Demonstration of Spatial Multiplexing by Digital Beamforming in 5G Fiber-Wireless Integrated Network

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Abstract: Multiple data streams sharing the same time-frequency resource block through digital beamforming technique are received at different angles of arrival by a 1-by-4 antenna array and decoded simultaneously in 5G fiber-wireless integrated access network. © 2021 The Author(s)

1. Introduction

A fiber-wireless integrated access network, where the fiber backhaul carries tremendous network capacity, and the front-haul wireless links provide additional flexibility in user connectivity, is an effective architecture for the next generation mobile data communications [1]. Due to the exponentially growing Internet traffic demand, it is inevitable to exploit the high-frequency resources to increase the system capacity in the era of 5G and beyond. However, the high-frequency signal such as millimeter wave (mmWave) has a higher propagation loss than the conventional RF signal. Beamforming is a promising solution which aims at connecting user equipment (UE) with narrow beamwidth through an antenna array. The beamforming technique provides extra antenna transmission gain to compensate for the high path loss. Moreover, beamforming extends to an orthogonal dimension: the angle of arrival (AoA) beams, in addition to time and frequency. This additional dimension of resources increases the system reliability and spectral efficiency. By digital beamforming, multiple signals received from the antenna array are stored separately and processed with independent digital signal processing (DSP) units to reconstruct the beams arriving from different directions. Although most of beamforming studies using analog phase shifters or delay lines [2-3], the experimental research based on the digital beamforming technique is relatively rare in the fiber-wireless access networks. By implementing the digital signal processing at the receiver, the system can estimate the angle-of-arrival (AoA), calculate the proper weight vectors, and amplify the signals of interest while suppressing the interference from other directions. By spatially spreading information over various directions to ensure more reliable data transmissions, the multi-beam transmission is a potential solution to handle the mmWave blockage issues.

In this paper, a proof-of-concept experiment is conducted for the downlink transmission from multiple Radio Units (RUs) to a User Equipment (UE) after a 15-km fiber transmission. The wireless part operates at around 26 GHz, namely the n258 frequency band in 5G NR. Received by a 1x4 antenna array, two independent 2 Gbps 16-QAM data streams are successfully recovered within the 7% FEC threshold in a range of AoA pairs. With digital beamforming applied, the system can simultaneously separate and decode signals sharing the same time and frequency resources from multiple beams/directions, which are otherwise not decodable. Furthermore, the digital beamforming performance is also evaluated with only one transmitter-side (Tx) antenna at different angles. In this case, the experimental results show a 1.08% to 1.65% improvement in the error vector magnitude (EVM).

2. Architecture and Experimental Designs

In our experiment, two transmitter antennas at two angles are implemented as two RUs. Beamforming is performed at the receiver. The performance of interference mitigation by digital beamforming is also evaluated. In the cases of only one antenna is used on the transmitter side, the performance with and without beamforming are compared. The potential signal impairment due to fiber-wireless transmission is also investigated.

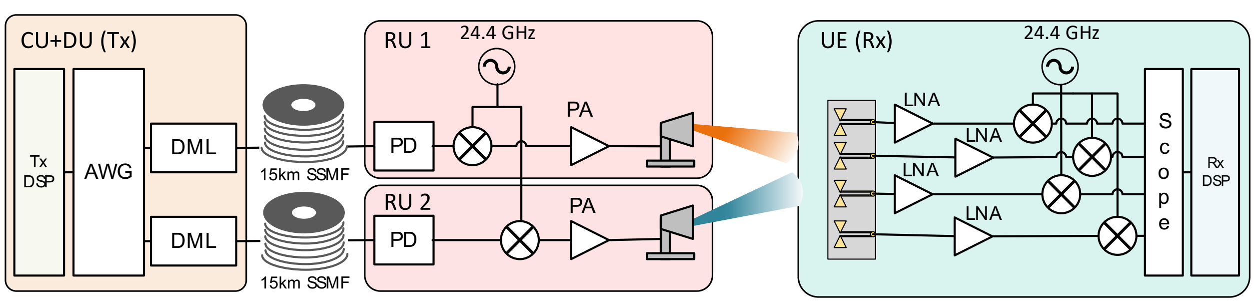

Fig. 1. Experimental setup of a fiber-wireless integrated system with the digital beamforming technique.
AWG: arbitrary waveform generator; DML: directly modulated laser; PD: photodetector; PA power amplifier; LNA: low noise amplifier.

