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MIMO-OFDM WDM PON with DM-VCSEL for femtocells application

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Abstract: We report on experimental demonstration of 2x2 MIMO-OFDM 5.6-GHz radio over fiber signaling over 20 km WDM-PON with directly modulated (DM) VCSELs for femtocells application. MIMO-OFDM algorithms effectively compensate for impairments in the wireless link. Error-free signal demodulation of 64 subcarrier 4-QAM signals modulated at 198.5 Mb/s net data rate is achieved after fiber and 2 m indoor wireless transmission. We report BER of 7×10^{-3} at the receiver for 16-QAM signals modulated at 397 Mb/s after 1 m of wireless transmission. Performance dependence on different wireless transmission path lengths, antenna separation, and number of subcarriers have been investigated.

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1. Introduction

Wireless networks based on radio over fiber (RoF) technologies have been proposed as a promising cost effective solution to meet ever increasing user demands for high data rate and mobility. Since it was first demonstrated for cordless and mobile telephone services in 1990 [1], extensive research has been carried out to investigate its limitation and develop new high performance RoF technologies. Multiple input multiple output (MIMO) is widely used to increase wireless bit rates [2] and improve larger area coverage than traditional single input single output (SISO) antennas. Such multiple antenna techniques, however, present a challenge for RoF systems, which have to ensure clean transmission of multiple signals between elements of the antenna array, and must mitigate signal path impairments which introduce crosstalk, attenuation and multipath fading [3]. Sophisticated receiver algorithms have to be implemented and receiver components synchronization needs to be very accurate to overcome these path-dependent effects [4].

Orthogonal frequency division multiplexing (OFDM) has emerged as one of the leading modulation techniques in the wireless domain. The combination of OFDM with MIMO provides an attractive solution because OFDM potentially offers high spectral efficiency and resilience to multipath fading. Specifically, MIMO-OFDM signals can be processed using relatively straightforward matrix algebra, and seems to be a promising candidate for RoF system because of the simultaneous compensation of multipath fading in wireless channels and dispersion effects in optical fiber links [5]. Furthermore, OFDM is a future candidate for femtocell application [6] because the interference can be reduced by using more frequency resources. In addition, for multi-carrier systems like OFDM, a large computational complexity will be introduced by using the classical MIMO channel estimation method based on the butterfly structure because an adaptive filter needs to be assigned for each OFDM subcarrier. Consequently, a training-based channel estimation method has the relatively low computational complexity at the receiver [7] and draws more interest in analyzing multi-carrier systems.

The goal of femtocells is to provide reliable communication using existing broadband internet connection and improve the indoor coverage [8]. Femtocells provide many benefits in terms of cost, power, capacity and scalability [6]. However, there are many challenges in the deployment of femtocell such as network architecture, allocation of spectrum resources and the avoidance of electromagnetic interference. One of the main impairments of wireless channels is frequency selective fading. It is especially so in intense multipath environments where the behaviour of the channel differs between different frequencies. This is particularly true in indoor and urban environments. The combination of the throughput enhancement [9] and path diversity [10] offered by MIMO technologies with the robustness of OFDM against frequency selective fading is regarded a very promising basis for femtocell multi-user wireless transmission applications [6]. A small sized femtocell access point (FAP) is usually located in a home or office where it also linked to a broadband internet connection as shown in Fig. 1. The recent explosive growth of the internet has triggered the introduction of a broadband access network based on fiber to-the-office (FTTO) and fiber-to-the-home (FTTH). Therefore, the increasing of wireless demands makes RoF as an enabling technology to support femtocell in the WDM network [11] for FTTH and FTTO network.

