Wideband Spectral Sensing by Integrated Photonics for Signal Separation and Localization

Yuxin Wang
Department of Electrical and Computer Engineering
Prnceton University
Princeton, USA
yuxinw@princeton.edu

Weipeng Zhang
Department of Electrical and Computer Engineering
Prnceton University
Princeton, USA
weipengz@princeton.edu

Bhavin J.Shastri
Department of Physics, Engineering Physics and Astronomy
Oueen's University
Ontario, Canada
Bhavin.shastri@queensu.ca

Paul Prucnal
Department of Electrical and Computer Engineering
Prnceton University
Princeton, USA
prucnal@princeton.edu

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***Abstract*—Wideband spectral sensing (WSS) becomes increasingly critical in the context of growing demands for bandwidth utilization, with photonics addressing the frequency agility challenges faced by traditional radio-frequency (RF) electronics. This paper presents a WSS framework employing integrated photonics for RF signal separation and localization.**

***Index Terms*—integrated photonics, wideband spectral sensing**

The 5G/6G market is witnessing an increasingly scarce spectrum resource due to the intensified demand for wireless communication. In this context, wideband spectral sensing (WSS) is pivotal for boosting spectral efficiency by detecting and allocating underutilized spectrum. For example, cognitive radio, a key application of WSS, exemplifies necessary dynamic adaptability for enhanced spectrum use and system robustness. However, inherent speed and frequency response limits often hinder conventional electronic systems, rendering them less ideal for ultra-wideband applications. In contrast, photonics signal processors, with low latency and energy consumption plus bandwidth capabilities extending to hundreds of terahertz, far exceed electronic systems' limitations. Current implementations of photonics-based approaches have shown considerable progress in enhancing radio-frequency (RF) signal processing performance, particularly in blind source separation (BSS). However, they typically lack the capacity for spatial tunability, a critical feature for precise source localization in strategic fields such as military and disaster response. In this paper, we introduce an experimental framework and algorithms aimed at achieving WSS to bridge the spatial tunability gap. Our method integrates a novel photonic chip with a dithering-controlled microring resonator (MRR) weightbank and algorithms to achieve separation and precise localization of mixed blind RF sources, representing a significant advancement in WSS technology.

I. METHOD

In our work, the WSS process encompasses two pivotal stages. The first step, BSS, extracts signals from their mixtures by assuming statistical independence and linear mixing. Employing a full-ranked mixing matrix A, BSS separates the signals by a calculated weighting A^{-1}. The MRR weightbank on photonic chips can perform linear weighted addition of original mixtures. This is achieved by current adjustments through thermally tuning individual MRRs, each corresponding to different wavelengths, and the summation of which can be obtained by a balanced photodetector (BPD). This capability is based on a photonic BSS algorithm comprising principal component analysis (PCA) and independent component analysis (ICA), targeting to calculate the minimal variance (standard deviation) and maximal kurtosis (non-Gaussianity), respectively (details in ref. [1]).

The second step involves precise localization of the retrieved signals. For a system processing two signals, spatially separating the receivers within a 2x2 multiple input multiple output (MIMO) arrangement at a fixed distance is necessitated, followed by integrating filters to individually assess the signals at each receivers. The cross-correlation function, $R_{x_1x_2}(\tau) = \sum_n x_1[n] \cdot x_2[n+\tau]$, provides a quantitative measure of the temporal similarity between two signals originating from the same source. The function's maximum indicates the optimal time-domain correlation, pinpointing the time delay of one signal relative to the other across the received signal streams. Based on geometric relationships, the precise location of blind sources on a predetermined line can be accurately identified respectively. For hardware implementations, high-frequency mixers can be used to compute cross-correlation and ascertain the time delay. To surpass the inherent frequency limits of electrical components, an alternative optical method is cascading the signal through modulators. Through these

