Wideband Spectral Sensing by Integrated Photonics for Signal Separation and Localization

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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 systeR

$R_{x_1 x_2}(\tau) = \sum_n x_1[n] x_2[n+\tau]$, 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

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.