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Space-division-multiplexed transmission of 3x3 multiple-input multiple-output wireless signals over conventional graded-index multimode fiber

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Abstract: In this paper, we experimentally demonstrate space-division-multiplexed (SDM) transmission of IEEE 802.11ac-compliant 3-spatial-stream WLAN signals over 3 spatial modes of conventional 50um graded-index (GI) multimode fiber (MMF) employing non-mode-selective 3D-waveguide photonic lantern. Two kinds of scenarios, including fiber-only transmission and fiber-wireless hybrid transmission, were investigated by measuring error vector magnitude (EVM) performance for each stream and condition number (CN) of the channel matrix. The experimental results show that, SDM-based MMF link could offer a CN<20dB well-conditioned MIMO channel over up to 1km fiber length within 0-6GHz, achieving as low as 2.38%, 2.97% and 2.11% EVM performance for 1km MMF link at 2.4GHz, 5.8GHz, and 200m MMF link followed by 1m air distance at 2.7GHz, respectively. These results indicate the possibility to distribute wireless MIMO signals over existing in-building commercially-available MMFs with enormous cost-saving.

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1. Introduction

Distributed antenna systems (DASs) using radio-over-fiber (RoF) technology have been employed as an infrastructure solution providing in-building wireless capacity and coverage improvement [1–4]. In a typical RoF-based DAS, standardized radio signals are modulated onto optical carriers and distributed over optical fibers, such as wireless local-area network (WLAN) signals and cellular signals [3]. Multiple-input multiple-output (MIMO), as an essential component of state-of-the-art mobile radio signals, is key to achieve extremely ambitious capacity goals through spatial multiplexing and spatial diversity techniques [4]. Latest wireless standards, like IEEE 802.11ac and Long Term Evolution Advanced (LTE-A), keep enhancing MIMO transmission with an extension to 8 spatial streams, while previous releases of IEEE 802.11n and LTE allow for 4 spatial streams [4, 5]. Straightforwardly, this could be realized by installing multiple parallel single mode fibers (SMFs) for each stream. However, future wireless communications envision a dense deployment of in-building small cells. This significantly increases the counts of separate SMF links for connections and raise the deployment cost and space occupation. In contrast, multiplexing signals into a single fiber transmission might be more cost-effective. Up to now, several multiplexing techniques for MIMO DAS have been proposed, including subcarrier multiplexing (SCM) [6], wavelength division multiplexing (WDM) [7] and polarization division multiplexing (PDM) [8].
However, such approaches need expensive multiplexer/demultiplexer (Mux/DeMux) components, severely limits their practical applications due to the high cost, especially for future larger number of spatial streams.

Recently, space-division-multiplexing (SDM), which exploits a new dimension in space, is under intensive study [9–12]. One possible approach for SDM is to use multicore fibers (MCFs) [11], where the data are multiplexed into multiple cores but still in a single fiber cladding. In this paper, we will concentrate on another approach of developing various modes in multimode fiber (MMF) as communication channels, also known as mode-division-multiplexing (MDM) [4, 12]. Since MMF has been widely deployed in buildings, the main original motivation behind utilizing MMF is the enormous cost-benefit arising from not having to install extra fiber [4]. Taking advantage of the inherent nature of modal dispersion, MMF behaves similar to wireless multipath propagation [13, 14]. Based on this analogy, the concept of MIMO transmission used in wireless communications can be also applied to MMF channel theoretically to enhance the total system capacity. The feasibility of this idea has been experimentally demonstrated for a 2x2 MIMO system over several kilometers MMF using commercial coupler [15] and liquid-crystal-on-silicon (LCOS) spatial light modulator [4] as the mode Mux/DeMux. However, both the two ways suffer from large losses. Instead, recent works on photonic lantern (PL) make mode multiplexing much simpler and more practical due to its low loss and compactness [16–21], which directly converts N SMFs into N modes of a MMF, and vice versa. Currently, there includes two fabrication techniques for PL: All-fiber PL and ultrafast laser inscription (ULI) three-dimensional (3D) waveguide PL [17]. The former one needs manual assembly fiber that makes it challenging to scale up to larger number of modes, while the latter one is fully automated providing accurate layout control, therefore it is much easier to support more modes without significantly increasing the fabrication cost [18]. Over recent years, 3D-waveguide PL supporting 3-spatial-mode (LP01, 2xLP11) [19], 6-spatial-mode (LP01, 2xLP11, 2xLP21 and LP02) [19, 20] and 15-spatial-mode (LP01, 2xLP11, 2xLP21, LP02, 2xLP31, 2xLP12, 2xLP41, 2xLP22 and LP03) [18, 19], have been developed successively. These allow the system to be flexibly upgraded to support more spatial streams without dramatically increasing insertion loss and system cost, and retain the deployed fiber resources by only replacing the mode Mux/DeMux in the central office (CO) and RAUs.

