A Novel Analog Photonic Method for Broadband Multipath Interference Cancellation

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***Abstract*—A novel analog optical technique for multipath interference cancellation of broadband signals is proposed. Multiple optical compensation branches are utilized to replicate wireless multipath channel effects. The duplicated signal is subtracted from the total received signal to recover the signal of interest while suppressing interference. The proposed architecture achieved 40 dB of cancellation over 200 MHz and 50 dB over 10 MHz. The depth and broadband nature of the cancellation demonstrates the precision of optical components and the validity of our interference cancellation scheme.**

***Index Terms*—Broadband interference cancellation, electro-optic modulation, multipath interference, RF photonics.**

I. Introduction

Wireless communication has experienced exponential growth, and a shortage of the wireless spectrum is expected. Efficient utilization of the spectrum has become an active area of interest. Interference cancellation plays a crucial part in increasing the capacity as it offers capabilities of full duplexing [1]. The ability to reject interference, while receiving a signal of interest (SOI) at the same frequency, is referred to as "co-channel interference cancellation". Optical methods have been achieved [2], [3].

To make the scenario more realistic, multipath interference must be considered. The interfering signal will travel multiple transmission paths due to reflection, scattering, and diffraction from various terrain features. The receiver will receive multiple delayed and attenuated copies of the interferer.

The RAKE receiver is a ubiquitous solution to mitigating multipath interference, incorporating the use of correlators to estimate the wireless channel and 'fingers' to compensate for each path. Adaptive methods achieving 5 to 20 dB of narrowband cancellation [4], FIR filters with 34- 41 dB of narrowband cancellation [5], and analog balun methods with 45 dB of cancellation across 10 MHz [1] have been experimentally demonstrated with no multipath compensation.

A unique technique called multipath interference cancellation (MPIC) has been proposed and studied [6]–[8]. The fundamental principal behind MPIC is the duplication and subsequent removal of the multipath replica from the received signal. Once the channel is estimated, the different paths traveled by the interfering signal can be duplicated, replicating the channel response. The duplicated signals are subtracted from the total received signal, leaving only the desired signal.

We elaborate on the solution described above and introduce an analog photonic method for canceling multipath interference from broadband signals based on discrete optical components. We are able to achieve 40 dB of cancellation across 200 MHz. To the authors' knowledge, this is the first letter that has experimentally implemented an optical broadband MPIC method. The work in this letter differs from previous approaches such as [3]. This architecture specifically is tailored for multipath co-channel interference techniques and introduces a photonic filter to duplicate channel effects, where the work in [3] is for line-of-sight (LOS) situations.

Our architecture offers several distinct advantages. Firstly, fiber optics offers the advantages of reduced size, weight, power, low transmission loss, and immunity to electromagnetic interference [9]. Every component of our architecture including optical modulators, attenuators, and delay lines can be realized on a single semiconductor substrate for extreme compactness [3]. Further, the optical system is cheaper or at least comparable in cost to RF systems. Moreover, implementation has thus far been relegated to digital signal processing (DSP) and theoretical simulations. Accurate reconstruction of the different paths is not a trivial matter, and we introduce an analog optical method for MPIC.

Most importantly, optics allows for the implementation of widely tunable broadband delay lines. RF electronics cannot practically handle wide bandwidths in the GHz range. Thus, RF systems are bandlimited and require multiple sets of equipments to be able to cancel across a broad band. *An optical system requires just one such set of delay lines*.

II. Architecture and Experimental Setup

The impulse function, $\mathrm{h(t)}$, related to multipath interference can be written as

$$h(t) = \sum_{n=0}^{N-1} \alpha_n \delta(t - \tau_n) \tag{1}$$

where α_n and τ_n represent the attenuation and delay related to the $\mathrm{n^{th}}$ multipath. The wireless channel response represents multiple time-delayed and attenuated signals.

Our architecture, shown below in Fig. 1, duplicates the channel response by creating a set of equivalent optical weights and delays and then subtract (remove) it from total received signal at the receiver, leaving only the SOI.

The "Tx" antenna is transmitting a broadband interference signal, represented by $\mathrm{n_0}$, which is known to the user and can be tapped out. As the interference signal is transmitted from the

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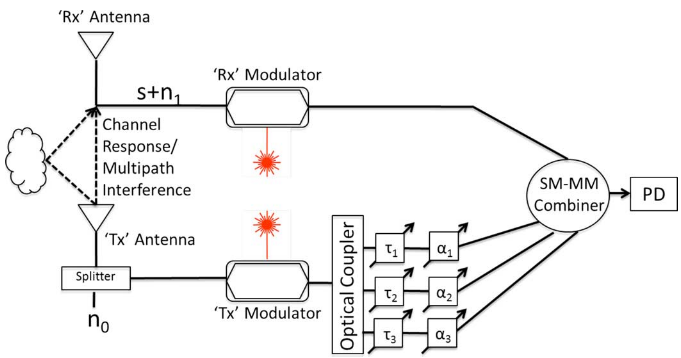

Fig. 1. Broadband MPIC architecture.

Tx to the Rx, it will undergo the channel response as described by (1) and be received as n_1 at the receiver.

