Hybrid Modulation-Based Scalable Radio-over-Fiber Links for Multi-Service Transmission

Abstract

Radio-over-fiber (RoF) is a fiber-wireless technology that facilitates simplified remote access points and shorter last-mile distances. Simultaneous transmission of radio frequency (RF) and baseband signals over an optical fiber can improve spectrum utilization in RoF links while supporting hybrid wired-wireless services over shared optical infrastructure. However, most existing hybrid wired-wireless techniques employ multiple photodetectors, complex receiver-side signal processing, dedicated dual-parallel modulators, or polarization-based devices. This thesis presents a hardware-efficient hybrid optical modulation scheme for RoF systems that overlays RF signals over a conventional intensity modulation direct detection (IMDD) links while employing only one additional optical modulator, and the detection is done using a single photodetector. This is achieved by initially modulating the optical carrier with a baseband signal and subsequently modulating this already modulated optical carrier with an RF signal. The scheme is validated through theoretical, simulation, and experimental results across different fiber lengths, RF and optical power levels, and data rates, demonstrating a statistically estimated acceptable bit error rate (BER) of with the necessary parameters outlined. The impact of baseband-RF signal beating interference is demonstrated through theoretical analysis and experimental results, and a simple mitigation technique based on deterministic signal subtraction is developed, which uses only simple averaging, subtraction, and multiplication operations and does not increase overall system complexity. In addition, the theoretical and experimental results also show that an erroneous detection of the baseband signal does not affect the BER of the RF signals. The scheme is shown to operate at both sub-6 GHz and mmWave frequencies, with data rates up to 15 Gbps and fiber lengths up to 60 km. As the scheme is frequency-agnostic, its performance can be further improved by using high-bandwidth components and higher RF/optical power levels.

The hybrid optical modulation framework is further extended to a frequency-division-multiplexed (FDM)-RoF system for the transmission of one baseband and multiple RF signals over the proposed hybrid modulation link without any further hardware modifications. We develop the mathematical framework and the closed-form analytical BER model of the proposed FDM-RoF link. The conditions for non-overlapping spectra for inter-channel interference isolation are outlined, and the minimum bandwidth requirement for the proposed link is derived. The experimental demonstration with three-channel FDM carries four information signals on one optical carrier, which is a fourfold link utilization compared to a conventional RoF link carrying a single signal. Further, the scheme is scaled for a wavelength-division multiplexing (WDM)-RoF architecture that transmits baseband and RF signals on each WDM channel, improving resource utilization compared to conventional WDM-RoF systems. The comprehensive simulations are performed for a wide range of system parameters, and a target BER of is demonstrated at a data rate of 15 Gbps per channel with 50 GHz channel spacing. The experimental results for two-channel WDM using commercial lasers confirm that the proposed hybrid modulation scheme is fully compatible with WDM operation. The WDM-RoF framework is further demonstrated using an in-house-developed electro-optic frequency comb optimized via a genetic algorithm, producing 11 comb lines with 12.5 GHz spacing and spectral flatness of within 1.8 dB. Finally, an integrated WDM-FDM-RoF framework is demonstrated, which supports flexible multi-user, multi-service transmission and improves the utilization of both spectral and hardware resources. Overall, the proposed hybrid WDM-FDM-RoF architecture provides a flexible and hardware-efficient solution for converged fiber-wireless access

networks and is well-suited for 5G and beyond networks with heterogeneous service requirements.