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# Coexistence and Transmission of Multiple Radios over Seamless Fiber-Wireless Systems

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## ABSTRACT

In this paper, we present efficient solutions for simultaneous transmission of multiple radio signals over seamless fiber–wireless systems, including radio signals in legacy microwave bands and in high frequency bands. At central stations, radio signals can be mapped onto the same optical transport channel using data mapping algorithms and/or subcarrier multiplexing technique. After the fiber transmission, the received signals can be down-converted, digitized, and de-mapped to recover the originally transmitted signals. We present and compare two different methods, including a radio-over-fiber system and optical up-conversion at remote sites and an intermediate-frequency-over-fiber system and an electrical up-conversion at remote sites. We experimentally confirm the suitability of both the transmission methods, and achieve satisfactory performance for all signals, including LTE-advanced, orthogonal frequency-division multiplexing, and filtered-orthogonal frequency-division multiplexing signals. In particular, the latter method can provide a high optical spectral efficiency and low fiber dispersion effect and is suitable for ultra-dense small cell deployment in future mobile networks.

**Keywords:** Fiber–wireless convergence, mobile fronthaul, radio-over-fiber, small cell networks.

## 1. INTRODUCTION

The transmission of millimeter-wave (MMW) signals over fiber systems has attracted much interest for applications to future mobile networks such as 5G and beyond. There are many use cases in which MMW signals are transmitted over fiber systems. In the first case, mobile signals in the MMW band in future networks are transmitted from central stations (CSs) to remote cells via fiber links. In the second case, MMW communications together with fiber links can serve as attractive solutions for resilient, flexible, and low-cost mobile fronthaul systems to connect baseband unit pools in CSs with remote antennas. In the third case, fiber–wireless systems can be used to distribute high-speed services to densely located user areas, such as in buildings or moving objects, where the use of fiber cables is not possible or too expensive. In these cases, promising options are a dual-hop network comprising a high-capacity fiber–MMW system for signal transmission to buildings/trains and a high-speed indoor/train wireless network in high-frequency regions for signal distribution to end users [1]. On the other hand, the coexistence of multiple radios, including multiple radio access technologies (RATs), services, operators, and signal components are considered an important solution for high-speed and heterogeneous communications and management in 5G and beyond networks. A new RAT in the MMW band can provide high throughput services to users. Legacy services such as 4G LTE-A or Wi-Fi signals can provide communications to other users and/or to distribute control data. Very low latency communications using single carrier signals can also be deployed to support delay sensitive applications such as vehicle-to-vehicle communications. Simultaneous transmission of multiple radios over the same fronthaul system is thus of particular importance to reduce the cost, power consumption, network complexity, and to support the fast deployment of new services.

Seamless fiber–wireless systems using photonic technologies for generating, transmitting, and up-converting to MMW signals are very attractive for the above-mentioned applications. There are different methods for realizing seamless fiber–wireless systems in the MMW band. The first method is to generate and transmit

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MMW radio-over-fiber (RoF) signals from a CS to remote antenna units (RAUs) over fiber links, and direct up-converting to MMW signals using a photomixing technique at RAUs [2-5]. This method helps to reduce the system complexity, especially the remote sites. However, the optical spectral efficiency is low because of the transmission of MMW signals over fiber links. With the rapid increase in the number of small cells in future mobile networks, it is expected that the cost of mobile transport systems that utilize this method will drastically increase. Another approach is to use an optical heterodyning method for the MMW signal generation at RAUs [6, 7]. In this method, mobile signals are transmitted from a CS to RAUs by an optical carrier signal, and at the RAUs, the modulated optical signal is combined with a reference optical signal for up-conversion to an MMW signal. This method helps to improve the optical spectral efficiency. However, the inclusion of a laser source at each RAU will significantly increase the cost, power consumption, and complexity required to manage such a system. The uncorrelated frequencies and phases of optical signals from different lasers also reduce the quality of the generated MMW signals, which subsequently degrades the performance of seamless fiber–wireless systems.

The intermediate-frequency-over-fiber (IFoF) system is an efficient method for the transmission of MMW signals from a CS to remote antennas [8]. In this method, signals at intermediate frequency (IF) are transmitted from CSs to RAUs via fiber links. At the RAUs, after being recovered from the received optical signals, the transmitted signals are up-converted to a desired frequency in the MMW band using an electrical up-conversion process. However, the inclusion of an electrical local oscillator (LO) signal source at each remote site will increase the system cost and complexity. The remote delivery of LO signals from CSs to RAUs via fiber links was previously proposed to reduce the system cost and complexity of the IFoF systems [9, 10]. However, in these works, only the performance over fiber links was investigated. In addition, only low-modulation-format signals were transmitted over fiber systems, and the frequency of the transmitted MMW signals was relatively low. For application to future mobile networks, there is a need for a more comprehensive performance investigation of high-modulation-format and high-frequency-MMW signal transmission over seamless fiber–MMW systems.

In this paper, we present and review our proposed methods for simultaneous transmission of multiple radio signals over seamless fiber–wireless systems. At CSs, a data-mapping algorithm and/or subcarrier multiplexing technique can map different radio signals, such as signal components in one RAT or signals from different RATs, onto the same optical transport channel. At remote sites, the signals can be received, down-converted, digitized, and de-mapped to recover the transmitted radio signals. We present and compare the performance of two different transmission methods, including an RoF transmission with an optical up-conversion at remote sites, and an IFoF system and electrical up-conversion at the remote cells for the simultaneous transmission different radio signals at different frequency bands.

