, millimeter wave systems often require higher antenna directionality and have comparatively smaller range or coverage than systems operating below 6 GHz. Third, relatively sparse deployments currently in millimeter-wave bands leave much of the spectrum open to new entrants and simpler interference avoidance mechanisms, whereas the more congested spectrum below 6 GHz presents many technical challenges for deployment of spectrum sharing such as spectrum sustainability and hidden nodes. Fourth, commercially viable radio hardware for millimeter wave access is less mature than radio hardware operating below 6 GHz, and the device cost is usually higher. As development of device technologies for millimeter wave accelerates, the cost gap should close rapidly. A promising method to compensate for the higher attenuation in millimeter wave bands is beamforming. To achieve high directional gain, either a large physical aperture or a phased-array antenna is employed. The energy from the aperture or multiple antennas is focused on one direction or a small set of directions. The cost of a large physical aperture is relatively high, especially in terms of installation and maintenance. Fortunately, the short wavelengths of millimeter wave frequencies in principle allows for integration of a large number of antennas into a small phased array, which would be suitable for application in commercial mobile devices. In millimeter wave beamforming, a phased array with a large number of antennas can compensate for the higher attenuation.
In this dissertation, we consider practical implementations of millimeter wave analog beamforming with one radio frequency (RF) chain and a phased array employing phase shifters. Traditionally, in a communication system with analog beamforming, the set of phase shifter values in a phased array are designed at a specific frequency, usually the carrier frequency, but applied to all frequencies within the transmission bandwidth due to practical hardware constraints. Phase shifters are relatively good approximations to the ideal time shifters for narrowband transmission; however, this approximation breaks down for wideband transmission if the angle of arrival (AoA) or angle of departure (AoD) is far from the broadside because the required phase shifts are frequency-dependent. The net result is that beams for frequencies other than the carrier "squint" as a function of frequency in a wide signal bandwidth \([1]\). This phenomenon is called beam squint \([2]\).

As we will see, beam squint translates to

In this paper, a novel analog architecture design to mitigate the impact of BS is proposed. The main idea behind the proposed design is to divide a wideband or ultra-wideband signal into chunks of comparatively narrowband signals using a bank of bandpass filters, followed by an additional phase shift with respect to the centre frequency of each filter. The advantage of our proposed design is that it does not rely on any compensation in the digital domain or use any specialized components such as a Rotman lens. It is therefore suitable for computational power constrained or delay-sensitive applications \([3]\), \([4]\), which do not have the liberty to calculate large compensation matrices in the digital domain. Table I provides a brief summary along with comments on the key design features of the aforementioned existing approaches to mitigate beam-squinting. The previously proposed methods are either specifically intended for a system employing hybrid precoding or require multiple radio frequency (RF) chains in the transceiver design. In comparison, our proposed design does not have such constraints and can be tailored for the aforementioned scenarios. Therefore to show a fair comparison and following the literature \([5]\), \([6]\), \([7]\), \([8]\), the performance of the proposed design is compared against an ideal system with no BS and a practical system with BS. Hence, this letter addresses the question in ultra-wideband mmW-enabled massive MIMO systems: “how to provide an order of magnitude capacity improvement without adding any computational complexity?”

![Fig. 1: System Model](image-url)
Here, $\varepsilon_{nf}$ is the ratio of subcarrier frequency to the carrier frequency $f_c$ for subcarrier $n_f$.

$$\xi_{nf} = 1 + \frac{(2n_f - N_f + 1)b_{frac}}{2N_f}. \tag{9}$$

Here $b_{frac} = \frac{B}{f_c}$ is the fractional bandwidth, $n_f \in \{0, 1, ..., N_f - 1\}$, and $N_f$ is the total number of subcarriers.

**Lemma 1.** Following the proposed analog architecture, the array gain with the PC factor $\pi\emptyset(k(n_f))$ is obtained as [9]

$$g_{pc}(\psi, \theta, n_f) = \frac{1}{\sqrt{N}} \sum_{k=1}^{K} \sum_{n=(k-1)K+1}^{kK} \exp \left( j \pi ((n-1)\varepsilon_{nf} + \phi_k(n_f)) \right), \tag{10}$$

where

$$x_{n_f} = \left( \xi_{nf} \sin \theta - \sin \psi \right),$$

and

$$\phi_k(n_f) = (K(k-1) + c_k) x_{c,n_f}.$$ 

Here the variable $c_k$ represents the index of antenna element which drives the subsequent layer of phase shifters within its antenna group of size $K$, and $\emptyset$. $x_{c,n_f}$ represents the ratio of the centre subcarrier frequency of each bandpass filter to the carrier frequency $f_c$. Hence, the value of $x_{c,n_f}$ remains constant for all the subcarriers of each filter.