Wavelength division multiplexed passive optical network (WDM-PON) systems can transparently deliver radio frequency signaling required to support hybrid fixed and wireless access networking systems. WDM-PON technology is therefore expected to further improve

the throughput in the wireless service area covered by RoF-MIMO antennas [12]. Previously, distributed feedback (DFB) laser diodes have been suggested for use in WDM-PON but have only gained limited industry attention because of the high cost [13]. Directly modulated

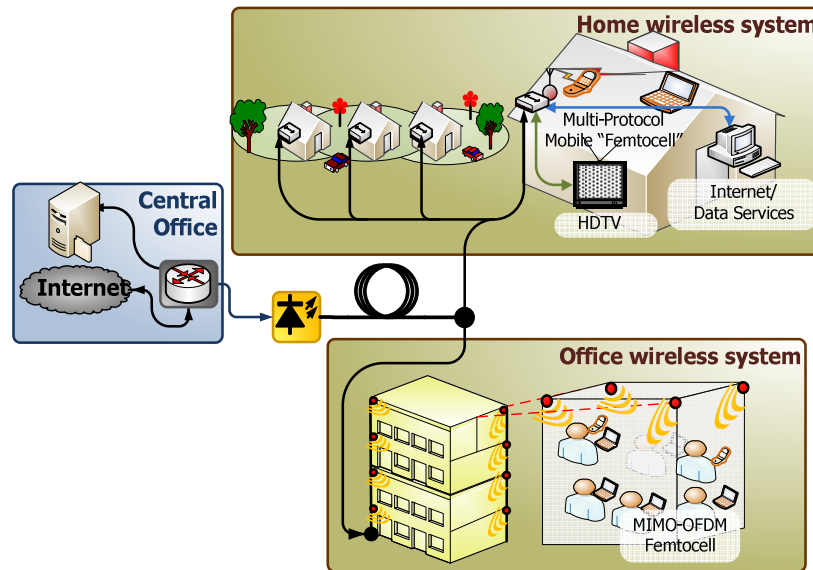


Fig. 1. Femtocell in home and office environment for radio over fiber network.

vertical-cavity surface-emitting lasers (VCSELs) have emerged as an attractive solution for WDM-PON due to the cost effective production, low power consumption [14], and low threshold and driving current operation [15]. Simulation work regarding integration of MIMO-OFDM technology with RoF has been presented in [3], and regarding integration of dense wavelength division multiplexing (DWDM) with MIMO-OFDM in [16]. The experimental work in [17] demonstrates the MIMO RoF concepts, but implemented separate fibers for each remote access unit (RAU).

Previously in [18], we have successfully demonstrated DM-VCSEL 2 x 2 MIMO OFDM over WDM-PON. The OFDM-MIMO training sequence algorithm are applied to compensate the receiver complexity will be further described in this paper. We give an overview of the experimental setup and present the performance evaluation and discussion. Additionally we add investigations of the influence on performance by the number of subcarriers in the OFDM signals, and we present initial experimental results of 16-QAM OFDM-MIMO at 397 Mb/s.

2. OFDM-MIMO training sequence algorithm

Multiple transmit-and-receive antennas in OFDM systems can improve communication quality and capacity. For the OFDM systems with multiple transmitter antennas, each tone at each receiver antenna is associated with multiple channel parameters, which makes channel estimation difficult. Fortunately, channel parameters for different tones of each channel are correlated and the channel estimators are based on this correlation. Several channel estimation schemes have been proposed for the OFDM systems with multiple transmit-and-receive antennas for space diversity, or (MIMO) systems for wireless data access [19]. Channel estimation is important for signal demodulation in MIMO systems, in particular when a large number of subcarriers and advanced multiplexing technique are employed. The training-based channel estimation method is computationally efficient because of its simple expression [20]. However, their transmission efficiencies are reduced due to required overhead of training symbols such as preamble or pilot tones that are transmitted in addition to data symbol. In our work we allocated three training symbols in each of the frame. We implemented different

training symbols for each sub-element of the MIMO-OFDM signal. This enables estimation on the receiver side of the MIMO wireless channel response using this MIMO-OFDM algorithm.

