Towards Terabit Digital Radio over Fiber Systems: Architecture and Key Technologies

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Abstract—To support massive deployment of broadband radio applications, such as 5G and high-definition videos for terrestrial televisions, large system capacity and high spectrum efficiency are intensively required for radio-over-fiber (RoF) systems. In this article, we propose a terabit digital RoF system capable of providing high-speed transmission, where multicore fiber (MCF) is introduced for access segment from the central unit to remote unit. Key technologies to enhance system capacity and spectrum efficiency, including MCF based self-homodyne coherent detection and compressed quantization schemes, are presented.

I. INTRODUCTION

Rapid developments of broadband services, e.g., emerging fifth-generation (5G) wireless technologies [1], terrestrial broadcast technologies [2, 3], make access networks face significant challenges of handling ever-increasing traffic for radio services. Copper-based solutions for data transmission between access points and central offices (CO) come with severe limitations in both transmission distance and data rate per user. To cope with reach and capacity crunch, optical fiber is considered as a promising media to deliver radio services thanks to its inherent merits of low loss, large capacity and high reliability. Particularly, radio-over-fiber (RoF) [4] is an attractive technique, because it can offer long transmission distance and high capacity between the CO and remote unit, allowing for centralized radio signal processing. Such features enable cloud radio access networks (C-RANs), where baseband unit (BBU) pool is located at the CO and advanced radio processing techniques (e.g. coordinated-multipoint transmission and reception) is carried out, leading to high cost- and energy-efficiency for radio service provisioning.

To serve the broadband radio services, both analog and digital RoF systems have been widely investigated, where ITU-T G. Sup55 [4] has provided a detailed description. In the analog RoF systems, radio signals are transported in an analog format over an optical fiber link, which has obvious advantages, such as high spectrum efficiency and subcarrier multiplexing. However, the analog RoF systems typically have a very limited dynamic range and are significantly affected by system nonlinear distortions and fiber dispersion effects. Therefore, limited transmission quality and distance make the analog RoF systems difficult to meet the requirements for high-capacity radio applications, such as 5G new-radio (NR) with high modulation orders [5] (e.g. 1024 level-quadrature amplitude modulation, 1024-QAM). There are a few channel equalization and compensation schemes proposed for the analog RoF systems. However, they are at the expense of increasing system cost, latency and power consumption, which might not be suitable for future radio services.

In contrast, the digital RoF systems deliver digitized radio signals over fiber, which are less susceptible to the nonlinear channel distortions, and hence allow for a longer transmission distance and better signal quality compared to the analog RoF systems. Besides, digital signals over fiber links enable common network infrastructure to deliver both fixed broadband and radio services to greatly save cost.

Pulse coding based common public radio interface (CPRI) protocol [6] has been standardized to transmit digitized analog signals between the central unit and remote unit. Besides, since high definition video transmission employing high order modulations is also sensitive to the nonlinear channel distortions, such a digital RoF system is also promising to be employed in terrestrial broadcast networks [2, 3]. However, when putting signal processing functions at the central unit, the system requires high transmission capacity due to a large number of quantization bits (QBs). For example, a site with 25 5G-NR channels requires a link rate of 101.38-Gbps for CPRI in wireless communications. As a result, the system needs large capacity to aggregate radio channels.

To address the capacity crunch in digital RoF systems, 8 options for function splitting have been defined by 3rd generation partnership project (3GPP), in which part of (or entire) the baseband processing functions can be moved towards the remote unit. CPRI is an encapsulation protocol possibly used for Option 8, which is the same as the conventional fronthaul having the entire baseband processing at the central unit, while enhanced CPRI puts focus on other options as well (e.g., Option 7 and 6 with split points located at the PHY level [6]), which moves part of the baseband processing functions to the remote unit and hence is able to reduce capacity requirement. Nevertheless, such a solution is at the expense of higher system complexity and cost at the remote units. Furthermore, driven by growing traffic demand, not only Option 8 but also the other options will need capacity improvement in future.

