Transparent transport of wireless communication signals in Radio-over-Fibre systems

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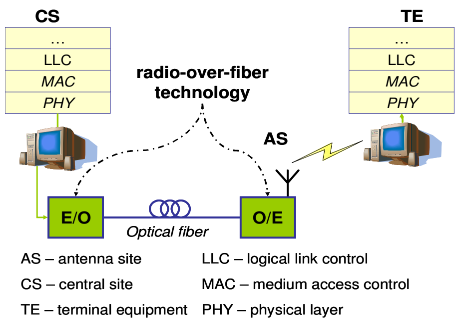
Abstract

The evolution of current wireless access communication networks, especially inside buildings, moves towards higher microwave carrier frequencies in order to support the ever-growing data traffic volumes. This causes significant infrastructure cost increments due to the complexity and increased number of antenna sites needed for a certain area of coverage. Radio-over-Fibre (RoF) distribution antenna systems can reduce costs by means of consolidating the radio access control and signal processing at a central site (CS), and delivering the radio signals transparently to the antenna sites (ASs). Employing the Optical Frequency Multiplication (OFM) technique, we show experimentally the feasibility of delivering different radio signal modulations (e.g., 16-QAM, 64-QAM) with different data rates (from 24 to 78 Mbps) at 17.8 GHz, while maintaining the required optical link transparency.
Additionally, the medium access control (MAC), duplexing schemes and multiple access methods of the different wireless systems put key requirements on the design of radio-over-fibre distribution networks, since the additional propagation delay inserted by the optical link has to be considered from the central controller for supporting such systems. Centrally-scheduled radio MAC schemes, like the ones defined in IEEE 802.16, enable the accommodation of the fibre link between the CS and the AS in exchange for a reduction in the radio bandwidth utilization, which decreases linearly with the fibre length.

Introduction

Radio-over-Fibre (RoF) distribution antenna systems have been identified as a promising option for the access architecture of the emerging wireless access communication networks, specially inside buildings, as a means of reducing infrastructure cost and antenna site complexity, and generating high microwave carrier frequencies optically. In this approach, the insertion of an optical link between the central station (CS) and the antenna site (AS) lies within the physical layer of the wireless system to be supported, independently of the radio-over-fibre technique employed (Fig. 1). The optical distribution system behaves as an analogue transmission system that shall not modify the nature of the radio signal format, but deliver it with the best possible accuracy at the remote antenna location, which acts as a transparent analogue repeater-interface from the optical medium to the radio medium. Since the radio control is located at the central site, a remote radio medium access control has to be performed, thus converting the optical domain in an extension of the radio domain access. Therefore, the radio characteristics and the wireless system requirements set the boundaries and limitations for the optical distribution system design.



CS	Controls both fibre and radio domain *Remote* radio medium access control
AS	*Dummy* analogue repeater-interface
Optical link	Extension of the radio domain access *Analogue* transport of radio signals *Transparent* for radio protocol stack

Fig. 1: Radio-over-fibre system approach

In this way, the radio-over-fibre technique employed in the distribution antenna system has to ensure *transparent transport* of the wireless signals delivered to the AS, because different modulation signals can be employed in the air interface during the same wireless connection; additionally, this optical link transparency enables a potential co-existence of different standards in a multi-standard distribution antenna system approach. Thus, the RoF link performance must remain unaltered.

Different RoF techniques have been developed to optically generate microwave frequencies and deliver wireless signals at a remote AS. The *optical frequency multiplication* principle (OFM) proposed in [1] (Fig. 2) is a cost-effective method for this purpose, which relies on techniques based on harmonics generation and FM-IM (frequency modulation-intensity modulation) conversion [2]. With this method, the light source λ_0 is frequency modulated by a periodic signal with sweep frequency f_{sw}, whereas the data signal is inserted by modulating the light intensity. This signal is passed through an optical periodic bandpass filter and then, launched into the photodetector. When a Mach-Zehnder interferometer is used as a bandpass filter, the signal at the output of the photodetector has frequency components at every harmonic of the sweep frequency f_{sw}, with relative amplitudes depending on f_{sw}, phase modulation index and free spectral range (FSR) of the filter. Thus, high-frequency microwave signals ($f_{RF}=N\cdot f_{sw}$), carrying transparently the data signals impressed by IM, can be obtained by remotely generating optical signals at relatively low f_{sw} frequencies. Experiments have demonstrated the high accuracy of the microwave carriers generated by OFM [3] and the feasibility of transporting typical radio signal modulations (e.g. 64-QAM) after several kilometres of multimode fibre (MMF) [4].

