Nonlinearity Reduction in Subcarrier Multiplexed Radio Over Fiber Systems

Tony Jose, Vijayakumar Narayanan

Abstract*: In subcarrier multiplexed (SCM) Radio over Fiber (RoF) systems, multiple radio frequency (RF) signals are combined in the electronic domain and transmitted simultaneously by modulating them on high-frequency optical carriers. The harmonic and intermodulation distortions generated due to the inherent nonlinearity of the laser transmitters causes severe performance degradation in multiuser RoF systems. This work aims to reduce the adverse effects due to the laser diode nonlinearity using external mechanisms. A predistortion technique is suggested for the suppression of the additional frequency components generated. A simulation study on the effect of nonlinearity on a three-user SCM-RoF system is carried out. A predistortion technique in which the input signals are preprocessed to mitigate the nonlinear effects is introduced into the system and the performance enhancement is verified.

Index Terms: Harmonic Distortion, Laser Diode, Nonlinearity, Predistortion, Radio over Fiber, Subcarrier Multiplexing.

I. INTRODUCTION

Ever since the advent of electronic communication systems, there has always been an increasing demand for advanced services over the communication channel. The introduction of fiber optic communications has enabled high-end services which require large amounts of data transfer. A wide variety of services like high-definition video streaming, multi-user gaming, and cloud-based applications are possible through the optical fibers which possess almost infinite bandwidth. While the wired communication is able to deliver such high bandwidths, there is an urge to have these services on portable devices. The unquenchable thirst to have high data rates over the wireless medium has put pressure on the wireless communication systems to modify their architecture to accommodate more services. A lot of research has done on the wireless communication system architectures to enhance their capacity. Advanced yet simple configurations like Radio over Fiber systems were developed for the purpose.

A. Radio over Fiber Systems

Since the bandwidth of wireless channels depends directly on the range of frequencies used, to increase the information carrying capacity, the carrier frequencies have to be increased [1], [2]. Higher frequencies undergo higher atmospheric attenuation which reduces the cell size. Even though this appears like an adverse effect, the reduction in cell size enables less number of users in a cell. The smaller the number of users in a cell, the higher the bandwidth allotted per person since the total bandwidth is shared over the total number of users. Another method to keep the cell size small is to decrease the transmission power of the antenna. However, as the cell size is reduced, more number of cells are required to cover the same area.

When a large number of cells or base stations are needed to cover the same area, the cost, and complexity of the system increases. To keep the system architecture simple and to retain the expenditure in the limits, the base stations have to be simple. In the conventional baseband over fiber systems, baseband data is transmitted to the base stations, and the baseband to RF conversion is done at the base stations. Each base station requires costly RF generator circuitries. Radio over Fiber is suggested for the simplification of base stations.

In Radio over Fiber systems, the RF signals are generated in a central station, and they are transported to the base stations over optical fiber. In the base stations, only simple optical to RF conversion is required which makes the base stations simple. All the signal generation, data modulation, and processing are consolidated at a central station where the costly equipment can be shared by multiple base stations and thereby reduces the cost [3].

B. Subcarrier Multiplexing

In Radio over Fiber systems, the baseband data is modulated onto RF carrier which is then modulated onto the optical carrier. A laser diode is used to generate the continuous wave light used as the optical carrier. The light can be modulated using external modulators like Mach-Zehnder or Electro-absorption modulator or by direct modulation of the laser. For simplicity and cost effectiveness, direct modulation is most considered. Direct modulation is adopted in this work.

During modulation of the RF carrier to the optical carrier, a dedicated wavelength can be allotted to a single RF frequency. This requires a large number of optical carriers one for each RF carrier. For better spectral efficiency, more than one RF carrier can be modulated on a single optical carrier. To enable such a modulation, different RF signals are combined in the electronic domain.

The technique of multiplexing multiple carriers of different frequencies is called subcarrier multiplexing (SCM) [4], [5]. SCM is similar to frequency division multiplexing, and it enables better utilization of the spectrum.

