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Physical Layer 1 Gb/s Secret Wireless Data Transmission at W-Band using a Photonic Duffing System

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Abstract: First demonstration of photonic-enabled 1 Gb/s secret wireless data transmission at W-band based on Duffing chaotic systems. The presented results validate a new methodology to increase security by exploiting chaos for gigabit data transmissions.

OCIS codes: (060.4510) Optical communications; (060.5625) Radio frequency photonics

1. Introduction

As wireless communications have become ubiquitous and essential to both businesses and consumers, the security of such systems has come into focus [1]. The broadcasting nature of wireless communications entails specific security challenges that must be addressed in order to guarantee data confidentiality. Traditional schemes are based on data encryption, where a secret key is used to cipher a message in such a way that a potential eavesdropper is unable to decode and/or get any information [1]. Latency requirements of emerging applications have put physical layer approaches on center stage, providing lower processing latencies and protocol transparency. An example is the use of very directive short range point-to-point millimeter-wave (mm-wave) communications systems (i.e. 30–300 GHz) [2]. Another interesting approach is the use of chaotic systems, the behavior of which cannot be predicted, unless its exact initial conditions are known a-priori [3]. Among chaotic approaches, a Duffing oscillator system (DOS) has successfully been used to codify binary signals for transmission and the same system has been reused in the receiver to decode the received signals [4].

In this paper, we propose and experimentally validate a secure wireless transmission based on the nonlinear second-order differential Duffing equation. We present two different ways of transmitting and receiving our proposed scheme achieving net bitrates up to 1 Gb/s. To the extent of our knowledge, this is the first time that a secret gigabit W-band hybrid photonic wireless data transmission is achieved by using a DOS to encode binary data streams.

2. Duffing Oscillator System

The DOS is based on the nonlinear second-order differential Duffing Eq. (1). Depending on the driving signals applied to the system governed by this equation, its behavior can change from periodic stable states to chaotic ones.

$$\ddot{x}(t) + b\dot{x}(t) - x(t) + x^3(t) = \gamma \cos(t) \quad (1)$$

The driving signal of the DOS is γ , e.g., bipolar pseudo-random binary sequences (PRBSs). By means of this driving signal, it is possible to map binary sequences into the different states of a DOS. The phase-plane diagrams of the two states which are used to transmit ‘0’ and ‘1’ (i.e., homoclinic orbit and chaos, respectively) are shown in Fig. 2(a) and Fig. 3(a). It is to be noted that these diagrams are already quantized by the sampling frequency of the arbitrary waveform generator (AWG) used in experiments. In these diagrams the x-axis correspond to the function $x(t)$, and the y-axis correspond to its first derivative $\dot{x}(t)$. However, the DOS described by Eq. (1) is limited and can only be driven by low-frequency signals. To make this system suitable for high-frequency signals, i.e., high data rates, and maintain its state of chaos, it can be modified by performing a change of variable [4]:

$$\frac{\dot{y}(t')}{\omega_d^2} + b \frac{\dot{y}(t')}{\omega_d} - y(t') + y^3(t') = \gamma \cos(\omega_d t') \quad (2)$$

where $t = \omega_d t'$ and $x(t) = x(\omega_d t') = y(t')$. The system described by Eq. (2) has no restrictions on the oscillating frequency ω_d enabling the DOS to run at frequencies of several GHz and therefore suitable for gigabit data rates [5].

3. Experimental Setup

We propose two schemes for Duffing signaling. The first is simpler and is based on optical intensity-modulation/direct-detection (IM/DD) and an RF envelope detector (ED) at the receiver. Further, to add security to

our system, in the second scheme an optical I/Q modulator is used, enabling the transmission of different signal in the in-phase (I) and quadrature (Q) components. In one of the components the actual data (i.e., as in the first setup) is transmitted, while the other carries a decoy signal, masking the actual data. At the receiver, to retrieve the I and Q components, instead of an ED, a mixer and a local oscillator are used to down-convert the received signal to an intermediate frequency (IF). Subsequently, by means of digital signal processing (DSP), carrier recovery and demodulation are performed.

Figure 1 shows the experimental setup used for optical signal generation, wireless transmission, and signal recovery. In both setups, at the transmitter side, a free running external cavity laser (ECL) at 1550 nm is used as light source, the output of which is modulated by a MZM. By driving the MZM with a sinusoidal tone of 44 GHz, generated by a vector signal generator (VSG), two optical lines with a separation of 88 GHz are obtained. An erbium doped fiber amplifier (EDFA) is used to amplify the signal and subsequently an arrayed waveguide grating (AWGG) separates the two optical lines to enable the modulation of one thereof.

