Mobile 14-GHz Bandwidth Fronthaul Link Supporting 128 RF-Chain Signals for 6G Ma-MIMO Beamforming

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Abstract: We demonstrate fronthual links with delay-division-multiplexing 14-GHz bandwidth 64-QAM OFDM for 128 RF-chain signals. The corresponding CPRI-based capacity is 860.16 Gb/s. With I/Q Volterra nonlinear compensation, EVMs can be improved from 7.5% to 6%.

1. Introduction

Compared with 5G to provide more wireless capacity, 6G wireless system increases the carrier frequency from millimeter wave (mmWave) band to terahertz (THz) band. The shorter wavelength allows more antennas to be placed on the remote radio head (RRH) of the 6G fronthaul (FH) to form a massive multiple-input multiple-output (Ma-MIMO) system with 100-1000 antennas in order to increase spatial diversity and spectral efficiency [1]. Combined with beamforming (BF) technology, the huge Ma-MIMO system can achieve better directivity and alleviate the limitation of THz transmission distance. The 6G system with better directivity can serve more users as shown in Fig. 1. Therefore, the FH link between baseband unit (BBU) and RRH requires more RF-chain signals, resulting in more capacity needed. Traditional BF architecture in the FH link can be divided into three categories: full digital, full analog, and hybrid BF. Among these categories, hybrid BF is the promising solution which has the performance as good as full digital BF with fewer RF-chain signals. Although hybrid BF can reduce the number of RF chains (N_{RF}), N_{RF} should be more than twice of the served user number (N_{UE}). e.g. $N_{RF} \geqq 128$ for $N_{UE} = 64$. Therefore, both large N_{UE} and the broadband transmission of THz band will result in more capacity needed in FH link, which will be one of the challenges in 6G wireless system.

Currently, the commercialized FH network protocol is the Common Public Radio Interface (CPRI) specification [2]. Because the digitized radio-over-fiber (D-RoF) architecture has low spectrum efficiency, it is generally believed that it cannot meet the transmission requirements for 6G. Therefore, a new protocol called enhanced CPRI (eCPRI) [3], which is generated by flexibly splitting the physical layer structure, also appears, which can effectively reduce the capacity that CPRI needs in the past. Another way to improve the capacity of the FH network is the analog radio-over-fiber (A-RoF) architecture. Many studies have used different multiplexing methods to transmit RF-chain signals in A-RoF, such as frequency division multiplexing (FDM) [4], wavelength division multiplexing (WDM) [5]. However, when N_{RF} increases to hundreds, the hardware or the digital signal processing (DSP) will become too complicated. Therefore, we propose a novel delay division multiplexing (DDM) scheme to simultaneously deaggregate different RF-chain signals into baseband. We demonstrate an A-RoF scheme to support DDM OFDM signal with 14-GHz bandwidth for 64 and 128 RF-chain signals (64×0.21875 GHz and 128×0.109375 GHz), which is corresponding to 860.16 (=14000/(20×8)×9.8304) Gb/s CPRI rate-7 transmission. The EVM performance of each RF-chain signal can meet the 3GPP 64-QAM specification.

2. Concept of Proposed A-RoF Mobile Fronthaul

Figure 2 shows A-RoF with analog and digital deaggregation, and our proposed system. The A-RoF based on analog deaggregation needs bandpass filters (BPFs) to filter out individual signals, and guard bands are needed. In addition, it is difficult to design a narrowband BPF in terms of hardware. The A-RoF based on digital deaggregation exempts the requirement for BPF in hardware, as shown in Fig. 2 (b). After deaggregation, each RF-chain signal locates at

