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Beam squint effect on high-throughput millimeter-wave communication with an ultra-massive phased array

Key words: Ultra-massive phased array; Millimeter-wave (mmWave); Beam squint; Zadoff-Chu; Single-carrier frequency-domain equalization (SC-FDE)

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Motivation

1. Millimeter-wave (mmWave) bands refer to the spectrum from 30 to 300 GHz. With the advantage of large available bandwidth, mmWave bands can be used to achieve high-throughput communication.
2. However, compared with the sub-6 GHz system, mmWave signals experience higher path loss in free space and have additional loss due to rain and oxygen absorption. Transmission distance is limited at mmWave bands.
3. For point-to-point long-distance transmission applications (e.g., wireless backhaul, inter-aircraft data link, and space satellite communication), a simple ultra-massive phased array (i.e., pure analog beamforming) can be deployed in mmWave systems to increase the transmission distance.

Main idea

1. When the number of antennas and the signal bandwidth are large, the antenna array response is frequency-dependent. Thus, there exists beam squint using standard analog beamforming.

2. From the communication viewpoint, the array response and the analog beamforming can be viewed a spatial equivalent channel.

3. To eliminate the deep fading points caused by beam squint, an advanced analog beamforming method is proposed based on the Zadoff-Chu (ZC) sequence.

Beam squint

1. We consider a mmWave LoS-MISO system, where the TX deploys an ultra-massive phased array, as shown in Fig. 1. The function of a phased array is to form a spatial beam pointing to the receiver.
2. Beam squint: the formed beam direction varies with frequency in the wideband case, as shown in Fig. 2 (on the next page).

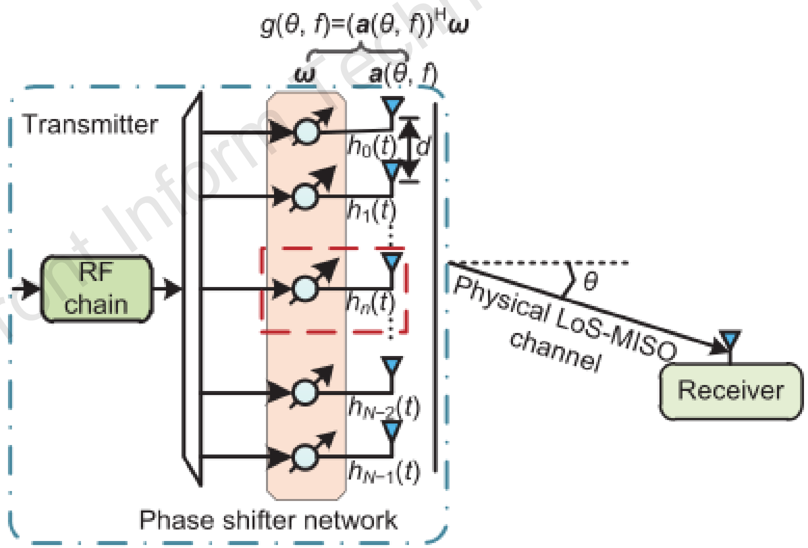

Fig. 1 Model of a line-of-sight multiple-input single-output (LoS-MISO) system where the transmitter deploys an ultra-massive phased array

Beam squint (Cont'd)