## 2. FIBER-WIRELESS SYSTEMS FOR MOBILE FRONTHAUL

There are two major systems for the transmission of MMW signals from a CS to RAUs over fiber links, including RoF systems and IFoF systems, as shown in Figs. 1(a) and (b), respectively. In RoF systems, radio waveforms in the MMW band are transmitted over fiber links, and radio waves for wireless transmission are generated directly by high-speed photodetectors (PDs) [11]. On the contrary, waveforms of microwave IF signals are transmitted over fibers in IFoF systems, while radio waves for wireless transmission are generated by a frequency up-convertor at the RAUs. RoF systems can provide a compact and low cost RAU. However, the optical spectral efficiency is low because each RAU occupies an optical bandwidth corresponding to the frequency of the MMW signal. The low optical spectral efficiency will ultimately limit the number of MMW signals to be transmitted simultaneously over a single fiber link from a CS to RAUs. Consequently, additional fiber-transport systems will be needed to serve dense-small-cell areas. This will increase the system cost, power consumption, and complexity. For the systems to moving objects, the decrease in the number of RAUs that can be connected and controlled by a CS via the same fiber ring will lead to an increase in the handover frequency, which in turn increases the communication interruptions [1]. Using IFoF systems with the remote delivery of LO signals, the optical spectral efficiency can be dramatically improved because IF signals are transmitted over fiber links. Although RAUs are relatively more complicated, optical components in low-frequency regions can be used, thus helping to reduce the system cost. Furthermore, the same optical LO signal can be distributed to many RAUs for signal up-conversion.

Nevertheless, the generation of a high-quality optical MMW signal is of paramount importance to maintain satisfactory performance for both RoF and IFoF systems. The generated MMW signal at RAUs should have

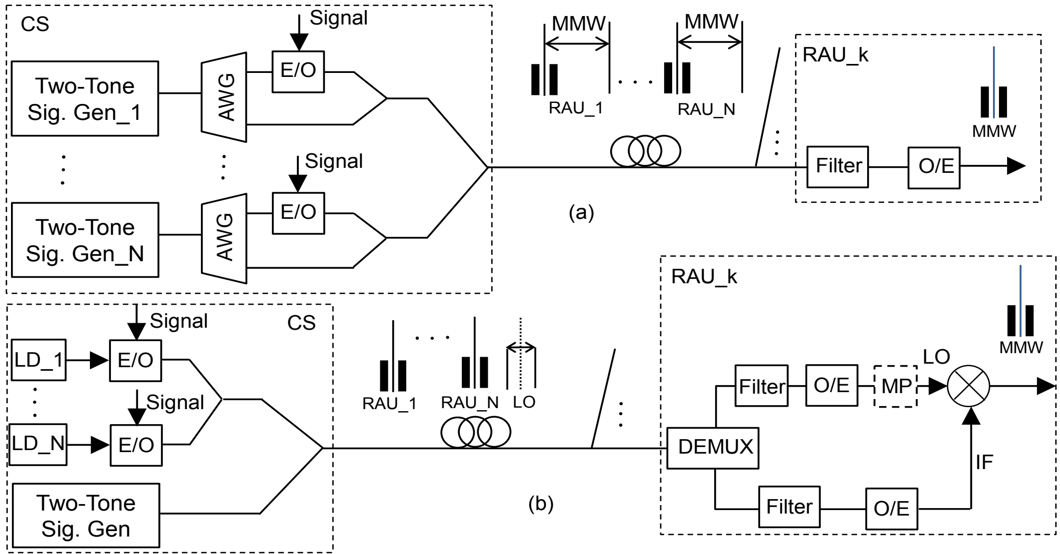


Figure 1. a) Radio millimeter-wave over fiber system. (b) Intermediate frequency over fiber with remote LO signal.

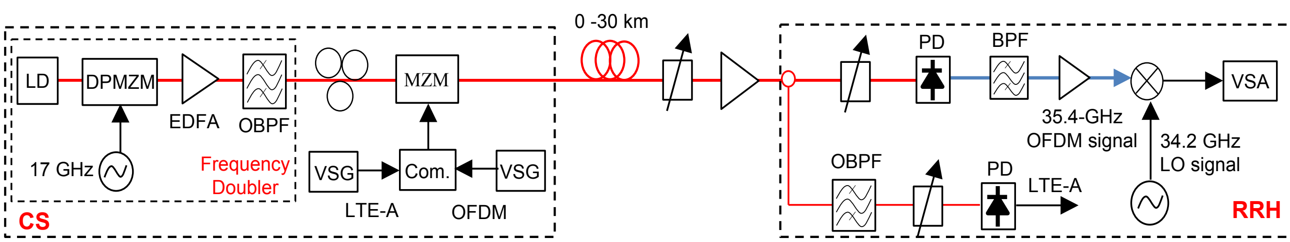


Figure 2. Experimental setup for simulatnoues transmission of LTE-A and OFDM signals over the RoF system and optical up-conversion at remote site.

high frequency stability, low phase noise, and a high signal-to-noise ratio. As is well known, heterodyning two independent lasers is a simple method for generating MMW signals. However, the frequency fluctuation and phase noise of the generated MMW signals are relatively high. A coherent two-tone optical signal generation using a high-precision optical-modulation technology [2] is more promising. However, it is relatively difficult and costly to generate many RoF signals in the MMW band for transmission to many RAUs using RoF systems. In IFoF systems, because the LO signals can be shared by many RAUs, the number of MMW signals that needs to be generated and transmitted over fiber links can be reduced. Furthermore, because the frequency of the generated LO signal can be electrically up-converted to a desired value, a low-frequency LO signal can be generated and transmitted over fiber links from a CS to RAUs. This helps to further improve the optical spectral efficiency and system cost because low-speed optical components can be used.

## 3. ROF SYSTEM AND OPTICAL UP-CONVERSION

### 3.1 Transmission of RAT signal in 40-GHz band

The use RATs in low MMW bands, such as those below 40 GHz, is considered very attractive to increase access capacity in 5G mobile networks [12]. This subsection presents a simple system for simultaneous transmission of legacy RATs in conventional microwave (MW) bands, such as LTE-A, and new RATs in low MMW regions.

