An MPSK Millimeter-Wave Point-to-Point Link With Radio Over Fiber Synchronous Baseband Receiver

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Abstract—This paper demonstrates a millimeter-wave point-to-point radio link of MPSK (QPSK, 8-PSK, and 16-PSK) modulation without using any analog to digital converter (ADC). The proposed point-to-point radio link, not only use the radio over fiber (RoF) concept to extend the transmit distance of the central unit and the remote radio unit, but also use the clock and data recovery (CDR) applied in the optical-electrical converter (OEC) to recover the MPSK intermediate frequency (IF) signals frequency offset. Compared with the traditional RoF link, the proposed point-to-point synchronous radio link eliminated the high-speed ADC requirement for the digital-intermediate-frequency-over-fiber (DIFoF) link, which can significantly reduce the complexity and the cost of the remote radio unit. Simultaneously, we have designed a simple symbol synchronization algorithm to realize the real-time point-to-point radio link on a Field Programmable Gate Array (FPGA). The proposed millimeter-wave radio link has successfully demonstrated 6 Gbps QPSK transmission and can tolerate the frequency offset up to 100 MHz.

Index Terms—millimeter-wave, synchronization, IFoF, carrier recovery, communication link.

I. INTRODUCTION

As the Fifth-Generation (5G) mobile systems gradually come into operation and Sixth-Generation (6G) on the horizon, the number of wireless access nodes and the communication speed increase explosively[1]. To meet the high communication capacity requirement, significant network densification, which deploys a large number of small cells, is widely acknowledged[2]. The backhauling (connecting cells with the central network) for small cells is seen as the biggest challenge for such dense deployment, where millimeter-wave (mmW) point-to-point (PtP) link and fiber link are two leading solutions[3]. MmW PtP links provide an easier small cell deployment, however, the hardware cost and power consumption are higher than those of fiber links[4].

To reduce the complexity of the mmW PtP link, the backhaul system often adopts the RoF concept to transfer the signal from a compact outdoor remote radio unit (RRU) back to a bulky, indoor central processing unit (CU), where a power-hungry central process unit is used for digitizing and demodulating the transmitted data[5]. Several RoF techniques are proposed for signal generation and detection for such RRU-CU interconnections. The state-of-art real-time RoF link and intermediate frequency over fiber (IFoF) link transmission performance are concluded in Fig. 1. At lower mmW frequencies, modulated signals can be directly generated and received using optical devices (RoF link), and real-time data transmission (uplink) and receiving (downlink) are demonstrated, however, only at data rates below 5 Gbps. [6],[7],[8]. At higher mmW frequencies, mmW frontends are often used to up/down-convert mmW signals to a lower intermediate frequency and transfer to a CU using the IFoF structure, [9],[10],[11],[12],[13],[14],[15]. The signal bandwidth that can be processed by the IFoF link is often limited by the speed of ADC. On the other hand, it can be seen, when high sampling rate oscilloscopes are used with offline signal processing, the transmission data rate is demonstrated as high as 40 Gbps. In this paper, we have proposed a real-time mmW PtP radio link for both IFoF architecture uplink and downlink with a data rate up to 6 Gbps with MPSK modulations.

An IFoF link can be used as an alternative to an RoF link in mm-wave communication systems when the mmW frequencies that beyond the cut-off frequency of a cost-effective photoreceiver. The IFoF transmissions can be divided...
into three main categories: analog-intermediate-frequency-over-fiber (AIFoF), DIFoF, and sigma-delta-intermediate-frequency-over-fiber (SDIFoF). AIFoF suffers from the nonlinearities of the optical link and photoelectric components [6][7]. To mitigate linearity limitation, the IF signal can be directly digitized by an ADC then transfer to CU as DIFoF using enhanced Common Public Radio Interface (eCPRI)[16]. The bandwidth is limited by the sampling rate of Digital-to-Analog converters (DAC) and ADCs.