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C. Adverse Effects of Laser Diode Nonlinearity

In Radio over Fiber systems, semiconductor laser diodes are the commonly used optical sources. When the technique of direct modulation is used, the inherent nonlinearity of the laser induces nonlinear distortions in the system. The nonlinear effects occur in the form of harmonic and intermodulation distortions. If a single RF frequency is used for optical modulation, the nonlinear transfer function of the laser produces additional frequency components in the output. The undesired products occur at integral multiples of the input frequency and are termed as harmonic distortions. Similarly, in systems like SCM where multiple frequencies are used, the nonlinearity creates frequency components at the sum and difference frequencies of the input signals. They are termed as intermodulation distortions [6].

For an input frequency f_1, the harmonic products occur at integral multiples $2f_1$, $3f_1$ etc. and they can be filtered out using devoted filters. But for the input signals f_1, f_2, the intermodulation products $2f_1$-f_2 and $2f_2$-f_1 occur very near to the inputs and are hard to remove by filtering. The additional frequencies may produce crosstalk and cause power loss which degrades the system performance severely [7]. Therefore, in systems like SCM-RoF, dedicated mechanisms are to be used for suppression of harmonic and intermodulation products.

D. Technique for Nonlinearity Reduction: Predistortion

The technique of predistortion is to preprocess the input signals before they are fed to the laser diode for modulation. The preprocessing or predistortion of input signals is done in such a way that the nonlinearity of the predistortion circuit compensates the nonlinearity of the laser diode. The predistortion circuitry can be constructed using analog or digital electronic components. The transfer characteristics of the laser diode used is measured, and its inverse function is implemented in the predistortion block. The effective transfer function of the predistortion block is inverse to that of the nonlinear transfer function of the laser diode [8]. Fig.1.1. depicts the basic principle of linearizing the laser diode using predistortion.

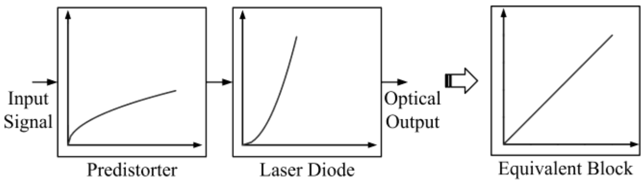

Fig.1.1. Principle of laser diode predistortion.

The predistortion circuitry is cascaded with the laser to create a linear relationship between the input current and output power [9], [10]. In our work, a predistorter is designed which in conjunction with laser diode enhances the SCM-RoF system performance.

II. NONLINEARITY REDUCTION IN SCM-ROF SYSTEM

Fig.1.2. illustrates the block diagram of a subcarrier multiplexed Radio over Fiber system with predistortion, for three users. Three users are using three separate frequencies to transmit data to three other users simultaneously.

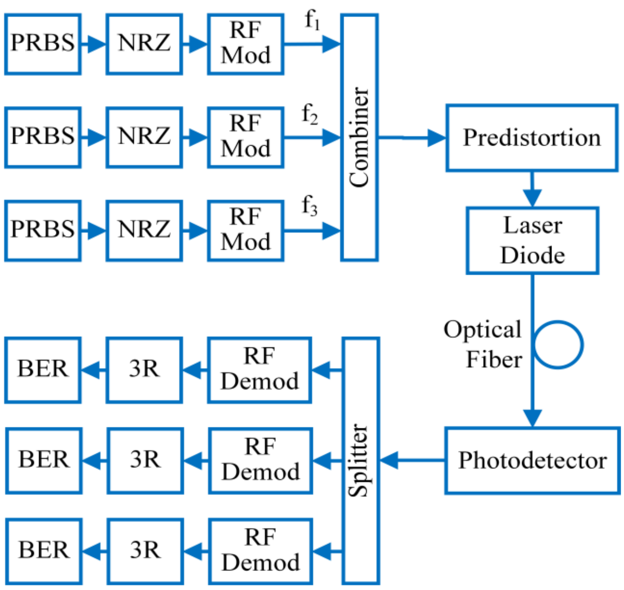

Fig.1.2. 3-user SCM RoF system with predistortion.