There are mainly two types of solutions to solve the capacity problem of digital RoF system employing pulse coding (e.g. CPRI):

Authors	Year	System	Dis. (km)	Highest CPRI-equivalent rate (Tbps)	Highest QAM order
X. Liu et al.	2014	Analog RoF	**40**	0.037	64
X. Liu et al.	2016	Analog RoF	5	0.059	64
X. Liu et al.	2016	Analog RoF	1	0.256	64
C. Han et al.	2016	Analog RoF	30	0.088	64
P. T. Dat et al.	2016	Analog RoF	20	0.190	**256**
B. G. Kim et al.	2017	Analog RoF	20	0.294	64
S.Ishimura et al. [8]	2017	Analog RoF	5	0.393	64
S.Ishimura et al. [8]	2017	Analog RoF	20	**1.032**	64
J. Wang et al. [9]	2017	Digital RoF	25	0.039	1024
M. Xu et al. [7]	2018	Digital RoF	**80**	**0.314**	1024
H. Li et al. [10]	2018	Digital RoF	20	0.124	4096
L. Zhang et al. [11]	2017	Digital RoF	20	0.201	4096
L. Zhang et al. [12]	2018	Digital RoF	20	0.150	**16384**
This work		**Digital RoMCF**	**33.6**	**5.210**	**4096**

Table 1. Reported CPRI-equivalent data rate and transmission distance in RoF systems (The works presented in the first six rows in Table 1 are cited in [8]).

- Implementing high-speed transmission link [7, 8];
- Using compressed quantization and coding to reduce the quantization induced overhead and improve spectrum efficiency [9-12].

A summary of the recent works reported on large-capacity RoF systems is shown in Table 1 [7-13], where Option 8 for function splitting is considered for calculations here. The CPRI-equivalent rates are used to evaluate the system capacity of supporting broadband radio channels. It can be observed that the difference between the analog and digital RoF systems is obvious. The analog RoF systems can hardly support radio signals with QAM orders larger than 256. Regardless which scheme is applied, an obvious trade-off between transmission distance and system capacity can be observed in the analog RoF systems. The longest transmission distance for the analog RoF systems reported so far is 40-km but only supporting 0.037-Tbps CPRI-equivalent rate. The highest CPRI-equivalent rate for the analog RoF system is 1.032-Tbps with fiber transmission up to 20-km. In contrast, the digital RoF system can easily support higher QAM orders, up to 16384, and realize a much longer transmission distance, up to 80 km. However, due to the limited system compression ratio, it is very challenging to achieve terabit CPRI-equivalent rate for the digital RoF systems. Recently, delta-sigma modulation [9] has been introduced in the RoF systems, while low-pass filters have been proposed to replace digital to analog convertors (DACs). However, such schemes require a high sampling rate and the performance relies on the intermediate frequency carrier index [11].

Future broadband radio services, such as 5G-NR, where massive-MIMO is expected to implement active phased array antennas (APPAs) with an array size of 128 and beyond, and the corresponding CPRI-equivalent rates increase to ~ 0.5-Tbps and beyond per sector. Since there may be more than 1 sector per cell depending on the deployment scenario, the required CPRI-equivalent rate can easily reach the terabit level, for which the existing digital RoF solutions hardly support. The research towards terabit digital RoF system is of great importance for future radio service provisioning.

In this article, we focus on the architecture and key technologies towards terabit digital RoF system realization. A digital radio-over-multicore-fiber (RoMCF) system is proposed. Three main scientific innovations are summarized as follow:

- **Multicore fiber (MCF)** that scales up the lane count per fiber and provides much higher bandwidth density compared with the conventional single core fiber is introduced to realize terabit RoF link capacity.
- **Self-homodyne detection** is able to be implemented thanks to the MCF link introduced in the system, where a remotely fed synchronized local oscillator (LO) transmitted through one core is shared by the signals from the other cores at the reception.
- **Compressed quantization** including lossy and lossless coding schemes is employed on top of the MCF link with the self-homodyne detection to further improve spectrum efficiency.

II. Digital RoMCF System

Figure 1 shows our proposed digital RoMCF system, which distributes the radio signals from the central unit to remote unit. The downstream configuration is presented in Figure 1. The upstream configuration follows the same operation principle, but in the opposite order.