#### 3.1.1 Experimental setup

The experimental setup for simultaneous transmission of an LTE-A signal at 2.6 GHz and an OFDM signal at 35.4 GHz using the RoF system and optical up-conversion at the remote site is shown in Fig. 2 [13]. We first

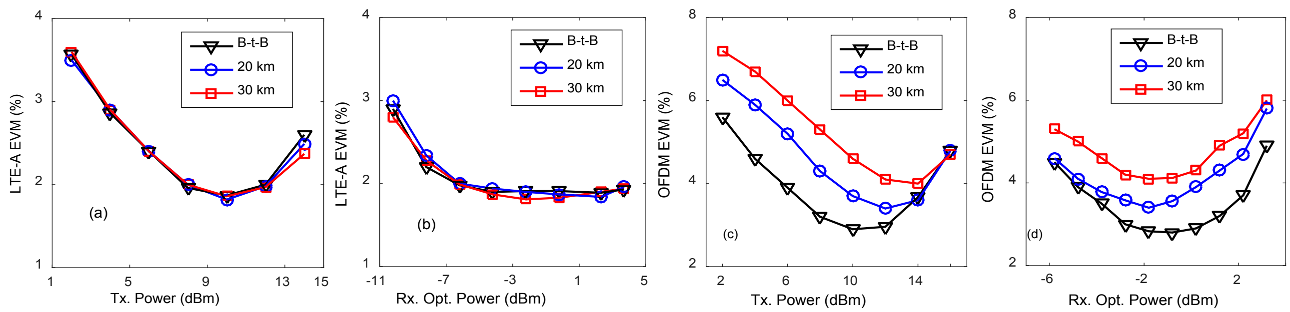


Figure 3. Experimental results for: (a) LTE-A signal for different transmit powers; (b) LTE-A signal for different received optical powers; (c) OFDM signal for different transmit powers; (d) OFDM signal for different received optical powers.

generate a coherent two-tone optical signal with a 34-GHz frequency difference between the two optical signals using an optical frequency doubler [13]. In principle, one of the two optical signals should be used for data modulation of the combined LTE-A and IF OFDM signals, the other signal works as a reference signal for signal up-conversion at the remote site. However, because the frequency difference between the two optical signals is small, in this experiment, we modulate both the optical signals by the combined radio signals. The modulated optical signal is transmitted over different fiber links to the remote site. A variable optical attenuator (ATT) and an optical amplifier (EDFA) are used to adjust the received optical power and compensate for losses. At the remote site, the received optical signals are separated by a 3-dB coupler. At one branch, one of the optical sideband signals is extracted by a narrow optical filter to recover the transmitted LTE-A signal. The optical signals in the other branch are inputted to a PD to convert to an electrical signal. An electrical band pass filter (BPF) is used to select the signal component at 35.4 GHz. The filtered signal is amplified by a low noise amplifier (LNA) to reach a sufficiently high level. In practical systems, this signal can be fed to an antenna at the remote radio head (RRH) to transmit to end users via a radio access network. In this experiment, to focus the evaluation on the optical fronthaul transmission, we transmit the signal over an RF cable before being down-converted to 1.2 GHz using an electrical mixer and an LO signal. The received LTE-A and the down-converted OFDM signals are sent to vector signal analyzers (VSAs) and finally demodulated by VSA software.

We should note that because the density and coverage of small cells of RATs in the conventional MW bands and of new RATs in the MMW bands are not same, the detection of the LTE-A and MMW OFDM RATs in Fig. 2 is not necessarily at the same location. This means that after optical separation at the receiver site, one of the optical signals can be further transmitted via another short optical fiber link to small cells in practical systems.

### 3.1.2 Experimental results

We investigate the performance of the LTE-A and OFDM signals after transmission over the system using error vector magnitude (EVM) parameter. The LTE-A signal is a standard-compliant signal consisting of 4 carrier components (CCs) with a total bandwidth of 40 MHz. OFDM signal has a bandwidth of 50 MHz and 64 subcarriers. Figures 3(a) and (b) show the performance of the 256-QAM LTE-A signal after transmission over the system. Because we transmit the LTE-A signal in a low frequency over a fiber link, the performance of the LTE-A signal is very satisfactory. The simultaneous transmission with the OFDM signal has a small impact on the LTE-A signal performance. Figures 3(c) and (d) show the performance of the 256-QAM OFDM signal for different transmit powers and received optical powers, respectively. Similar to the LTE-A signal, satisfactory transmission is confirmed for the OFDM signal. However, the performance is relatively degraded when increasing the fiber lengths because of fiber dispersion effects. This is because both optical sidebands of the generated optical two-tone signal are used for the data modulation. This effect would be more severe if a wide-bandwidth signal is transmitted over the system. To reduce the dispersion effect and improve the signal performance, we can use only one of the optical sidebands for the data modulation. However, because the frequency difference between the two optical sidebands is relatively small, it is not easy to separate the two optical sidebands by an optical de-multiplexer. Optical narrow filters can be used for the signal separation. However, the differential delay and

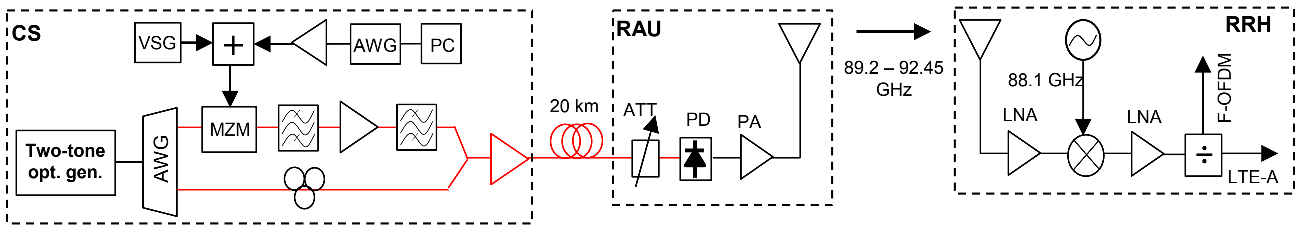


Figure 4. Experimental setup for simultaneous transmission of LTE-A and F-OFDM signals over fiber–wireless system [15].