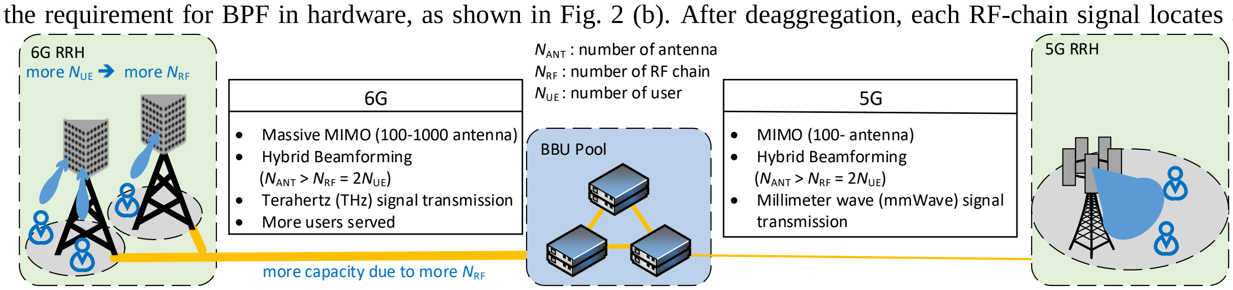

Fig.1 5G and 6G fronthual and beamforming concept

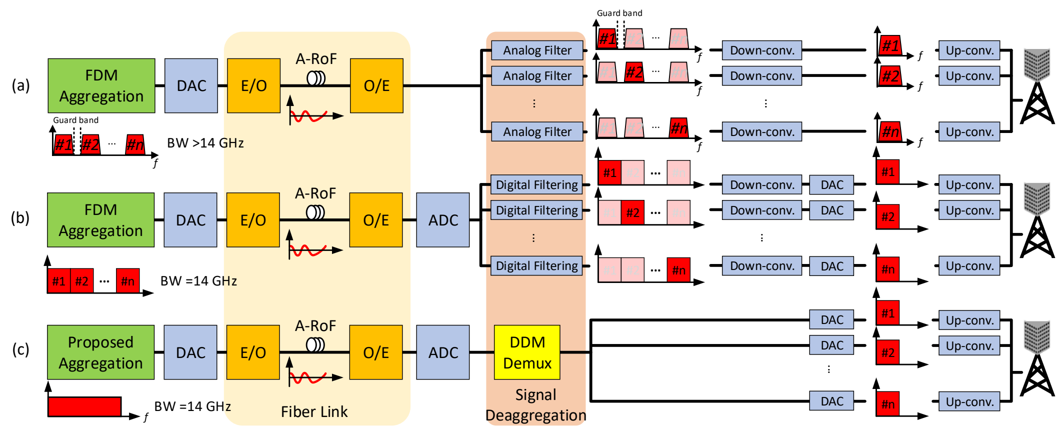

Fig. 2 Comparison of different fronthual systems, (a) A-RoF, (b) DSP-A-RoF, (c) proposed DSP-A-RoF

different frequency. Hence, down conversion of each signal for DAC is needed, which is still complicated. Therefore, we proposed the architecture that does not require a guard band and BPF to deaggregate the signals, as shown in Fig. 2 (c). After deaggregation of each RF-chain signal, these signals locate in the baseband without additional frequency conversion.

In our proposed scheme as shown in Fig. 3, we obtain each RF-chain signal at different time with sub-Nyquist sampling rate to cause the predictable aliasing and different phase response of the corresponding signal. Therefore, we can preprocess the signals based on the aliasing and phase difference [6]. Figure 3 shows the proposed scheme with the case of 4 RF-chain signals. $\mathbf{R}$, Φ, $\mathbf{H}$, $\mathbf{S}$ denote the received signal, aliasing matrix, channel responses and transmitted signal. $\mathbf{S}_m$ and $\mathbf{R}_m$ indicate the m-th transmitted and received RF-chain signal. $\Phi_{m,n}$ denotes the phase and the n-th aliasing of the m-th RF-chain signal.

