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Synchronized signaling delivery for broadband 60 GHz in-building optical wireless network based on digital frequency division multiplexing and digital Nyquist shaping

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Abstract: A simple and low-cost synchronized signaling delivery scheme has been proposed for a 60 GHz in-building optical wireless network with 12.7Gbps throughput based on digital frequency division multiplexing and digital Nyquist shaping.

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1. Introduction

The current explosion of communication traffic volume is driven by an insatiable appetite for high speed internet connectivity and video-based content delivery to wireless and mobile terminal users especially for in-building network scenarios. Increasing carrier frequency to 60 GHz millimeter-wave with 7 GHz license-free band is a promising candidate for very high throughput (VHT) wireless service. Considering the high air-link loss at 60 GHz, the radio-over-fiber (RoF) technology is proposed to extend the reach of 60 GHz wireless signal for the ubiquitous wireless service coverage [1–4]. Moreover, in-building networks should provide the control signaling channel for functions related to data communication like optical routing, and also for the sensors and actuators served for in-building automation. Therefore, it is pivotal to have signaling information delivery for in-building networks. The bit rate of signaling channel is usually set to 1% of user data to allow enough budgets for future applications. Traditionally, the signaling data is embedded into designated time slots. The process of signaling insertion and detection is consequently operated at the full line rate speed. For RoF systems, one more process of down conversion from radio frequency to baseband is required. This will introduce additional complexity and instability to systems. A separate wavelength for signaling can encounter such problem; but such system will be more complicated and extra synchronization is of demand. In this paper, we propose a simple low-

cost signaling insertion and detection scheme having capability to achieve synchronization through digital frequency division multiplexing (D-FDM). To suppress the inter-channel interference (ICI) between signaling and user data, digital Nyquist shaping is employed.

2. Operation principle

2.1 Digital frequency division multiplexing (D-FDM) and digital Nyquist shaping

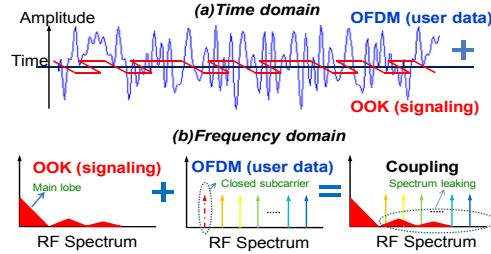


Fig. 1. Principle of D-FDM for: (a) time domain and (b) frequency domain.

The principle of D-FDM is depicted in Fig. 1. Low speed Polar non-return-to-zero (Polar-NRZ) signal for control signaling is coupled with OFDM signal by simply adding their digital values in time domain before digital-to-analog conversion shown in Fig. 1(a). This process will synchronize the signaling with OFDM signal, which is extremely important to time-varying application like optical routing. To reduce ICI, as shown in Fig. 1(b), the OFDM subcarriers overlapping main lobe of Polar-NRZ spectrum are reserved (carrying no bits). This is because the main power of Polar-NRZ signal is within its main lobe. To further reduce ICI, the digital Nyquist shaping is employed. Nyquist shaping is used to cut off or roll off unwanted spectrum without additional inter-symbol interference at sampling instants. The digital Nyquist shaping is achieved by convolving normalized sinc function $f(t/T) = \sin(\pi t/T)/(\pi t/T)$ with Polar-NRZ signal. Its cutoff frequency is $f_{\text{cutoff}} = 0.5 \times T^{-1}$, where T is the period of symbol rate of Polar-NRZ signal. For practical implementation of the sinc function, its tails are truncated to reduce the number of discrete samples. The sinc function is chosen since it can completely suppress unwanted spectrum and introduce little distortion to the remained part. The waveforms and RF spectrum with and without Nyquist shaping are shown in Fig. 2.

