1. Introduction

The broad bandwidth and low loss-per-unit-length of photonic links make them potentially useful for the transmission of low-noise and high-frequency analog microwave signals. Such microwave-photonic links are useful in several precision radio-frequency (RF) applications including: radar antenna remoting, synchronization of distributed RF systems, and time/frequency transfer for geo-location. However, the performance requirements of such precision RF applications often differ from those of conventional digital fiber-optic communications. Microwave-photonic links often require greater linearity and higher signal-to-noise levels than digital communications links—particularly at offset frequencies below 1 MHz [1]. Due to this increased sensitivity to nonlinearity, amplitude, and phase noise, system designers must characterize and minimize a wide range of electrical and optical noise effects that may limit the performance of microwave-photonic links.

In this work, we present an overview of the dominant noise sources in microwave-photonic links. We describe the origins of these noise sources and outline their dependence on system and device parameters. We also list complex interactions within microwave-photonic links that couple noise sources to, or distort, the transmitted microwave signals. In addition, we will outline several techniques for suppressing the various noise and distortion effects in microwave photonic links. Finally, we describe the tradeoffs between the various noise-suppression techniques. The information provided in this work will aid in the optimization of microwave-photonic links for specific applications.

2. Noise sources and distortion effects in microwave-photonic links

The need for high signal-to-noise ratios in microwave-photonic links makes such links especially sensitive to amplitude and phase noise sources. Fig. 1 shows a schematic diagram of a basic microwave-photonic link. All such links include a transmission laser, an electro-optic modulator, a transmission medium (such as optical fiber), and a photodetector for converting the microwave signal used to modulate the laser back into an electrical signal. All of these components contribute to the link noise. The laser's relative intensity and phase noise can degrade the amplitude and phase noise of microwave signals transmitted over the link. In addition, shot and electrical noise in photodetectors contribute to the noise levels of microwave-photonic links.

The transmission medium also induces noise on the microwave signal. Fiber-induced noise sources include: environmental effects such as temperature and pressure fluctuations; linear optical effects such as chromatic dispersion; and nonlinear effects which include self-phase modulation, Brillouin and Rayleigh scattering [2]. Inelastic Rayleigh scattering is especially detrimental to analog microwave-photonic links. Fig. 2 shows the intensity noise spectra of 10 GHz microwave signals transmitted over photonic links of various fiber lengths. The additional
noise in the links longer than 1 m is due to Rayleigh scattering in the optical fibers. Fig. 2 shows that optical-scattering-induced noise can be a significant noise source in links as short as 40 m. Due to the narrow bandwidth of the Rayleigh scattering process (<1 MHz), Rayleigh-scattering-induced noise is concentrated at low offset frequencies that limit precision analog microwave photonic links. The imperviousness of conventional digital communications systems to such low-frequency noise has led to relatively little research into the effects of Rayleigh scattering in optical fibers. In this work, we describe the manner in which these fiber-induced noise sources depend on system parameters such as laser intensity and fiber length.

The noise sources in microwave-photonic links interact in complex ways to degrade the transmitted microwave signals. In this work, we list some of the mechanisms that couple various noise sources together. For instance, laser frequency noise can be converted into microwave phase noise via chromatic dispersion in optical fibers. In addition, nonlinearities in microwave-photonic links can convert noise from one form to another. Intensity-dependent phase-delays in photodetectors and electrical amplifiers convert amplitude noise into phase noise [3, 4]. Fig. 3 shows plots of the dependence of microwave phase-delay on optical intensity in photodetectors with various reverse bias voltages. Fluctuations in the laser intensity lead to increased microwave phase noise. Similarly, phase dependent optical processes such as the Kerr effect and Rayleigh scattering can potentially convert optical phase noise into intensity noise. Finally, nonlinearities in microwave-photonic links can distort transmitted signals even in the absence of noise. For example, nonlinearities in the modulator can mix microwave signals of different frequencies leading to spurious modes. In this work, we will outline the dominant coupling and distortion effects and the manner in which they degrade link performance.

4. Noise suppression techniques and link optimization

Several techniques have been developed for suppressing individual noise and distortion sources in microwave photonic links. For instance, in-phase and quadrature (IQ) modulation – coupled with coherent detection – has been utilized to increase the linearity of links for applications such as radar remoting that require high spur-free dynamic range [1]. Increased optical power has been shown to both improve modulation linearity and reduce additive noise in microwave-photonic links. Spread-spectrum techniques such as laser frequency modulation can be used to suppress the effects of both Rayleigh and Brillouin scattering in optical fibers. Finally, balanced detectors and active feedback can be used at microwave receivers to reduce both environmental and device noise.

However, such suppression techniques often entail tradeoffs. For instance, IQ modulation and coherent detection increase the coupling between optical and microwave phase noise. Increased optical power in fibers exacerbates nonlinear degradation due to the Kerr effect as well Rayleigh and Brillouin scattering. Finally, spread-spectrum techniques can introduce spurious noise spikes in microwave signals – particularly in broadband links. By outlining the precise effect of various noise sources on system parameters and listing the tradeoffs between the various suppression techniques, the information presented in this work will aid system designers in optimizing microwave-photonic links for their specific applications.

4. References