Improved Receiver Techniques for Radio over Multimode Fiber Systems

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Abstract—**Multimode fiber links can offer a useful approach for low cost and short Radio over Fiber (RoF) systems. However, in these connections the distortion effects are higher than in a singlemode fiber system. These effects can be compensated by a suitable optical receiver. In this paper an improved receiver structure is investigated for Radio over Multimode fiber systems. N-QAM radio signal transmission is simulated and measured on multimode fiber connections. Several improved compensating reception methods are compared with simple detection. From the different improved methods and installations an optimum solution is chosen for Radio over Multimode Fiber systems.**

Keywords- multimode fiber; receiver; photodetector; Radio over Fiber

I. Introduction

Optical fiber links can provide advantageous solutions for radio communications and information distribution systems. Several concepts of radio over fiber (RoF) systems have been studied in the past few years, and each of them seems to be very attractive because of the low loss and extremely wide bandwidth necessary for mobile broadband services [1]. In a mobile system using a radio over fiber link a central office (CO) is serving a lot of remote antenna units (RAUs). In many applications the size of a mobile cell is very small, therefore, a lot of RAUs must be installed in these networks [2]. Because of the high number of RAUs needed, the cost of the network deployment and operation increases. Thus the main goal in RoF communication systems is to reduce the cost of the RAUs and this way the cost of the deployed and future networks as well [3].

The application of multimode fibers (MMF) can be a cost effective solution for RoF systems. The core diameter of multimode fibers is significantly larger than that of a single mode fiber. Due to the high Spurious Free Dynamic Range (SFDR) requirements, RoF is also favourable for indoor applications. Sometimes MMF links are already installed in buildings, in this case the cost of installation can be avoided [1, 5]. For indoor RoF applications, distances are relatively short, therefore choosing MMFs is the reasonable choice.

However, the signal transmission in Radio over MMF links can be poor compared to Radio over single mode fiber links because of the increased modal dispersion effects found in MMFs. Therefore the main task is to improve transmission quality in a Radio over MMF system by reducing the effect of modal dispersion.

II. System Model

Several methods exist for modal dispersion compensation, for example changing the refractive index profile of the fiber, applying pre-distortion or post-distortion. The changed refractive index method equalizes the different propagation velocities of the modes in the fiber. The application of graded index (GI) fibers is a well known method to reduce the effect of modal dispersion [4]. However, graded index fibers are more expensive than the step index (SI) fibers. On the other hand pre- and post-distortion methods are more complicated because they require additional digital signal processing.

In this paper a receiver structure is proposed to reduce the impact of modal dispersion. The receiver compensates the effect of the modes in the optical domain, however, it doesn't focus on modal delays but it reduces number of modes. Ideally, by using a mode filter or mode stripper at the input of the receiver, the number of modes can be reduced to one. This receiver structure can be optimal for installed radio over multimode fiber systems, because it could decrease the modal dispersion without changing the optical network. This receiver method is shown in "Fig. 1".

By applying this receiver structure the higher order modes are filtered out. However, some power is transmitted in these higher order modes, thus the mode filtering can cause some power loss in the connection which results in signal to noise ratio (SNR) reduction. If the noise of the receiver is high enough, mode filtering can cause limitation in the communication. In this case an improved receiver structure was made and investigated in order to solve the high attenuation of mode filter. These receiver methods were tested by simulations and measurements.

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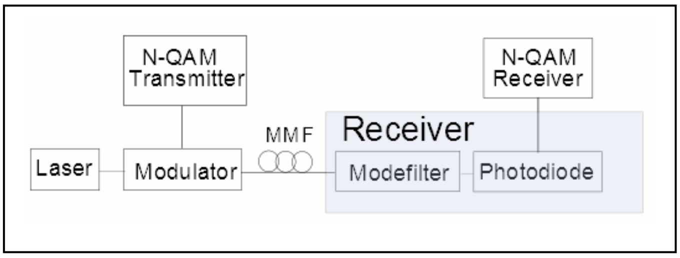

