A Novel Radio-over-Fiber System Using the xy-MIMO Wireless Technique for Enhanced Radio Spectral Efficiency

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Abstract By combining two different system technologies of optical polarization division multiplexing and wireless multiple-input, multiple-output spatial multiplexing, we have successfully demonstrated 2-Gb/s or 5-Gb/s wireless signal transmission over a 60-GHz wireless channel with a doubled spectral efficiency.

Introduction

Optical polarization division multiplexing (PDM) is a promising technique to increase the data rates per wavelength. Using PDM, two independent signals are carried by two orthogonal electromagnetic wave polarizations (x-polarization and y-polarization) of a single wavelength inside a single-mode fiber (SMF). These two polarizations are separated at the receiver and detected individually by two photodetectors. However, to construct the received signals from the two polarizations individually, the random rotation of the two orthogonal polarizations along the fiber has to be processed and corrected before separating the two polarizations in the optical receiver. Thus, complicated feedback circuits and optical polarization trackers are often required in a PDM optical communication system.

If two independent radio signals can be carried by two orthogonal polarizations using the 2x2 multiple-input multiple-output (MIMO) technique, then the MIMO wireless receiver can automatically detect and correct the optical polarization rotation in the fiber. In radio-over-fiber (RoF) systems with the two optical polarizations carrying different radio signals, the fiber transmission subsystem behaves like a linear 2x2 MIMO channel. After the two radio signals are transmitted by two antennas modules, the MIMO receiver can treat the polarization rotation inside the fiber as a part of the wireless channel, which can be directly estimated by the MIMO demodulation algorithm. The technique that uses both PDM and MIMO techniques is referred to as the xy-MIMO technology in this paper. To demonstrate the xy-MIMO transmission, we experimentally set up a 2-Gb/s dynamic xy-MIMO wireless transmission in the RoF system and a 5-Gb/s fixed xy-MIMO wireless transmission system, both of which transmit on-off keying (OOK) signals with spectral efficiency of 2 bit/s/Hz.

Principle of xy-MIMO

In a RoF system, when two independent radio signals are carried by two orthogonal polarizations of optical waves in optical fibers (Fig. 1), they will experience a slow polarization rotation, which can be described by a matrix similar to a wireless channel matrix:

\[
\begin{bmatrix}
    r_x \\
    r_y
\end{bmatrix} = \begin{bmatrix}
    \cos \theta & \sin \theta \\
    -\sin \theta & \cos \theta
\end{bmatrix} \begin{bmatrix}
    t_x \\
    t_y
\end{bmatrix},
\]

where \(r_x\) and \(r_y\) are the normalized received radio signals of two polarizations respectively. The symbol \(\theta\) is the rotational angle; \(t_x\) and \(t_y\) are the original transmitted signals. At the xy-MIMO transmitter, two photodetectors transfer the two received radio signals to two antennas respectively. In the condition of a short wireless distance and line-of-sight (LOS) transmission, the signals interfere each other and undergo a wireless channel that can be represented by a well-conditioned matrix \(H_{\text{MIMO}}\). Assuming that we have a flat-fading channel and two identical wireless receivers, the two received signals \([r_{A1} \ r_{A2}]^T\) can be expressed by

\[
\begin{bmatrix}
    r_{A1} \\
    r_{A2}
\end{bmatrix} = H \begin{bmatrix}
    t_x \\
    t_y
\end{bmatrix},
\]

\[
H = \begin{bmatrix}
    h_{11} & h_{12} \\
    h_{21} & h_{22}
\end{bmatrix} = \begin{bmatrix}
    \cos \theta & \sin \theta \\
    -\sin \theta & \cos \theta
\end{bmatrix}.
\]

The total channel matrix \(H\) varies with time. Due to all the optical fibers installed at fix positions, the polarization rotation usually varies much slower than the wireless channel. The MIMO transceiver use a prefix training sequence.
to estimate the time-variant total channel matrix $H$ and recover the original transmitted data from Eq. (3). Once the estimated channel matrix is obtained, the MIMO transceiver can use either channel diversity or spatial multiplexing to improve the transmission performance. For example, the transmission condition of a 60-GHz radio wireless systems is usually LOS and short-ranged. Therefore, the two original signals, which are simultaneously transmitted by x- and y- polarizations, can be distinguished directly from the invertible matrix of Eq. (3), hence doubling the data rate without occupying additional time intervals or signal bandwidth by spatial multiplexing.