In this paper, we experimentally demonstrate SDM transmission of IEEE 802.11ac-compliant 3-spatial-stream WLAN wireless signals over 3 spatial modes of conventional 50μm graded-index (GI) MMF employing non-mode-selective 3D-waveguide PL. PL can also have mode selectivity that inputting light into any one of the SMF inputs will excite just one specific mode at the MMF output, rather than a combination of the fiber modes [21]. Compared to non-mode-selective PL, it might seem much superior to act as a high-performance spatial Mux/DeMux, but faced with lower yield and greater cost due to the more critical requirements for manufacture technology. Besides, since the mode coupling in MMF is inevitable and could be faithfully undone by MIMO algorithm, it is not necessary to use relatively expensive mode-selective PL here for wireless MIMO signals transmission. To evaluate the link performance, we measured error vector magnitude (EVM) values for each stream and condition number (CN) of the channel matrix. First experimental measurements were performed with fiber-only link. It is shown to offer a CN < 20dB well-conditioned MIMO channel over up to 1km fiber length within 0-6GHz, and the smaller the CN is, the less SNR degradation will be. At the specific frequencies of 2.4GHz and 5.8GHz, EVM of as low as 2.38% and 2.97% were respectively attained for 1km MMF link. Next, a fiber-wireless hybrid transmission platform was built to further evaluate the system performance. The results are just as we expected, that the CNs still remained in the acceptable range of under 20dB and achieved a EVM performance of 2.11% after 200m MMF followed by 1m air distance at 2.7GHz.
The remainder of this paper is organized as follows: Section 2 describes the experimental setup and evaluation principles for this study; Section 3 presents the experimental results and analyses for fiber-only transmission and fiber-wireless hybrid transmission, respectively; Section 4 concludes this paper.

2. Experimental setup and evaluation principles

2.1 Experimental setup

Figure 1(a) shows the SDM-based experimental setup for 3x3 MIMO signals transmission over a single GI-MMF. Two three-port 3D-waveguide PLs were used as the spatial multiplexer (PL-Mux) and demultiplexer (PL-DeMux) respectively, which has a triangular core arrangement matching with OFS GI few mode fiber (FMF) supporting three spatial modes (LP01, LP11a and LP11b). Figure 1(b) shows the picture of the PL. The fiber to fiber insertion loss from SMF to FMF is 1.7dB or less across the 3 channels. To couple the optical waveguides into/out MMF, we directly spliced 11um FMF pigtails of PL-Mux/PL-DeMux with 50um MMF. Two additional all-fiber mode filters each with 1m MMF pigtail were

Table 1. Parameters of 3x3 MIMO wireless signal setup.

| Parameters          | Values       |
|---------------------|--------------|
| Carrier Frequency   | 2.4GHz/5.8GHz/2.7GHz* |
| Spatial Streams     | 3            |
| MCS Index           | 7            |
| Modulation Format   | 64-QAM       |
| Coding rate         | 5/6          |
| Channel Bandwidth   | 80 MHz       |

*2.4GHz/5.8GHz for fiber-only transmission, 2.7GHz for fiber-wireless hybrid transmission.
added to suppress the excitation and detection of the unwanted higher order modes. We measured the total end-to-end optical losses for the three channels that were 5.15dB, 4.0dB and 6.56dB at 1550 nm respectively, when the two 3D-waveguide PLs directly coupled to the two spliced mode filters (we will take this as the back to back (B2B) link in the following parts).