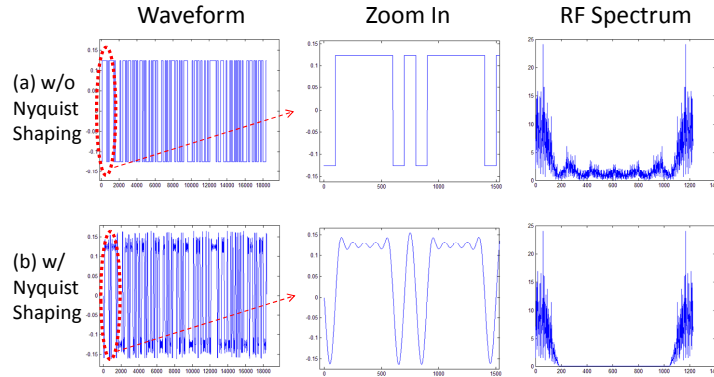


Fig. 2. Process of Nyquist shaping: (a) without and (b) with Nyquist shaping

Without Nyquist shaping, the waveform of Polar-NRZ signal is rectangular and its spectrum is extended far beyond 1st null. With Nyquist shaping, the spectrum of Polar-NRZ signal is well confined between 0 Hz - 1st null. To avoid complicated convolution process,

waveform of convolved “1” is placed in the look-up table and recalled when “1” appears. Its inverted waveform is recalled when “-1” appears. This process is for downlinks, and analog FDM can be used for uplinks.

2.2 Low frequency detection for RoF signal

In this section, a mathematic model will be built to analyze the low frequency detection (LFD) of the RoF signal. The electrical field of optical mm-wave with OFDM signal modulated can be expressed as [5]: $E(t) = [A_{+1} \times \cos(\omega_o + \omega_m)t + A_{-1} \times \cos(\omega_o - \omega_m)t] \times (1 + \gamma S(t))$, where A_{+1} and A_{-1} denote amplitudes of upper and lower sidebands, respectively. The ω_o and ω_m denote angular frequency of optical carrier and driving LO. Optical modulation index is denoted by γ . $S(t)$ is the presentation of OFDM signal, which can be expressed as

$$S(t) = \sum_{k=1}^N (a_k \cos k \Omega t + b_k \sin k \Omega t) \quad (1)$$

where N denotes the number of subcarriers in a OFDM symbol, Ω is the 1st sub-carrier frequency, $k \Omega$ is the frequency of k_{th} subcarrier. a_k and b_k represent complex symbols of in-phase and quadrature components for the k_{th} subcarrier. After square-law detection of photodiode, the output current can be expressed as [5]:

$$I(t) = \frac{1}{2} \mu (A_{+1}^2 + A_{-1}^2) [1 + 2\gamma S(t) + \gamma^2 S^2(t)] + \mu A_{+1} A_{-1} \cos(2\omega_m t) [1 + 2\gamma S(t) + \gamma^2 S^2(t)] \quad (2)$$

It is obvious that the baseband (BB) OFDM is identical to OFDM at mm-wave. Thus we can detect the BB OFDM to get signaling data. As discussed in section 2.1, the signaling data is inserted in the lower frequency part of BB OFDM and thus a low speed (100MHz level) PD can detect the signaling data.

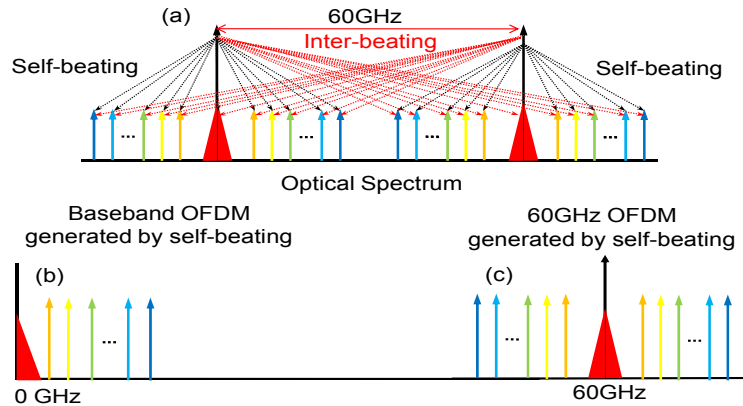


Fig. 3. Beating process and low frequency detection: (a) optical spectrum of data modulated optical mm-wave; (b) RF spectrum of detected BB signal; (c) RF spectrum of detected 60 GHz signal.

