# Real-Time FPGA Demonstration of Hybrid Bi-directional MMW and FSO Fronthaul Architecture

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**Abstract:** We experimentally demonstrate a converged hybrid bi-directional mobile fronthaul by integrating MMW and FSO links with real-time FPGA processing. We achieve long-term stability under practical 5G operation scenarios with EVM variations of <0.7% for 16-QAM.

**OCIS codes:** (200.2605) Free-space optical communication; (060.4254) Networks, combinatorial network design.

## 1. Introduction

While optical fibers are considered one of the most important enabling technologies of 5G, their deployment can be one of the major factors slowing down its proliferation. Newly proposed 5G architectures, such as Next Generation Fronthaul Interface (NGFI), call for two cascaded function splits resulting in three new network transport parts, namely: fronthaul, midhaul and backhaul [1], as shown in Fig. 1. This implies that a conventional eNB in 4G LTE is now transformed into three new units which are geographically distributed, namely: Central Unit (CU), Distributed Unit (DU) and Remote Radio Unit (RRU). Furthermore, since millimeter wave (MMW) is being adopted for the access instead of the conventional radio wave frequencies, highly dense and heterogeneous RRUs are to be expected. All these factors impose economic and technical challenges for deploying and interconnecting new 5G sites.

Beside optical fibers, MMW and free space optics (FSO) can be utilized to provide connectivity when deploying fiber is difficult or costly like in some dense urban areas or rural areas as depicted in Fig.1. Integrated MMW-FSO technology, as an alternative solution, is gaining a lot of momentum due to low cost, rapid deployment and huge bandwidth. However, they both suffer from high propagation loss which limits transmission range. Therefore, MMW and FSO cannot be used alone and they need to be integrated with fiber. Moreover, due to their different absorption characteristics under different atmospheric weather conditions, employing combining techniques is very crucial [2–4].

Even though hybrid MMW-FSO has been extensively studied, most of these studies are considering uni-directional communication and mostly they are based on offline DSP [5]. Generally, offline DSP algorithms don't consider real implementations factors like available on-chip resources and computational precision and response speed requirements [6]. To the best of our knowledge, there has been no realtime implementation of bi-directional converged MMW/FSO networks. In this paper, we are considering two practical cases for analysis under realtime bi-directional environment. First, we will test the converged case where a long reach fiber is followed by a MMW/FSO link. In the second case, we will study the case where MMW and FSO are cascaded in a bi-directional setup to emulate futuristic real 5G scenarios.

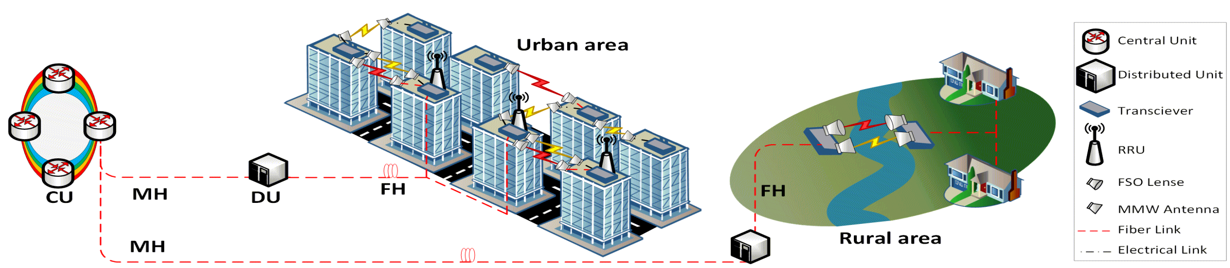


Fig. 1: (a)Evolution towards 5G (b)Use cases of fiber-wireless integrated system with hybrid MMW and FSO links

## 2. Bi-directional Converged MMW/FSO Testbed Design and Discussion

In this paper, we designed and constructed a realtime testbed that can be used to study different 5G heterogeneous scenarios. The first scenario is where the RRU is chosen to be analog and all the DSP processing is done at the DU and/or CU. The usage of analog RRU is a promising option for multifold reasons like reducing the fronthaul bandwidth requirement, reducing RRU cost and processing latency. In this case, the signal from the User Equipment (UE) travels through MMW and might be subject to interferences or other adverse wireless effects. Then, at the analog RRU, the signal is converted to the optical domain where also some conversion noise can take place. Afterward, the signal is transmitted over 10km fiber where other optical effects like signal dispersion and other non-linear effects can occur.

The demand of bi-directional communication may further degrade the signal quality. The second scenario is whereas that relays or Distributed Antenna Systems are integrated with MMW and FSO. Since the analog signal is traversing different medias and links like fiber, MMW and FSO, all impacts through out the transmission line are accumulated [7].

The RF interface including digital-to-analog converters (DACs) and up-converters was implemented using a software defined radio (SDR) platform as shown in Fig.2. The up converter can be tuned at different intermediate frequencies to generate signals at different frequencies. A single 20 MHz signal contains 1200 subcarriers where 400 are used as zeros and pilots. The channel spacing is 15 KHz and the FFT size is 2048 with extended cyclic prefix of size 512.

