Bio-Inspired Photonics and Microwave Photonics for Dynamic and Smart RF Systems

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Abstract: Bio-inspired and microwave photonics offer dynamic, natural, and effective solutions to tackle critical challenges in emerging RF systems. This paper discusses several small-scale bio-inspired and dynamic microwave photonic technologies to facilitate the advancement of RF systems. © 2020 The Authors

1. Introduction

Emerging RF system involves usage of both terrestrial and non-terrestrial networks for multifunction anywhere and anytime wireless service. Therefore, RF systems are being challenged to adapt to rapid changes that are associated with the change in service, security need, topography, and atmospheric properties. Looking back to our nature, there are lots of strategies and neural algorithms that have been proven to be effective for animals to adapt to their environment, which could be the natural solution towards the critical challenges in modern technologies. Furthermore, the flexibility of photonics offers dynamic solutions for emerging RF systems to rapidly adapt to changes. Over the last ten years, continuous research efforts have been made in the fields of microwave photonics, neuromorphic photonics, and bio-inspired photonics. From dynamic RF devices based on photonic technologies [1], to photonic neural network to mimic brain like functions [2], to bio-inspired optical microstructure [3], the possibilities are endless. In this paper, we focus on the progress we made to improve the reliability, availability, and security of a dynamic and smart RF systems. First, mimicking the jamming avoidance response in Eigenmannia using photonics will be discussed. Next, optical approach for dynamically tailoring wideband RF spectrum will be presented. Then, the application of spike timing dependent plasticity in angle/direction-of-arrival detection is discussed. Finally, the use of ocean camouflage strategies for optical steganography will be presented.

2. Jamming Avoidance Response (JAR) for Mitigating Jamming in Radar Systems

JAR in Eigenmannia mitigates frequency jamming from another close-by electric fish, where phase and amplitude information between the two electric fish are used to determine if any action should be taken to avoid potential jamming [4]. First, the JAR algorithm identifies the zero crossing points in the fish's electric field. Next, the algorithm compares the phase between the beat signal (between the fish and the jammer) and the fish's electric field to determine their phase relationship. Then, the algorithm examines the beat signal envelope and identifies the rising and falling envelopes. Finally, a logic unit is used to determine whether the jammer is at a higher or lower frequency by examining the amplitude and phase information obtained. With the use of photonics phenomena, a photonic JAR has been experimentally demonstrated and has successfully automatically avoid jamming as the jammer is moving spectrally close by [4]. Fig. 1 shows the spectral waterfall of the JAR process to ensure the availability of the communication channel under intentional and inadvertent jamming.

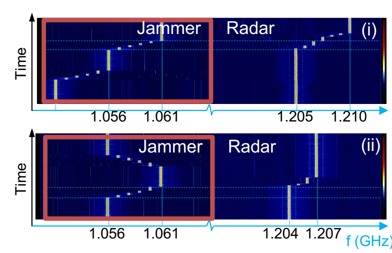

Fig. 1: RF spectral waterfall showing the optical JAR in action [4].

3. Wideband RF Spectral Tailoring for a Reliable and Dynamic RF System

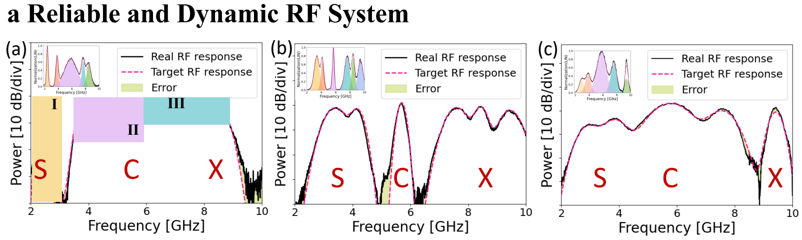

Fig. 2: Experimental results of dynamic adaptive RF spectral shaper with optimized decomposition and reconstruction algorithm [5].

As emerging RF systems provide virtually anywhere coverage that involves both usage of terrestrial and non-terrestrial networks, properties of the transmission channel changes rapidly based on the change in topography, atmospheric properties, and the required type of service. To maintain the quality of transmission and enable adaptation in heterogeneous and multiband communications, there is a critical need to tailor the RF spectrum dynamically accordantly. We have designed a customizable microwave photonic RF spectral shaper with over ten adaptive spectral control points over wideband operation frequency range of 10 GHz, covering various bands (S, C, and X) simultaneously with step resolution of as fine as tens of MHz [5]. A two-step algorithm that breaks down the target spectral response into a unique series of Gaussian functions and convert the parameters into a sum of photonic FIR response has been designed and demonstrated (Fig. 2).

