Fiber–wireless integrated mobile backhaul network based on a hybrid millimeter-wave and free-space-optics architecture with an adaptive diversity combining technique

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Received 10 February 2016; revised 15 March 2016; accepted 22 March 2016; posted 23 March 2016 (Doc. ID 259278); published 19 April 2016

We propose and experimentally demonstrate a novel fiber–wireless integrated mobile backhaul network based on a hybrid millimeter-wave (MMW) and free-space-optics (FSO) architecture using an adaptive combining technique. Both 60 GHz MMW and FSO links are demonstrated and fully integrated with optical fibers in a scalable and cost-effective backhaul system setup. Joint signal processing with an adaptive diversity combining technique (ADCT) is utilized at the receiver side based on a maximum ratio combining algorithm. Mobile backhaul transportation of 4-Gb/s 16 quadrature amplitude modulation frequency-division multiplexing (QAM-OFDM) data is experimentally demonstrated and tested under various weather conditions synthesized in the lab. Performance improvement in terms of reduced error vector magnitude (EVM) and enhanced link reliability are validated under fog, rain, and turbulence conditions. © 2016 Optical Society of America

OCIS codes: (060.2330) Fiber optics communications; (060.2605) Free-space optical communication; (060.5625) Radio frequency photonics.

http://dx.doi.org/10.1364/OL.41.001909

Fifth-generation wireless mobile networks promise to provide 1000 times more capacity and 25 times more average cell throughput with respect to the current long-term evolution systems [1–5]. Cellular densification with large numbers of small cells is considered as a key solution, which requires the mobile backhaul (MBH) to provide flexible, scalable, and reliable data transmission and connection between cellular base stations (BSs) and the core network [1–3]. Optical fibers, millimeter wave (MMW), and free-space optics (FSO) are considered the three most promising solutions [1–3]. Fiber-based MBH links, which are ideal media for data transmission due to their ultralow loss, are not always available or cost-effective when considering the deployment cost and installation challenges, especially in dense urban areas or emergency situations [1,2]. Wireless solutions based on MMW and FSO have attracted much research interest as an appealing alternative, due to their low cost, abundant bandwidth, flexibility, and rapid deployment. However, they are limited by short delivery distance due to high propagation loss, and impairments from specific weather conditions [1]. Therefore, the concept of a converged system including both fiber and wireless links has attracted a lot of research interests [1–7]. Fiber–wireless integrated systems are expected to provide a cost effective, scalable, and high capacity MBH for the future cloud radio-access-network (C-RAN) [3]. In [2–6], architecture concepts were presented, which involve the use of MMW and radio-over-fiber technologies for converged optical wireless access networks.

Owing to their drastically different channel response, FSO and MMW links exhibit complementary transmission characteristics under various atmospheric and weather conditions [1,8–10]. Therefore, the hybrid link with both FSO and MMW transmission will be a good solution for joint deployment. In previous work, several studies have been reported about the hybrid MMW/FSO link design, such as hardware/software switching schemes based on the availability of different channels [8] and joint bit-interleaved coding schemes between MMW and FSO based on instantaneous channel state information [9]. To avoid the complexity of feedback channels, the adaptive diversity combining technique (ADCT) was proposed [10], where numerical results show that hybrid MMW/FSO system with ADCT has superior performance compared to each individual system (FSO-only/MMW-only) in all weather conditions. However, there have been few reports to experimentally investigate hybrid MMW/FSO in a fiber-based MBH system, especially for the fiber–wireless integrated networks.

In this Letter, we propose and experimentally demonstrate a novel fiber–wireless integrated backhaul based on the hybrid MMW and FSO architecture with adaptive combining technique. The 60-GHz radio-frequency (RF) signal is produced by the photonic MMW generation method, and both MMW and FSO signals are modulated and fully integrated with optical fiber.
The improved error vector magnitude (EVM) performances and better reliability of 1-GHz frequency-division multiplexing (OFDM) 16 quadrature amplitude modulation (QAM) signals are verified under different weather conditions.