$$\mathbf{R}=\mathbf{\Phi HS}\Rightarrow\begin{bmatrix}\mathbf{R}_1\\ \mathbf{R}_2\\ \mathbf{R}_3\\ \mathbf{R}_4\end{bmatrix}=\begin{bmatrix}\mathbf{\Phi}_{1,1} & \mathbf{\Phi}_{1,2} & \mathbf{\Phi}_{1,3} & \mathbf{\Phi}_{1,4}\\ \mathbf{\Phi}_{2,1} & \mathbf{\Phi}_{2,2} & \mathbf{\Phi}_{2,3} & \mathbf{\Phi}_{2,4}\\ \mathbf{\Phi}_{3,1} & \mathbf{\Phi}_{3,2} & \mathbf{\Phi}_{3,3} & \mathbf{\Phi}_{3,4}\\ \mathbf{\Phi}_{4,1} & \mathbf{\Phi}_{4,2} & \mathbf{\Phi}_{4,3} & \mathbf{\Phi}_{4,4}\end{bmatrix}\mathbf{H}\begin{bmatrix}\mathbf{S}_1\\ \mathbf{S}_2\\ \mathbf{S}_3\\ \mathbf{S}_4\end{bmatrix} \quad (1) \ ; \quad \mathbf{\Phi}_{m,n}=\begin{bmatrix}e^{j\theta_{m,n}} & 0 & 0 & 0\\ 0 & e^{j2\theta_{m,n+1}} & 0 & 0\\ 0 & 0 & e^{j3\theta_{m,n+2}} & 0\\ 0 & 0 & 0 & e^{j4\theta_{m,n+3}}\end{bmatrix} \quad (2)$$

With preprocessing the signal in BBU, each RF-chain signal can be obtained sequentially by using 1/M Nyquist sampling rate starting at different time in RRH. Since the RF-chain signals will interfere each other when those are sampled at incorrect time, the time synchronization of the ADC sampling is very important. To compensate the synchronization error of the sampling time, we calculate the sampling time error from the phase difference between an RF-chain signal and its reference signal with only 1/M FFT size. Moreover, we can feedback the error and adjust the system with the right sampling time [7]. We only need to synchronize the first RF-chain signal, and the other RF-chain signal can be sampled sequentially.

3. Experiment setup and Discussion

Figure 4 shows the experimental setup of the proposed FH link. The baseband OFDM I/Q signals with 7-GHz bandwidth are generated by an arbitrary waveform generator (AWG, Keysight M8195A) with sampling rate of 28 GSample/s. The FFT size is 2048 and the data format is 64 QAM. The I and Q signals are combined with 39.5 GHz sinusoidal wave. The combined signal was used to drive a dual-parallel Mach-Zehnder modulator (DP-MZM), which was biased at $V_{\pi/2}$ and V_{π} to suppress the optical carrier power. The generated signal consists of one 14-GHz OFDM-modulated signal and one optical subcarrier, as shown in Fig. 4. After 25-km single-mode fiber (SMF) transmission,