At the CO, the signals from the core networks are first decapsulated, where analog modulations according to the protocol of the radio services are performed to generate radio signals. Then the signals are digitized by quantization and mapped to symbols of advanced modulation formats. After

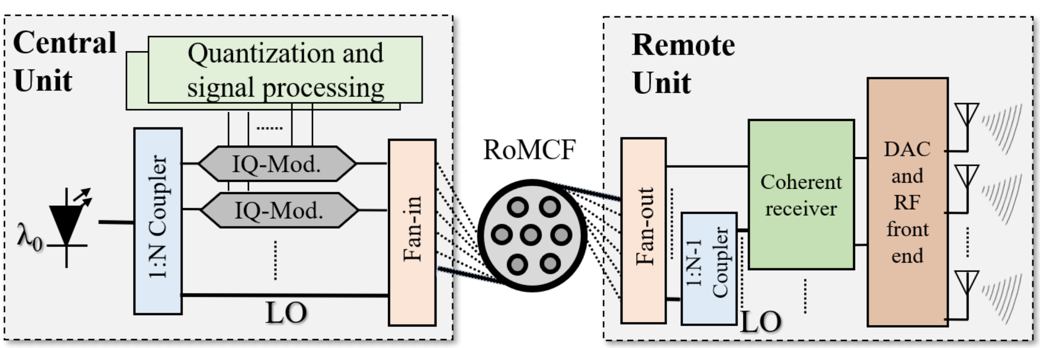

Figure 1. Proposed RoMCF system.

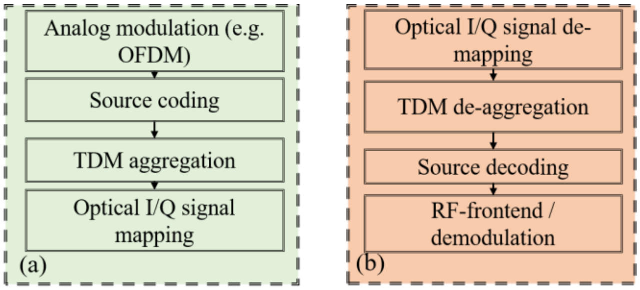

Figure 2. a) The transmitter flow and b) the receiver flow of proposed RoMCF system.

that, the signal sources are distributed to different optical modulators equipped with different wavelengths and different MCF cores, where SDM is utilized to increase the capacity. The digital signals are coupled to the fan-in module attached with the MCF, and the SDM signals are transmitted through the MCF to the remote unit.

At the remote unit, the SDM signals are first demultiplexed through the fan-out module, and then the signals are forwarded to different radio frequency frontends. With the digitization of radio signals over the fiber link, the deterioration effects of interference and fading from the fiber link can be greatly reduced. The advanced signal processing modules to further improve the system transmission and radio coordination performance can be placed at the central unit, which is shared by the remote units in the network.

To further increase the system capacity, wavelength division multiplexing (WDM) could also be introduced in the RoMCF system, where wavelength multiplexer and demultiplexer need to implement for WDM signals. In this manner, specific wavelengths and cores can be assigned to different end users (e.g. remote radio units in 4G and 5G) for connecting to the CO.

III. Key Technologies

The proposed RoMCF system utilizes SDM to improve the system capacity, which can easily realize terabit transmission rate with the mature devices and transmission techniques. To further increase the system capacity per lane and improve the spectrum efficiency suffered from a high number of QBs, supporting more aggregated radio channels, there are two promising key technologies that can be considered in the proposed RoMCF system:

- Using coherent transmission link, where one core of MCF is assigned to remotely feed synchronized LO for self-homodyne detection;
- Employing compressed quantization techniques for digitizing radio signals.

A. Self-homodyne Link Through MCF

Figure 1 shows the self-homodyne link configuration for improving the capacity per lane in the proposed RoMCF system. The signal processing flow at the central unit and the remote unit are shown in Figure 2a and Figure 2b, respectively. The signals from the central unit firstly go through the modulation module to form the wireless signals according to the format of the air interface. For instance, orthogonal frequency division multiplexing (OFDM) with 122.88 MSa/s are used as the modulation per carrier in 5G-NR configuration [5]. Then signals are digitalized at the encoder for source coding and arranged in frames, before the carrier aggregation through time division multiplexing (TDM). After aggregation, the digital signals of in-phase (I-way) and quadrature-phase (Q-way) are mapped to optical I/Q signal formats. After digital to analog converter (DAC), the signals are loaded to the optical I/Q modulators. A laser is split by a 1: N optical coupler, where N is the number of cores in MCF. Then, N-1 branches are used as the light sources for I/Q modulation and one branch is reserved for the LO that is used for self-homodyne detection at the receiver side. N-1 branches of modulated digital radio signals and one LO branch are coupled to the MCF by a fan-in module.