The One-bit Sigma-Delta modulation (SDM) technique is a solution to generate and digitize analog waveform using a high-speed comparator or optical-electrical converters (OEC), which are cheaper and consuming less power than traditional analog/digital converters[17]. SDM takes advantage of the high sampling rate of comparators or OECs to convert a narrowband analog signal into multi-level digital samples[18]. With SDM techniques, the SDIFoF link can be used for wideband signal transmission, where the OEC is used as DAC to generate modulated signals for transmission. However, the viable processing analog bandwidth is typically less than 1/10 of the sampling rate, which leads to a limited bandwidth[19]. In practical communication systems, the asynchronous clock between transceivers will lead to the symbol frequency offset (SFO) and carrier frequency offset (CFO). SFO and CFO cancellation is either depending on applying differential encoding at the transmitter with differential demodulation at the receiver or adding a pilot signal (single tone [20], or pseudo-noise (PN) data [21]) at the transmitter and performing signal processing based on such pilot as the reference.

In this paper, we propose an IFoF mmW PtP synchronization link. Unlike previously reported works, the IFoF link in the mmW PtP synchronization system is not only used to extend the transmission distance between the RRU and the CU, but also used to synchronize received IF signals. The OEC built-in CDR hardware is used to perform pilot-less CFO cancellation, and we also propose an algorithm is used for SFO cancellation for real-time data transmission. The proposed link has been verified in an E-Band (71-76 GHz) PtP link testbed with QPSK, 8-PSK, and 16-PSK modulation. This PtP system achieves a 6 Gbps error-free (BER< $10^{-12}$) transmission in the E-Band test with frequency offset tolerance up to ±100 MHz.

The paper is organized as follows: section II introduces the proposed mmW PtP baseband synchronization communication system architecture. In section III, the IFoF synchronization algorithm is introduced. In section IV, the experimental setup of the mmW PtP link testbed and the experiment results are presented. Finally, the paper is summarized in section V.

II. PROPOSED PtP MMW LINK STRUCTURE

The proposed mmW PtP radio link comprised a CU (IF signal generation and reception) and separated RRUs (for mmW up and down/conversion). The CU and the RRU are connected by fibers, which allows RRUs to be conveniently deployed in the urban scenario. One such scenario is illustrated in Fig. 2a. A small base station is mounted on the street light pole to enhance mobile user coverage. However, the fiber...
network is not available at this installation location. Therefore a fronthaul PtP link is required to connect base station data traffic to the building nearby with a fiber network access. The mmW PtP link is either designed as a compact form (CU and RRU integrated together) on the light pole side or designed as a distributed case as an outdoor RRU and an indoor CU (as in the building side). This PtP link dual-directional transmission can be made by frequency division duplex (FDD). In the following discussion, we only focus on the signal directional transmission path for simplicity. For the transmitter path, the user data is generated and modulated in the CU and transferred as a fixed 10 Gbps binary stream over the fiber and upconvert to mmW frequency in the RRU. For the receiver path, the received mmW signal is down-converted by the RRU to the IF signal, where frequency offset occurs due to asynchronous local oscillators (LO) between the transmitter and the receiver. The down-converted IF signal passes through a low pass filter (LPF) to filter out unwanted high frequency spurious and fed into an OEC. The IF signal is digitized by the OEC into a one-bit binary stream and transferred over the fiber back to the CU. It should be noted that this OEC has a built-in CDR feature that operates at 10 Gbps. This CDR module helps the system perform carrier recovery for the MPSK demodulation, which will be detailed discussed in section III. At the CU side, the received binary stream is then processed by an FPGA in the CU for symbol recovery and demodulation. After the demodulation, the user data is recovered, and the bit error rate (BER) and error vector magnitude (EVM) can also be calculated. The proposed mmW PtP radio link, with the characteristic of separated RRU and CU, allows a compact and low-cost RRU design.

III. PtP SYNCHRONIZATION BASEBAND LINK

As mentioned in the previous sections, the proposed mmW PtP radio link contains neither ADC nor DAC. The analog MPSK IF signal waveform processing is accomplished with high-speed binary streams that are transferred over fiber. The principle of such one-bit waveform generation and acquisition is explained in detail in this section.