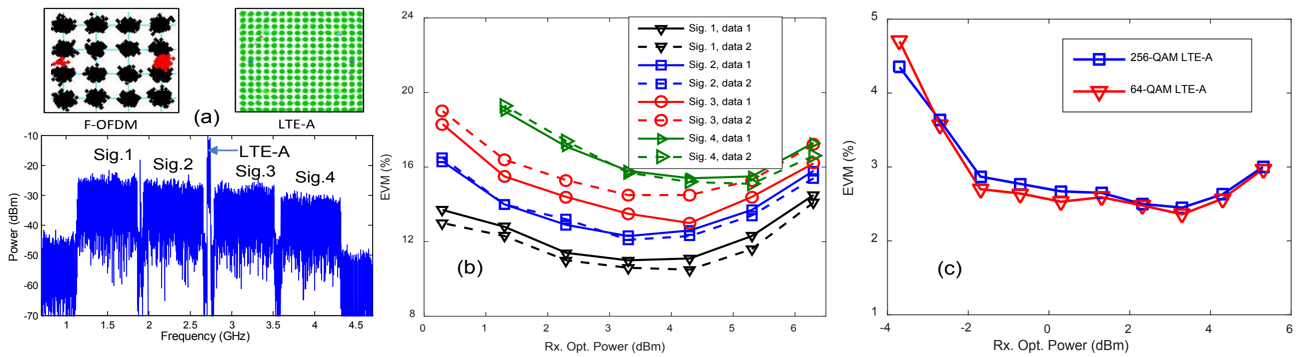


Figure 5. Experimental results: (a) received spectrum and constellations of 16-QAM F-OFDM and 256-QAM LTE-A signals; (b) performance of F-OFDM signal for different received optical powers; (c) performance of LTE-A signal for different received optical powers.

the phase difference between the two separated optical signals will cause phase error in the generated radio signal. Consequently, the performance and stability of the transmitted wireless signals will be degraded, especially when the fiber transmission range is long [14].

### 3.2 Transmission of RAT/MFH signal in 90-GHz band

The use of new RATs in high MMW region, such as above 90-GHz bands, would be important for 5G phase 2 or beyond 5G networks to meet high capacity communications in hot spot areas. In addition, the use of MMW mobile fronthaul (MFH) links is very attractive when the use of fiber cable is not available. The simultaneous transmission of RATs in conventional MW bands and new RATs or MFH links in the high MMW bands is thus important and should be considered. In this subsection, we present a simple solution for the simultaneous transmission using an RoF system and optical up-conversion at remote sites. For the RAT/MFH links in the MMW bands, we use filtered-OFDM (F-OFDM) signal for high-spectral efficiency transmission of multi-band/carrier aggregation (CA) signals.

#### 3.2.1 Experimental setup

The experimental setup for simultaneous transmission of LTE-A and F-OFDM signals over a seamless fiber–wireless system is shown in Fig. 4 [15]. To prove the concept, we transmit an LTE-A signal consisting of two 20-MHz CCs and an F-OFDM signal consisting of four CCs with a total bandwidth of 3.2 GHz over a seamless 20-km fiber and 1-m 90-GHz wireless link. The LTE-A signal is a standard-compliant signal and generated by a signal studio in a personal computer and downloaded to a vector signal generator (VSG). The four 800-MHz F-OFDM signals are generated offline by Matlab and downloaded to an arbitrary waveform generator (AWG). These four signals can represent different CCs or different MIMO signal components in new RATs or MFH links. The LTE-A and F-OFDM signals are combined by a power combiner before modulating an optical signal. The F-OFDM signals can be flexibly arranged so the LTE-A signals can be inserted at an appropriate position.

For seamless up-conversion of received optical signals to a radio signal at the remote site, a two-tone optical signal is generated at the CS. The block diagram of this two-tone optical signal generator is similar to the optical frequency doubler in Fig. 2. However, the bias point of the main MZM in this generator is shifted from a minimum to a maximum bias point to generate even sidebands. As a result, the signal generator works as an optical frequency quadrupler. To reduce the fiber dispersion effect, only one of the optical signals is used for the data modulation of the combined LTE-A and F-OFDM signals. The other optical sideband is used as a reference signal for up-conversion of the optical signals to an MMW signal at the remote site. The combined LTE-A and F-OFDM signals are converted to an optical signal by an MZM, which is biased at a null point to generate a double-sideband signal with a carrier suppression. One of the sidebands is cancelled by an optical filter. The modulated and reference optical signals are then combined by a 3-dB optical coupler, amplified, and transmitted via a 20-km fiber cable to the remote site. The received optical signal is inputted to a high-speed PD for direct up-conversion to an MMW signal (from 89.2 to 92.45 GHz). The signal is amplified before being emitted into free space by a 23-dBi horn antenna. After transmission over the free space, the signal is received by another antenna, amplified, and down-converted to an IF band. The down-converted signals are amplified and separated to recover the LTE-A and F-OFDM signals. The LTE-A signals are sent to a VSA and demodulated by a VSA software. The F-OFDM signals are sent to an oscilloscope and finally demodulated offline by Matlab.

In practical systems, the LTE-A signal can be detected and extracted at the RAU without being transmitted over the MMW link. In this case, a 3-dB optical coupler can be used to divide the received optical signal. One of divided optical signals can be used to recover the LTE-A signal using an optical filter and a PD. The other signal can be inputted to a high-speed PD to generate MMW RAT/MFH signal as in this experiment. In our experiment, however, we consider a more general case in which the LTE-A signal is also transmitted over the MMW link.

### 3.2.2 Experimental results

In our experiment, we use F-OFDM method for aggregating different signal components because it presents a better out-of-band leakage interference and higher spectral efficiency [16]. This is very important when we need to aggregate a large number of signals to an optical channel, such as for massive MIMO signal components and/or RATs. The F-OFDM method also provides a flexible mapping solution owing to its capability of supporting asynchronous transmission. The F-OFDM components can be flexibly arranged to insert the LTE-A signals at an appropriate position so we do not need to convert the carrier frequency of the LTE-A signal at the receiver site. In this experiment, the F-OFDM signals are generated offline in Matlab and each of the F-OFDM signals comprises 256 subcarriers of which 170 subcarriers at the centre are used for data 1 modulation, 60 subcarriers at the edge are for data 2 modulation, 8 subcarriers are for pilots, and 17 subcarriers at borders are null. The signals are placed next to each other without any additional guard bands. An empty space of 50 MHz is inserted between signal 1 and 2 to insert LTE-A signals.