3. Experimental setup

Experimental setup of the system is illustrated in Fig. 2. In the central office (CO), two different real valued 64-subcarrier 4-QAM OFDM baseband signals with 198.5 Mb/s net data rate (excluding the training symbols) and 312 MHz of bandwidth are generated by an arbitrary waveform generator (ArbWaveGen). The OFDM symbols are arranged in frames of 10 symbols. The first 3 symbols implement the training sequence, and 10% cyclic prefix is added. A dual channel baseband MIMO-OFDM signal is generated in the ArbWaveGen, which is then up-converted to a 5.65 GHz radio frequency (RF) carrier; the signal in one arm is up-converted using a mixer and the other arm implements RF up-conversion using the vector signal generator (VSG).

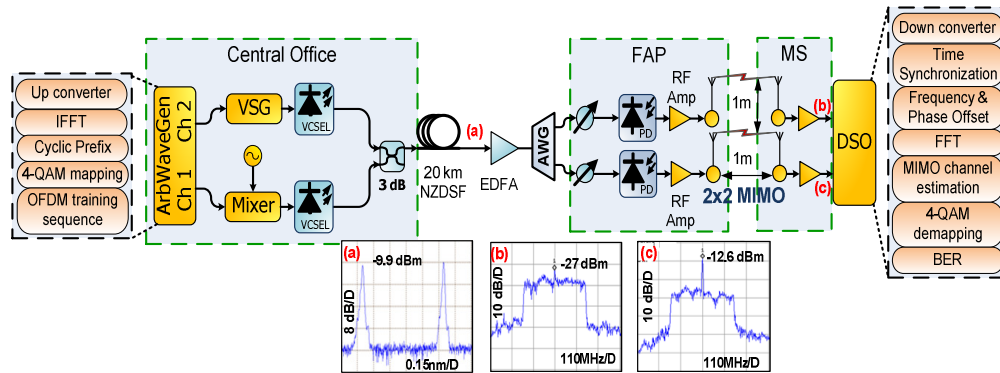


Fig. 2. Experiment setup for all-VCSELs for WDM-PON with 4-QAM OFDM signals over 20 km NZDSF and 2x2 wireless MIMO. RF carrier frequency of 5.65 GHz was used for both branches of the MIMO channel.

Different training sequences are used for each sub-element of the MIMO-OFDM signal; this enables estimation of the MIMO wireless channel response. The electrical MIMO-OFDM signals directly modulate two VCSELs operating at different bias levels to generate different wavelengths of 1535.29 nm and 1536.09 nm. The two optical signals are combined using a 3 dB coupler; they propagate through 20 km non-zero dispersion shifted fiber (NZDSF). The NZDSF is employed due to improved dispersion performance in the PON system [21]. The optical spectrum of the CO transmitter output is shown in Fig. 2(a). After 20 km NZDSF transmission, the downstream WDM signals are divided using an arrayed waveguide grating (AWG). After the photodetector, RF amplifiers boost the signal with 20 dB gain, at the FAP antenna. The wireless signals propagate through 1 meter distance. Elements of the 2x2 antenna array implemented at both femtocell access point (FAP) and mobile station (MS) are vertically spaced by 1 meter; vertical polarization is implemented for the wireless link for femtocell network. At the MS receiver, the signals are captured by two antennas and amplified by a 20 dB gain electrical amplifier. The RF OFDM signals are sampled by a digital sampling scope (DSO), with 20 Gs/s sampling rate. The electrical MIMO-OFDM spectrum is shown in Fig. 2(b) for the VSG and Fig. 2(c) for the mixer.

A digital signal processing (DSP) enabled receiver at the MS uses the different training sequences implemented on sub-elements of the MIMO-OFDM wireless transmission to identify the MIMO signals radiated from each antenna element, and demodulates the OFDM signals. Signal down-conversion, time synchronization, frequency and phase offset removal and fast Fourier transform (FFT) processing are implemented in DSP. Compensation for crosstalk and multipath fading is done using a minimum-mean-square-error (MMSE) algorithm. The bit error rate (BER) is calculated after symbol demapping. Transmission quality was assessed using BER sensitivity to received optical power metric. We consider a

BER of 2×10^{-3} , since forward error correction (FEC) techniques may be applied to obtain error free transmission when the 7% of FEC overhead are taken into account.