Figure 1. RoF block scheme with the proposed receiver

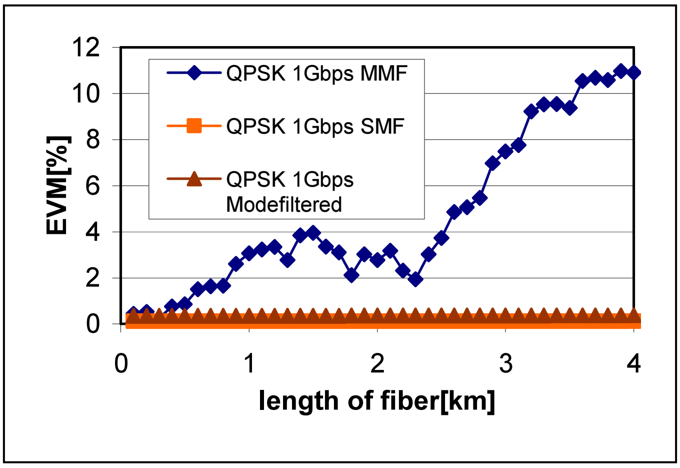

Figure 2. EVM vs fiber length when the noise level is low

III. Simulation Results

In order to evaluate the conventional radio over multimode fiber system with the improved receiver structure simulations were made using VPI Transmission Maker 9.0 [6]. To model the improved receiver, an ideal mode filter was used. The ideal mode filter means in this case that at the output of the mode filter only one mode with reduced power propagates. During the simulations this ideal mode filter was modeled by a single mode fiber and an attenuator. The attenuation was set to 10dB. This value was based on coupled power ratio (CPR) measurements.

The transmitter parameters were set to ideal values. It means that the modulator was linear and chirpless and the relative intensity noise of the laser was neglected. These considerations were quite realistic in a radio over multimode fiber system. The direct modulation is taken to be almost linear, and the receiver is the main noise source in the system. During the simulations the power of the laser was 1mW and the modulation depth was 100%. The simulated N-QAM signals were QPSK and 16QAM modulation formats, and at the receiver the error vector magnitude (EVM) was simulated. The carrier frequency of the radio signals was 2 GHz. The carrier frequency should not be set too high, because at higher frequencies, together with the already present modal dispersion, the degrading effects of chromatic dispersion become apparent.

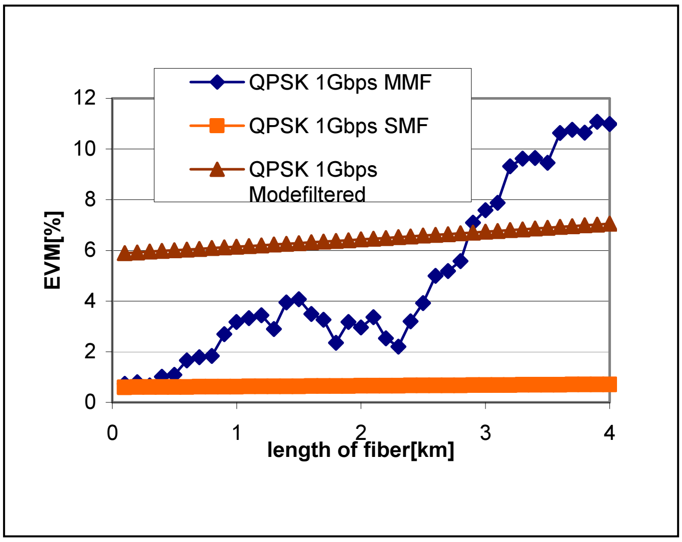

Figure 3. EVM vs. fiber length when the noise level is higher

A. Compensation with mode filter

First, the receiver with mode filter was tested by simulations and compared to the conventional multimode fiber system and single mode fiber system as well. In "Fig. 2" the noise level of the receiver was low. The thermal noise was set to 10^{-12} A/√Hz. Because of the low level of noise, the modal dispersion dominated, and the attenuation of the mode filter was not significant compared to the dispersion. The mode filtered EVM results were almost as good as if only a singlemode fiber would be in the connection. In this case the modefiltering receiver technique can provide a robust solution to dispersion compensation.