The SOI is represented by "s" and is received by the "Rx" receiver antenna, along with n_1. We assume that "s" is very weak, just 10–15 dB above the noise floor. The interference signal is much stronger, broadband, and can completely overpower the signal of interest. A simple bandstop filter cannot be used to cancel the multipath interference since both s and n_0 overlap at some common frequency.

Two continuous wave (CW) lasers operating at 1551.61 and 1551.85 nm are used. Two electro-optic modulators (EOMs) modulate the signals onto optical carriers. The approach is to bias the "Tx" and "Rx" modulators on opposite parts of the linear portions of the modulator transfer function. The RF input signals are π-shifted from each other and the optical intensities will destructively interfere when summed.

The "Tx" branch is used to create the optical compensation branch. A parallel set of weighted fiber delay lines processes n_0, with each branch corresponding to one replica. A set of thermo-optic optical attenuators with 30 dB of range provides the weighting. Tunable delay lines with a tuning range of $\sim 83\ \mathrm{ps}$ give the user fine adjustments. To cancel dynamically changing multipath, one needs widely tunable delay lines. Bit-switched optical lines provide sufficient range and resolution, with more than 7-b control and 12.8 ns range and can be paired with the existing delay line [10]. RF delay lines can first give the user wide coarse delays.

Each delayed-and-attenuated n_0 enters an input of a SM-MM combiner. When coherent optical signals are combined using a conventional fused coupler, fluctuations in the relative phase result in changes of the coupling ratio, resulting in interference noise or beating at the output. Beat noise is severe and has a squared power relationship. The combiner couples signals from several single-mode fibers to distinct modes of a multimode fiber, allowing same wavelength signals to be combined without optical beat noise [11].

The "Rx" branch, with the SOI and n_1, is modulated and enters another input of the combiner. The signals are π-shifted, and we use one branch to subtract from the other.

The output signal received at the multimode photodetector is equal to $s + n_1 - \sum \alpha_n n_0(t - \tau_n)$. If we are able to perfectly replicate the delays and weights, then $\sum \alpha_n n_0(t - \tau_n)$ simply becomes n_1 and we are able to retain only our SOI.

In real-world over-the-air systems, pulses will replace the perfect deltas described in (1). When multiple optical taps are used to compensate for each multipath pulse, much like sampling is done, cancellation will be comparable.

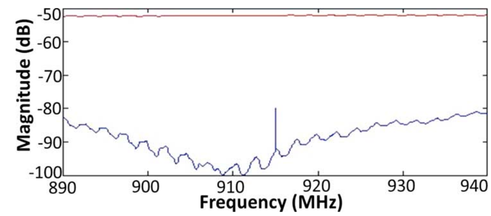

Fig. 2. Spectrum of a two-branch system before (top, red) and after (bottom, blue) cancellation of a 50 MHz broadband interferer around 915 MHz.

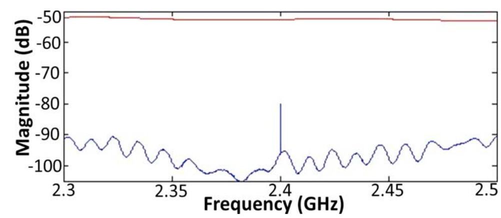

Fig. 3. Spectrum of a two-branch system before (top, red) and after (bottom, blue) cancellation of a 200 MHz broadband interferer around 2.4 GHz.

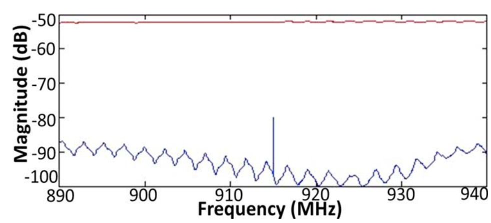

Fig. 4. Spectrum of a three-branch system before (top, red) and after (bottom, blue) cancellation of a 50 MHz broadband interferer around 915 MHz.

III. Experimental Results and Discussion

We demonstrate our broadband MPIC architecture. A signal generator generates the interference signal (n_0). The signal is split using an RF splitter, and RF attenuators and different lengths of RF cables are used to generate the delayed-and-attenuated replicas characteristic of wireless multipath interference, creating n_1. Strong interferers $\sim\ -52\ \mathrm{dBm}$ were created around 900 MHz and 2.4 GHz, to represent the GSM and WiFi bands. Weak SOI $\sim -80\ \mathrm{dBm}$ were generated.

To maximize cancellation, optical delay and attenuation were as closely matched to the RF delay and attenuation as possible. Delays between the RF branches were measured and fibers were spliced to match. Cancellation profile was viewed from a VNA, and fiber delay lines were manually fine-tuned to find the optimal point of cancellation. A voltage controller was used to adjust the attenuator with the same method. The entire system is put together after each RF branch is individually compensated by a different optical branch.