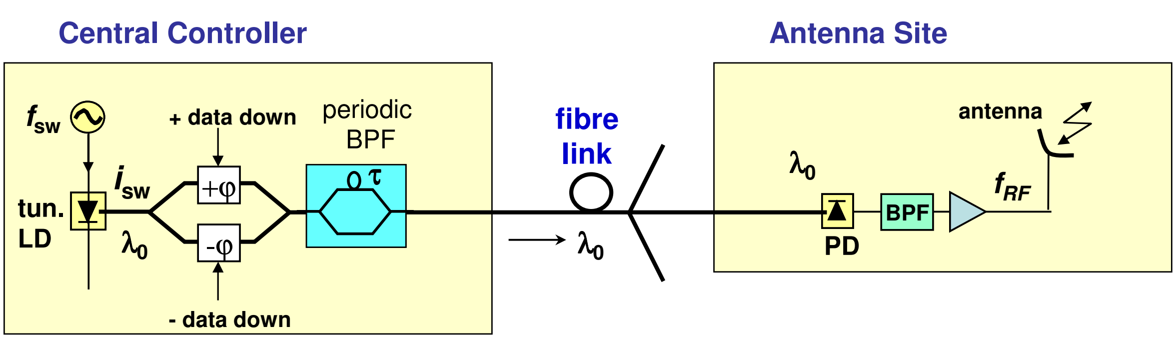


Fig. 2: Basic Optical Frequency Multiplication Scheme

In addition to the transparency requirements stated above, the RoF distribution antenna system design has to consider as well how the *additional propagation delay* introduced by the fibre link affects the network performance, since it might outrun the timing boundaries of the radio medium access schemes and round trip delays defined for the air interface.

In the following, we analyse the link transparency provided by the OFM principle and the effects of the additional propagation delay in an emerging wireless access standard, namely IEEE802.16-TDD, for a RoF point-to-point link scenario.

Link Transparency Evaluation with OFM

The following experiment has been set up to study the transparency of the OFM radio-over-fibre link when transporting different radio signal modulation formats.

Experimental Setup

The OFM system experimental setup is depicted in Fig. 3. A laser source frequency (λ_0=1310 nm) was swept by an optical phase modulator with a sweep frequency f_{sw}=2.8GHz. A Mach-Zehnder intensity modulator (IM) was used to introduce the radio signals into the system. The QAM radio signals, with an output average power of 13dBm, were put onto a subcarrier f_{sc}=1GHz before entering the optical OFM system. The intensity modulated swept light source was amplified by a semiconductor optical amplifier (SOA) and launched into a Mach-Zehnder interferometer (MZI) with 10 GHz free spectral range (FSR). The output of the MZI was launched into a 4.4km 50µm-core MMF link, and recovered by a 25 GHz IR photodetector to generate the RF harmonics of the f_{sw}. The output of the photodetector was amplified by a low noise amplifier (LNA) and analyzed by a vector signal analyzer (Rhode & Schwarz FSQ-40). At the output of the photodetector, the QAM signals were obtained along with all the generated harmonics of f_{sw} at the high frequencies $f_{RF}=n\cdot f_{sw}\pm f_{sc}$. On the upper sideband of the 6th harmonic, the QAM signals carried by f_{sc} were recovered at f_{RF}=17.8GHz.

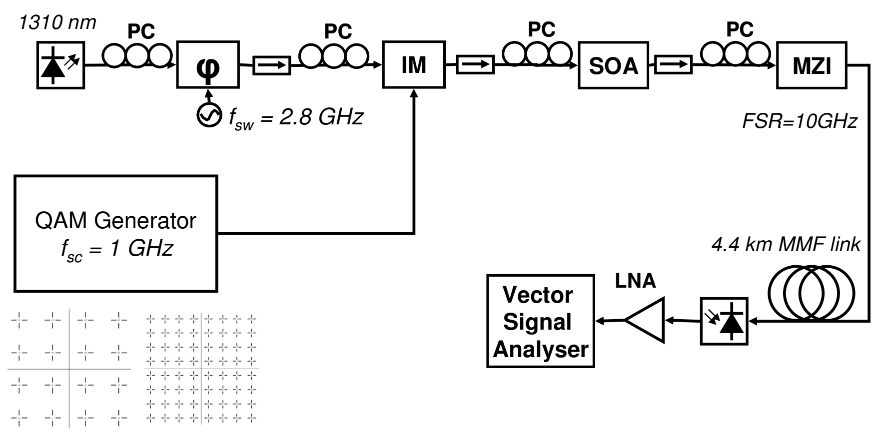


Fig. 3: Experimental setup; (PC: polarization controller)

