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Physical-layer confidentiality by chaotic encoding in radio-over-fiber systems

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Abstract: Confidential wireless transmission of a 150 Mb/s chaotic encoded signal with an artificial signal to noise ratio of 0 dB is experimentally demonstrated at 28 GHz. The chaos is generated by a digitally implemented Duffing oscillator system.

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

1. Introduction

Centralized hybrid millimeter wave (mmWave) photonic architectures are ideally suited to implement high capacity and low latency radio access networks in the next generation of mobile communications [1]. One of the major challenges to face when wireless interfaces are involved is data confidentiality. Physical layer encryption and masking algorithms have gained special attention because of their advantages in terms of low processing latency and protocol transparency [2]. Some recent works have proposed the use of chaotic signals, whose behavior cannot be predicted without the knowledge of their initial conditions, to encode the amplitude or phase in a noise-like environment [3, 4]. An interesting approach for chaos generation in analogue radio-over-fiber (RoF) systems is the use of a Duffing oscillator system (DOS) [3]. This solution relies on using chaotic/non-chaotic symbols with a substantial power difference and a decoy sequence to generate a continuously chaotic signal [3].

In this work, we propose a chaotic encoding algorithm based on using two states of a digitally implemented DOS (one of them with chaotic behavior) with equal average power per symbol and artificial white Gaussian noise, added before wireless transmission. The knowledge of the chaotic parameters used at the encoding stage allows recovering the original data stream in noisy environments, with an artificial signal to noise ratio (ASNR) down to 0 dB, without the need for bandwidth consuming decoy signals. A confidential transmission with a maximum data rate of 200 Mb/s and different ASNR is experimentally validated in a RoF system at 28 GHz (Ka-band).

2. Chaotic encoding scheme

The chaotic behavior is implemented by a DOS, defined by the second-order ordinary differential equation [3]:

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

where δ denotes the damping factor and $\gamma \cos(t)$ is the driving signal. For a fixed value of δ , the output of the DOS changes between three states, one of which is chaotic. The proposed coding scheme uses different amplitudes γ_0 and γ_1 to map different logic symbols (0s and 1s) onto different states of the DOS. However, the previously described system can only effectively be driven by low frequency signals. A change of variable ($t = \omega_d \tau$) must be performed to make the system suitable to be driven by high frequency signals, leading to the following expression:

$$\frac{\ddot{y}(\tau)}{\omega_d^2} + \delta \frac{\dot{y}(\tau)}{\omega_d} - y(\tau) + y^3(\tau) = \gamma \cos(\omega_d \tau) \quad (2)$$

where ω_d denotes the internal Duffing frequency. Figures 1 (a) and (b) show the phase plane diagrams of the symbols used for encoding. These graphs show the first derivative of the output signal $\dot{y}(\tau)$ with respect to $y(\tau)$. The chaotic symbol presents a zero-mean aperiodic and irregular time evolution (similar to noise), which is highly dependent on the Duffing parameters. The non-chaotic symbol is a zero-mean and periodic signal with an amplitude comparable to the chaotic one. Artificial Gaussian noise is first injected into the non-chaotic symbols to have the same average power per symbol and later to the entire signal to mask the data. As a result, a potential eavesdropper cannot distinguish between noise and the actual data. However, the chaotic variations can be detected in noisy environments under the knowledge of the Duffing parameters used for encoding. The signal in time and frequency before and after adding the artificial noise is also shown in Figs. 1 (c)-(f).

Fig. 1. Summary of the proposed chaotic encoding scheme experimental demonstration. (a) Phase plane diagram of chaotic symbol; (b) phase plane diagram of non-chaotic symbol; (c) output of DOS system in time; (d) transmitted signal with artificial noise in time; (e) output of DOS system in frequency; (f) transmitted signal with artificial noise in frequency; (g) experimental setup; (h) DSP block diagram at the transmitter side; (i) DSP block diagram at the receiver side.

3. Experimental setup

Figure 1 (g) shows the experimental setup used to validate the proposed chaotic encoding scheme. A continuous wave (CW) laser is used as an optical source for a Mach-Zehnder modulator (MZM) biased at the null transmission point and driven by a sinusoidal tone of 14 GHz. Consequently, two optical lines corresponding to the first harmonics are generated with a frequency difference between them of 28 GHz. These two spectral lines are boosted by an erbium doped fiber amplifier (EDFA) and demultiplexed using a wavelength selective switch (WSS). The power of one of the tones is controlled by a variable optical attenuator (VOA) while the other is modulated with the proposed chaotic scheme using a second intensity modulator and an arbitrary waveform generator (AWG).