At the remote site, the digital radio signals and LO after MCF transmission are de-coupled by a fan-out module. LO is used at the receiver for self-homodyne detection. The signals are received by the coherent receiver, which is composed of 90° optical hybrid and balanced photodetector (BPD). After analog to digital convertor (ADC), the signals are demodulated to the TDM framed signals with optical signal de-mapping. Then, the signals are de-aggregated by de-framing. Finally, the digital signals are converted to analog by the corresponding source decoding module and modulated to different antenna-carriers by radio frequency frontend.

Thanks to self-homodyne detection, the merits of coherent communication, such as large-capacity, high-sensitivity could be adopted in the RoMCF system. Besides, the self-homodyne link through MCF relaxes the laser linewidth requirements, eliminates the need for a carrier frequency tracking, and simplifies the phase noise compensation in the receiver side. When WDM is employed, this approach can also reduce the number of LO lasers to the wavelength number. Thus, it becomes a cost-effective alternative that enhances the digital RoF system capacity and scalability while reducing the complexity of the receiver and power consumption.

Without loss of generality, other link configuration schemes, such as direct detection, heterodyne detection scheme, can also be employed in the RoMCF system, where all the cores can be used for data transmission while more complicated system configuration is required.

B. Compressed Quantization Schemes

The main challenge of the digital RoF systems (also including the proposed digital RoMCF system) is the sacrificed spectrum efficiency for the digitization of radio signals. The digitization process employed in the RoF system is a ‘double-edged sword’. On one hand, it improves the system performance against channel distortions. On the other hand, a large number of QBs are typically required, which introduce a capacity crunch on the fiber link, resulting in a smaller number of radio channels to be aggregated. In the previous part, SDM coped with self-homodyne coherent link configuration can greatly increase the system capacity, this section further discusses methods to increase the spectrum efficiency, which effectively provides extra gains to increase the aggregated number of radio channels and CPRI-equivalent rates in the RoMCF scheme.

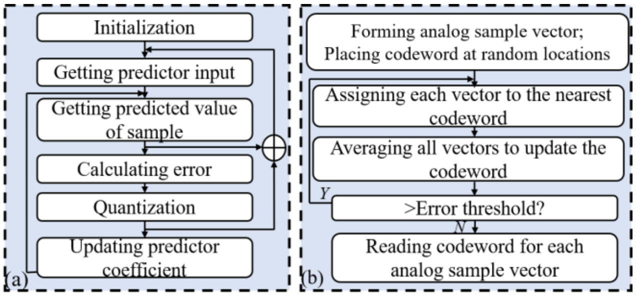

Figure 3. Lossy coding scheme with a) differential coding and b) vector coding.

The most straightforward way to reduce the capacity pressure caused by digitalization is to decrease the number of QBs, i.e., compressed quantization, which is mainly performed at the source coding of the radio analog signals [14]. In the proposed digital RoMCF system, both lossy and lossless coding schemes can be used for compressed quantization.

1) Lossy coding schemes

The analog radio signals typically adopt multicarrier modulation formats, because it has flexible subcarrier loading and yields high spectrum efficiency at the air interface. Among various multicarrier modulation schemes, OFDM is widely adopted thanks to its simple processing flow. In OFDM modulation, only part of the subcarriers are loaded with user data and the rest are set as the guard band. For instance, for 5G-NR, 1600 subcarriers are loaded with data with 2048 points inverse fast Fourier transform (IFFT), which results in oversampling in multicarrier modulation. As a result, the neighboring samples of the analog signals always exhibit strong sample-to-sample correlations. Such correlations can be utilized to reduce the redundancy during quantization of the analog signals.