4. Results and discussion

Figure 3 presents BER results obtained as the MIMO signal propagates through the system: we distinguish between signal elements upconverted using mixer (solid symbols) and VSG (hollow symbols). Figure 3(a) presents BER variation with received optical power (ROP) at different wireless distances between FAP and MS; results are assessed at 1 m (circle), 2 m (square) and 3 m (triangle). We fixed the separation spacing between the elements of the FAP and MS antenna arrays at 1 meter. The insets show received constellation diagrams observed at the MS; clear 4-QAM OFDM constellations are obtained. The increasing of power penalty is observed as wireless transmission distance increases. With a fixed transmit power, the increased path loss associated with longer wireless transmission lengths results in reduced receiver signal to noise ratio (SNR), leading to increased BER. This agrees well with experimental observations. The MIMO-OFDM signal could be received error free after 2 meters of wireless transmission. This can be clearly seen from the 4-QAM OFDM constellation diagram in Fig. 3(a). After 3 meters wireless transmission, the signals could still be demodulated with a BER below FEC limit of 2×10^{-3} . We observe that the increase of the distance between FAP and MS reduces the performance.

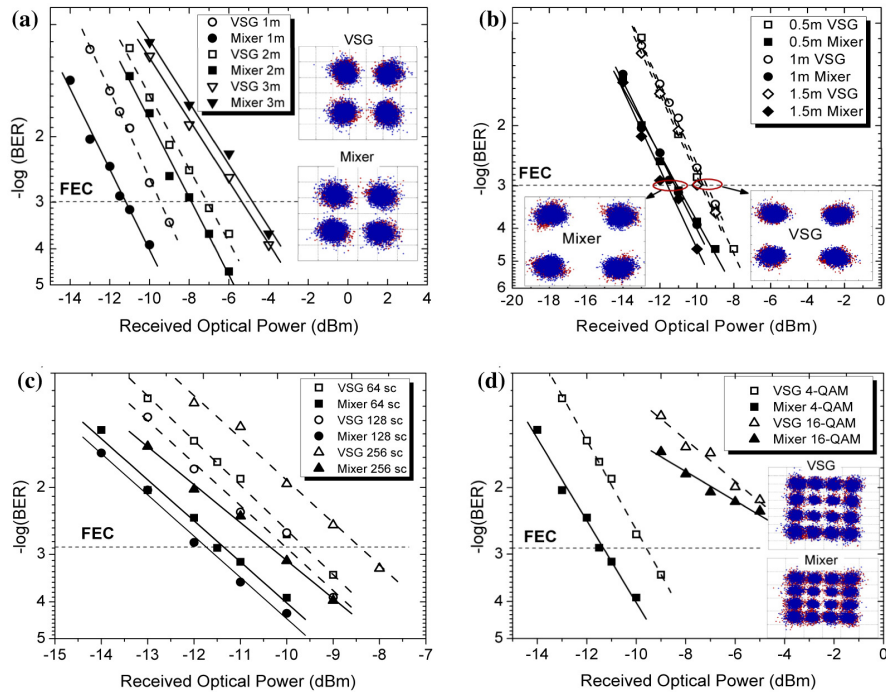


Fig. 3. Showing variation of (a) BER with ROP after fiber transmission, at various distances between RAU and MS; and (b) BER with ROP after fiber transmission, for different antenna separation, with fixed 1 meter distance between RAU and MS. (c) BER with ROP with 4-QAM modulation using different subcarriers: (d) BER with ROP for 4-QAM and 16-QAM modulation scheme with 64 subcarriers and fixed 1 meter distance between RAU and MS. MIMO signal elements which are upconverted using mixer (solid symbols) and VSG (hollow symbols) are identified. Insets show constellation obtained at FEC limit ($BER = 2 \times 10^{-3}$).