Figure 1 shows the proposed fiber–wireless integrated MBH network architecture based on the hybrid MMW and FSO links. In this network, both MMW and FSO links are integrated with a fiber-based system. From the service gateway and mobility management entity (S-GW/MME) of the core network to the BSs, fiber is mainly used for long-distance backhaul links for the main BSs. At the remote end with dense small cell sites, hybrid MMW and FSO links are used for more flexible and scalable deployment of remote BSs. In the proposed hybrid architecture, the MMW is generated by the photonic method for seamless integration with fiber, and the FSO beam is also collimated from the fiber. Since the FSO and fiber links work at the same wavelength, they are completely compatible. Finally, due to the complementary characteristics to atmospheric and weather, the hybrid MMW and FSO links are used to ensure reliability. In our proposed system, the MMW and FSO links transmit the same data, and we utilize a joint signal processing scheme with the adaptive combining based on the MRC algorithm to improve the signal reliability under different weather conditions.

The principle of adaptive diversity combining for the fiber–wireless integrated system with hybrid MMW and FSO links based on MRC is shown in Fig. 2. Since seamless fiber–wireless integration is proposed here, the MMW and FSO links share the same electrical-to-optical process. However, the optical-to-electrical (O/E) process is carried out in different order. The O/E process of MMW link is in the main BS at the MMW transmitter side, while it is in the remote BS for the FSO link. Assuming the digital signal from the S-GW/MME to BS is $S_m$, and after fiber transmission, the received optical power of the two branches for the MMW and FSO links is $P_m$ and $P_f$, respectively. After wireless delivery by MMW and FSO, respectively, the received digital signals are $S_m$ and $S_f$ (after O/E). The two signals are

$$S_m = P_m \gamma_m g_m h_m S_m + n_m, \quad S_f = P_f \rho_f g_f \gamma_f S_f + n_f. \quad (1)$$

Here $\rho_m$, $g_m$, $h_m$, and $\rho_f$, $g_f$, $h_f$, $n_m$, and $n_f$ are the responsivity of O/E conversion, wireless average channel power gain, wireless power fading, and additive white Gaussian noise (AWGN) of the MMW and FSO channels, respectively. According to [9,10], we have the MMW and FSO fading gain with $\epsilon\{h_m\} = 1$ and $\epsilon\{h_f\} = 1$. For the sake of simplicity, the AWGN of MMW and FSO satisfy that the variance $\sigma_m^2 = \epsilon\{|n_m|^2\}$, $\sigma_f^2 = \epsilon\{|n_f|^2\}$. Then the normalized signal-to-noise ratios (SNRs) of the two channels are [9]

$$\gamma_m = \frac{P_m^2 \rho_m^2 g_m^2}{\sigma_m^2}, \quad \gamma_f = \frac{P_f^2 \rho_f^2 g_f^2}{\sigma_f^2}. \quad (2)$$

For MRC, we set the combined signal after the normalized combining gain coefficients of MMW and FSO links as $\alpha$ (alpha), and $1 - \alpha$, respectively. Then the combined signal is $S_c = \alpha S_m + (1 - \alpha) S_f$. According to the MRC, by choosing the optimal combining gain of each channel, the SNR of the signal at the output of the combiner is the sum of the SNRs of each sublink. In practice, we choose $\alpha$ satisfying $\alpha = \sqrt{\gamma_m / (\sqrt{\gamma_m} + \sqrt{\gamma_f})}$ [10]. In this case, we have the combined signal $S_c$ with SNR of

$$\gamma_c = \gamma_m + \gamma_f. \quad (3)$$

Therefore, the achieved SNR of the hybrid links is higher than the single cases, and it ensures reliability under different weather conditions. Under different weather conditions, the average channel power gains $g_m$ and $g_f$ can change tremendous in a contrary way, which makes the hybrid links with ADCT a promising scheme to maintain the link availability and reliability.