Lossy source coding is an effective means to remove the redundancy during quantization of the analog signals and reduce the number of QBs. The 'lossy' here means the quantization process is not perfectly revertible due to quantization noise, which is inevitable during digitization. In the proposed RoMCF system, we consider two types of lossy coding schemes, namely scalar coding and vector coding [12]. For the former one, differential coding [11] is implemented as the instance.

The flow chart of differential coding is shown in Figure 3a. Utilizing the correlation among neighboring samples, a linear predictor is used to predict the sampled signal s from the previous samples, and the quantization is carried out based on the error e between with sampled signal and its prediction. Meanwhile, the difference between the sampled signal and the predicted signal can be optimized to minimize the quantization noise, and hence the number of QBs can be reduced. For prediction, at the beginning of the analog radio signals, the first several samples are selected as training data to update the predictor coefficients. Then, the encoding and decoding of the user samples are performed based on the prediction coefficients obtained from the training data. In the implementation, Levinson-Durbin algorithm and Lloyd algorithm are used for optimization.

The flow chart of vector coding is shown in Figure 3b. Compared with differential coding, vector coding uses high-dimension mapping instead of linear predictor to remove the redundancy of digitized analog radio signals. The quantization process is composed of 3 steps, namely, 1) vector construction, 2) vector clustering and 3) multidimensional quantization. Firstly, the consecutive analog samples are grouped into high-dimension vectors and the initial codewords are distributed randomly. Then, the codewords are updated iteratively with the principles shown in Figure 3b until the mean error is less than the error threshold. Finally, the codeword is assigned for each sample vector. Thanks to the redundancy of analog signals, more redundant information space can be removed by increasing quantization dimensions, because the formed vectors are more centralized at the highly-frequent regions.

Considering both differential coding and vector coding, it can be observed that both of them utilize the redundancy from high-correlation properties of neighboring analog samples. Such a correlation has not been utilized in radio communications, but it can be beneficial for compressed quantization in the proposed RoMCF system. More mathematical derivations can refer to [11, 12].

2) Lossless coding schemes

Because of the high peak-to-average-power-ratio (PAPR) of multicarrier signals, like OFDM, there might still be some redundancy after lossy source coding, referred to as entropy redundancy. All codewords share the same number of QBs. However, most of the codewords are distributed at the low-amplitude region and only few codewords are distributed at the high-amplitude region.

Lossless source coding is promising to reduce such entropy redundancy. The idea of lossless source coding is very simple, where the codewords occurred more frequently are implemented by shorter codes while the codewords occurred less frequently are implemented by longer codes. We introduce both Huffman coding (see Figure 4a) and arithmetic coding (see Figure 4b) for compressed quantization in the proposed system.

Figure 4a shows how to construct a Huffman code-tree. For Huffman coding, the codewords are sorted by their probabilities of occurrences in a descending order. The codewords are sorted according to their probability. Two nodes with the lowest probabilities are chosen and assigned with value 0 and 1, respectively. Then these two nodes

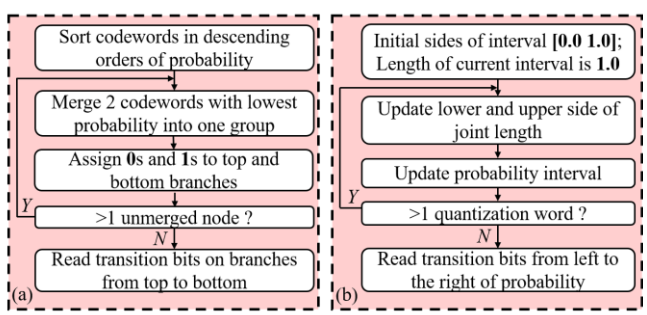

Figure 4. Lossless coding scheme with a) Huffman coding and b) arithmetic coding.