2x1-Gb/s Dynamic xy-MIMO Transmission
To demonstrate the xy-MIMO RoF transmission, we set up a 60-GHz RoF downlink system with PDM and a 2x2 MIMO subsystem. As shown in Fig. 2, the LOS transmission of wireless signals enables us to deploy spatial multiplexing to increase the channel capacity of the 2x2 MIMO subsystem to 2bit/s/Hz. In the experiment, 1-Gb/s pseudorandom bit sequences (PRBS) of a bit length of $2^7-1$ was modulated directly on a tunable laser diode (LD) in the RoF gateway router. Using a 40-GHz phase modulator (PM) and optical interleaver (IL), the baseband data were up-converted to 60-GHz radio by the process of optical carrier suppression (OCS). The optical radio signals were then separated into two optical paths by an optical coupler (OC) and adjusted to a x-polarization and a y-polarization respectively by polarization controllers (PCs). A m-bit delay was added to one optical path to make the two radio optical signals carry two uncorrelated PRBSs, representing two independent data sequences. The two radio signals were then combined by a polarization multiplexer (PolMux) and sent to the wireless access point (WAP) by a standard SMF.

The WAP used another PolMux to separate the two orthogonal polarizations of the received signals and used two photodetectors (PD) to convert the optical signals into electrical radio signals. Being amplified by radio-frequency power amplifiers (PAs), the radio signals were sent to the MIMO receiver by the antenna modules, which consisted of two horn antennas with 15-DBi directional gains. The output radio power after the PA was measured as 1mW. The received radio signals were down-converted to the baseband at the MIMO receiver, which then recorded the signals by a 4-GSample/s digital oscilloscope. Figure 3 shows an example of 40-ns recorded samples and their eye diagrams. After the channel estimation process, the recorded signals were demodulated and recovered to the two original data sequences.

2x2.5-Gb/s Fixed xy-MIMO Transmission
The experiment setup of a 2x2.5-Gb/s xy-MIMO RoF system for fixed-to-fixed wireless transmission is similar to the dynamic one except that it no longer requires the prefix training sequence to estimate the channel matrix since the channel matrix is time-invariant. To measure the bit error rate (BER) performance of the fixed wireless transmission by a high-speed
on-off keying bit-error-rate tester (BERT), we intentionally set up the receiver and transmitter antenna arrays with specific spatial locations. As shown in Fig. 4, four antennas were placed at specific locations so that the radio phase of the two transmitted signals are just different from 90 degree. Assuming that the two radio signals are already aligned by a PC before the PolMux, and the distances from the two transmitter antennas to one of the receiver antenna are $d_1$ and $d_2$ respectively, then the received in-phase signals of the MIMO receiver can be expressed by

$$r_{A1} = \Re\{e^{j\phi}e^{-jk_0d_1}a_1e^{-jk_0(d_1-d_2)}\}
\begin{bmatrix}
\cos \hat{\theta} & -\sin \hat{\theta} \\
\sin \hat{\theta} & \cos \hat{\theta}
\end{bmatrix}
\begin{bmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{bmatrix}
\begin{bmatrix}
t_1 \\
t_2
\end{bmatrix}, \quad (3)$$

where $\phi$ is the phase of the local oscillator in the receiver $A_1$, and $\hat{\theta}$ is the estimated rotation angle of the optical polarizations; $a_1$ and $a_2$ represent the fractions of the received power resulting from the propagation loss; $k_0$ is the propagation constant of air. Therefore, if we can set the distance difference $(d_1 - d_2) = \pi/2$ and let the local oscillator phase $\phi$ compensate the propagation phase $-jk_0d_1$, the received signal $r_{A1}$ can be obtained from Eq. (5):

$$r_{A1} = a_1t_x. \quad (4)$$

If we transmit the original signals with the format of the non-return-to-zero on-off keying (NRZ-OOK), the received signals then can be directly detected by the OOK BERT.

In the experiment, two 2.5-Gb/s independent OOK signals are sent to the xy-MIMO RoF system. In a wireless transmission distance of 50cm, we remove the two transmitter PAs resulting from the high directional gains of the fixed horn antennas. The resolved BER measurements are shown in Fig. 5. After 10-km-SMF transmission, there is negligible increase of optical-signal-to-noise ratio (OSNR) requirement. The OSNR was measured by an optical spectrum analyzer (OSA) at the resolution of 0.1nm. In a wireless transmission distance of 10ft, the PAs are added before the two transmitter antennas to boost the radiative power, and an OSNR penalty of 2.5dB is observed after 10-km-SMF transmission.

Conclusions

Taking advantage of the similar behavior between optical polarizations along the optical fiber system and the wireless channel, we proposed a converged system to integrate the optical PDM technology with wireless MIMO technology to demonstrate a simple, spectral-efficient RoF system. Two independent OOK signals can be transmitted through the RoF system respectively carried by two orthogonal polarizations and the received signals can be easily recovered from the wireless MIMO receiver. Using the MIMO spatial multiplexing technique, the 2-Gb/s dynamic xy-MIMO system and 5-Gb/s fixed xy-MIMO system has been successfully demonstrated with a spectral efficiency of 2-bit/s/Hz.

References