Examples of received spectrum with the inserted LTE-A signals and constellation maps of a 16-QAM F-OFDM signal (data 1) and a 256-QAM LTE-A signal are shown in Fig. 5(a). Clear separation between signals and clearly separated clusters could be received. Figure 5(b) shows EVM performance of the F-OFDM signals for different received optical powers. Satisfactory performance could be confirmed for 16-QAM signals. The performance of signals at high-frequency region is relatively degraded because of the non-flat frequency response of the system. We also observe that increasing transmit powers of the LTE-A signals has a quite small impact on the performance of the F-OFDM signals. The performance of edge subcarriers (data 2) is quite similar to those in the centre (data 1), except F-OFDM signal 3, which is closest to the LTE-A signals. Figure 5(c) shows the performance of the LTE-A signal for different received optical powers. All the signals are successfully transmitted and received with EVM values much better than the requirements dictated in the standard, i.e., 8 percent for 64-QAM and 3.5 percent for 256-QAM signals.

## 4. IFOF SYSTEM AND ELECTRICAL UP-CONVERSION

RoF systems and optical up-conversion technology are attractive solutions for transmission of mobile RAT/MFH signals in the MMW bands. It is also attractive for simultaneous transmission of RATs in the conventional MW bands and RAT/MFH in the MMW regions. However, there are several issues that should be considered. First,

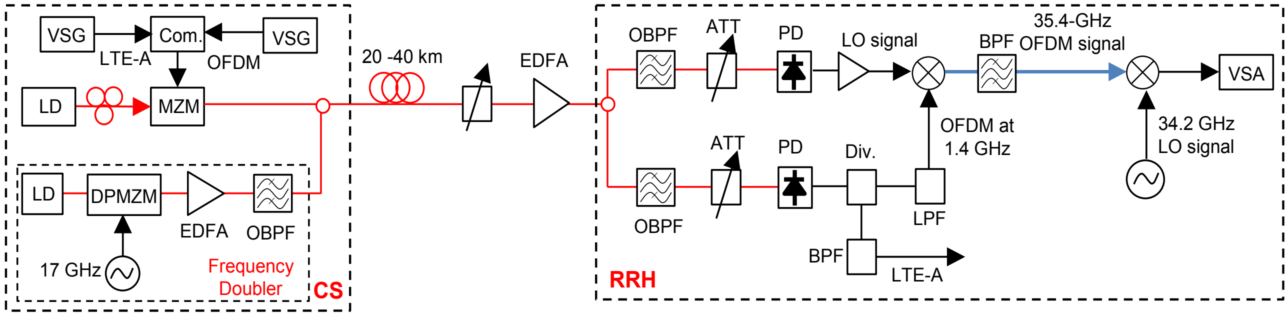


Figure 6. Experimental setup for simultaneous transmission of LTE-A and MMW OFDM signals over the IFoF system using remote delivery of LO signal [13].

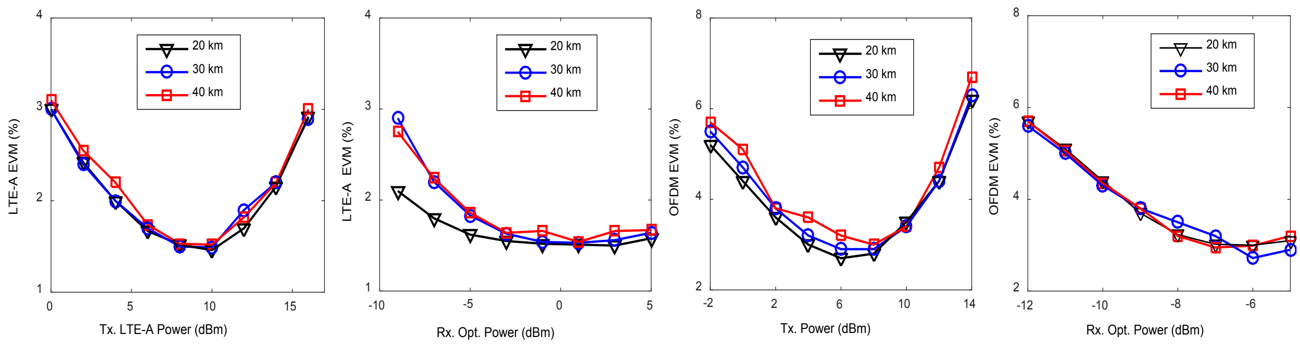


Figure 7. Experimental results for 256-QAM OFDM signal: (a) for different transmit powers; (b) for different received optical powers; (c) for different transmit LTE-A powers; (d) for different received optical LO powers. Fig. 4. Experimental results of 256-QAM LTE-A signal: (a) for different transmit powers; (b) for different received optical powers; (c) for different transmit OFDM signal powers.

the performance is relatively degraded because of fiber dispersion effects and/or phase error induced from delay differential, especially for radio signals in low MMW bands. Second, the optical spectral efficiency is quite low and expensive optical components are needed, especially for transmission of RAT/MFH signals in high MMW bands. In this section, we present a different approach for more efficient transmission using an IFoF system and electrical up-conversion at the remote sites.

## 4.1 Transmission of RAT signal in 40-GHz band

### 4.1.1 Experimental setup

The setup for simultaneous transmission of an LTE-A signal at 2.6 GHz and an OFDM signal at 35.4 GHz over a fiber link is shown in Fig. 6 [13]. In our system, instead of transmitting directly the OFDM signal in the MMW band over the fiber link, we transmit a much lower-frequency signal at an IF band to the RRH, and subsequently up-convert the signal to the desired MMW band using an electrical up-conversion. To reduce the system cost and complexity of the remote sites, we also transmit an LO signal from the CS to the RRH for the signal up-conversion. At the CS, an LTE-A signal at 2.6 GHz and a wideband OFDM signal at 1.4 GHz are generated and combined before modulating an optical signal from a laser diode (LD). We also generate a two-tone optical signal by an optical frequency doubler which is similar to the one in Fig. 2. The modulated optical signal and the two-tone optical signal are then combined by a 3-dB optical coupler. The combined signals are amplified and transmitted to the RRH via single-mode fiber links. An ATT is used to adjust the received optical powers and the received optical signal is amplified by an EDFA to compensate for the transmission and division losses.

