Effect of optical losses on the transmission performance of a radio-over-fiber distributed antenna system

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The effects of optical losses on a directly-modulated radio-over-fiber (RoF) system used for distributed antenna networks are determined. The results show that with a properly designed bidirectional amplifier, the RoF link can tolerate over 20 and 16 dB of optical losses for down- and up-links, respectively. Simulation results are also consistent with the experimental data. These findings can contribute to the design of RoF distributed antenna systems with different topologies.

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The radio-over-fiber (RoF) technology is a proven, efficient solution for wireless signal distribution[1,2]. The combination of RoF with a distributed antenna system (DAS) can provide extended coverage and dedicated capacity for areas such as airports, shopping malls, and smart buildings[3]. In a RoF-DAS, the radio frequency (RF) signal is modulated onto an optical carrier at the central office (CO), and then transmitted to a remote antenna unit (RAU) through an optical fiber. This approach can significantly reduce the complexity of the RAU and realize the centralized management of the system. However, the RoF link is a quite noisy link, in which optical losses attenuate the RF signal power and thereby increase the noise figure (NF), finally making the signal drowned by noise.

Generally, most of the optical losses in a RoF system are caused by DAS networking components with different topologies. In the RoF-DAS, which has a star topology, one of the main techniques is wavelength division multiplexing (WDM)[4−6]. The array waveguide grating (AWG) used in WDM is an optical passive component that exhibits a certain insertion loss. In RoF systems with bus or tree topologies[7,8], an optical coupler and an optical add-drop multiplexer can introduce higher optical losses. If the topology is more complicated and no optical amplification is adopted, the signals transmitted on the optical fiber are attenuated to a low level and eventually become drowned by the noise of the optical link. Therefore, the optical-loss-induced impairment of the RoF-DAS transmission performance must be determined. The results can guide RoF-DAS designers in determining whether a system requires an additional amplifier or an erbium-doped fiber amplifier (EDFA) as well as the optimal location for the device.

In this letter, we study the effect of optical losses on the RoF-DAS distribution of wireless fidelity (WiFi) signals, which are the most widely used wireless local area network (WLAN) standard. The optical losses of the complicated RoF-DAS are simulated by a tunable optical attenuator in a point-to-point RoF link. The transmission performance of the system as a function of optical losses is evaluated in terms of data throughput. To the best of our knowledge, this study is the first to systematically discuss the effects of optical losses on the practical wireless signal transmission performance of RoF-DAS.

The experimental setup is schematically shown in Fig. 1. We use an access point (AP) as the WiFi signal source. The RF signal generated from the AP is modulated onto the optical carrier by the RF optical transceiver that operates at 1 550 nm in the CO. The signal is transmitted over a 100-m single-mode fiber (SMF) and then reconverted to an electric signal in the remote RF optical transceiver. The gain of the power amplifier (PA) in the RF optical transceiver is set to approximately 27 dB to compensate for optical-to-electrical (O/E) and electrical-to-optical (E/O) conversion losses and thus regain the original overall optical link gain of approximately 0 dB. Following the RF optical transceiver is a bidirectional amplifier (BDA) consisting of a PA, a low-noise amplifier (LNA), and a RF switch. The PA in BDA, which has an approximately 16-dB gain, is used to amplify the RF signal to ensure sufficient area coverage. WiFi is a half-duplex communication technology. Thus, we use a RF switch to enable the half-duplex operation. RF switches have higher isolation capacities than traditional circulators, thus ensuring that downlink signals do not leak to the uplink ones. An electric signal is eventually transmitted through a dipole antenna from the BDA. However, the wireless signal from the user device encounters a significant decrease in air and is thus too weak when it arrives at the antenna for the uplink. Therefore, we use a LNA with a 40-dB gain in the BDA to amplify for signal amplification. The signal is then remodulated onto the optical carrier by the RF optical transceiver and subsequently sent to the CO. Finally, the RF optical transceiver in CO recovers the signal, which is then transmitted back to the AP through the circulator. The AP RF bandwidth, which determines the noise

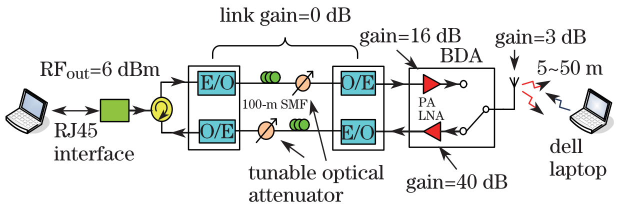

Fig. 1. Experimental setup for the evaluation of the effects of optical losses in WiFi-over-fiber systems.