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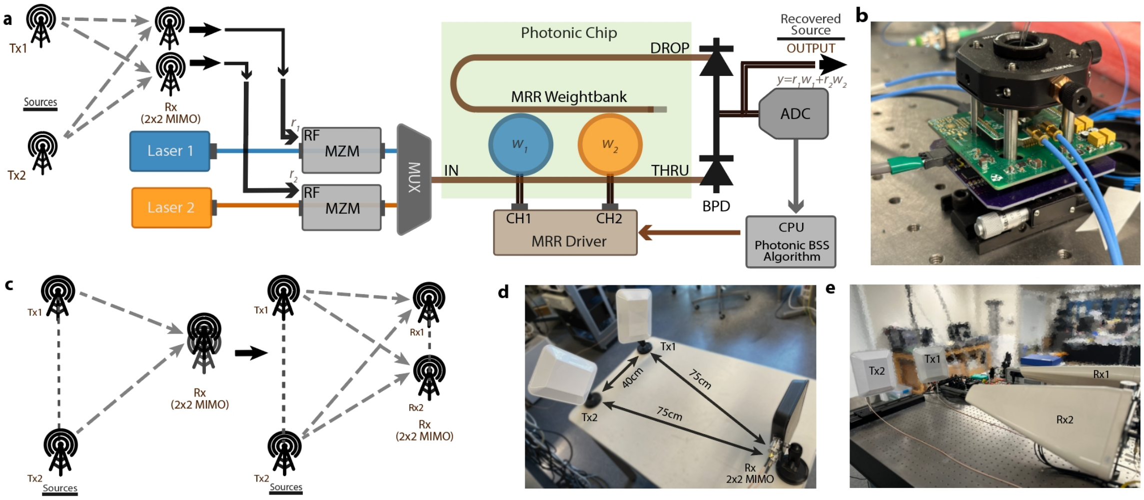

Fig. 1. (a) Schematic of the WSS system. MZM, Mach-Zehnder modulator. MUX, wavelength dependent multiplexer. (b) Fully packaged photonic processor. (c) Schematic illustration of RF signal transmission between antennas. (d), (e) Antenna configurations for the two-step WSS process.

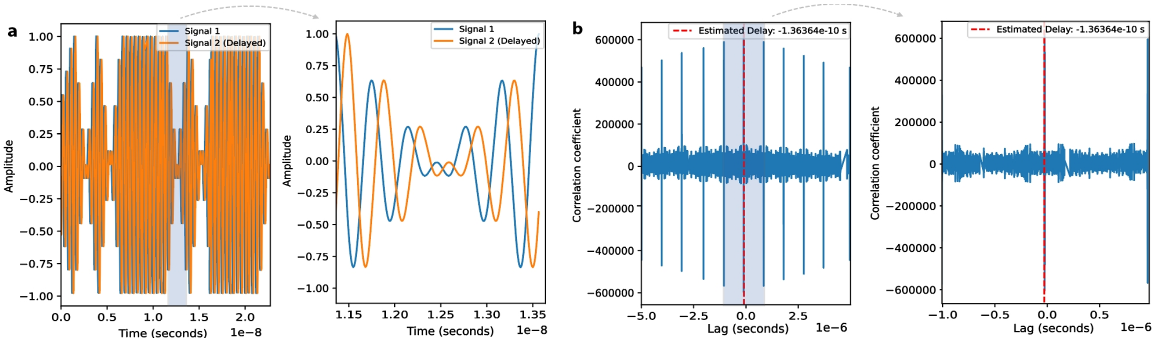

Fig. 2. (a) BPSK signal and delayed version. (b) Cross-correlation for time delay estimation

two steps, we achieve WSS encompassing the separation and localization of blind RF sources.

II. RESULTS

Based on the described experimental system, we successfully demonstrated our designed WSS photonic processor within a wireless transceiver setup in the first stage, simulating the emission and mixing of two source signals. As illustrated in Fig. 1(d), two antennas (Southwest Antennas 1009-002; 1.7-2.5 GHz) transmit signals and a broadband jammer is applied to mix them in the air. Then, the mixed signals are received by a 2x2 MIMO antenna (Southwest Antennas 1055-368; 1.7-2.5 GHz). The demonstrated photonic WSS system is capable of processing RF signals with carrier frequency up to 19.2 GHz and a baseband reaching 1.6 GHz (an instantaneous bandwidth of 3.2 GHz). Following this step, the signal-to-noise ratio improves by 14.7 dB (from 20.8 to 35.5 dB) using signal modulation in binary phase-shift keying (BPSK) format at 50 MHz baud rate and 2.1 GHz carrier frequency, with constellation's Q value doubling [2].

In the step of separated RF sources localization, the model of the source previously mentioned was retained, along with the separated receiving antennas (Maswell AN_MASTER_005; 600 MHz-6 GHz). A 2 GHz carrier frequency was utilized alongside Python-generated 400-bit, 400 MHz BPSK signals and randomly generated time delays (indicative of the sources' precise positions). Experimental findings, as depicted in Figure 2 (b), include a detailed examination of cross-correlation as a function of time delay. For a specified actual time delay of 137 ps, the computed error was merely 0.46%. The emergence of peaks every 1 microsecond in the cross-correlation diagram is attributed to the signal's 1-microsecond periodicity. The outcomes substantiate the efficacy of the method in accurately separating and localizing blind RF sources, and the broadband coverage can be translated into the agility of processing multiple commonly used bands. Examples of included bands are cellular (620 MHz-6.425 GHz) and Wi-Fi (2.4 GHz, 5-7.125 GHz).

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