At the transmitter side, randomly generated data is mapped with QPSK, 16 or 64 QAM and then modulated using OFDM algorithm. Then, Zaddoff-Chu method is used to generate primary synchronization signal for synchronization at the receiver side. Afterward, the signal goes through the IFFT stage to produce the time domain IQ samples. The CP is then inserted to facilitate overcoming of the carrier frequency offset problem. The last stage includes a 30.72 MSa/s DAC and up-converter. The similar procedure but in reverse order is performed at the receiver side.

## 3. Experimental Setup and Results

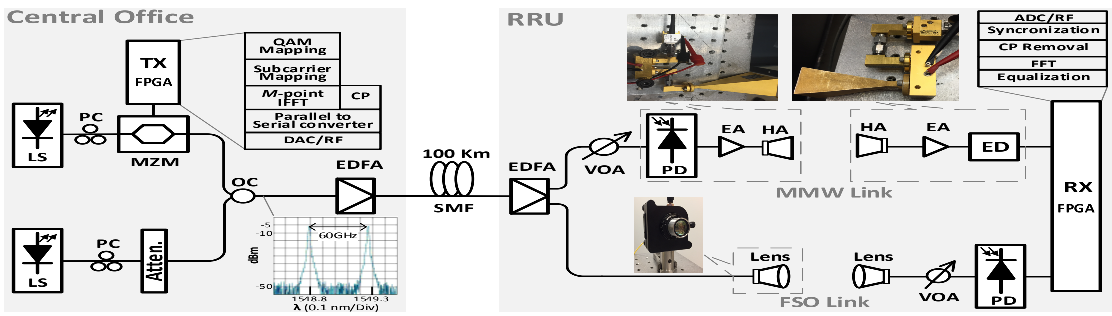


Fig. 2: Experimental setup for long-reach hybrid MMW and FSO links testbed

The experimental setup for testing the first scenario is shown in Fig.2. To generate the 60 GHz signal, two tunable laser sources (LS) are operating at 1548.79 and 1549.27 nm. The output signal of the upper laser is modulated using a Mach-Zehnder Modulator (MZM) biased at 1.5v. The modulating signal is generated from the TX with a bandwidth of 20 MHz at a carrier frequency of 250 MHz and a power of 10 dBm. The signal of the other laser is attenuated to match the power level of the MZM output before coupling the two signals using an optical coupler (OC). The 60 GHz signal is amplified using an Erbium-doped fiber amplifier (EDFA) before transmission through a 100km single mode fiber (SMF). At the receiving side, the signal goes through a second stage of amplification to increase the optical power budget especially for the FSO link. The signal is then split into FSO and MMW links. For the FSO link, the signal is received by a photodiod (PD) and then to the RX. For the MMW link, the signal first goes to the PD and then to transmission. After the MMW signal is received, it is amplified using electrical amplifier (EA) before it passes through an envelope detector (ED) for down-conversion.

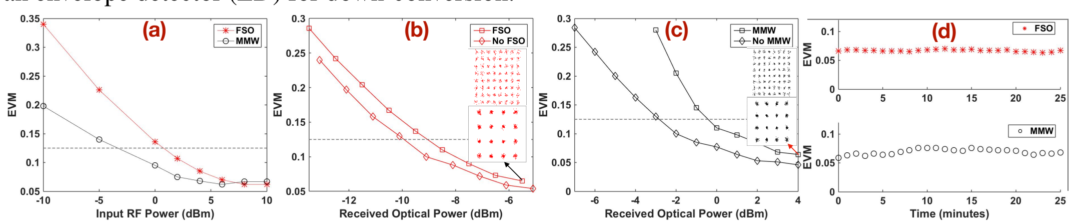


Fig. 3: Results for the long-reach hybrid MMW and FSO links experiment

The results obtained from first experiment are shown in Fig.3. Fig.3(a) shows an optimal input RF power for both links occurs at 10 dBm and consequently it was used for the rest of this experiment. Fig.3(b) shows the Received Optical Power (ROP) for both cases when the FSO is used or excluded. The result shows that there is a penalty of 1 dBm when FSO is added to the system. Similarly, repeating the same test for the MMW link induces a penalty of 2.7 dBm as shown in Fig.3(c). On the other hand, Fig.3(d) shows the stability results for both links and it shows that FSO can achieve quite higher system stability with variation in EVM equals to 0.7% compared to 1.7% for MMW link.