The PRBS generator produces a pseudo-random binary sequence which acts as the data to be transmitted. This data is unique for each user. The data is coded into non-return to zero format by the NRZ generator. The NRZ coded data is then used to modulate the RF carrier. The baseband to RF carrier modulation is done using an electronic amplitude modulator. The data of three users are modulated on three separate frequencies. In the simulation, the frequencies selected are f_1=5 GHz, f_2=10 GHz, and f_3=15 GHz.

The three RF carriers 5, 10 and 15 GHz are selected in such a way that the harmonic and intermodulation products overlap. Such a configuration, which is the worst case, is necessary to evaluate the performance of the system and to verify the performance enhancement due to the predistortion technique. The three RF frequencies for the three users can be denoted as three channels. The peculiarity of the particular frequency selection is that the second and third channels suffer from the harmonics of the first channel. The third channel has masking effects from the intermodulation products of the first and second channels. Therefore, the third user/channel is the most affected due to nonlinear distortions, and hence it is selected for performance evaluation.

The three channels are combined together in the electronic domain using combiner element. The output of the combiner will contain the three frequencies f_1, f_2 and f_3 subcarrier multiplexed. The SCM channels are fed to the laser diode for transmission. The laser transmitter modulates the electric signals to the optical carrier and confines the light to a single mode fiber for transmission.

In the simulation, an optical carrier of 193.1 THz frequency and 10 dBm optical power is selected. The fiber used is standard single mode type having a typical attenuation factor of 0.2 dB/km. The fiber runs a length of 50 km. A PIN photodiode is used at the receiving end to convert the optical signals back to the electronic domain.

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The received signal is split into three using a splitter to divide the signals among the three receivers. Each user filters and demodulates the RF signal intended for them by selecting the appropriate frequency. The demodulated RF signals reproduce the data transmitted. The data is then 3R processed to correct the amplitude, shape, and timing. With the help of bit error rate analyzers, the output bits are compared with the input data to measure the number of error bits occurred. Bit error rate (BER) is generally accepted as a measure of system performance.

III. RESULTS & DISCUSSION

The frequency spectrum of the received electrical signal containing the three transmitted frequencies and their harmonic and intermodulation products is depicted in Fig.1.3. The three RF channels 5, 10, 15 GHz and their distortion products are visible. This is when no predistortion compensation is used.

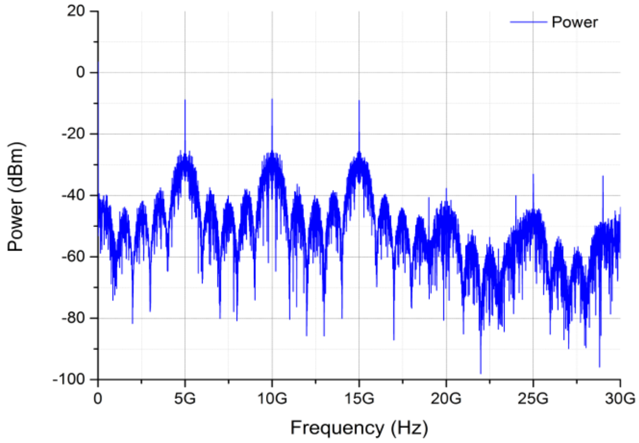

Fig.1.3. Received RF signal when predistortion is not used.

The frequency spectrum of the received electrical signal when the predistortion technique is applied is depicted in Fig.1.4. The reduction in the harmonic and intermodulation products due to the application of the predistortion technique is visible.

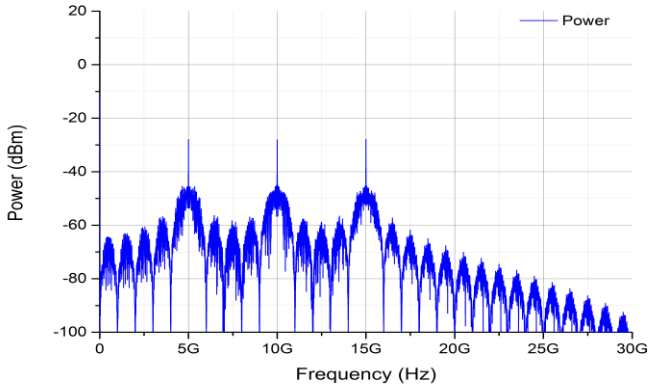

Fig.1.4. Received RF signal when predistortion is used.