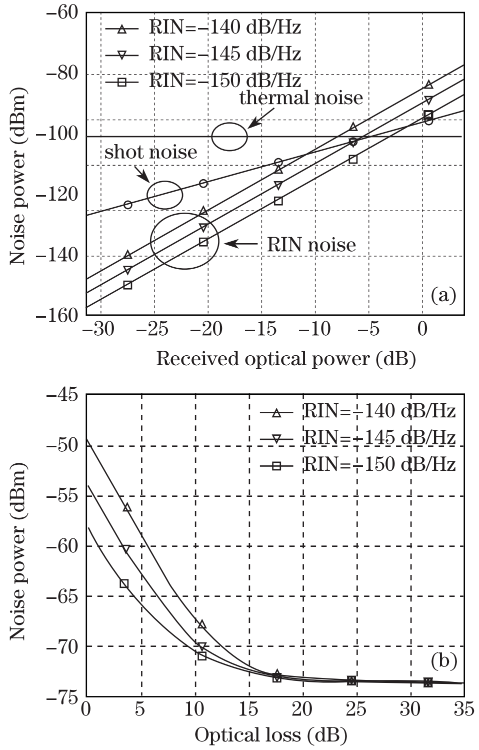

Fig. 2. (a) Three types of noise in the RF optical transceiver; (b) total noises in the RF optical transceiver.

bandwidth in the RF receiver, is 22 MHz.

To evaluate the system performance more accurately, we measure the transmission data throughput for both downlink and uplink signals. We then determine the difference between the values. According to the IEEE 802.11g standard, the minimum signal-to-noise ratio (SNR) that satisfies the modulation format of a 64 QAM with a 54-Mbps data rate is generally 25 dB[9]. However, when the system SNR is below 25 dB, a high-order modulation format is downgraded to lower-order ones such as 16QAM, which results in an obvious decrease in the tested data throughput.

In the optical link, we use a tunable optical attenuator to control the optical losses. As the optical losses increase, the optical power received by the photodetector decreases, which affects the noise in the RF optical transceiver. All noises in the optical link are generally of three types: relative intensity noise (RIN), shot noise, and thermal noise[10]. These noises can be expressed as[11]

$$P_{\rm RIN}=\frac{I_{\rm d}^2}{2}10^{\frac{\rm RIN}{10}}R_{\rm S}\Delta f, \tag{1}$$

$$P_{\rm shot}=2qI_{\rm d}R_{\rm S}\Delta f, \tag{2}$$

$$P_{\rm thermal}=kT\Delta f, \tag{3}$$

where $I_{\rm d}$ is the photodetector current, q is the charge of the current carrier, $R_{\rm S}$ is the matched resistance, k is the Boltzmann's constant, T is the absolute temperature, and Δf is the noise bandwidth, which is equal to the RF bandwidth (i.e., 22 MHz).

Equations (1)–(3) show that RIN and the shot noise are functions of the photodetector current, which varies with the detected optical power. When the received optical power in the photodetector is high, the RIN in the laser is the dominant one. Nevertheless, the shot noise dominates as the received optical power decreases. In addition, the ultimate noise floor of the RF optical transceiver depends on the thermal noise, which is constant at approximately −174 dBm/Hz at 290 K. Figure 2(a) shows the changes in the RIN noise, shot noise, and thermal noise against the received optical power.

The optical losses also affect the RoF link gain, which can be expressed as[11]

$$G_{\rm link}=\left(S_{\rm l}R_{\rm d}L_{\rm fib}\right)^2, \tag{4}$$

where $S_{\rm l}$, $R_{\rm d}$, and $L_{\rm fib}$ are the laser P–I curve slopes that determine the modulation efficiency, the photodetector responsivity, and the optical fiber losses, respectively. Equation (4) implies that a 1-dB optical loss will result in a 2-dB electrical loss, which reduces both the signal power and the system noise. However, the effects of optical losses on the signal power and on the system noise are different, which lead to variations in the SNR system. Figure 2(b) shows that when the optical losses increase to approximately 20 dB, the total noise in the RF optical transceiver no longer changes and is approximately −74 dBm as determined by the thermal noise. However, the signal power encounters a 2-dB decrease with each 1-dB increase in the optical loss. Therefore, to meet the 25-dB SNR requirement of a 64 QAM system with a 54-Mbps data rate, the minimum output signal power of the RF optical transceiver must be −49 dBm. When the signal power decreases to below −49 dBm, the normal WiFi service can no longer be provided, and the tested data throughput drops below 20 Mbps in our experiment.

The RF signal power injected into the RF optical transceiver in the downlink is fixed, whereas the signal varies at different wireless distances in the uplink. Thus, the optical loss tolerance of the uplink changes with the wireless distance. The free-space path loss $L_{\rm p}$(dB) is given by[12]

$$L_{\rm p}=32.4+20\log\left(f\right)+20\log\left(d\right), \tag{5}$$

where f is the frequency (MHz) and d is the wireless transmission distance (km). For a 2.4-GHz RF WiFi signal, the path loss $P_{\rm l}(d)$ (dB) in the air is given by[13]

$$P_{\rm l}\left(d\right)=P_{\rm l}\left(d_0\right)+20\log\left(\frac{d}{d_0}\right)+{\rm FAF}, \tag{6}$$

where $P_{\rm l}(d_0)$ is the free-space path loss at a 1-m reference distance and FAF is a constant called the floor attenuation factor (dB). The RF signal power received by the antenna is directly determined by the wireless distance. Thus, the signal power injected into the RF optical