The digital signal processing (DSP) algorithm used to generate the chaotic behavior is depicted in Fig. 1 (h). A pseudo-random bit sequence (PRBS) with length 2^{15} bits is created and upsampled to the number of samples per symbol (SPS). This parameter and the sampling rate of the AWG define the data rate. The sampling rate of the AWG is 12 Gbaud/s and SPS is varied between 120, 80 and 60 samples, meaning that the data rate changes between 100, 150 and 200 Mb/s respectively. In a further step, each logic 0 and 1 is mapped onto a different amplitude of the driven signal feeding the DOS (γ_0 and γ_1). This data stream together with the parameters which define the oscillator system (δ and ω_d) are used to solve the Duffing second order differential equation using the trapezoidal rule. Finally, zero-mean Gaussian noise is artificially added to achieve different values of ASNR (30, 10, 5 and 0 dB).

After the data modulation, the two optical signals are coupled back and amplified by a second EDFA, before being transmitted through 10 km of standard single mode fiber (SSMF) to reach a remote antenna unit. At this point, a second VOA is used to control the optical power launched into a photodiode (PD). The maximum optical power required at this point without saturating any component of the radiofrequency chain is 3.9 dBm. The PD is used to convert the optical signal into the radiofrequency domain by optical heterodyning of the two tones [1]. The signal transporting the chaotic modulation at a carrier frequency of 28 GHz is amplified by a medium power amplifier (MPA) with gain of 30 dB and radiated by an 18.5 dBi standard gain horn antenna. A second horn antenna with the same characteristics is used after a wireless distance of 2.2 m to recover the signal. A 15 dB gain low noise amplifier (LNA) boosts the electrical signal before being down converted by a mixer. The local oscillator (LO) at the receiver is fixed at 25.1 GHz, which results in an intermediate frequency of 2.9 GHz after the mixing. Finally, a digital storage oscilloscope (DSO) is used to record traces for off-line processing.

The DSP stages implemented at the receiver are depicted in Fig. 1 (i). First, a phase locked loop is digitally implemented for carrier phase recovery and the captured signal is resampled to ensure that the number of samples per received symbol is integer. Afterwards, the characteristics of the chaotic signal are used to extract the data by filtering the internal Duffing frequency and detecting the envelope of the signal. The amplitude of the chaotic symbols can be distinguished from the non-chaotic ones by setting an appropriate threshold for data demodulation.

Fig. 2. BER results and phase plane diagrams for three different bit rates: 100 Mb/s, 150 Mb/s and 200 Mb/s.

4. Results

Figure 2 shows the bit error rate (BER) results and their linear regressions, after computing 327680 bits on each measurement, and compared them to the limits imposed by the forward error correction (FEC) techniques with 7% and 25% overhead. Three different data rates are evaluated: 100 Mb/s, 150 Mb/s and 200 Mb/s. The data rate is given by the SPS and the sampling rate of the AWG. If SPS is low, the bit rate is higher at the cost of using less cycles of the DOS and increasing the BER. This effect can be seen on the phase plane diagrams of the transmitted symbols depicted below each BER curve. Four different powers of the artificial noise are also evaluated with a ASNR of 30, 10, 5 and 0 dB, respectively. If the power of the artificial noise increases, the security of the data is higher although the BER also increases.

In the case of 100 Mb/s, the curves corresponding to ASNR of 30, 10 and 5 dB are clearly below the 7% FEC limit. The distance between the 5 dB and 10 dB lines is slightly larger than between 10 dB and 30 dB. The BER increment is substantially higher when the ASNR is 0 dB. This curve is at the limit with respect to 7% FEC line but certainly below the 25% limit. The relative position between the four cases is approximately kept in the other two charts with an increment in BER, as expected. For a data rate of 150 Mb/s, the BER is maintained below the 25% limit in all cases and 0, 5 and 10 dB of ASNR are also below the 7% limit for the optical power incident on the PD in the range between 1 and 4 dBm. Finally, the BER increases in the 200 Mb/s case, where the ASNR of 0 dB is completely above the 25% FEC limit and the rest above the 7% limit, but below 25% limit.

5. Conclusions

We have experimentally demonstrated a chaotic encoding scheme based on a Duffing oscillator system and artificial noise for physical layer cloaking in radio-over-fiber systems. The proposed algorithm is based on the transmission of two symbols with the same average power with an inherent chaotic behavior in one of them. Successful transmissions were achieved at 28 GHz with a data rate of 150 Mb/s and ASNR of 0 dB and with a data rate of 200 Mb/s and ASNR of 5 dB. These results serve as a step towards the implementation of low latency physical layer masking algorithms for wireless interfaces in future generation of radio access networks.

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