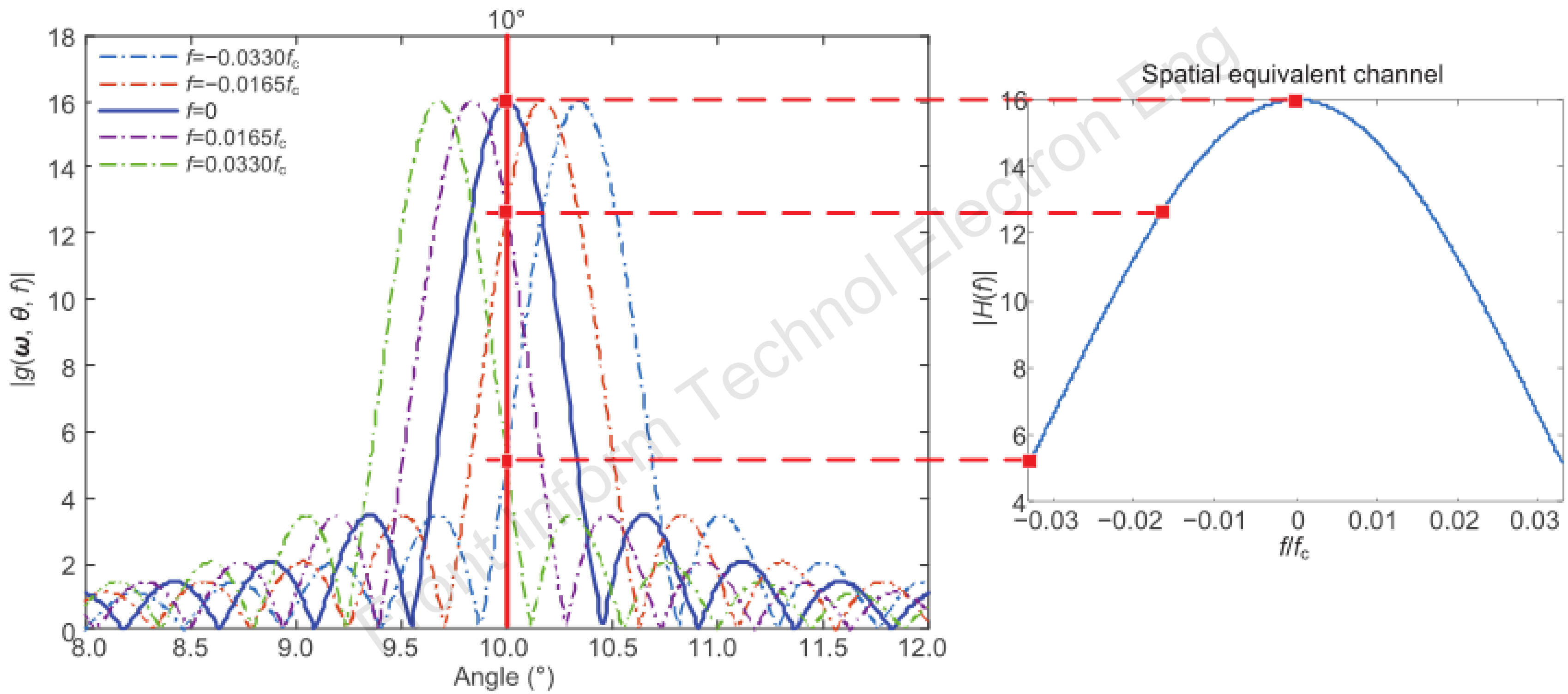

Fig. 2 Beam squint in an ultra-massive phased array with the number of antennas $N = 256$ and the expected beam direction $\theta_0 = 10°$. The right subfigure is the corresponding amplitude frequency response of the spatial equivalent channel in the LoS-MISO system

Spatial equivalent channel

1. From the communication viewpoint, we view the array response and the analog beamforming as a spatial equivalent channel, which consists of multiple paths with equal power and constant time delay.
2. The influence of beam squint on the system is divided into two aspects: frequency selection of the channel with multiple deep fading points (Fig. 4) and array gain loss (Fig. 5).

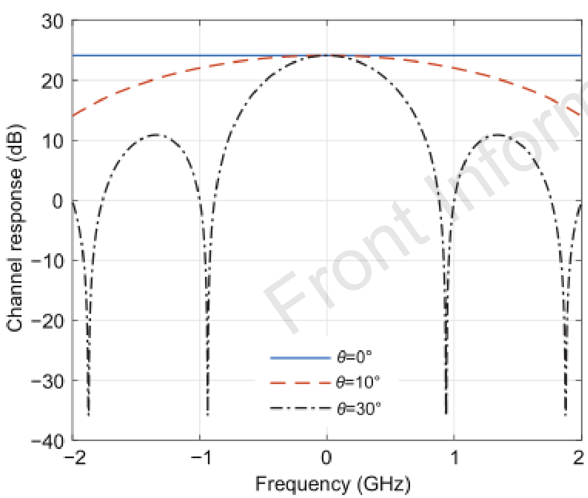

Fig. 4 Frequency-domain response of the spatial equivalent channel in the standard beamforming method with $\theta = 0°$, $10°$, and $30°$ ($N = 256$, $f_c = 60$ GHz)

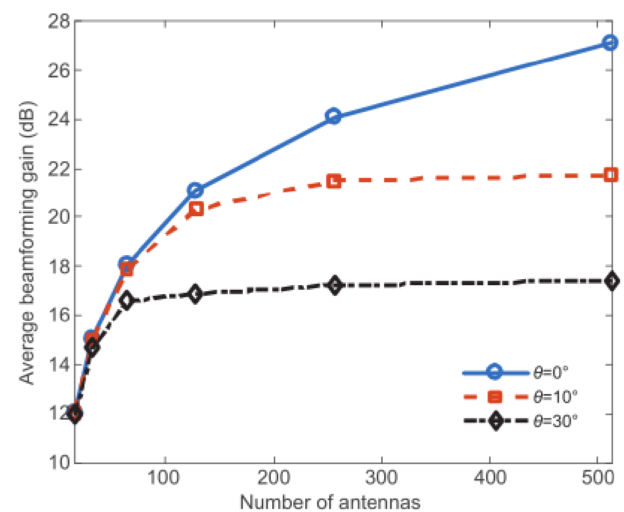

Fig. 5 Average beamforming gain versus the number of antennas N with $\theta = 0°, 10°$, and $30°$ ($B = 4$ GHz, $f_c = 60$ GHz)

Advanced analog beamforming

In essence, the frequency-domain response of the equivalent channel is the discrete Fourier transform of the beamforming weight in terms of the antenna index (spatial sampling). Thus, we can design a sequence which has a constant magnitude Fourier transform. The ZC sequence is a constant amplitude zero autocorrelation (CAZAC) sequence, which meets our requirements perfectly.