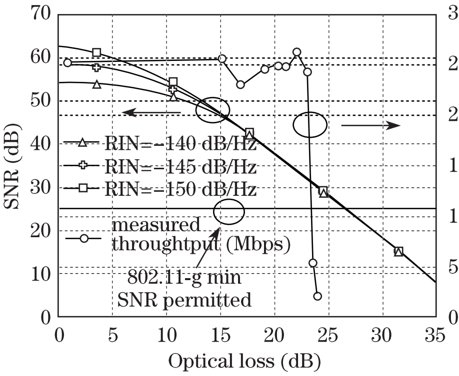

Fig. 3. Comparison of the calculated SNR and the measured throughput against the optical losses of the downlink.

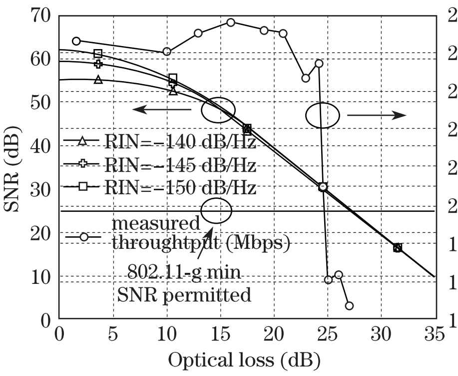

Fig. 4. Comparison of the calculated SNR and the measured throughput against the optical losses of the up-link at a 5-m wireless distance.

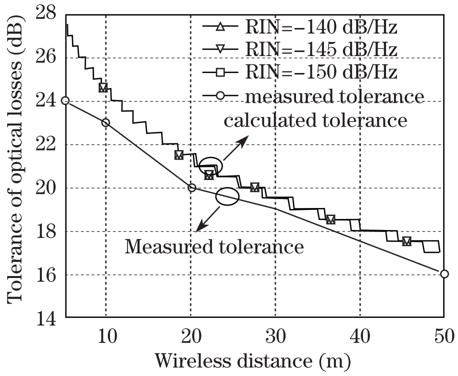

Fig. 5. Calculated and measured optical loss tolerances of the the up-link at different wireless distances.

transceiver decreases by 6 dB when the wireless transmission distance is doubled. Therefore, the wireless distance should be considered in the calculation of the optical loss tolerance of the uplink.

We simulate the system SNR using MATLAB. The experiment is conducted using the setup shown in Fig. 1. We use two laptops, one of which is connected to the Compex AP through a RJ45 interface, whereas the other is placed approximately 5 m away from the remote antenna. An adapter, a TL-WN422G+ from TP-LINK, is used to replace the one in the laptop in order to change the antenna direction in a random manner and to guarantee the accuracy of the results. The software used to analyze the data throughput is IxChariot.

The simulated SNR and measured data throughput (Figs. 3 and 4) demonstrate the effects of optical losses in the down- and up-links, respectively. The measured results (Fig. 3) indicate that the optical loss tolerance of the downlink can exceed 20 dB. Moreover, the tested data throughput significantly decreases to approximately 5 Mbps when the optical losses exceed 23 dB. This result is caused by the trigger switch in the BDA instead of the degradation of the modulation format. In this case, the low RF power input to the BDA is insufficient to trigger the RF switch. Therefore, the optical loss tolerance of the downlink exceeds the measured value.

We also measure the optical loss tolerance of the uplink at an approximately 5-m wireless distance. Figure 4 shows that the measured data throughput is maintained at approximately 24 Mbps when the optical losses are kept below 25 dB. However, the data throughputdrops to about 18 Mbps as the optical losses continue to increase. This experimental result is nearly consistent with the 27-dB optical loss tolerance simulation result for the RoF system.

According to Eq. (6), the optical loss tolerance of the uplink changes with the wireless distance. This trend is numerically simulated in Fig. 5. Both the calculated and measured tolerances decrease as the wireless distance increases because the WiFi signal emitted by the laptop encounters higher path losses with increasing distance. However, for the uplink, the system can still tolerate approximately a 16-dB optical loss at a 50-m wireless distance.

In conclusion, we study the effects of optical losses on WiFi transmissions based on a simplified RoF-DAS. The experimental results show that the optical loss tolerance of the downlink exceeds 20 dB, whereas that of the uplink exceeds 16 dB, both within a 50-m wireless distance. This result is highly consistent with the simulation results. This work can serve as a reference in the application of RoF-DAS to WiFi distribution services. The results can also be used in the performance evaluation and feasibility analysis of systems to improve the reliability of wireless services. Furthermore, complex network topologies are recommended for future RoF-DAS. Regardless of the topology, optical powers in the network node are generally different from one other. The unification of the optical power of all nodes is ineffective and expensive because the process requires several electrical amplifiers or EDFAs. Nevertheless, an effective and cheap solution is what the market demands. Therefore, the need for an additional EDFA must be determined, and its appropriate location must be identified.

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