The experimental setup is depicted in Fig. 1. The 0.5 Gbaud 16-QAM signals operating at the central frequency 1.75 GHz are generated by MATLAB and sent to the arbitrary waveform generator (AWG). The electrical signal is converted to the optical domain by a directly modulated laser (DML) with a bandwidth from 5 kHz to 2.5 GHz at 1550-nm central wavelength. After 15-km standard single-mode fiber (SSMF) transmission, the optical signal arrives at the corresponding RU and is converted back to the electrical domain via a photodetector (PD). The signal is then upconverted to around 26 GHz and transmitted by a horn antenna after being boosted by a power amplifier (PA) with a 25-dB gain. The wireless distance between the horn antenna and the receiver is about 40 cm, which is considered far-field at 26 GHz. The impinging signals are collected by a homemade four-element uniformly spaced linear array on the receiver side (Rx). Each element of the PCB board antenna array is connected to a low noise amplifier (LNA) to boost the received signal and then down-converted by a mixer with RF frequency at around 24.4 GHz. The resulting signals are observed and obtained from the oscilloscope for further DSP that will be discussed in Section 3.

3. Digital Signal Processing

Fig. 2 illustrates the workflow of DSP. In the Rx DSP, where most of the digital beamforming processing is located, the signals collected by the antenna array are resampled, frame-synchronized, and processed through a series of digital beamforming implementations, including an initial phase calibration, AoA estimation, an array factor or weight vector calculation, and the signal reconstruction.

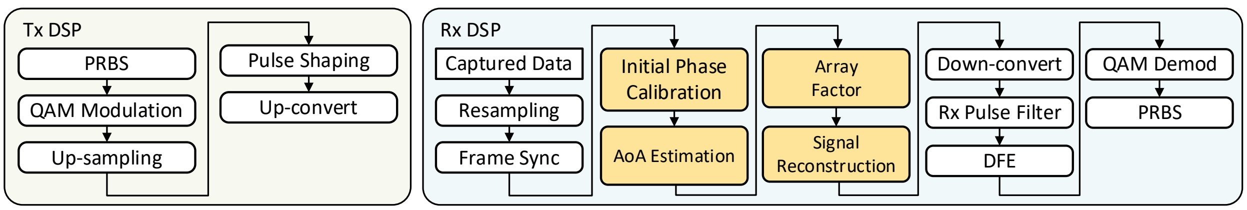

Fig. 2. Workflow of transmitter-side and receiver-side digital signal processing. Digital beamforming steps are shaded in orange color.

The initial phase calibration is a critical step to compensate for the existing phase differences among the four parallel paths due to unequal cable lengths, uneven bending scenarios, and other unbalance from equipment. A circular shifter performs the initial phase calibration on MATLAB for each receiving path. After the calibration, there should be almost no relative delay or phase difference among all parallel paths when the signal is transmitted from 0 degrees or equivalently right in front of the antenna array. The AoA estimation is the second stage of the digital beamforming. Rather than scanning the entire codebook to approximate the AoA, the digital beamforming can directly estimate the AoA from the received data. The root-MUSIC algorithm is implemented in the experiment [4], which is related to the eigendecomposition of the signals' covariance matrix on the receiver-side. However, minor modifications are needed to approach the optimal performances in the scenarios of multiple antennas on the transmitter-side. Based on the angle-of-arrival, the array factor or the weight vector are generated and applied to reconstruct the signal from each specific angle-of-arrival with the formula $\Delta\phi = \frac{2\pi d \sin(AoA)}{\lambda}$, where $\Delta\phi$ is the phase, d is the antenna distance, and λ is the wavelength. Eventually, the beams coming from different AoAs are extracted separately and down-converted back to the baseband. After going through the Rx pulse filter, and the decision feedback equalizer with nine forward taps and three feedback taps, the QAM symbols are recovered. The EVM and the bit-error-ratio (BER) of the corresponding binary sequences are the two criteria for performance measurements in this experiment.

4. Experimental Results and Analysis

This section includes the experimental results of three major topics: the possible signal degradation due to the 15-km fiber, the digital beamforming evaluation under one transmitter-side antenna scenario, and the analysis of the spatial multiplexing case with two transmitter-side antennas and the aid of digital beamforming. Fig. 3(a) shows the EVM versus received optical power for both back-to-back and 15-km fiber scenarios. The two curves align well which indicates that the decision feedback equalizer has successfully eliminated any discrepancies induced by the fiber transmission. Nevertheless, the 15-km fiber decreases the maximum optical power (ROP) that the system can achieve. According to Fig. 3(a), the minimum EVM occurs around 1dBm optical power. The non-linear effect limits the performance in the high-power region. Thus, the power attenuation due to the 15-km fiber does not degrade the overall system performance.