The received optical signals are separated by a 3-dB optical coupler to recover the transmitted modulated and two-tone optical signals using optical band-pass filters (OBPFs). After being converted to the electrical signal

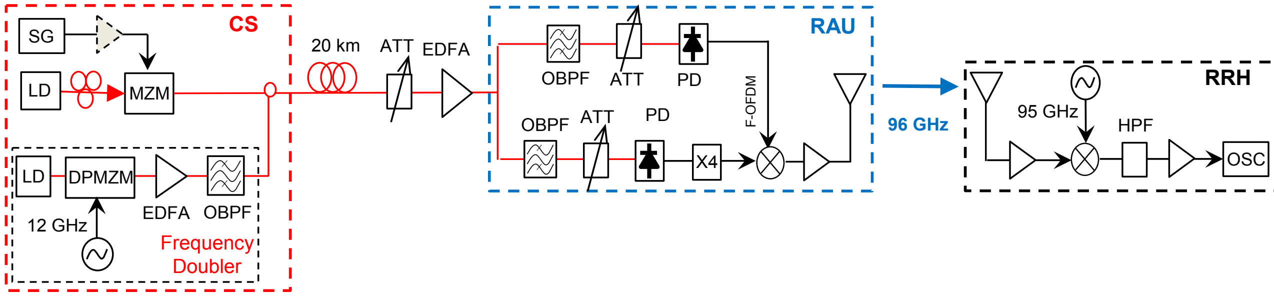


Figure 8. Experimental setup for transmission of LTE-A signals over a fiberwireless system.

by a PD, the electrical signals in the modulated optical branch are divided and electrically filtered to recover the transmitted LTE-A and the OFDM signals. For the LO signal, in this measurement, a 17-GHz synthesized electrical signal is transmitted from the CS to the RRH. At the RRH, because of the beating note between the two first-order sidebands of the two-tone optical signal at the PD, a 34-GHz LO signal is generated. This signal is electrically amplified to a sufficiently high level before being mixed with the recovered IF OFDM signal for up-conversion to the MMW band. Finally, the mobile signal at 35.4 GHz is selected using an electrical bandpass filter. Similar to the system in Fig. 2, the up-converted signal in this system can be fed to an antenna at the RRH to transmit to end users via a radio access network. However, in this experiment, we transmit the signal over an RF cable before down-converting to the IF band at 1.2 GHz using an electrical mixer to focus our transmission on the optical fronthaul system. The recovered LTE-A and OFDM signals are then inputted to VSAs and finally demodulated by a VSA software.

### 4.1.2 Experimental results

In this experiment, we transmit the same signals with those in the optical up-conversion method (Fig. 2) over the system. A standard-compliant LTE-A signal at 2.6 GHz with four CCs and a 50-MHz bandwidth OFDM signal at 1.4 GHz are combined before modulating an optical signal. Figures 7(a) and (b) show the performance of the 256-QAM LTE-A signal for different transmit powers and different received optical powers, respectively. The transmission can easily satisfy the requirement with a sufficiently large power range. Figures 7(c) and (d) show the performance of the 256-QAM OFDM signal after transmission over the IFoF system, up-conversion to 35.4 GHz, and down-conversion to 1.2 GHz. All the signal transmission is successful with satisfactory EVM performance. Compared to the optical up-conversion method, the effect of fiber dispersion in this system is relatively small. This is because the signal is transmitted over the fiber link in the low frequency band and only an optical signal is modulated by the combined radio signals. This advantage is very important, especially when a wide-bandwidth signal is transmitted over the fiber link.

## 4.2 Transmission of RAT signals in 90-GHz band

### 4.2.1 Experimental setup

Similar to the optical up-conversion method, we investigate the simultaneous transmission of a RAT signal in the MW band and another RAT/MFH signal in the 90-GHz band. The experimental setup for the transmission over a seamless fiber–wireless system at 96 GHz is shown in Fig. 8. This demonstration is to emulate the transmission of very-high-frequency-MMW signals over fiber links, which can be used for optical fronthaul systems for mobile MMW signals or seamless fiber–MMW fronthaul systems for mobile signals in the microwave bands. In our system, instead of transmitting the MMW signal directly from the CS to RAUs, mobile signals at IF bands are transmitted to RAUs, and are subsequently up-converted to the MMW band using an electrical up-conversion with an LO signal delivered remotely from the CS. To prove the concept, we transmit a multiband CA F-OFDM signal followed up by a multiband CA LTE-A signal over the system. For the LTE-A signal, a multiband signal with ten CCs and a total bandwidth of 100 MHz is generated by two VSGs. All of the signals are standard compliant, and are generated offline using a commercially available signal studio for LTE-A signals. For the F-OFDM signals, a four-CC signal with a total bandwidth of 1.6 GHz is generated offline in Matlab, downloaded

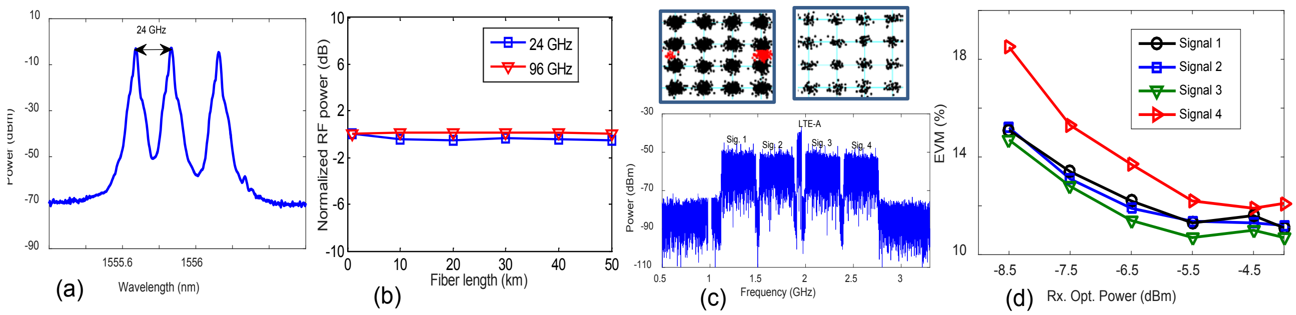


Figure 9. (a) Optical amplifiers' transient characteristics; (b) Performance for different received optical powers; (c) Performance for different transmit LTE-A signal powers.