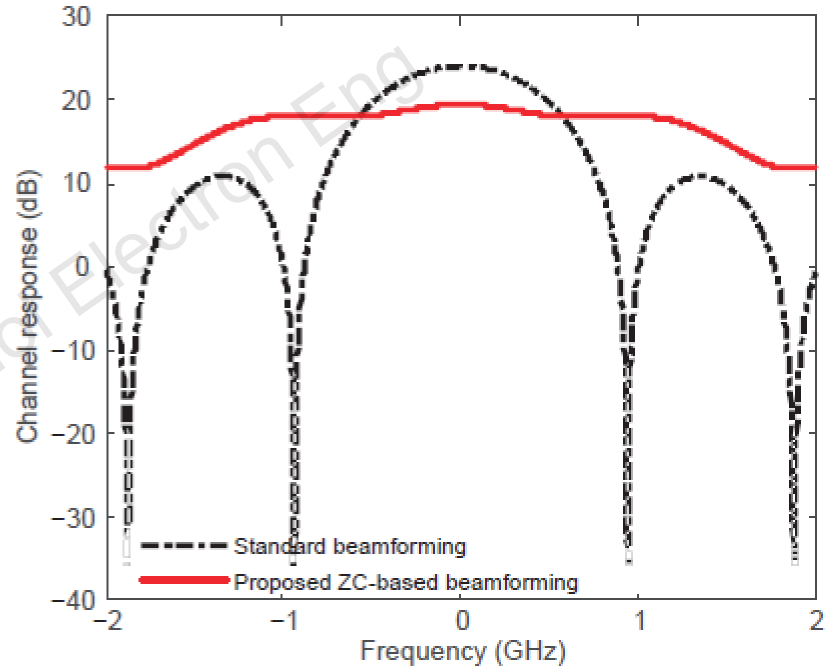

Fig. 6 Frequency-domain response of the spatial equivalent channel in the proposed ZC-based beamforming method ($\theta = 30°$, $N = 256$, $f_c = 60$ GHz)

Bit-error-rate (BER) results

The BER results of the mmWave SC-FDE system are shown in Fig. 8. The ZF and MMSE equalizers are applied at RX. We can observe that the proposed beamforming method can eliminate the ISI caused by beam squint and the BER performance is improved.

Table 1 Summary of system parameters in simulation

Parameter	Value
Carrier frequency f_c (GHz)	60
Carrier wavelength λ_c (mm)	5
Transmission bandwidth B (GHz)	4
Modulation	QPSK
Roll-off factor α	0.25
Symbol rate f_{sys} (Gsymbol/s)	3.168
CP length in a symbol block M_{CP}	64
Symbol length in a symbol block M	512
Up-sampling ratio at RX ρ	2
FFT size at RX K	1024
Number of antennas N	256
Antenna spacing d	$0.5\lambda_c$ (2.5 mm)

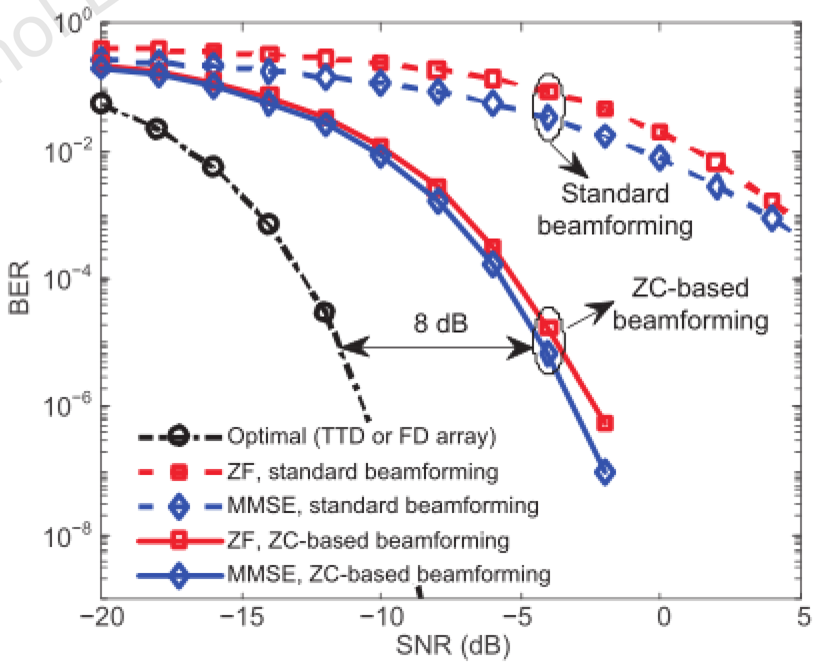

Fig. 8 BER performance versus SNR with $\theta = 30°$

Conclusions

1. The beam squint effect on a mmWave SC-FDE system was investigated. From the communication viewpoint, the characteristics of a spatial equivalent channel were analyzed (two aspects: array gain loss and frequency selection) .

2. Based on the ZC sequence, a novel analog beamforming method was proposed which can eliminate the deep fading points caused by beam squint.