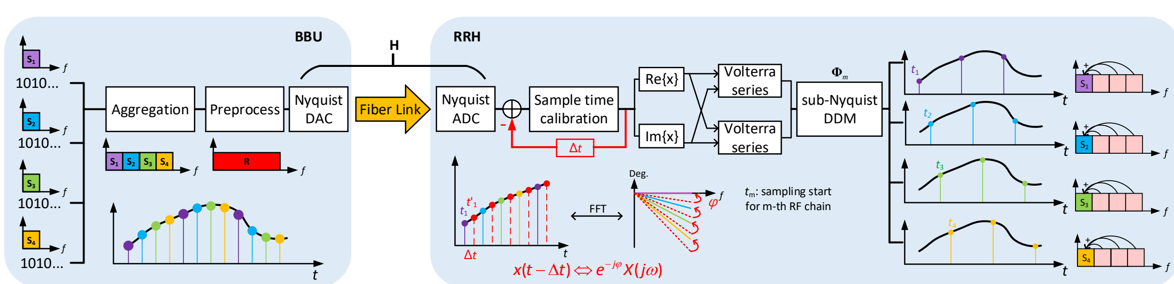

Fig. 3 Principle of proposed DDM scheme

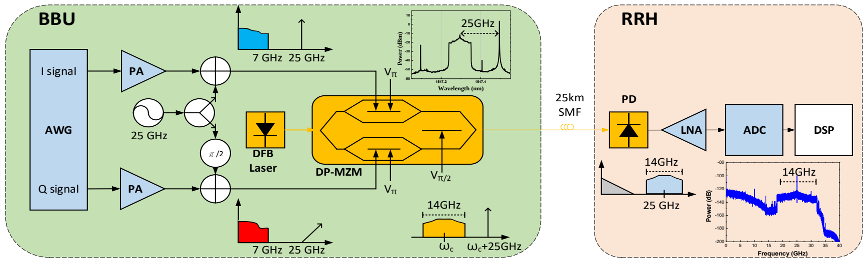

Fig. 4 Experiment setup for proposed FH link

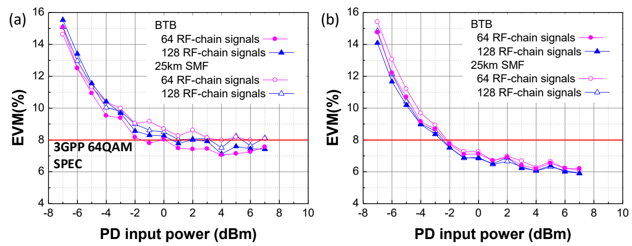

Fig. 5 EVM performance (a) without and (b) with IQ Volterra nonlinear compensation

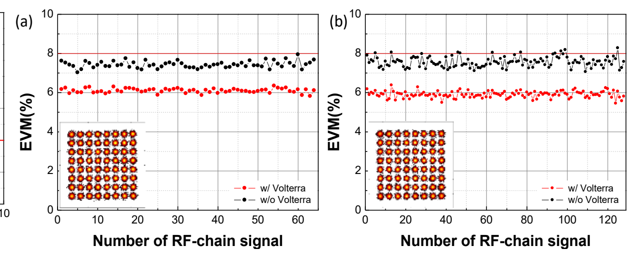

Fig. 6 EVM performance of (a) 64 and (b) 128 RF-chain when PD input power at 7 dBm

the OFDM signal at 25 GHz is generated by the photo detector (PD). An offline DSP is used to deaggregate the RF-chain signal.

Figure 5 (a) shows EVM performance of 64 and 128 RF-chain signals for back-to-back (BTB) case and 25-km SMF transmission. The EVM performance can be less than 8% and meet 3GPP specification. However, the floor of EVM performance can be observed around 7%, due to I/Q imbalance and nonlinear transfer function of DP-MZM. Since the bandwidth of I/Q signals are 7-GHz, the amplitude and phase responses of two signals are not easy to keep the same, resulting in I/Q imbalance. Moreover, the V_π mismatch between MZ-a and MZ-b and the phase misalignment from MZ-c will give more I/Q imbalance to the generated signal. Moreover, the nonlinear transfer function of DP-MZM will cause the nonlinear distortion. Therefore, a I/Q dual-input nonlinear model based on Volterra series is used to compensate I/Q imbalance and nonlinear distortion simultaneously [8]. Volterra nonlinear compensation and DDM signal deaggregation work in series because both of them are operated in time domain.

Figure 5 (b) shows the EVM performance with I/Q Volterra nonlinear compensation. The EVM floor can be improved from 7% to 6%. The sensitivity penalty of 8% EVM is less than 1 dBm after 25-km SMF transmission. Figure 6 shows the EVM of each RF-chain signal when PD input power is 7 dBm. The average EVM performance of each RF-chain signal can be improved about 1.5% for the both case of 64 and 128 RF-chain signals. Moreover, the EVM deviation among RF-chain signals can be reduced when I/Q Volterra nonlinear compensation is applied. Notably, the corresponding CPRI capacity for 14-GHz OFDM signal needs to be 860.16 Gb/s.

4. Conclusion

We successfully demonstrate an A-RoF scheme with 14-GHz OFDM signal based on DDM signal aggregation and deaggregation. Our proposed FH links can provide up to 128 RF-chain signals without inserting guard bands, and no frequency conversion is needed in RRH, which is suitable for 6G Ma-MIMO FH and BF technology. Both EVM performance of 64 and 128 RF-chain signals can meet the 3GPP 64 QAM specification. To compensate I/Q imbalance and nonlinear transfer function of DP-MZM, the I/Q Volterra nonlinear compensation are utilized, and the EVM can be improved from 7.6% to 6.1%. The corresponding CPRI capacity needs to be 860.16 Gb/s.

5. References

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