A. MPSK Signal generation

As illustrated in Fig. 2, the MPSK signal is generated by an FPGA in the CU in the format of the binary stream. Assuming MPSK signal has a symbol rate of $f_{sym}$, centered at an IF frequency of $f_{IF}$, and the binary stream data rate is $f_{RoF}$. For simplicity, we choose $f_{IF} = k \cdot f_{sym}$, where $k$ is an integer. For MPSK, there are $2^M$ possible modulation points. We choose $f_{RoF} = j \cdot f_{IF}$, where $j \geq 2^M$ is also set as an integer. Taking a simple case of BPSK modulated symbol as an example, when $f_{IF} = 2.5\text{GHz}$, $f_{RoF} = 10\text{GHz}$ and $f_{sym} = 0.625\text{GHz}$. With $j = 4$, every 4 bits of binary code can be used to represent an IF carrier waveform period. As shown in Fig. 3, a 10 Gbps binary code ‘1001100110011001’ generated in the CU corresponding to a square wave with a frequency of 2.5 GHz. Circular shift the 16-bit code by 2 bits, as ‘0110011001100110’, resulting in a square wave at the same frequency but 180-degree phase shifted. Notice that this binary code, every 16-bit can represent a BPSK modulated symbol at $f_{sym} = 0.625\text{GHz}$. This code is generated in the CU and transferred to the RRU via fiber. Through a bandpass filter (BPF) at the RRU side, the analog IF signal waveform can be obtained for up-conversion to mmW in the RRU.

B. MPSK Signal Receiving and Recovery

On the receiver side, the mmW Rx frontend in the RRU downconverts the mmW signal to the received IF signal, as shown in Fig. 2. It should be noticed that the received IF signal has a different carrier frequency of $f_{IF} + \Delta f$. However, the symbol rate $f_{sym}$ remains the same as the transmitted signal. The down-converted IF signal is then processed by a CDR function, which will adjust the digitized bitstream rate according to the zero-crossing edges in the received optical waveform[22]. As a result, when the received IF signal is centered at $f_{IF} + \Delta f$, the received binary stream rate is $f_{OEC} = j \cdot (f_{IF} + \Delta f)$. Noted that the received binary stream rate is not integer times of the symbol rate anymore due to the frequency offset $\Delta f$. Therefore a symbol timing recovery (STR) is required for the correct demodulation.

To elaborate such STR procedure, we assume that the binary stream rate $f_{RoF} = j \cdot f_{IF} = j \cdot k \cdot f_{sym}$ at the transmitter side. Due to the frequency offset, the received binary stream rate $f_{OEC} = j \cdot (f_{IF} + \Delta f) \neq l \cdot f_{sym}$, where the ratio between symbol rate and receiver binary stream as $l = j \cdot k \cdot (f_{IF} + \Delta f) / f_{IF}$ is not an integer. Given $\Delta f \ll f_{IF}$, we can approximate $l$ as a time-variant integer $l_n \in [j k - 1,j k, j k + 1]$. Assume the received binary stream as $S[n] \in [-1,1]$. Within a single transmission symbol, the IF carrier waveform repeats with the continuous phase. This yields in the $n^{\text{th}}$ received symbol $(s_{n+1} + n < n < s_{n+1})$, $S[n] = S[n + j]$. Based on this assumption, we can make STR operation by defining an error function:

$$
\varepsilon = \sum_{k = l_n}^{l_{n+1} - 1} S[k] \otimes S[k + j] \tag{1}
$$
STR is made by choosing a \( l_{n+1} \in [l_n + jk - 1, l_n + jk + 1] \) that has minimize \( \varepsilon \), where \('\oplus'\) is a bitwise exclusive-or (XOR) operation.