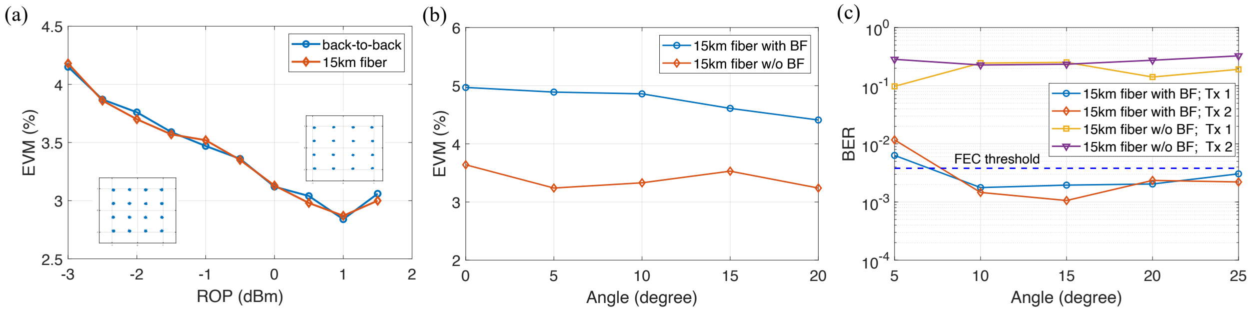

Fig. 3. (a) EVM versus ROP back-to-back or with 15-km fiber; (b) EVM versus angle with one Tx-antenna; (c) EVM versus angle with two Tx-antennas. BF: Beamforming

For the one Tx-antenna case shown in Fig. 3(b), the EVM evaluation over 0 to 20 degrees decreases by 1.08% to 1.65% with the digital beamforming. The antenna configuration is shown in Fig. 4(a), and the angle increases clockwise. The system without beamforming decodes the signals using only one Rx-antenna of the antenna array. Therefore, the EVM improvement is brought by the directional antenna gain of digital beamforming. The benefit of digital beamforming is significant in the case of multi-beam transmission, where the beams from different directions are separated and decoded simultaneously. Fig. 3(c) illustrates the results for the two-Tx-antenna case. Antenna 1 is fixed at 0 degree, while antenna 2 moves from 5 to 25 degrees clockwise. At every 5 degrees steps, both signals received from Antenna 1 and Antenna 2 are captured and decoded. Without the aid of digital beamforming, the BER of signals from Antenna 1 and Antenna 2 are both very high. The signals sent from Antenna 1 and Antenna 2 interfere with each other when no digital beamforming applies. In contrast, the digital beamforming boosts the gain toward the interest of angle and suppresses the interference from the other beam. Thus, the BER is improved from 0.23 to 1.5×10^{-3} from Antenna 2 at 10 degrees as the digital beamforming kicks in. The BER remains lower than the 7% OH HD-FEC threshold of 3.8×10^{-3} from 10 to 25 degrees. The BER at 5 degrees is higher than the average since the separation between the antennas is at the minimum.

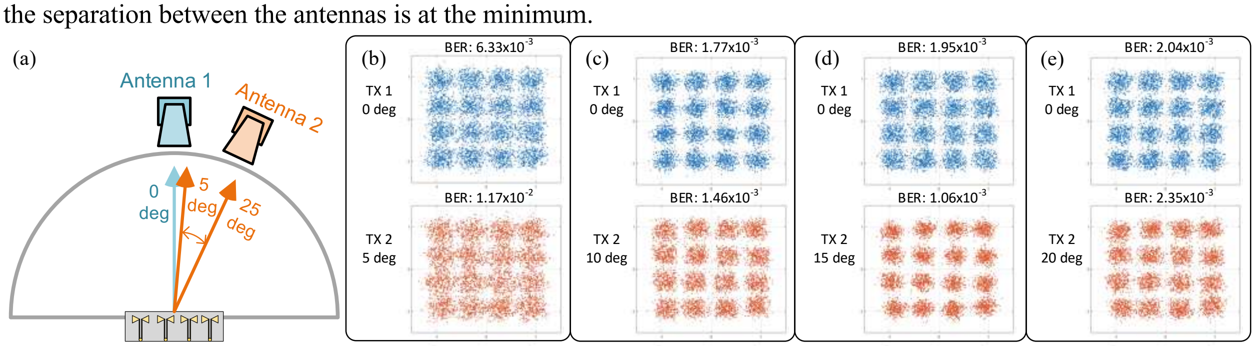

Fig. 4. (a) Antenna configuration; (b)-(e) Constellations and BERs for both antennas from 5 to 20 degrees.

In Fig. 4(b)-(e), the constellations at different AoA separations indicate the performance of digital beamforming's interference mitigation. The received symbols are clustered in 16 groups, which correspond to the 16-QAM signals from each antenna. If the interference were severe, the constellation would be similar to 256-QAM or a small 16-QAM modulated by another big 16-QAM constellation.

5. Conclusions

In this paper, a novel digital beamforming technique is designed and experimentally demonstrated for multiple data streams occupying the same time-frequency resource block in a fiber-wireless integrated access network that can enhance system capacity and mitigate interference simultaneously. Two transmission cases are investigated and compared; the first with a single transmitter-side antenna, and the second with multi-beam transmission by two transmitter-side antennas. The potential impairment due to the fiber transmission and the effect of interference mitigation are also examined. As a result, two distinct 2 Gbps data streams propagating through two directions can be received separately and decoded successfully at the receiver after a 15-km fiber and 40-cm wireless transmission.

6. References

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