In this paper, two aspects of the link performance were experimentally validated. Test case1 was carried out only with RoF link to qualify the performance over fiber, while test case2 was carried out with fiber-wireless hybrid transmission to qualify the whole transport performance over air environment. (1) In test case1, three low-cost 5MHz-linewidth cooled distributed feedback (DFB) lasers at a wavelength of around 1550 nm were used as the laser sources, and the output optical power was around 7dBm. Figure 1(c) shows the optical spectrum of one of the lasers. After the direct modulation, each spatial stream on the SMFs was multiplexed into a spooled MMF with 80mm radius via the PL-Mux. Figure 1(d) shows the refractive index (RI) profile of the 50um GI-MMF we used, and its cladding index is 1.45601. At the receiver side, the signals were demultiplexed and outputted to three individual SMFs with the help of the PL-DeMux, then detected by photodiodes (PDs). (2) Based on test case1, the received electrical signals from PDs were amplified with 25dB-gain RF power amplifiers (PAs), then fed to three omnidirectional antennas (5dBi-gain), as shown in Fig. 1(a) red part.

Three Keysight modular M9381 PXIe vector signal generators (VSGs) and three modular M9391 PXIe vector signal analyzers (VSAs) were employed to build a 3x3 MIMO hardware test platform. IEEE 802.11ac-compliant signals with 215-1 pseudorandom sequence length were generated by Keysight WLAN N7617B signal studio software and analyzed by Keysight 89601B vector signal analysis software. The experimental parameters were listed in Table 1.

### 2.2 Evaluation principles for MIMO channel

Mathematically, this system can be described as a $M \times N$ transmission matrix $H$, irrespective of the exact mode Mux/DeMux components used. $M$ and $N$ respectively represent the number of receivers and transmitters, here, $M = N = 3$. Each element $h_{ijh}$ of $H$ is a complex number containing the changed electrical magnitude and phase information of the transfer coefficient between the $i$-th receiver and $j$-th transmitter pair. Then, the total Shannon capacity for this $N \times N$ channel can be expressed by [13]:

$$
C = \log_2 \left\{ \det \left[ I_N + \frac{\rho}{N} H H^H \right] \right\} \text{bits/s/Hz} \tag{1}
$$

Where $I_N$ is the $N \times N$ identity matrix, $\rho$ is the received signal-to-noise ratio (SNR) for the single-input single-output (SISO) system. In test case1, $H$ can be specifically modelled by $H = H_{\text{F}}$, while in test case2, $H$ is the product of fiber channel and wireless channel, given by $H = H_{\text{wireless}} H_{\text{F}}$, where $H_{\text{F}}$ represents the channel matrix of the fiber-only link and $H_{\text{wireless}}$ represents the free-space radio propagation channel matrix.

From Eq. (1), it is easy to find that SNR is a deciding factor with respect to system performance. It could be improved by increasing transmit (tx) signal power or reducing link power loss as small as possible to obtain a better transmission quality. However, as stated in Eq. (1), the condition of the channel matrix $H$ is also a contributing factor in MIMO operation, qualified by a calculation of CN. Practically, the CN is given in logarithmic form as follows [4]:

$$
\text{CN(dB)} = 20 \times \log_{10} \frac{\sigma_{\text{max}}}{\sigma_{\text{min}}} \geq 0 \text{dB} \tag{2}
$$
Where $\sigma_{\text{max}}$ and $\sigma_{\text{min}}$ respectively represent the maximum singular value and the minimum singular value of the channel matrix $H$. Small values for CN imply a well-conditioned matrix while large values indicate an ill-conditioned matrix. Applying to wireless communications, it can provide an important indication of whether the MIMO channel under consideration can be spatially multiplexed. Regardless of the performance imbalance of optical transmitters and receivers, the level of CN is largely dependent on fiber length, fiber bending, and splice condition. Normally, in order that the RoF channel has minimum impact on the fiber-wireless hybrid channel, the CN of $H_{\text{RoF}}$ is desired to be less than 20dB but as small as possible for a realistic in-building wireless propagation environment [4].