The signal processing flow diagram of an FPGA implementation in the CU is shown in Fig. 4. The binary stream received from the OEC is converted into a 20-bit parallel bus with a built-in demultiplexer (DeMUX) to reduce the FPGA operational clock. The data on this parallel bus and its \( j \)-bit delayed copy is processed by an STR block, with the STR approach described by Eq. 1. The STR block control a first-in-first-out (FIFO) to create a variable length IF signal vector:

\[
\mathcal{R} = \begin{bmatrix} S[l_n + 1] \\ S[l_n + 2] \\ \vdots \\ S[l_n + 1] \end{bmatrix}
\]  

(2)

A numerically controlled oscillator (NCO) generates the carrier waveform of \( f_{IF} \) (and its 90-degree out of phase copy), which are represented by a binary stream at a sampling rate of \( f_{OEC} = j \cdot (f_{IF} + \Delta f) \) and output as 20 bit-width parallel bus. The parallel bus is reshaped by the STR-block-controlled FIFOs to give vectors \( L_0 \) and \( L_{90} \) that match the size of vector \( \mathcal{R} \). The received quadrature baseband signal can be obtained using:

\[
I_{BB}[n] = (\mathcal{R} \otimes L_0) + (\mathcal{R} \otimes L_0)^T \\
= \sum_{k=l_n+1}^{l_n+j+1} S[k] \otimes L_0[k]
\]

(3)

\[
Q_{BB}[n] = (\mathcal{R} \otimes L_{90}) + (\mathcal{R} \otimes L_{90})^T \\
= \sum_{k=l_n+1}^{l_n+j+1} S[k] \otimes L_{90} S[k]
\]

With demodulated baseband signals \( I_{BB}[n] \) and \( Q_{BB}[n] \), the received constellation diagram can be monitored, the transmitted bit can be recovered, and the BER performance can be calculated.

IV. EXPERIMENTAL RESULTS

The proposed mmW PtP radio link was tested in two steps: firstly, an instrument-generated modulated IF signal is used to test the IFoF synchronization baseband link; secondly, the proposed PtP synchronous baseband transceiver (CU) is tested with an E-band commercial frontend (RRU), in which the entire single directional transmission mmW PtP radio link is tested. The test detail and results are presented in the following subsections.

A. IFoF synchronization baseband link test

The proposed PtP synchronization baseband transceiver is firstly tested with modulated IF signal input. The BER performance, EVM performance, and frequency offset tolerance of the proposed radio link are studied. The experimental setup is shown in Fig. 5a, a modulated IF signal is generated using a 65-Gsps 12-bit Keysight M8195A arbitrary waveform generator (AWG). The IF signal passed through an LPF (cutoff frequency of 8 GHz), which filters out the unwanted high-order spurious signal from the AWG. An XFP (Finisar FTLX1413D3BLC) is employed as the OEC in the test, convert the MPSK IF signal into the optical signal. The optical signal is transmitted through the fiber. An FPGA (Altera Stratix V GT Evaluation Board) is used at the receiver side as the digital signal processing (DSP) platform. The FPGA platform contains an XFP module of the same type used at the receiver side. The XFP on the FPGA is equipped with a
The CDR that converts the optical data stream on the fiber into the binary electrical stream and adjusts the data rate of the binary stream. The binary stream is demodulated by the FPGA and then stores in the Random Access Memory (RAM). Then the demodulated data transferred back to the PC for BER and EVM result analysis.