When the noise of the receiver increased, the efficiency of the compensator receiver structure decreased. Because of the higher noise level (10^{-10}A/√Hz), the thermal noise was the dominant factor in the distortion, as seen in In "Fig. 3". The compensator receiver was efficient if the length of the RoF link was longer than 3km. In a typical indoor RoF application at higher thermal noise levels the new receiver method is not the best approach.

The results were similar if the modulation was changed to 16QAM "Fig. 4". The main difference between the EVM results for 16QAM and QPSK when the noise level is higher was that the mode filter method became worse than for QPSK signals. This difference was due to the different peak to average power ratio (PAPR) of 16QAM and QPSK. In order to set the optical modulation depth to 100%, the two radio signals had to have the same amplitude. However they had different average power, thus the SNR was different. That means this method had different efficiencies for different modulations because of the different PAPR. When the thermal noise was higher, the mode filter compensation method had limitations. Therefore this method had to be improved by the application of another version of the receiver.

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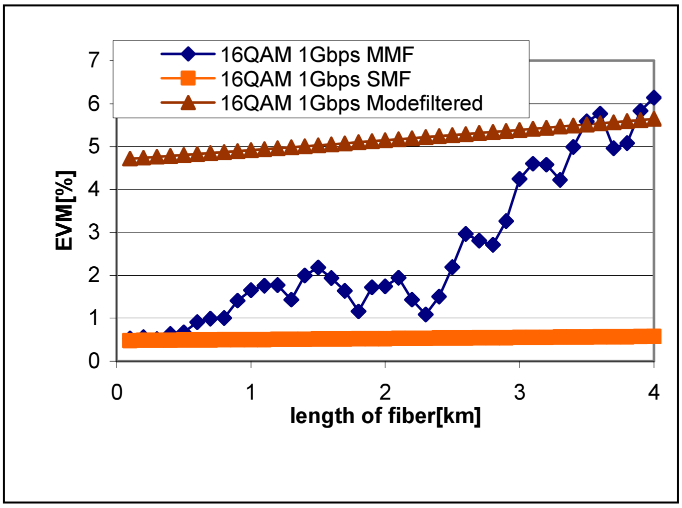

Figure 4. EVM vs. fiber length when the noise level is higher for 16QAM

B. *Simulations with the improved reciever structure*

To improve the mode filter receiver method, the SNR at the end of the receiver had to be increased. To solve this problem, the PIN photodiode was replaced by an avalanche photo diode (APD). If the thermal noise is the dominant noise in the system, the use of an APD improves overall EVM values. When the optical power of the laser is as low as in our case, the shot noise could be much lower than the thermal noise, that is why APD was advantageous.

In "Fig. 5" the mode filter method was compared with the combination of the mode filter and APD. When a mode filter and an APD were applied the EVM results were much better than in the case when a mode filter and a PIN was applied. As "Fig. 5" and "Fig. 3" show, the mode filtered receiver method was suitable for longer connections, however, mode filter and APD method was efficient for shorter links as well.

During the simulation of the improved mode filter and APD method, the thermal noise was set to 10^{-10}A/√Hz, and the multiplication of the APD was set to 10.