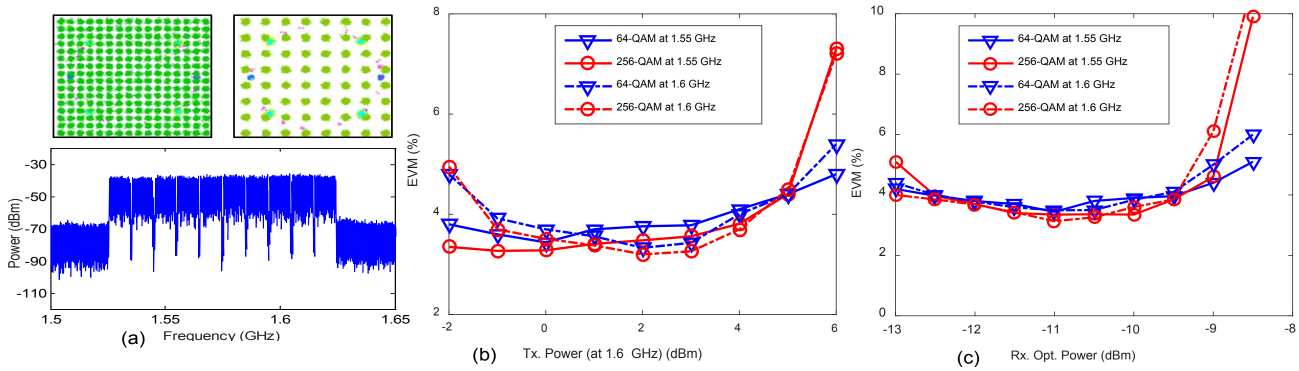


Figure 10. Performance of CA LTE-A signal transmission: (a) spectrum and constellations, (b) for different transmit powers, and (c) for different received optical powers.

to an AWG, and transmitted over the system. These signals can be combined with other RAT signals in the MW band before modulating optical signal, similar to the previous experiments.

The generated signals modulate a lightwave signal from a LD at an MZM. The modulated signal is combined with an optical LO signal generated from a two-tone optical signal generator. For up-conversion the signal to 90-GHz band at the remote site, we can generate an optical LO signal with a frequency difference equal to the frequency of the required electrical LO signal (at 90-GHz band in this experiment) using an optical frequency quadrupler, similar to the one in Fig. 4. However, an LO signal with a much lower frequency difference can also be generated from the CS, transmitted to the remote site, and subsequently up-converted to the desired frequency using a frequency multiplier [17]. This can help to increase the optical spectral efficiency and allow to use low-speed optical components to reduce the system cost. In our experiment, we use an optical frequency doubler which is similar to those in previous experiments to generate the two phase- and frequency-stabilized optical signals with a frequency difference of 24 GHz by feeding a 12-GHz synthesizing signal to the two-tone optical signal generator. The modulated and the generated two-tone optical signals are combined and transmitted to an optical receiver via a 20-km fiber link. The received optical signal is amplified by an EDFA and separated by a 3-dB optical coupler. The signals are then filtered to recover the transmitted modulated and LO optical signals. After being converted to electrical formats by the PDs, the 24-GHz signal is up-converted to 96-GHz LO signal using an electrical frequency quadrupler, and mixed with recovered IF signals to form a radio-on-radio signal at 96 GHz. The signal is amplified by a power amplifier (PA) before being emitted into free space using a 23-dBi horn antenna. After transmission over a 2.5-m free-space link, the signal is received by another horn antenna at an RRH, amplified by an LNA, and down-converted to an IF band for analysis. The signals are then amplified by another LNA before being separated by a power divider and sent to VSAs.

### 4.2.2 Experimental results

Figure 9(a) shows the received optical spectrum which consists of an optical LO signal with a frequency difference of 24 GHz and a modulated optical signal. Figure 9(b) shows the normalized power fluctuations of the detected 24-GHz and 96-GHz LO signal after transmission over different fiber links. We can achieve a stable LO signal and the effect of fiber dispersion on the transmission of the LO signal is small. The high stability and low phase noise of the generated LO signals in this method are of particular importance to have a high signal transmission performance. We then measure the performance of the F-OFDM signals. In our experiment, we generate four sub-band signals and transmit them over the fiber-wireless system. These four signals can be independent and have different parameters and formats. However, for the sake of simplicity, in the experiment we generate the four signals with the same parameters, including 256 subcarriers of which 170 subcarriers at the centre are used for data 1, 60 subcarriers at the edge are for data 2, 8 subcarriers are for pilots, and 17 subcarriers at borders are null. The four signals are placed next to each other. An empty space of 60 MHz is inserted between signal 2 and 3 to insert the LTE-A signal. Figure 9(c) shows the received electrical spectrum and constellations of data 1 and data 2 of one sub-band signal. Figure 9(d) shows the EVM performance for different received optical powers. Satisfactory performance could be confirmed for 16-QAM signals. The performance of signal 4 is relatively degraded, especially when reducing the received optical powers, because of non-flat frequency response of the system.