The AWG generates IF signals with QPSK, 8-PSK, and 16-PSK modulations of different symbol rates $f_{sym}$ and different IF frequencies $f_{IF}$, the generated IF signal is then fed into the proposed PtP synchronization baseband link during the test. The test results as shown in Fig. 5b-5c, the x-axis represents $f_{IF}$, and the y-axis represents $f_{sym}$. At each point, different color exhibits the measured EVM for that IF frequencies $f_{IF}$ and symbol rate $f_{sym}$ combination. From right to left, QPSK, 8-PSK, and 16-PSK modulation results are shown. Noted that the IF signal's sampling rate at the receiver is $f_{OEC}$ must be an integer multiple of the carrier frequency. When there is a frequency offset, the OEC CDR automatically adjusts $f_{OEC}$ to $f_{OEC} = j \times (f_{IF} + \Delta f)$, where $j$ is related to the modulation orders. It can be seen that each modulation has a specific frequency operational $f_{IF}$ range (or lockable range, LR), which can be expressed as $D_L/2^M - D_H/2^M$, where the $D_L$ is the lowest binary stream bits rate the CDR can be endurance, the $D_H$ is the highest binary stream bits rate the CDR support, in our case the XFP module supports 8.5∼11.32 Gbps[23]. In this PtP synchronization baseband link performance test, the QPSK carrier frequency LR is 2.3∼3 GHz, the 8-PSK carrier frequency LR is 1.15∼1.5 GHz, and the 16-PSK carrier frequency LR is 600∼750 MHz. Furthermore, we should point out that lower carrier frequencies, i.e., below 1 GHz, 8-PSK and QPSK can also be demodulated. However, we only presented the highest reliable modulation order for certain carrier frequency/symbol rate combinations in this figure. Since $f_{OEC}$ must be an integer multiple of the carrier frequency $f_{OEC} = j \times (f_{IF} + \Delta f)$, so under different IF carrier frequencies $f_{IF}$, the same symbol rate $f_{sym}$ has different oversampling rate (OSR). As shown in Fig. 6, for a
constant symbol rate, the EVM performance is improved with the carrier frequency increase when the AWG output signal has a constant EVM performance.

It can be seen from the Fig. 5b-5c, to demodulate 16-PSK, the OEC requires oversampling rate higher than 16. So the upper limit of $f_{IF}$ is 0.75 GHz and $f_{sym}$ of 0.6 Gbaud. This also implies less phase error margin for XFP CDR to detect the IF waveform zero-crossing. The best EVM results for 16-PSK is 0.56% with $f_{IF} = 750$ MHz, $f_{sym} = 200$ Mbaud. On the other hand, a 6 Gbps QPSK modulated IF signal can be successfully received with an EVM of 14.25% and a BER of $1.2 \times 10^{-12}$.

The operation of MPSK demodulation depends on the ability of CDR in the XFP to recovery the IF signal without phase error. When the IF signal is upconverted to the mmW frequency and transmitted through the mmW link, the IF signals receive performance is deteriorated by the increasement of the phase noise. Therefore it is important to repeat the similar test together with commercial mmW RRU units.

B. MmW PtP radio link test at E-band

The proposed PtP synchronization radio link is tested at E-band with commercial mmW frontends: the Gotmic gTSC0023 at the transmitter (Tx) and the Gotmic gRSC0015 at the receiver (Rx), which are operated at 78 GHz. Two signal generators (Agilent E8257D) supply the LO signals to the transmitter and receiver modules separately. An mmW digital controlled attenuator is inserted between Tx and Rx to study the dynamic range of the mmW PtP synchronization radio link. The IF signal input of the Tx and IF signal output of the Rx is connected to an FPGA at the CU via fibers using OECs, which is described in the previous sections. Therefore the mmW frontends as RRU can be separately deployed away from the CU.

QPSK, 8-PSK, and 16-PSK modulation signals are transmitted through the proposed mmW PtP radio link. EVM is offline processed with PC with waveform captured and stored in the FPGA, and BER is tested in real-time communication with software programmed within the DSP. The measurement results are summarized and plotted in Fig. 7b-7c. It can be seen that the performance is slightly degraded due to non-linearity, bandwidth limitation, and phase noise introduced by the mmW
frontends. For example, as shown in Fig. 7b, the 3 Gbaud QPSK central at 3 GHz mmW PtP radio link has an EVM of 14.85% and a BER of $8.39 \times 10^{-12}$ compared with the EVM of 14.25% and the BER of $1.2 \times 10^{-12}$ in the baseband link test. But still, the test result satisfies the 3GPP requirement, in which the bound of the QPSK EVM is 17.5% [24]. A 1.5 Gbaud 8-PSK transmission with a 1.5 GHz IF frequency exhibits an EVM of 5.59% and a BER of $1.25 \times 10^{-18}$. Similarly, the EVM of 750 Mbaud 16-PSK transmissions with the IF frequency of 750 MHz is 5.14%, and the BER is $5.68 \times 10^{-9}$. The modulated IF signal experiment exhibits that the proposed PtP radio link can tolerate a wide range of $f_{IF}$ offset and still support error-free data transmission. The test constellation diagrams are shown in Fig. 8 with different modulations.