Duffing signals are generated by a 25 GHz AWG at a sampling rate of 65 GSa/s. In our first setup, one channel of the AWG is used to drive a second MZM and in the second setup two channels of the AWG are used to drive the I and Q inputs of an I/Q modulator. The outputs of the AWG are amplified with driver amplifiers to obtain suitable voltage magnitudes to drive the modulators. A variable optical attenuator (VOA) is used to set equal power in both the unmodulated and modulated optical signals and an optical coupler combines the two. A second EDFA and VOA are used to set the launch power into 10 km of standard single-mode fiber (SMF). After fiber transmission, a high-speed photodiode (PD) converts the optical signal to the electrical domain, where the signal is amplified by a 10 dB medium power amplifier (MPA) before wireless transmission over 2 m. A pair of horn antennas, with 20 dBi gain each, are used for wireless transmission. At the receiver, the transmitted signal is amplified by a 20 dB low noise amplifier (LNA). After amplification, in our first setup, an ED with a 3 dB bandwidth of 3 GHz is used to convert the transmitted signal to baseband. In our second setup, heterodyne down-conversion to an IF of 12 GHz is performed using a balanced mixer. The mixer is driven by a 76 GHz local oscillator (LO) generated by a passive frequency doubler fed with a sinusoid of 38 GHz from a second VSG. Lastly, in both setups, the signal is amplified by a 17 dB gain electrical amplifier (EA) and then recorded by a digital storage oscilloscope (DSO) at a sampling rate of 80 GSa/s for offline DSP.

4. Experimental Results

To successfully map a binary sequence to the different DOS states, a sufficient number of samples must be assigned to each symbol/state so the DOS can converge. Further, to achieve high bitrates, a high oscillating frequency ω_d is set and the number of samples is chosen accordingly. At the receiver side, the absolute of the average of each symbol time slot is computed and subsequently the decision is taken. Table 1 shows the main parameters of four DOSs tested in the first experimental setup. For all, the driving signal γ is a non-zero mean bipolar PRBS with a length of $2^{11}-1$ bits. For each system the offset and magnitude of γ is set to ensure the DOSs to oscillate between its states. In each case, $x(t)$ is used to drive the second MZM. As an example, Fig. 2(a) shows the phase-plane diagrams of the states in which DOS 4 oscillates, where the transitions between states are noticeable. Figures. 2(b)–(c) show a time-domain segment and the spectrum of the received signal after wireless transmission and envelope detection. In the spectrum, the 2 GHz oscillatory frequency is clearly visible. Figure 2(d) shows the histogram of the received signal after averaging and computing the absolute value and, finally, Fig. 2(e) gives the bit error rates (BERs) of the four systems after processing 122880, 122880, 40960, and 32980 bits, respectively. It is clear, that more samples per symbol, i.e., lower bitrates, lead to a better BER performance since the DOS oscillates longer in each of its states, producing a more accurate estimation based on its average.

Since in the first scheme only $x(t)$ is transmitted, even if the data is mapped in chaotic states, it might be possible to decode the transmitted message in time-domain. As can be noticed in Fig. 2(b), after envelope detection,

Fig. 1. Experimental setup. (a) Setup of first scheme, and (b) setup of second scheme.

Duffing System	ω_d [GHz]	b	Samples/Sym	Bitrate [Gb/s]
DOS 1	5	1.2	65	1.0000
DOS 2	4	1.3	60	1.0833
DOS 3	3.5	1.3	195	0.3333
DOS 4	2	1.4	240	0.2708

Table 1. Duffing systems main parameters.

Fig. 2. DOS 4 (a) phase-plane diagrams, (b) time-domain signal, (c) spectrum, (d) $x(t)$ histogram, and (e) BER versus samples per symbol.

Fig. 3. IQ scheme (a) phase-plane diagrams, (b) time-domain signal, (c) spectrum, (d) DOS 1 $x(t)$ histogram, and (e) DOS 3 $\dot{x}(t)$ histogram.

usually it is possible to determine the transitions between the states of the DOS, and therefore the transmitted data. To overcome the preceding issue, in our second scheme, the first derivative $\dot{x}(t)$ of a second DOS is transmitted together with the $x(t)$ of the DOS containing the actual data. Thus, $\dot{x}(t)$ exhibits as well a chaotic behavior and, since it does not have a DC component, it was found experimentally that IF carrier recovery is relaxed. In addition, the second DOS is chosen with a different symbol rate to further improve the masking effect. To test the proposed scheme, $x(t)$ of DOS 1 is transmitted simultaneously with $\dot{x}(t)$ of DOS 3. Figure 3(a) shows the phase-plane diagrams of the states of both DOSs. After wireless transmission and heterodyne down conversion, Figs. 3(b)–(c) show a time-domain segment and the spectrum of the received signal. In the spectrum, the IF of 12 GHz and the oscillatory frequencies of both DOSs (3.5 GHz and 5 GHz) are clearly visible. Furthermore, the time-domain signal does not exhibit any correlation with the transmitted data. Through offline DSP, after carrier recovery by means of a Costas loop, the histograms of both received signals, i.e., I and Q components, are shown in Figs. 3(d)–(e). As can be seen from the histogram of the I component, i.e., DOS 1, the transmitted data could be inferred, while there is no useful information in the Q component (mask). After processing of 122880 bits, the achieved BER is 9.7656×10^{-5} .

5. Conclusion

We experimentally demonstrated a prospective solution for wireless physical layer security systems with net bitrates up to 1 Gb/s by means of chaotic systems and statistical decision. Future work includes the implementation of analog DOS transceivers and its synchronization scheme to validate real-time transmissions.

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