We then transmit a 10-CC LTE-A signal over the system and the performance is shown in Fig. 10. In this experiment, the 10-CC LTE-A signal is generated by combining two 5-CC LTE-A signals from two different VSGs. The total bandwidth of the generated signals is limited to 100 MHz because of the limited internal bandwidth of the VSGs being used. Figure 10(a) shows the spectrum and constellations of received signals after being transmitted over the converged fiber and 96-GHz wireless system. Clear spectra and constellations can be observed for both 64-QAM and 256-QAM signals. Figures 10(b) and (c) show the measured EVM results for 64-QAM and 256-QAM signals for different LTE-A signal transmit powers and different received optical powers, respectively. All of the transmitted signals are successfully received and demodulated with satisfactory performance. The EVM values are better than the requirements dictated in standards, even for a high-modulation level of 256 QAM. This confirms the potential of our proposed system for the transmission of future mobile signals.

The system is applicable for transmission to multiple antenna sites [18]. In such applications, an optical LO signal can be shared by several remote antennas, helping to increase the optical spectral efficiency and the cost efficiency of the system. The system is also scalable to the increase of remote cell numbers. The transmission to a new remote cell can be easily added using a new wavelength for data modulation and another one for an optical LO signal delivery. The high spectral efficiency of the system makes it particularly suitable for ultra-dense small cell deployment, such as in the ultra-dense urban areas.

## 5. CONCLUSION

In this paper, we review our proposed systems for simultaneous transmission of legacy RAT signals in the conventional microwave bands and RAT/MFH signals in high frequency bands over fiber links. The radio-over-fiber system using an optical up-conversion at remote sites can help to simplify the remote antenna sites. The intermediate-frequency-over-fiber with an electrical up-conversion at the remote sites can help to increase the signal performance and optical spectral efficiency. We experimentally confirm the successful transmission of LTE-A and OFDM/F-OFDM signals over the systems. Satisfactory performance after transmission over the system without the need for any compensation techniques is successfully achieved. The system is scalable to the remote cell numbers. The scalability of the proposed system allows it to meet future deployment demands in terms of capacity, multiple radios, and the number of wireless services. The proposed systems present promising solutions for future mobile networks such as 5G because of their low cost, simplicity, and high spectral efficiency. In addition, digital signal processing-assisted algorithms for waveform mapping and impairment compensation can be exploited to further enhance the performance and capability of the system.

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## REFERENCES

[1] P. T. Dat et al., WDM RoF-MMW and linearly located distributed antenna system for future high-speed railway communications, *IEEE Communication Magazine*, 53 (10), 86-94 (2015).

[2] A. Kanno et al., Coherent Radio-Over-Fiber and Millimeter-Wave Radio Seamless Transmission System for Resilient Access Networks, *IEEE Photonics Journal*, Vol. 4, No. 6, pp. 2196-2204 (2012).

[3] L. Cheng et al., Coordinated multipoint transmissions in millimeter-wave Radio-over-Fiber systems, *J. Lightwave Technol.*, Vol. 34, N0. 2, pp. 653-660, (2016).

[4] D. Zibar, et al., High-capacity wireless signal generation and demodulation in 75-to 110-GHz band employing all-optical OFDM, *IEEE Photon. Technol. Lett.*, 23, 810 (2011).

[5] C.-T. Lin et al., Optical direct-detection OFDM signal generation for radio-over-fiber link using frequency doubling scheme with carrier suppression, *OPTICS EXPRESS 6056*, Vol. 16, No. 9 (2008).

[6] F. Paresys et al., Bidirectional Millimeter-Wave Radio-Over-Fiber System Based on Photodiode Mixing and Optical Heterodyning, *J. OPT. COMMUN. NETW.*, Vol. 5, No. 1, pp. 74-80 (2013).

[7] C. Tang et al., A 30 Gb/s full-duplex bi-directional transmission optical wireless-over fiber integration system at W-band, *OPTICS EXPRESS*, Vol. 22, No. 1, 239 (2014).

[8] C. Lim et al., Fiber-Wirless Networks and Subsystem Technologies, *J. Lightwave Technol.*, Vol. 28, No. 4, Feb. 15 (2010).

[9] T. Ismail et al., Transmission of Gb/s DPSK Millimeter-Wave Wireless Data Over Fiber Using Low-Cost Uncooled Devices with Remote 40-GHz Local Oscillator Delivery, *J. Lightwave Technol.*, Vol. 26, No. 21, pp. 3490-3496 (2008).

[10] C. Lim et al., Millimeter-Wave Broad-Band Fiber-Wireless System Incorporating Baseband Data Transmission over Fiber and Remote LO Delivery, *J. Lightwave Technol.*, Vol. 18, No. 10, pp. 1355-1363 (2010).

[11] P. T. Dat et al., Full-Duplex Transmission of LTE-A Carrier Aggregation Signal Over a Bidirectional Seamless Fiber-Millimeter-Wave System, *J. Lightwave Technol.* 34 (2), 691-700 (2016).

[12] C. Dehos et al., Millimeter-wave Access and Backhauling: The Solution to The Exponential Data Traffic Increase in 5G Mobile Communications Systems?, *IEEE Communication Magazine,* Vol. 52, Iss. 9, pp. 88-95.

[13] P. T. Dat et al., Simultaneous Transmission of 4G LTE-A and Wideband MWW OFDM Signals over Fiber Links, *Proc. MWP*, 2016.

[14] P. T. Dat et al., High-Capacity Wireless Backhaul Network Using Seamless Convergence of Radio-over-Fiber and 90-GHz Millimeter-Wave, *J. Lightwave Technol.* 32 (20), 3910-23 (2014).

[15] P. T. Dat et al., 190-Gb/s CPRI-Equivalent Rate Fiber-Wireless Mobile Fronthaul for Simultaneous Transmission of LTE-A and F-OFDM Signals, *Proc ECOC*, pp. 926-928, 2016.

[16] N. T. Van et al., Transmission of multiband wireless signals over a seamless IM/DD fiber-MMW system, *IEICE Electronics Express*, Vol. 13, No. 15, pp1-8, 2016.

[17] P. T. Dat et al., High-spectral efficiency millimeter wave-over-fiber system for future mobile fronthaul, *Proc. ECOC*, 2015, P7.8.

[18] P. T. Dat et al., High-Capacity and High-Spectral-Efficiency Seamless Fiber-Wireless System for High-Speed Trains, *Proc. OFC*, 2016, Tu3B.6.