The experimental setup is shown in Fig. 3. One distributed feedback (DFB) laser 1 working at 1553.96 nm is used as light source. A broadband OFDM signal is generated by an arbitrary waveform generator, which drives the Mach–Zehnder modulator (MZM). The OFDM signal is coded by 16 QAM symbols, with fast Fourier transform (FFT) size of 2048 and 1024 data subcarriers. The occupied data bandwidth is 1 GHz, and the cyclic prefix (CP) is 6.25% of the FFT size. The OFDM signal is carried on an intermediate frequency (IF) of 720 MHz to enable intensity modulation and direct detection. One erbium-doped fiber amplifier (EDFA) is used before the fiber transmission.

After 20-km fiber transmission, the optical signal is split into two branches at the main BS for the MMW and FSO links. Insets (i) and (ii) of Fig. 3 show the optical spectrum of signals in the two branches before EDFA. The output power of two EDFAs is kept at 1 dBm. In the upper branch, a pair of fiber collimators are used as the antennas of the FSO link. One collimator is used to collimate the FSO beam propagating from the tip of the fiber. The collimated beam diameter of the FSO signal is 7 mm with a full-angle beam divergence less than 0.016°. After 1.83 m of line-of-sight (LoS) free-space transmission, another optical collimator is used to collect the received FSO light and collimate it into the fiber at the remote BS side, with a total insertion loss of about 4 dB. The collected FSO signals are detected by a low-speed photodetector (PD) with 10-GHz, 3-dB bandwidth and also sampled by a digital storage oscilloscope (DSO) with 10-GHz sampling rate for joint off-line digital signal processing (DSP). In the lower branch,

![Fig. 2. Principle of adaptive diversity combining for fiber–wireless integrated system with hybrid MMW and FSO links based on MRC.](image-url)
the 60-GHz MMW signal is generated by the optical beating method with a local oscillator (LO) DFB laser 2. The LO laser 2 with 4-dBm output power works at 1553.49 nm, with about 58.75-GHz frequency difference from laser 1. Both lasers have a linewidth of 10 MHz. One polarization controller (PC) is used for the polarization alignment between the signal and LO.

The combined optical signals are detected by a high-speed PD with 50-GHz, 3-dB bandwidth and upconverted to MMW. In practice, the power of the LO should be optimized to provide an optimal heterodyne gain for MMW signal generation. A pair of horn antennas with 25-dBi gains is used to deliver the MMW signal, with 1.83 m of LoS wireless transmission distance with propagation loss of about 73 dB. The transmission distance is limited by the gain of the power amplifiers and wireless antennas. At the remote BS side, the broadband MMW signal is down-converted to the IF again after the envelop detector (ED).

Inset (ii) of Fig. 3 shows the experimental setup of the fiber–wireless integrated MBH network based on the hybrid MMW and FSO links traversing a weather chamber synthesized in our lab with the adaptive combining technique. (PA: power amplifier; MZM: Mach–Zehnder modulator; EDFA: erbium-doped fiber amplifier; PC: polarization controller; PD: photodetector; ED: envelop detector; DSO: digital storage oscilloscope.)

Fig. 3. Experimental setup of the fiber–wireless integrated MBH network based on the hybrid MMW and FSO links traversing a weather chamber synthesized in our lab with the adaptive combining technique. (PA: power amplifier; MZM: Mach–Zehnder modulator; EDFA: erbium-doped fiber amplifier; PC: polarization controller; PD: photodetector; ED: envelop detector; DSO: digital storage oscilloscope.)