The receiver LO is deliberately adjusted away from the transmitter frequency to study the receiver’s frequency offset tolerance. The test result is demonstrated in Fig. 9. For 16-PSK modulation, it requires $f_{OEC}$ to be 16 times higher than $f_{IF}$. Limited by the maximal speed of the OEC $D_H$, it left less margin for frequency offset error. Only 12 MHz frequency offset is allowed for maintaining BER-free transmission. The frequency offset range of the BER-free transmission of the mmW PtP link can increase to 50 MHz and 160 MHz for the 8-PSK and QPSK transmission cases, respectively. And the measurement shows that this link can tolerance $\pm 100$ MHz frequency offset with the 6 Gbps QPSK transmission.

We also studied the dynamic range of the mmW PtP synchronization radio link. However, it should be noticed that we did not include a variable gain amplifier (VGA) at the IF signal stage. The dynamic range has only exhibited the proposed RoF baseband synchronization link’s sensitivity, which can be improved if VGA is added. The result is shown in Fig. 10, that the 21 dB dynamic range is achieved in a 1 Gbaud 8-PSK transmission at 1.5 GHz carrier frequency.

V. CONCLUSION AND DISCUSSION

This paper demonstrates an mmW PtP radio synchronization link. A CDR-based MPSK modulation carrier synchronization is tested based on the mm-wave IFOF transmission architecture. We also proposed an STR algorithm to realize the real-time transmission on the FPGA. The measurement results of the transmission performance with different modulation types, different carrier frequencies, and different symbol rates have been studied. The test result shows that the proposed PtP radio link has successfully transmitted 6 Gbps QPSK transmission over a 78 GHz wireless link with frequency offset $\pm 100$ MHz, and the received signal has an EVM at 14.85% and BER at $8.39 \times 10^{-12}$, which satisfies the 3GPP requirement. Compare with the traditional ROF link design. The proposed PtP radio link does not need the high-speed ADC or high sample rate SDM at the RRU; hence it provides low complexity and low cost for the RRU design. Furthermore,
suppose a higher bit rate OEC is applied in the proposed PtP radio synchronization link. In that case, the higher achievable data rate can be attained, which can take the mm-wave or sub-
THz communication system’s vast bandwidth property better. Overall, we think this mmW PtP radio synchronization link is one of the essential potential choices for realizing the high bandwidth wireless communication systems due to the low complexity and low-cost property.

This work is also compared with previously reported RoF data transmission as summarized in the Table I.

As shown in Table I, with ARoF and powerful offline processing, an offset-QAM-based filterbank multicarrier (FBMC-OQAM) and 2 × 2 multiple-input multiple-output (MIMO) is applied to improve the system capacity, [25], [29], which can achieve 80 Gbps transmission at the 90 GHz RF frequency. There is also IEEE 802.11ad packet modulated at 88.9 GHz succeeded transmitted through the IFoF mmW link[28]. The IFoF link and distributed antenna can also be used in the data transmission on the high-speed train (HTS), in which a switched wavelength-division multiplexing is used to transmit 20 Gbps modulated at W-band[27]. There are some experiments based on the multi-tone communication is also demonstrate the 24 Gbps transmission capacity, [26], [30]. The state-of-art real-time RoF link and IFoF link transmission performance are concluded in Fig. 1, and Table I. and the offline IFoF link transmission performance is also included in this summary. Due to the limitation of the high-speed ADC and DAC, the achievable data rate of the real-time IFoF transmission is much lower than the offline transmission. The real-time IFoF mmW link applied in the HTS experiment has achieved a data rate of 1.5 Gbps[9]. A 1.6 Gbps orthogonal frequency-division multiplexing (OFDM) modulation outdoor transmission is successfully real-time transmitted by applied analog-IFoF link[10]. The IFoF-based distributed antenna system (DAS) with 2×2 MIMO has achieved 2 Gbps transmission in the indoor scenario[11], the same setup with 4×4 MIMO has successfully transmitted around 9 Gbps in the IFoF-based mobile fronthaul[12]. The SDIfoF based on the QSFPP-100G in the experiment is also demonstrated the 960Mbps transmission[13]. The IFoF link can also be used in the 8K videos transmission[14]; in this experiment, the sum-data rate can achieve 5 Gbps. Furthermore, a simple synchronization IFoF link use BPSK achieves a 1 Gbps data-rate[15]. As it can be seen from the table, this work demonstrated an ADC-less MPSK real-time wireless transmission solution at 70/80 GHz mmW band.