The principle of low frequency detection is illustrated in Fig. 3. The optical spectrum of 60 GHz optical mm-wave with OFDM signal modulated is principally depicted in Fig. 3(a). The two vertical black arrows denote two sidebands of optical mm-wave. Colored arrows around them denote subcarriers of modulated OFDM signal. The beating process includes two parts, namely, self-beating and inter-beating. Self-beating refers to beating between one sideband and the subcarriers around it, which generates baseband (BB) OFDM signal shown in Fig. 3(b). The self-beating process allows low frequency detection for OFDM signal on 60

GHz optical mm-wave. Inter-beating refers to beating between one sideband and subcarriers around the other sideband which generates 60 GHz OFDM signal shown in Fig. 3(c). Since signaling (Polar-NRZ signal) is inserted in the low frequency part of BB OFDM as shown in Fig. 3(b), PD bandwidth required for detection is only a little higher than signaling bandwidth. The detected signaling can be further processed using low speed logical circuit. Thus high-speed PD and logical circuit, and down conversion scheme can be avoided.

3. Experimental setup, results and discussion

Figure 4 shows the experimental setup to demonstrate proposed signaling insertion and detection scheme in a 60 GHz OFDM-RoF system. The OFDM signal is generated from the Tektronix AWG 7122B at 10 GSa/s. The size of IFFT is 256 and the subcarriers used for data, pilots and high frequency guard interval are 192, 8, and 56, respectively. The subcarriers are arranged to satisfy the Hermitian symmetry with respect to their complex conjugate counterparts to allow the real-valued IFFT output. The period of OFDM symbol is 25.6 ns. The symbol rate for each subcarrier is 39 MSps. 16QAM is employed in subcarrier modulation. The cyclic prefix is 1/8 of an OFDM period, which corresponds to 32 samples in every OFDM symbol. One training symbol is inserted in front of 64 data OFDM symbols for timing and channel estimation. The net bit rate of OFDM signal is 12.72 Gbps. The bit rate of Polar-NRZ signal is 100 Mbps and one Polar-NRZ symbol lasts for 10ns. The fcutoff of sinc function is set to 100MHz and its digital waveform is sampled at $f = 100 \times \text{fcutoff}$ agreeing with the sample rate of OFDM signal. The truncation size of sinc function is $10 \times T$. The three lowest frequency subcarriers are closed reserving 117 MHz bandwidth.

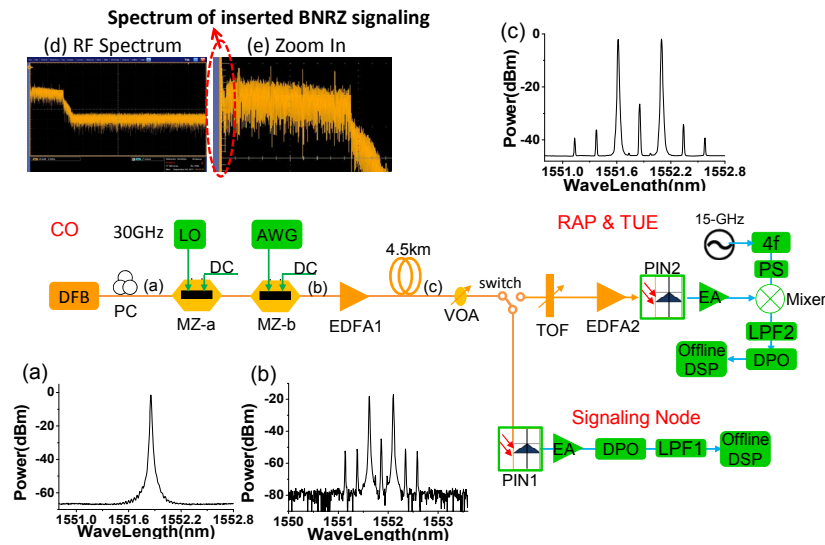


Fig. 4. Experimental setup and measured results: (a)-(c): measured optical spectrum; (d)-(e): measured RF spectrum.