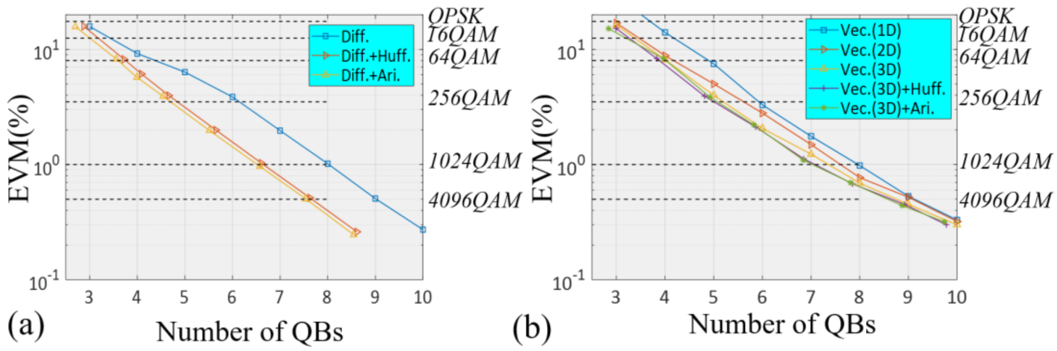

Figure 5. a) EVM versus number of QBs for differential coding and lossless coding; b) EVM versus number of QBs for vector coding and lossless coding.

are merged into a new node with the weight as sum of weight of its two child nodes. If there are still unmerged nodes, the algorithm continues to find two nodes with the lowest weight, which are assigned value 0 and 1, respectively, to be merged as a new node. Finally, for every codeword, the coded bits are read from the root to the leaf node.

Although Huffman coding in principle approaches the entropy of quantization, the code length for each codeword should be integer, which produces rounding errors. Arithmetic coding overcomes this problem. Figure 4b shows how to construct arithmetic coding. In the initial stage, all possible codewords are in the range [0.0, 1.0). In every iteration, a new quantization word with an updated cumulative probability range is handled. Then, the range is updated accordingly. Finally, when all quantization words are handled, a probability in the middle of the range is selected. For arithmetic coding, the compression efficiency of arithmetic coding is always better or identical to that of Huffman coding.

IV. Proof-of-concept Demonstration

To demonstrate feasibility of the proposed RoMCF system, proof-of-concept experiments are carried out according to system scheme in Figure 1 and our previous work in [15], where the quantization sequence is generated by either differential coding or vector coding and then further coded by either Huffman coding or arithmetic coding. OFDM and 2048-IFFT points are used. The sampling rate per OFDM symbol is 122.88-MSa/s with the bandwidth of 100-MHz. At the transmitter side, the sequence is mapped to 28-Gbaud 64-QAM constellations followed by Nyquist pulse shaping. It is output from the DAC (50-GSa/s) and then loaded to the IQ-modulator. The light from the laser is split using a polarization maintaining 50:50 splitter. One is used as the transmitter laser, and the other one transmitted after 7-core MCF is used as the LO at the receiver side. The output light from the IQ modulator is amplified by an erbium-doped fiber amplifier (EDFA), divided into 6 branches using a 1:8 splitter, decorrelated, and then coupled into the low-crosstalk MCF via a fan-in module. After 33.6-km MCF, the channels are demultiplexed by a fan-out module. A noise loading module consisting of an optical attenuator and an EDFA, is placed to adjust a channel optical signal-to-noise ratio (OSNR). Finally, the signals are coherently detected and stored in the ADC (80-GSa/s). For all cores, we have achieved error-free 64-QAM transmissions after hard-decision forward error correction (HD-FEC) threshold.

The error-vector-magnitude (EVM) performance for 5G-NR is shown in Figure 5a and Figure 5b. They are measured with error-free coherent transmissions over 33.6-km MCF after HD-FEC. The thresholds of different modulation orders are referred to 3GPP standard (3GPP TS 36.104 V12.6.0). First, we measure the EVM performance with differential coding and lossless coding, where the number of QBs after lossless coding is calculated as effective QBs (QBs before lossless-coding/compression-ratio). In average, Huffman coding reduces ~1.4 QBs and arithmetic coding reduces ~1.6 QBs. With only 7.5385 QBs, 4096-QAM based 5G-NR signals can be delivered over the proposed RoMCF system with error-free transmission. Besides, we also measure the EVM performance with vector coding and lossless coding. It can be observed that lossless coding does not help much for vector coding because there is very little information redundancy after vector coding. Compared with differential coding, vector coding can improve the system performance by increasing the quantization dimension and achieves better EVM performance compared with differential coding at the same number of QBs. The aggregated 5G-NR channels and the CPRI-equivalent rates are summarized here, where 64B/66B line code, and 1/16 processing overhead are considered. The supported QAM orders vary from 4, 16, 64, 256, 1024 to 4096. With 4-QAM, the highest number of aggregated 5G-NR channels that can be achieved is 1285, whereas with 4096-QAM, up to 460 aggregated 5G-NR channels can be supported. The corresponding CPRI-equivalent rates (*28Gbaud*4*(1-7%)*6*15/QBs*) vary from 1.56-Tbps to 5.21-Tbps.