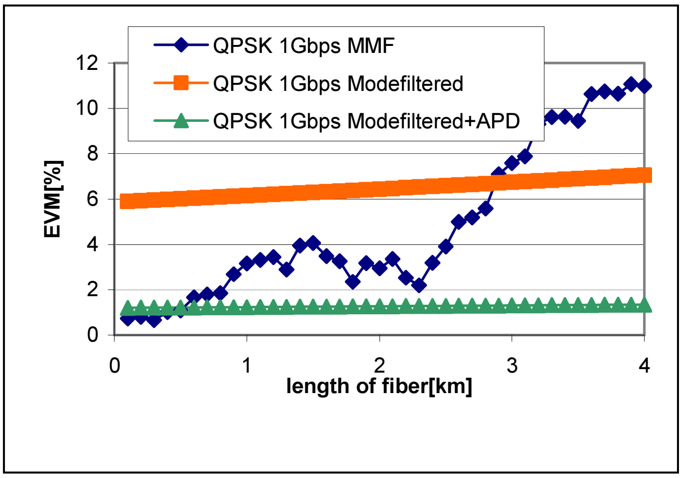

Figure 5. EVM versus fiber length when the noise level is high

IV. Measurement Results

After the simulations the mode filter compensation technique was also investigated by measurements. The measurement set up is a little bit different from the simulation set up. Instead of fiber length sweep, the symbol rate of the N-QAM source was changed. The length of the multimode fiber was 2km during the experiments.

As it was necessary to use a chirpless optical modulator, Mach-Zehnder modulator was applied, with a small modulation depth, to guarantee the modulation linearity. Although in a low cost RoF connection the application of the Mach-Zehnder modulator is not typical, to demonstrate the efficiency of the mode filtering method and to compare the measurement and simulation results, a linear chirpless modulation had to be used.

The consequence of the small modulation depth was the small power of the signals. Because of that the EVM values were much worse than in the simulations. Furthermore, at the end of the PIN diode an electrical low noise amplifier was applied. By changing the bias of the amplifier, the SNR of the output was set. In order to compare a reference measurement with the mode filter methods, the same SNR values had to be set by properly biasing the low noise amplifier.

The optical power of the laser was similar to the laser power used in the simulations, however, the Mach-Zehnder modulator used in the measurements had also a significant optical insertion loss. The photodiode was a PIN diode with approximately 0.9 responsivity. The applied mode filter was a combined multimode and single mode patch cord with a fiber mandrell to reduce the higher order modes. This mode filter was not ideal.

The measurements were made with two radio modulation formats, BPSK and QPSK. These modulations were optimal for the measurement set up, because of the low level of the detected signals. Due to the low power and frequency capacity of the measurement set up, the symbol rates were scaled. Thus the symbol rates were much smaller than the symbol rate of the simulations, but they were suitable to demonstrate the effect of the mode filter method.

The measurement results can be seen in "Table I". At higher symbol rates the EVM increases, because of the impact of modal dispersion. The measured results were compared at the same SNR. Although the mode filter was not ideal, the results show the significant improvement. At the same symbol rate the mode filtered receiver had smaller EVM values than the conventional receiver method. These results demonstrated the efficiency of the mode filtering method, similarly to the simulations. Thus the mode filtering method could improve the quality of the communications.

For a better comparison between the simulation and measurement results, simulations were made on a system with 8Msps QPSK as well. The EVM results were 1.2% on the MMF system without mode filter, and 0.2% on the mode filtered system. The length of the fiber was 2km, as in the measurements. The simulation results were somewhat different from the measurement results, however, the improvement by applying the mode filter method was noticeable. The imperfections of the measurement set up could cause the difference between the simulation and measurement results. In the measured system the noise level was higher than in the simulated system, furthermore the elements in the measured system added additional distortion.

TABLE I. MEASUREMENT RESULTS

Modulation type	Receiver	10ksps	100ksps	1Msps	8Msps
BPSK	**Conventional**	3.3%	4%	12%	28%
BPSK	**Mode filtered**	3.2%	2.6%	5%	12%
QPSK	**Conventional**	3.6%	4%	10%	28%
QPSK	**Mode filtered**	3%	3.5%	7%	16%

V. CONCLUSION

To summarize, improved receiver techniques were investigated for radio over multimode fiber systems by simulations and measurements. A modal dispersion compensator receiver method was shown and its improvement was also tested by simulations. The modal dispersion compensator receiver with mode filter was not only simulated but also measured.

The improved receiver techniques could reduce the effect of modal dispersion and improve the quality of communication in RoF networks using a multimode fiber. Although in systems with higher thermal noise the mode filter technique had limitations, but applying a mode filter and an APD together could provide a low EVM communication in RoF systems up to 4km. These improved receiver structures could be a favourable modal dispersion compensating method for indoor RoF applications as well.

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