The amplitude (V_{pp}) of Polar-NRZ signal is set to 30 mV while the amplitude (V_{pp}) of OFDM signal is 1 V. The RF spectrums of the combined signal of Polar-NRZ and OFDM are depicted in Fig. 4(a). DFB-laser with 1 dBm launch power, is modulated to generate 60 GHz optical mm-wave via a MZM (MZ-a) biased at null point with 30 GHz electrical local oscillator (LO). A MZM (MZ-b) is used for OFDM signal modulation. The optical spectrum of OFDM modulated optical mm-wave is depicted in Fig. 4(b). The optical signal is amplified to 0 dBm before launched to 4.5 km single mode fiber (SMF). after transmission, its received optical power (ROP) is -1.5 dBm with optical spectrum shown in Fig. 4(c). An variable optical attenuator (VOA) is used to control ROP for measurement. Two optical receivers are

constructed for both signaling node, and antenna point (RAP) and terminal users (TU). The signaling node receiver comprises a 10 GHz photo-diode (PD, PIN-1) and a 6 GHz low noise amplifier (LNA1). The signal after LNA1 is filtered by a 4-order Butterworth LPF (LPF1) with 100 MHz 1 dB pass bandwidth and then sampled at 1.25 GSample/s by a real time oscilloscope (DPO). The RAP-TU receiver contains a preamplifier (EDFA-2) and a 75 GHz PD (PIN-2). After PD, electrical 60 GHz OFDM is generated and amplified by an 8 GHz narrow band amplifier centralized at 60 GHz. The 60 GHz OFDM is then down converted via a 60 GHz electrical mixer with 60 GHz LO. The 60 GHz LO is generated from an electrical frequency quadruple multiplier cascaded with a 15 GHz microwave source. An electrical phase shifter (PS) is used to adjust the phase of 60GHz LO. A LNA (LNA2) is followed by a 6GHz low-pass filter (LPF2) to retrieve BB OFDM signal which is further sampled at 25Gsample/s by a DPO and processed off-line. The system evaluation is carried out to assess the followings: (i) The impact to OFDM signal induced by signaling insertion; (iii) Evaluation of low-pass filters for signaling detection; (ii) The EVM performance of OFDM before and after fiber transmission; (iv) The Q factor of signaling data before and after fiber transmission. The constellations of OFDM signal over 4.5 km SMF are depicted in Fig. 5 with ROP of -16 dBm, which include OFDM signal (a) without Polar-NRZ, (b) with no-shaped Polar-NRZ and (c) with Nyquist shaped Polar-NRZ. Comparing Fig. 6(a)-6(b), it is evident that the inserted Polar-NRZ introduce interference to the OFDM signal whereas for the Nyquist shaped Polar-NRZ, the interference is not obvious.

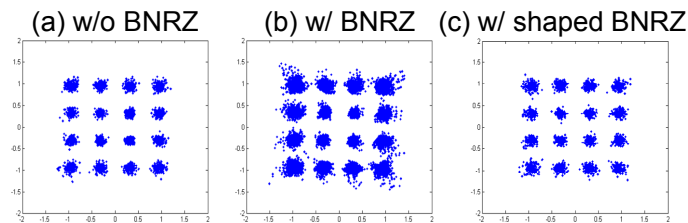


Fig. 5. Constellations of OFDM signals (a) without and (b) with Polar-NRZ, (c) with Nyquist shaped Polar-NRZ

Here we discussed the detection performance of three traditional analog LPFs/HPFs including Butterworth LPF/HPF, Chebyshev I LPF/HPF and elliptic LPF/HPF with one to four orders. To exactly present the properties of such analog filters, all these filters are realized in the digital domain by using direct-form IIR. Their 1 dB pass band frequencies are all 100 MHz equal to first null point of the Polar-NRZ signal. The bandwidth of the combined signal is 4 GHz and sampled by a 50 GSa/s RTO. The oversample is helpful to accurately perform the analog filtering. The signaling inserted OFDM signal at 60 GHz optical mm-wave over 4.5 km single mode fiber (SMF-28) is detected and separated by using different LPFs and HPFs mentioned above. The signal is detected at received power of -16 dBm. As shown in Fig. 6, for all types of LPFs, the eye diagrams get clearer as the orders increase because the high order LPFs can better suppress the out band interference. The background color is intentionally set to blue for illustration purpose. The ripple of '1' line and '0' line in the eye diagrams declines as long as the out band interference reduces. This will reduce the decision error probability. On the other hand, the rise and fall time is another issue related to the eye diagram quality. As shown in Fig. 6, Butterworth LPFs retain the shortest rise and fall time for 2 to 4 orders. Thus the following measurement for signaling data is based on 4th order Butterworth filter.