We first measure the EVM performances of different channels without and with ADCT versus received optical power under the clean weather condition. The received optical powers of the two branches are measured before the EDFAs. Fig. 4 shows the EVM performances of MMW only, FSO only, and hybrid MMW and FSO links with ADCT versus the received optical power after 20-km fiber transmission. We can see that, compared with the MMW or FSO only case, the EVM performances have been significantly improved by using adaptive combining of the two hybrid links. Due to the receiver SNR limitation caused by PDs and power amplifiers in MMW and FSO links, there are two EVM floors for both the MMW and FSO only cases above 8% and 7%, respectively. However, by using the ADCT with hybrid MMW and FSO links, we can achieve a significant improvement by reducing the EVM floor to 4%. The optimal combining gain coefficient alpha under different received optical power is also plotted in Fig. 4 on the right axis.

Figures 5(a), 5(b), and 5(c) show the experimental results (calculated SNR based on EVM performances [11]) of MMW only, FSO only, and hybrid MMW and FSO links with ADCT under the foggy, turbulent, and rainy channels, respectively.
In order to study the complementary characteristics for different weather conditions, only one simulator is turned on each time. For the foggy channel, the data is measured for the 12-min time. Here, we keep the received optical power at about 0.04 ml/s. For the turbulence channel, only the heater in the weather chamber is running with a power of 1500 W. The data is sampled and measured during 11 min. Finally, the raining channel is tested by using the sprinkler in the weather chamber. Three different flow rates are tested here as stage 1, stage 2, and stage 3. The flow rates of stages in the weather chamber are 5, 25, and 75 ml/s, respectively. Three samples are measured in each stage for EVM calculation.

The optimal alpha in all measurement conditions is also plotted in Fig. 5. From Figs. 5(a) and 5(b), we can see that the FSO channel is very sensitive to the fog and turbulence. After 6 min running, the SNR is lower than 15 dB for the FSO only case in Fig. 5(a), which corresponds to an EVM of about 17%. Serious SNR degradation is observed for the FSO channel under the turbulence in Fig. 5(b). However, fog and turbulence have no obvious impact on the MMW signals. The SNRs of MMW channels under foggy and turbulent channels are above 21 dB, which corresponds to the EVM of 9%. On the contrary, the MMW is more sensitive to the rainy weather compared with the FSO link, as shown in Fig. 5(c). Larger performance degradation is observed by increasing the flow rate of the rain generator. However, as analyzed above, the hybrid links with ADCT have the best performances under all conditions, with SNRs all above 21.5 dB, which corresponds to an EVM of 8.5%. Even when one link is unavailable, that is, FSO link after 10 min of the humidifier running with SNRs lower than 10 dB, the performance of the hybrid link is guaranteed and the EVM approaches that of the MMW link.

Finally, Figs. 6(a) and 6(b) show the EVM and the calculated SNR [11] of the hybrid links of sample 7 in the foggy channel and rainy channel versus alpha, respectively. The blue and red dashed lines in these figures indicate the theoretical optimal alpha and combined SNRs based on Eq. (3), respectively. For the foggy channel, the optimal alpha is around 0.6, while it is about 0.3 for the rainy channel. We can see that the experimental results are very close to those of the theoretical values, which verifies the analysis of Eq. (3). We believe the small differences between theoretical values and experimental results are due to the imperfect AWGN in practical systems. When alpha is 0, there is only FSO, while there is only MMW when alpha is 1. As a comparison, insets (i), (ii), and (iii) in Figs. 6(a) and 6(b) show the constellation of FSO only, hybrid MMW and FSO with ADCT, and MMW only cases. Obvious performance improvement can be observed by the constellations.

In conclusion, a novel fiber–wireless integrated MBH network based on a hybrid MMW and FSO architecture with ADCT is proposed and demonstrated. Experimental transportation of 4-Gb/s 16QAM-OFDM backhaul data is demonstrated, and ADCT is used at the receiver side to fully exploit the complementary channel response of MMW and FSO links. Thanks to the ADCT, performance improvements in terms of EVM reduction as well as enhanced link reliability are experimentally tested in the lab and verified under various synthesized atmospheric/weather conditions. This ADCT technique developed for hybrid MMW and FSO MBH links can greatly increase the transport reliability of next-generation mobile networks.

REFERENCES