After fiber transmission, the effect of antenna separation on performance is assessed by varying the spacing between the elements of the FAP and MS antenna arrays, while preserving 1 m transmission distance between FAP and MS. The results obtained with antenna spacing of 0.5 m (square), 1 m (circle) and 1.5 m (diamond) are presented in Fig. 3(b). We observed similar performance without any penalty for all separations for both

channels in Fig. 3(b). This shows that the good transmission was obtained at different antenna separation higher than 0.5m. 4-QAM constellation diagrams for 0.5 m antenna separation are shown for both channels in the Fig. 3(b); these obtained at BER 2×10^{-3} .

Figure 3(c) shows the different number of subcarriers transmitted in the system over wireless transmission with 4-QAM modulation scheme. The 64 subcarriers represent by (square), 128 subcarriers (circle) and 256 subcarriers (triangle). Theoretically increasing the number of subcarriers should be able to give better performance in a sense that we will be able to handle larger delay spreads. This statement can be supported by looking at the Fig. 3(c) when the number of subcarriers increased from 64 to 128 the ROP performance become better. But several typical implementation problems arise with a large number of subcarriers. When we have large numbers of subcarriers, we have to assign the subcarrier frequencies very close to each other with same amount of bandwidth. We know that the receiver needs to synchronize itself to the carrier frequency very well, otherwise a comparatively small carrier frequency offset may cause a large frequency mismatch between neighboring subcarriers. When the subcarrier spacing is very small, the receiver synchronization components need to be very accurate, which is still not possible with low-cost RF hardware [4]. We observe that at 256 subcarriers, the performance is degraded. We attribute this degradation to a combination of RoF nonlinearities and receiver synchronization to the narrowly spaced subcarriers. Thus, a reasonable trade-off between the subcarrier spacing and the number of subcarriers must be achieved.

A performance comparison between different modulation scheme also been done in this experiment. Figure 3(d) shows the performance evaluation of 4-QAM (square) and 16-QAM (triangle). The insets show received constellation diagrams observed at the MS; 16-QAM OFDM constellations are obtained at BER of 7×10^{-3} with 397Mb/s net data rate. At higher amplitudes, the constellation symbols are dispersed widely compared with the one at the center because the nonlinearity of the VCSELs. The BER curves for 16-QAM also do not reach the standard FEC limit because the higher the modulation format requires higher power to increase the signal to noise ratio (SNR).

5. Conclusions

We have presented the MIMO-OFDM signal distribution in a WDM-PON system using DM-VCSELs optical sources with wireless MIMO transmission. This provides potentially a cost effective solution for future femtocells access networks. MIMO-OFDM algorithms effectively compensate for impairments in the wireless link. We also investigate the effects of various wireless transmission path lengths, antenna separation, various number of subcarriers in OFDM and different modulation schemes to see the ability of the MIMO-OFDM algorithm to estimate the MIMO wireless channel response. We report error free transmission after 20 km NZDSF and 2 meter 2x2 wireless MIMO-OFDM. The 4-QAM signals modulated at 198.5Mb/s net data rate with 5.65 GHz radio over fiber signaling transmission for WDM-PON system. For 16-QAM, after 1m wireless transmission a BER of 7×10^{-3} is reported at the receiver. MIMO-OFDM has a good potential to be implemented for indoor systems because the complexity at the receiver side can be reduced with training sequence algorithm. The maximum number of subcarriers that are allowed in this system is 128 because of the tradeoff between the subcarrier spacing and the number of subcarriers must be achieved. However, for higher modulation technique, powerful receiver algorithm is required to synchronize the signals and higher power to drive the transmission signal. Future work needs to be done for the upstream to demonstrate the bidirectional WDM PON with MIMO in femtocell application. We believe this work can be a potentially attractive candidate for future femtocells network especially for indoor office environment.