4. Spike Timing Dependent Plasticity (STDP) for Angle/Direction of Arrival

The most fascinating ability of neuron is the ability to learn and adapt, which is governed by the synaptic weight plasticity between neurons. STDP is the most popular synaptic weight plasticity models that adjusts the interconnection strength between neurons based on the temporal relationship between pre-synaptic and post-synaptic activities – Fig. 3(a). STDP has been achieved using photonics [6-7] and applied to supervised learning [7]. Here, a creative application of STDP in RF system is presented – STDP algorithm for angle/direction-of-arrival (AOA) detection and 3D localization [8]. AOA detection rely on the order and delay between the pulses received by two co-located antennae, similar to how STDP operates. Therefore, photonic STDP is a natural way for AOA detection and 3D localization. Fig. 3(b) shows how the detected AOA is related to a STDP response.

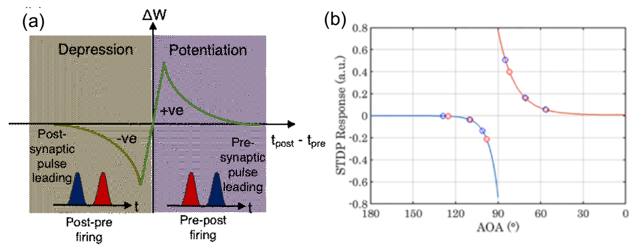

Fig. 3: (a) Illustration of STDP (b) AOA detection using STDP [8].

5. Camouflage Strategies of Marine Hatchetfish for Optical Stealth Transmission of RF Signal

Cryptography is an effective way to ensure the security of an RF system, that requires both encryption and steganography for scrambling and hiding the sensitive signal in plain sight. While intensive research has been focusing on encryption, steganography is an essential part of cryptography. We borrow underwater camouflage strategies from Marine Hatchetfish – silvering and counterillumination, to hide the sensitive RF signal during fiber transmission. Silvering is achieved using photonic based finite impulse response (FIR) [5] while counterillumination is achieved using wideband optical comb carrier. Fig. 4(a) shows that the stealth signal is invisible in the eyes of the attacker, while Fig. 4(b) shows the successfully recovered OFDM signal at the designated stealth receiver [9].

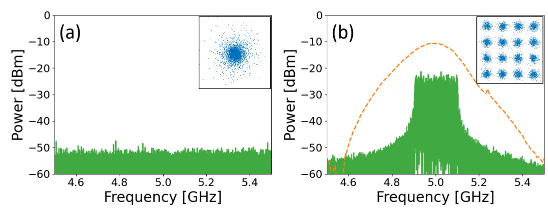

Fig. 4: (a) Stealth signal is invisible to the attacker (b) Stealth signal reappears at the designated stealth receiver [9].

5. Summary

Inspired by the nature and the unique properties of photonics, a number of novel photonic systems have been designed to provide effective and dynamic solutions to the critical challenges in RF systems.

6. References

[1] M. P. Fok and J. Ge, "Multiband Microwave Photonics Filters," MDPI Photonics: Special Issue – Microwave Photonics 2017, vol. 4, iss. 45 (2017).

[2] A. N. Tait, T. F. de Lima, E. Zhou, A. X. Wu, M. A. Nahmias, B. J. Shastri, and P. R. Prucnal, "Neuromorphic photonic networks using silicon photonic weight banks," Scientific Reports, vol. 7, iss. 1, pp. 7430 (2017).

[3] S. Tadepalli, J. M. Slocik, M. K. Gupta, R. R. Naik, and S. Singamaneni, "Bio-optics and bio-inspired optical materials," Chemical Reviews 117, no. 20, pp. 12705-12763 (2017).

[4] R. Lin, J. Ge, T. P. T. Do, L. A. Perea, R. Toole, and M. P. Fok, "Biomimetic Photonics - Jamming Avoidance System in Eigenmannia," Optics Express, vol. 26, iss. 10, pp. 13349-13360 (2018).

[5] Q. Liu and M. P. Fok, "Adaptive photonic RF spectral shaper," Optics Express, vol. 28, iss. 17, pp. 24789-24798 (2000).

[6] R. Toole, A.N. Tait, T. Ferreira de Lima, M. A. Nahmias, B. J. Shastri, P. R. Prucnal, and M. P. Fok, "Photonic Implementation of Spike Timing Dependent Plasticity and Learning Algorithms of Biological Neural Systems," Journal of Lightwave Technology, vol. 34, no. 2, pp.470 – 476 (2016).

[7] M. P. Fok, Y. Tian, D. Rosenbluth, and P. R. Prucnal, "Pulse Lead/Lag Timing Detection for Adaptive Feedback and Control based on Optical Spike Timing Dependent Plasticity," Optics Letter, vol. 38, iss. 4, pp. 419 – 421 (2013).

[8] R. Toole and M. P. Fok, "Photonic Implementation of a Neuronal Algorithm Applicable Towards Angle of Arrival Detection and Localization," Optics Express, vol. 23, iss. 12, pp. 16133-16141 (2015).

[9] Q. Liu and M. P. Fok, "Bio-inspired Photonics – Marine Hatchetfish Camouflage Strategies for RF Steganography," submitted to Optics Express.