This section illustrates the effects of beam squint on channel capacity for a ULA, with the understanding that there are similar effects in the case of a UPA. Although in general the effect of beam squint on capacity depends upon the AoD, the transmitter beam focus angle, the AoA, and the receiver beam focus angle, we consider for simplicity the case of no beam squint at the transmitter and study the beam squint of a single array at the receiver. Therefore, only the AoA and the receiver beam focus angle are examined here.

Consider a continuous-time AWGN channel with bandwidth $W$ Hz, power constraint $P$ Watts, and additive white Gaussian noise with power spectral density $N_0/2$. Following the passband-baseband conversion and sampling at rate $1/W$, this can be represented by a discrete-time complex baseband channel [10]

$$y[m] = x[m] + w[m],$$

where $w[m]$ is CN (0, $N_0$) and is i.i.d. over time. Note that since the noise is independent in the I and Q components, each use of the complex channel can be thought of as two independent uses of a real AWGN channel. The noise variance and the power constraint per real symbol is $N_0/2$ and $P / (2W)$ respectively. Hence, the capacity of the channel is

$$C = \frac{1}{2} \log \left( 1 + \frac{P}{N_0 W} \right).$$

This is the capacity in bits per real dimension, or degree of freedom. Since there are $W$ complex samples per second, the capacity of the continuous-time AWGN channel is

$$C = B \log_2 \left( 1 + \frac{N}{S/N} \right).$$

**Corollary 1.** Assuming Gaussian signalling [11] and following [12], the achievable capacity for the derived array gain in Lemma 1 can be expressed as

$$C_{pc} = B \frac{1}{N_f} \sum_{n_f=0}^{N_f-1} \log \left( 1 + \frac{P |g_{pc}(\psi, \theta, n_f)|^2}{B\sigma^2} \right). \tag{11}$$
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Fig. 3: Capacity with and without PC for $f_c = 60$GHz, $N_f = 2048$, $N = 256$, $\psi = 0.8$, $K = 64$, $b = 16$, and $L = 3$. The plotted capacity is averaged over the set $\{0 - 0.1, 0, 0 + 0.1\}$.

III. NUMERICAL RESULTS

In this section, we analyze the performance of the novel proposed architecture. Fig. 2 shows the comparison between the array gain of the proposed model with PC (Lemma 1) and the array gain of a typical system with BS. It is observed that the proposed design improves the array gain of the subcarriers on the left and right of the main lobe. For example, the $\xi_{nf} = 1.03$ and $\xi_{nf} = 0.97$ improvement in array gain is approximately 10dB. Hence, in applications where the reliability of the information on all subcarriers are of equal importance or in scenarios where we do not have the liberty to calculate large compensation matrices in the digital domain, the proposed design can provide significant improvement in the array gain that will consequently improve the achievable rate. This improvement in the array gain is a direct result of those additional antenna driving elements, i.e., the bank of bandpass filters and the additional phase shifters. In addition to that, Fig. 2 also shows the impact of linear approximation of $c_k$ on the array gain by comparing the array gain curves of Lemma 1 and Theorem 1. It can be observed that the linear approximation of $c_k$ provided in theorem 1 is very tight for a wide range of subcarriers. The effect of this approximation on capacity is illustrated in Fig. 3.

Fig. 4: Capacity with and without PC for $f_c = 60$GHz, $N_f = 2048$, $N = 128$, $\psi = 0.8$, $K = 64$, $b = 16$, and $L = 3$. The plotted capacity is averaged over the set $\{0 - 0.1, 0, 0 + 0.1\}$.

Fig. 5: Capacity with PC for $f_c = 60$GHz, $N_f = 2048$, $N = 256$, $\psi = 0.8$, $K = 64$, and $L = 3$. The plotted capacity (Corollary 2) is averaged over the set $\{0 - 0.1, 0, 0 + 0.1\}$.

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Beam squint is a concern for millimeter wave beam forming. In this paper, an analog architecture design to mitigate the issue of beam-squinting in wideband and ultra-wideband communication systems is proposed. We provided a detailed analytical model of the proposed design and illustrated its performance using numerical results. The results show that the significant gain in capacity can be achieved by the proposed design, for a range of signal bandwidths. Moreover, since the proposed design does not require any computation of large compensation matrices in the digital domain, it can be a promising solution for the delay sensitive applications. It is worth mentioning that this work can be extended to find the optimal values of the size of the bank of filters $L$ and $C_k$, which represents the index of antenna element which drives the subsequent layer of phase shifters, for a given signal bandwidth. Also, parameter $b$ which approximates the $C_k$ to a linear function $(k-1)b$ can be optimized for a given signal bandwidth to maximize the array gain and consequently the achievable capacity.

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