On the other hand, the ill-degree of the channel matrix would affect the system SNR but related to the demultiplexing algorithm [22]. In our experiment, Keysight 89601B VSA software uses zero-forcing (ZF) approach for MIMO signal recovery. As a result, the received data are decoded by inverting $H$ and then multiplying with the received signal vector. Consequently, unless the transmission is unitary, this operation will introduce an extra multiplicative factor to the noise and lead to a deterioration of SNR [13, 22]. But in reality, due to the non-ideal factors, such as the launching/detection imperfection, fiber bending loss, connection loss, and so on, the transmission is usually non-unitary. For ZF algorithm, the post-processing SNR at the each channel is given by [22, 23]

$$\text{SNR}_j = \frac{\text{SNR}_i}{\sum_{i=1}^{N} |h_{ji}|^2}, \quad i = j, \ldots, N$$

(3)

Here, $\text{SNR}_i$ is the SNR at each receiver when $H$ is unitary, while $\sum_{i=1}^{N} |h_{ji}|^2$ is the amplification factor to the noise, or in other words equivalent power penalty to the signal to maintain the SNR of unitary transmission.

3. Experimental results and discussions

3.1 Fiber-only transmission scenario

Figure 2 solid lines show the measured CN for the 3x3 MIMO channel matrix versus different carrier frequency, when the RF input power is 0dBm. Because the transmission is non-unitary, all the CN values of MMF RoF link are greater than 0dB, but significantly less than 20dB within the entire range of 0-6GHz. The results have preliminary proven that the MMF channel would be better enough to support MIMO transmission for most of today’s wireless services. Using Eq. (3), the corresponding power penalties were also calculated, as shown in Fig. 2 via dash lines. It is clear that the increased CN is accompanied by noise enhancement and SNR degradation, thus it needs higher power penalty to maintain the system performance.
Although IEEE 802.11ac standard only working at 5GHz band in practice, considering most modern WLAN standards are also operating in 2.4GHz band, we choose 2.4GHz and 5.8GHz both as the specific carrier frequencies to perform a series of detailed measurements.

Figure 3 shows the normalized frequency response of the channel coefficients and the associated CN as a function of subcarrier frequency at 2.4GHz and 5.8GHz, respectively. In physical layer (PHY), IEEE 802.11ac standard uses 245-subcarrier orthogonal frequency division multiplexing (OFDM) spaced 312.5 kHz for 80MHz channel bandwidth. It is obvious that, the nine channel coefficients for the 3x3 MIMO operating fluctuate flatly over all subcarriers, so does the associated CN calculated from the complex channel coefficients before normalizing. The upper three figures respectively represent the measured results for the carrier frequency of 2.4GHz with B2B, 200m, 1km MMF links. The respective averaged CN values over 245 OFDM subcarriers are 10.23dB, 10.18dB and 9.85dB, with corresponding power penalty values of 4.02dB, 3.83dB and 3.52dB. The lower three figures respectively represent the measured results at 5.8GHz with B2B, 200m and 1km MMF links. The respective averaged CN values over 245 OFDM subcarriers are 11.38dB, 9.90dB and 9.34dB, with corresponding power penalty values of 4.81dB, 3.40dB and 3.19dB. It is consistent with the previous analysis that a well-conditioned MIMO channel has a smaller SNR reduction.
Fig. 3. Measured channel coefficients and associated CNs as a function of subcarrier frequency within 80MHz bandwidth for different RoF links and carrier frequencies: (a) B2B at 2.4GHz; (b) 200m at 2.4GHz; (c) 1km at 2.4GHz; (d) B2B at 5.8GHz; (e) 200m at 5.8GHz; (f) 1km at 5.8GHz.