To understand the performance of the SCM RoF system under the effect of nonlinear distortions, the received power vs. BER of the third channel of the system is plotted. As mentioned before, the selection of the third channel is because of its vulnerability. The received power vs. BER of the third channel of the designed SCM RoF system without using the predistortion compensation technique is depicted in Fig.1.5.

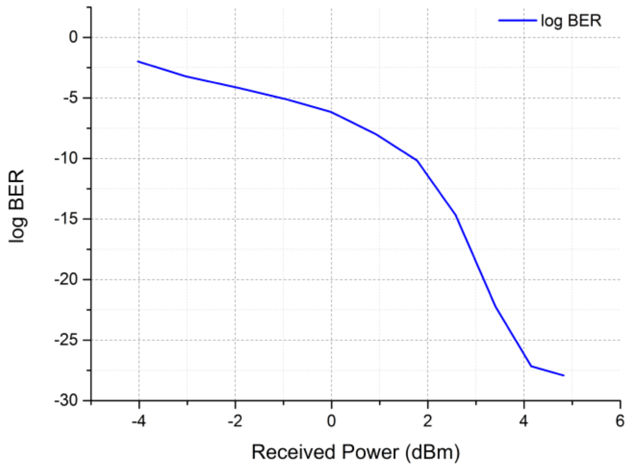

Fig.1.5. BER vs. received signal power of the 3rd channel when predistortion is not used.

BER denotes the ratio of error bits occurred to the total bits sent. A good performance system is characterized by a small BER value. 10^{-9} is often considered as a satisfactory BER for satisfactory performance of the system. From Fig.1.5., it can be understood that the system required a received power of about 1.5 dBm for the satisfactory BER performance of 10^{-9}. The BER vs. received power performance of the system after applying the predistortion technique is shown in Fig.1.6.

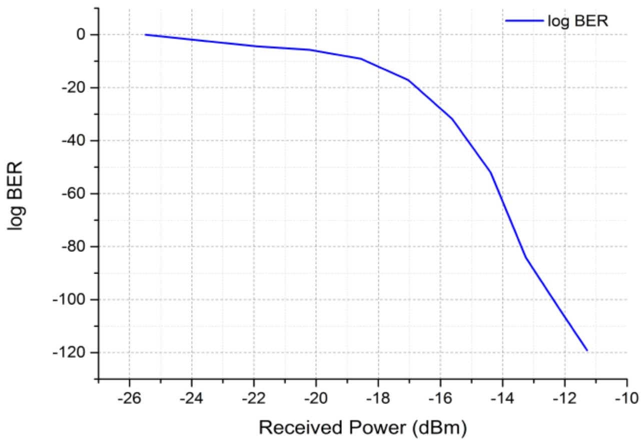

Fig.1.6. BER vs. received signal power of the 3rd channel when predistortion is used.

From Fig.1.6., it is clear that system the system is able to deliver the satisfactory BER even at very low received powers of about -20 dBm. The small BER at low received power denotes the quality of the system. Or it can be explained as the ability of the signals to reach longer distances without losing the quality.

IV. CONCLUSION

The inherent nonlinearity of the laser diode cannot be avoided, and its effect on the multiuser Radio over Fiber systems is severe. In order to compensate the effects of nonlinearity, a predistortion circuitry is designed, tested and its effect is verified in a 3 user subcarrier multiplexed Radio over Fiber system.

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From the frequency spectrum of the received signals, the reduction of distortions can be fathomed. The BER vs. received power performance verifies the performance enhancement of the system by the application of the predistortion technique. Using the predistortion technique, the system is able to deliver satisfactory BER at very low received powers compared to the system without compensation. Therefore, it can be concluded that the predistortion is a promising technique for nonlinearity reduction in laser diodes.

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