**TABLE I**

| Ref | RoF method | RF freq. (GHz) | Aggregate Photodiode capacity (Gbps) | Single-band data-rate (GHz) | Number of bands | Uplink\Downlink | Modulation | EVM | Photo diode type | Optical wave length (nm) |
|-----|-------------|----------------|------------------------------------|---------------------------|----------------|---------------|-----------|-----|----------------|----------------------|
| [8] | SDfoF+realtime | 2.365 | 0.14 | 10 | 0.14 | 1 | No | Yes | 16-QAM | 1.6% | SFP | 850 |
| [7] | ARoF+realtime | 12 | 4.8 | 15 | 4.8 | 1 | Yes | No | OFDM,16-QAM | 6% | DML | |
| [13] | SDIfoF+realtime | 25.07 | 1.92 | 40 | 0.96 | 2 | No | Yes | 64-QAM | 6.4% | QSFP | 850 |
| [15] | AlFoF+realtime | 28 | 1 | 10 | 1 | 1 | Yes | No | BPSK | | |
| [6] | ARoF+realtime | 10.5125 | 2.28 | 15 | 1.14 | 2 | Yes | No | OFDM,16-QAM | 8% | DML | 1532.69,1536.95 |
| [9] | AlFoF+realtime | 90 | 1.5 | 90 | 1.5 | 1 | Yes | No | multi tone| DQPSK | 14% | MZM | 1548.5~1549.5 |
| [11] | AlFoF+realtime | 28 | 2 | 6 | 1 | 2 | Yes | No | multi tone:| 64-QAM | 7.5% | DML | 1550,1510,1570, |
| [14] | AlFoF+realtime | 96 | 5 | 50 | 5 | 1 | Yes | No | multi tone:| DQPSK | 8% | MZM | 1530,1270,1330 |
| [10] | AlFoF+realtime | 60 | 1.6 | 10 | 1.6 | 1 | Yes | No | OFDM,16-QAM | 10.5% | DML | |
| [12] | AlFoF+realtime | 28 | 9.042 | 6 | 2.5 | 4 | Yes | Yes | 64-QAM | 8% | DML | |
| [25] | ALiFoF+offline | 91 | 80 | 100 | 40 | 2 | No | Yes | FBMC,| OQAM | 30% | optical IQ modulator +DPMZM | |
| [26] | ARoF+offline | 64 | 12 | 10 | 12 | 1 | No | Yes | multi tone:| QPSK | 13.2% | EML | 1557.3 |
| [27] | AlFoF+offline | 95 | 20 | 100 | 20 | 1 | No | Yes | OFDM,16-QAM | 14.6% | optical IQ modulator | 1530~1570 |
| [28] | AlFoF+offline | 88.9 | 7 | 100 | 7 | 1 | No | Yes | 16-QAM | 5.9% | optical IQ modulator | 1550 |
| [29] | AlFoF+offline | 81 | 18 | 100 | 9 | 2 | Yes | No | FBMC,| OQAM | 13.8% | MZM | |
| [30] | AlFoF+offline | 60 | 24 | 10 | 24 | 1 | Yes | No | multi tone:| 16-QAM | 12% | MZM | 1550 |
| This work | AlFoF+realtime | 78 | 6/4.5 | 3 | 12 | 6/4.5 | 3 | Yes | Yes | 8-PSK,| 16-PSK | 15% | XFP | 1310 |

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