The setup for the second experiment is shown in Fig.4. For the DL, a 2.5 GHz distributed feedback (DFB) LD at the central office is modulated by a 250 MHz and 0 dBm signal. The modulated signal passes through a 25 km SMF and 1m FSO link. At the receiver side, the DL and UL are segregated using an Optical Circulator (OC) and the received signal is first amplified by an EDFA before it goes into a PD. To generate the MMW signal, the output of the PD is sent to a mixer. An RF signal generator is used to generate a 15GHz signal that passes through a quadrupler to the

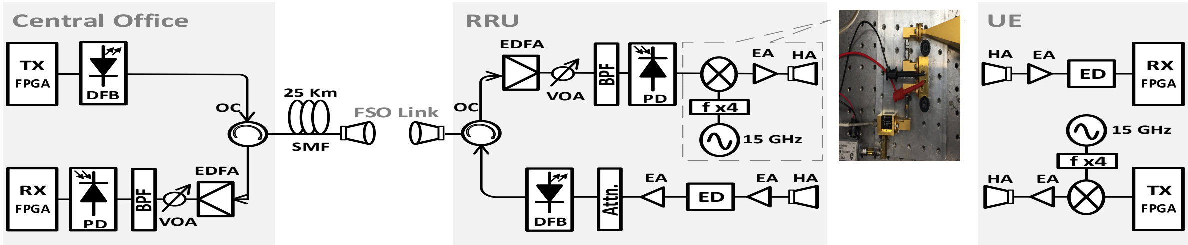


Fig. 4: Experimental setup for bi-directional hybrid MMW and FSO links testbed

other arm of the mixer. The modulated MMW signal is amplified before transmission. At the UE side, the received signal is amplified and fed into an ED and lastly to the RX.

For the UL, the signal from the TX at the UE side is generated with a power of -20 dBm and a frequency of 250 MHz and fed into the mixer. The other arm of the mixer has a similar signal that was used for the DL case. Then, the MMW signal goes through amplification, transmission and another amplification before it is fed into an ED. Since the output of the ED was so low that it cannot modulate the DFB LD, another stage of amplification was needed. At the central office side, the signal is amplified before passing through a PD then to RX. It is worth mentioning that for both UL and DL, an optical filter was necessary to filter out the unwanted signals leaking back from the circulators. And the sensitivity for both RX is adjusted to -20 dBm.

Fig. 5 shows the results for the second experiment. By changing the input RF power, we observed the lowest EVM at -4 dBm for all DL cases and for the UL in case of no MMW as shown in figures 5(a,d) consequently. When the MMW link is used in the UL, the output of the TX is directly connected to one of the mixer arms. Thus, the RF power of the TX is reduced to suite the mixer and the MMW amplifier. Fig.5(b) shows the ROP for the case of DL where the addition of the MMW link results in about 7 dBm penalty compared to FSO only system. The hybrid system has almost similar performance as the solo MMW link. However, by looking at the UL ROP results shown in Fig.5(e), we can see that the impact of the MMW on the system is greatly reduced. This is because when the MMW link was removed, no adjustments were done at any point. We just wanted to show the impact of the MMW link itself and re-tuning the amplifiers would impact the comparison fairness. Another observation is that the FSO link, regardless of its position in the system, has small impact on the system performance. Figures 5(c,f) show the system stability of both DL and UL consequently over 30 minutes period. The variations of the EVM percentage of 16-QAM modulation, shown according to the order from top to bottom, are 0.7%, 0.5%, 0.55%, 0.7%, 0.7%, and 0.6%, respectively.

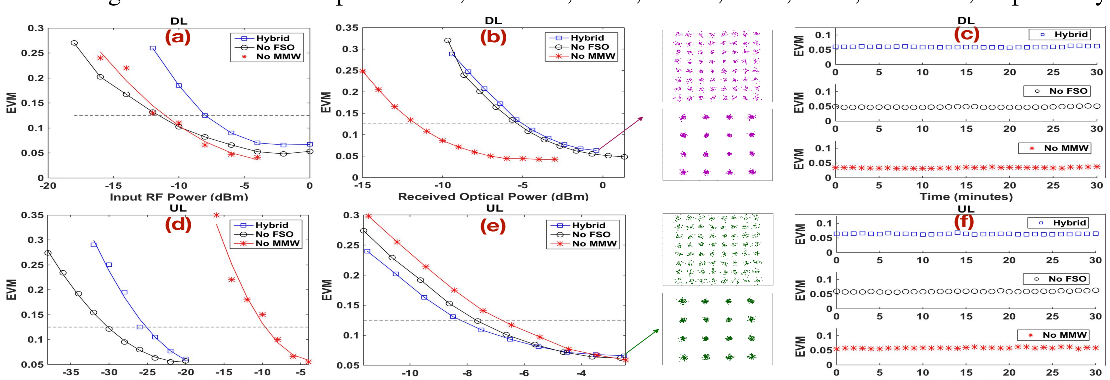


Fig. 5: Results for the bi-directional hybrid MMW and FSO links experiment

## 4. Conclusion

Real-time implementation of heterogeneous transmission technologies is an essential step towards 5G realization. We have developed the required DSP algorithms for function integration in 5G hybrid wireless-optical networks. We have experimentally demonstrated a real-time bi-directional testbed by integrating MMW and FSO technologies for mobile fronthaul. Two 5G-inspired experiments are conducted using over 25 km long fiber to verify the required functionality and stability of system operation. Our results show a long-term transmission stability of the hybrid MMW-FSO links with EVM variation of $<0.7\%$ for 16-QAM modulation.

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