We first test our architecture with two RF paths and two optical compensation branches. Cancellation before (top, red) and after (blue) is shown in Figs. 2 and 3. We were able to achieve at least $\sim\ 30\ \mathrm{dB}$ of cancellation across 50 MHz and $\sim\ 40\ \mathrm{dB}$ across 10 MHz for the 900 MHz interferer. Around 40 dB across 200 MHz and $\sim\ 50\ \mathrm{dB}$ of cancellation across 10 MHz were achieved around the 2.4 GHz range. The weak SOI is successfully recovered from the interference for both cases.

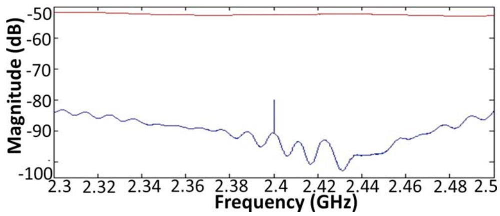

Fig. 5. Spectrum of a three-branch system before (top, red) and after (bottom, blue) cancellation of a 200 MHz broadband interferer around 2.4 GHz.

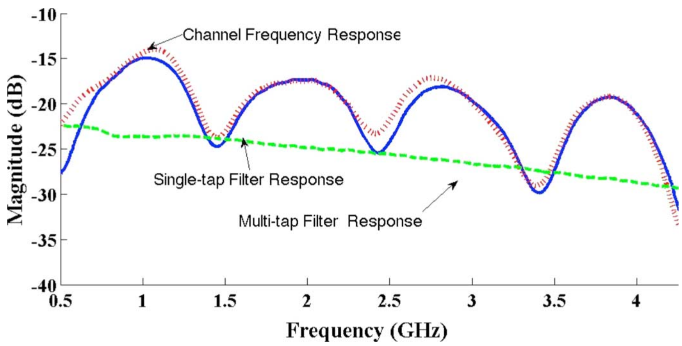

Fig. 6. Magnitude response of the channel, compensating multi-tap filter, and compensating single-tap filter.

We expanded our experiment to include three RF paths. Cancellation before (top, red) and after (blue) is shown in Figs. 4 and 5. We were able to achieve ~ 35 dB of cancellation across 50 MHz and ~ 40 dB across 10 MHz in the 900 MHz band. Around 35 dB across 200 MHz and ~ 45 dB of cancellation across 10 MHz were achieved in the 2.4 GHz range. The SOI is successfully recovered.

The performance demonstrated above shows substantial cancellation across an extremely wide bandwidth, rivaling and even bettering the performance by LOS methods [2], [3].

While we are able to achieve impressive cancellation, it is possible that the aggregate power of the residual broadband signal is not weak. However, since our SOI is now clearly above the interference signal, we can simply place a narrow RF bandpass filter to filter out the residual signal.

The channel magnitude response for the three-path interference is shown above as the red dotted line in Fig. 6. In order to be able to duplicate this response, a multi-tap filter must be used. Further, delay and attenuation of the optical paths need to be as closely matched to the RF weights and delays as possible. The magnitude responses of the three-tap filter and a single-tap filter with the largest weight are plotted as the blue line and green dotted line. It is clear that the multi-tap filter very closely matches the channel response (deviations arise from small degradation of the modulator transfer function), while the single-tap filter is vastly different. The phase response of the difference between the two arms is plotted in Fig. 7. The solid blue line depicts the difference between the multi-tap filter and the channel, which is straight line at -180 degrees. Phase measures delay, and we can see that delays can be matched. The dotted red line shows the difference between the single-tap filter and the channel, which differs more with frequency.

While cancellation profiles are impressive, ripples are seen. This is from mismatched impedance between RF splitters, attenuators, and cables. Small mismatches in the frequency profiles

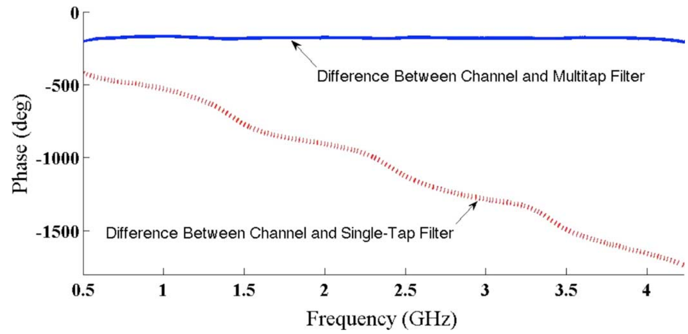

Fig. 7. Phase response of the difference between the channel and multi-tap filter and difference between the channel and single-tap filter.

of the two EOMS prevent greater cancellation across a broader bandwidth. Performance could be improved by matching the EOMs, by fabrication methods or RF equalizers.

IV. Conclusion

In this letter we introduce a novel analog optical method for cancellation of multipath interference of broadband signals. Optical components are broadband, so that only a single set of components is needed to be fully reconfigurable across many bands of frequencies. In addition, our use of a special SM-MM combiner allows the user to combine signals of the same wavelength, and we should potentially be able to use a single laser source for the entire architecture while scaling the number of compensation taps up to the limit of ASE noise.

We experimentally demonstrate cancellation of up to the third multipath, with a maximum cancellation of ~ 40 dB over 200 MHz and ~ 50 dB over 10 MHz.

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