V. Discussions

This section discusses on the impact of the proposed digital RoMCF system on cost, DSP complexity and latency.

1) System Cost

The major differences between the proposed RoMCF system and the conventional digital RoF system that heavily impact the system cost are mainly the following three aspects: 1) using MCF instead of conventional single core fiber as transmission media; 2) self-homodyne based coherent transceivers instead of intensity modulation and direct detection (IM/DD) transceivers; 3) coherent and quantization DSP.

The system capacity is significantly increased by multiple spatial channels in MCF, of which the system cost per bit/s has a great potential to be lower than that having multiple single core fibers deployed in parallel. Although the cost of MCF is quite high currently, it is expected to be lower with higher technology mature level and massive deployment.

Although the coherent transceivers often cost more compared to the IM/DD, the coherent system can achieve larger system capacity and higher optical power budget, allowing for a higher number of end points for sharing. Hence, the cost per end point might be able to be reduced.

Furthermore, the DSP that required by compressed coding makes the proposed RoMCF system possible to improve transmission performance and consequently support more radio channels, having a great potential for cost reduction on a per-radio channel basis. More details about analysis of DSP complexity that also reflects the system cost are presented in the following sub-section.

2) DSP complexity and latency

Compared with conventional digital RoF system, the DSP introduced in the proposed RoMCF system are mainly composed of the coherent signal equalization, lossless coding and lossy coding. Here, the DSP induced latency is discussed along with the complexity since the latency is highly affected by the DSP complexity.

After coherent detection, signal equalization, even for 28Gbaud 64QAM signals, is relatively simple thanks to the self-homodyne detection supported by the MCF link. The MCF is not only useful for capacity improvement, but also relaxes the LO linewidth requirement at the receiver side. As a result, the carrier phase recovery is simplified. In the proof-of-concept experiments, a two-stage filtered blind phase search (F-BPS) with only 8 test phases is implemented, and the BER of 28Gbaud 64QAM signals can achieve below HD-FEC. The processing latency of QAM signal equalization with low pass filtering in the F-BPS results in negligible processing latency. However, to realize the error-free transmission, the HD-FEC is needed and typically causes more processing latency than the signal equalization.

For the lossless coding, the Huffman en-(de)coding and arithmetic en-(de)coding use a look-up table. The transmission of the lossless coding codebook can be done during the training stage, and it does not take extra latency for data signal processing. The DSP latency mainly comes from the look-up table searching, which could be low with parallel computing.

For the lossy coding, the differential coding has lower complexity than the vector coding. The differential encoding needs linear addition arithmetic operations per complex-valued symbol with the order of linear predictor memory length [11], which is usually less than 5. The decoding processing also performs the same linear arithmetic operations. Besides, the differential coding is also competitive with respect to latency, which is equal to the aforementioned memory length. Comparatively, the vector encoding needs more arithmetic operations at the transmitter side because the vector clustering needs time for convergence during training stage. Once the encoding has converged to the pre-defined error threshold, the vector encoding and decoding turn to be a look-up table, which is quite simple, and the corresponding processing latency is related to the codebook size.

The latency of the entire DSP flow at reception is in the magnitude of 10μs, where FEC often occupies a big portion. This exact value of the latency is highly dependent on chip technology, which will be further reduced by advancing application-specific integrated circuit (ASIC) for the RoF systems.

VI. Conclusions

The self-homodyne coherent detection link configuration and compressed quantization schemes over RoMCF system are proposed for terabit transmission supporting broadband radio services. Proof-of-concept experiments achieved QAM orders vary from 4 to 4096, supporting 460 aggregated 5G-new-radio channels with 4096-QAM and 1285 with 4-QAM, respectively. The corresponding CPRI-equivalent rates vary from 1.56-Tbps to 5.21-Tbps.

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