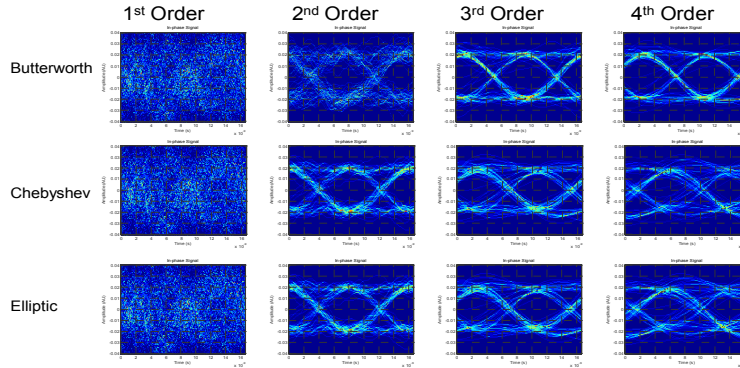


Fig. 6. The eye diagrams of the signaling inserted OFDM signal at 60 GHz optical mm-wave over 4.5 km SMF with different detection low pass filters.

The EVMs of OFDM signal with and without inserted Polar-NRZ signal are measured for optical BTB and over 4.5 km SMF. Plots are shown in Fig. 7(a). No high pass filter is implemented to suppress the Polar-NRZ signal. The Polar-NRZ insertion induced power penalties for EVM of 11.2% are both 0.8 dB for BTB and 4.5 km transmission demonstrating that this signaling insertion and detection scheme does not increase system penalty considerably. The power penalty for EVM of 11.2% is 1.7 dB after 4.5 km transmission for Polar-NRZ inserted OFDM. This is mainly due to the frequency selective fading for double sideband modulation. The curves of Q factor of Polar-NRZ signal versus ROP for BTB and 4.5 km SMF transmission are depicted in Fig. 7(b). The power penalty at $Q = 5.5$ (corresponding BER is about 1.95×10^{-8}) is 1.2 dB for 4.5 km SMF transmission.

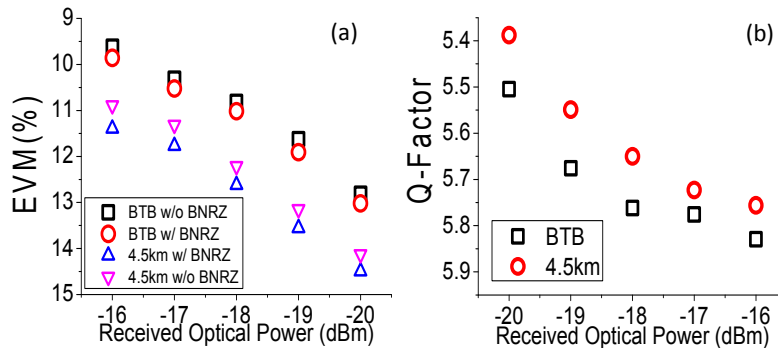


Fig. 7. Measured system performance for BTB and 4.5 km SMF transmission: (a) EVM for user data, (b) Q factor for signaling data

4. Conclusion

We demonstrated a signaling insertion and detection scheme based on digital frequency multiplexing and Nyquist shaping for 12.7 Gbps throughput 60 GHz in-building optical wireless networks. The power penalty of signaling insertion is less than 0.8 dB. Based on achieved results, we believe the proposed scheme can provide reliable and low-cost signaling delivery channel for 60 GHz in-building optical wireless network.

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