Figures 4(a) and 5(a) shows the measured EVM performance to qualify the recovered signals under different RF input power. The EVM at each point is calculated with the root mean square (RMS) of the three spatial stream EVM values. For the LD we used, normally when the RF input power is around 0dBm or less, it works at the linear region where the system performance is dominantly influenced by SNR. Thus, when increasing the RF input power, the EVM performance is also improved. But as the RF input power keeps increasing to greater than 0dBm, the LDs will gradually go into its nonlinear region, then the system performance will become severely affected by the degree of LDs’ nonlinearity, instead of SNR. The stronger the nonlinear effects, the larger the EVM value is. Comparing all the three curves, we could find that as the fiber length increased, the EVM performance deteriorate more quickly, in particular for 1km fiber link. In the authors’ view such a behavior follows from the modal noise. Due to the intermodal interference, the coherent source generates a speckle pattern at the output plane of the MMF [24]. Since the mode phase is very sensitive to the changed temperature and perturbations on fiber, the speckle pattern is thus constantly fluctuating over time. However, the mismatch of core diameter of MMF and FMF makes the MMF-FMF structure at the receiver side behave like a spatial filtering that only transmits part of this pattern. Therefore, the optical power at the output of PL-DeMux will fluctuate along time. As the fiber length increased, the power fluctuation will become stronger and faster, thus resulting in a more severe performance degradation. Given the EVM threshold of 4.47% defined in WLAN standard for 64-QAM with 5/6 coding rate [25], the link dynamic range for B2B, 200m and 1km MMF link are 20.75dB, 20.73dB, 14.72dB at 2.4GHz, and similarly, the corresponding values at 5.8GHz are 17.29dB, 16.88dB, 11.80dB respectively. Figures 4(b) and 5(b) show the measured constellation diagrams for 200m and 1km MMF link where the links attain their best EVM performance. Evidently, all MIMO streams can be recovered with high quality.
3.2 Fiber-wireless hybrid transmission scenario

Furthermore, we also build a line-of-sight (LOS) wireless environment to investigate the system performance (seen in Fig. 1(a)). In this experimental setup, the distance between every pair transmitting and receiving antennas is 1m and the separation for the transmitting/receiving antennas is 0.1m. The output optical power of lasers was changed by three variable optical attenuators (VOAs) with 1dB insertion loss placed after the LDs. The maximum optical tx power is 6.50dBm. The optimal RF input power at the input of the LDs were set as 0dBm. Three 25dB-gain PAs were used after each PD to compensate for the free space path loss of wireless links. It needs to emphasize that, the experiment was conducted in a comprehensive office building of scientific research, where several kinds of standardized wireless signals are simultaneously existed everywhere, especially for Wi-Fi working at 2.4GHz and 5.8GHz. In order to avoid these wireless interferences, we chose 2.7GHz as the carrier frequency, rather than 2.4GHz and 5.8GHz.
Figures 6 and 7 show the normalized frequency responses and associated CNs for B2B and 200m MMF link with different optical tx power, respectively. Owing to the more complicated multipath propagation in air environment, both the nine channel coefficients and CNs in each figure vary with the subcarrier frequency, but the overall trend is roughly consistent. Combined with the preceding analysis, it is apparent that the CNs for the fiber-wireless hybrid RoF link is much greater than that of fiber-only RoF link. However, it still remains in the acceptable range of under 20dB.

Figure 8 shows the measured EVM performance versus different optical tx power. Compared to B2B scenario, 200m MMF link presents a nearly identical EVM performance with no obvious deterioration. From the two curves, we can observed that the required minimum optical tx power at the EVM limit for this link is around −0.5dBm. The received
constellations for the three spatial streams with 200m MMF link followed by 1m air distance are depicted as the insets.

Fig. 8. EVM performance of fiber-wireless hybrid transmission for different optical tx power.

4. Conclusion

In this paper, we experimentally demonstrate SDM transmission of IEEE 802.11ac-compliant 3-spatial-stream WLAN signals over 3 spatial modes of conventional 50um GI-MMF employing non-mode-selective 3D-waveguide PL. The results are as expected that, SDM-based MMF link could offer a CN< 20dB well-conditioned MIMO channel over up to 1km fiber length within 0-6GHz, achieving as low as 2.38%, 2.97% and 2.11% EVM performance for 1km MMF link at 2.4GHz, 5.8GHz, and 200m MMF link followed by 1m air distance at 2.7GHz, respectively. These results indicate the possibility to distribute wireless MIMO signals over existing in-building commercially-available MMFs with enormous cost-saving.

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