Measurement Results

Fig. 4 shows the error vector magnitude (EVM) values estimated by the vector signal analyser for the 16-QAM and 64-QAM signals at the input of the OFM link (at 1GHz, from the signal generator), and for the 16-QAM and 64-QAM signals recovered at 17.8GHz after the MZI (back-to-back) and after 4.4km of MMF transmission.

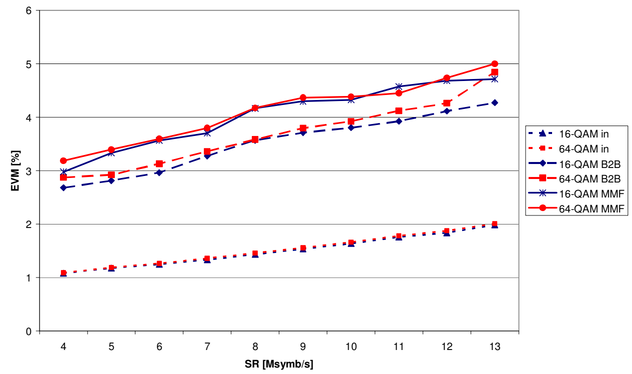


Fig. 4: Estimated EVM of the 16-QAM and 64-QAM signals obtained at 17.8GHz: input (at 1GHz), back-to-back and after 4.4km of MMF transmission (EVM: error vector magnitude; SR: symbol rate)

The estimated EVM values from the signal generator at 1GHz are practically the same for both 16-QAM and 64-QAM modulations and increase with the symbol rate from 1.1% to 2.0% for 4Msymb/s to 13Msymb/s, respectively. After the OFM link, the radio signals recovered on the upper sideband of the 6th harmonic at 17.8GHz were evaluated before and after 4.4km MMF transmission. The signal degradation observed for both modulation types is practically the same. In the back-to-back case, the estimated EVM increases by a factor of about 2.3. For example, the EVM of the 12Msymb/s 64-QAM signal observed at 1GHz was 1.873%; the recovered signal at 17.8GHz suffered an EVM of 4.261%. The optical power loss of 2.1dB inserted by the optical fibre introduces an additional signal deterioration of factor 1.1, which results in a total EVM increase of factor 2.53; e.g., the EVM observed for the 12Msymb/s 64-QAM signal after MMF transmission was 4.734%. The open I-eye and Q-eye diagrams obtained for this signal are shown in Fig. 5.

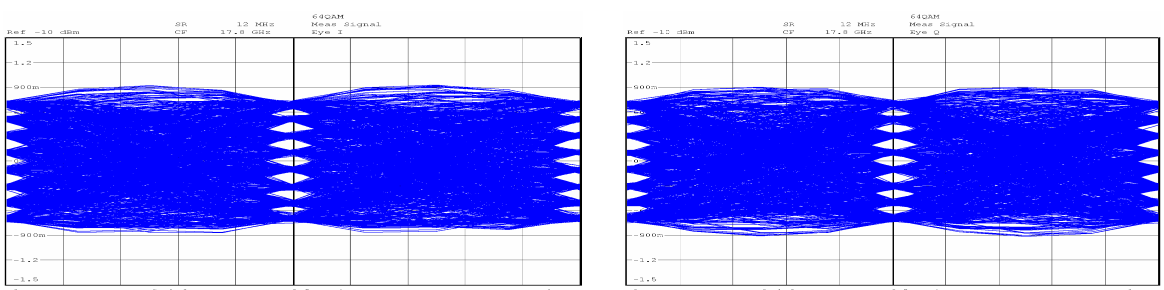


Fig. 5: I-eye and Q-eye diagrams of the 12Msymb/s 64-QAM signal (72Mbps) recovered at 17.8GHz after transmission over 4.4km of MMF

In order to assess the OFM radio-over-fibre link performance, the signal-to-noise ratio (SNR) has been estimated for the 16-QAM and 64-QAM signals at 1GHz at the input of the link, and for the 16-QAM and 64-QAM signals recovered at 17.8GHz after the MZI (back-to-back) and after 4.4km of MMF transmission (Fig. 6).

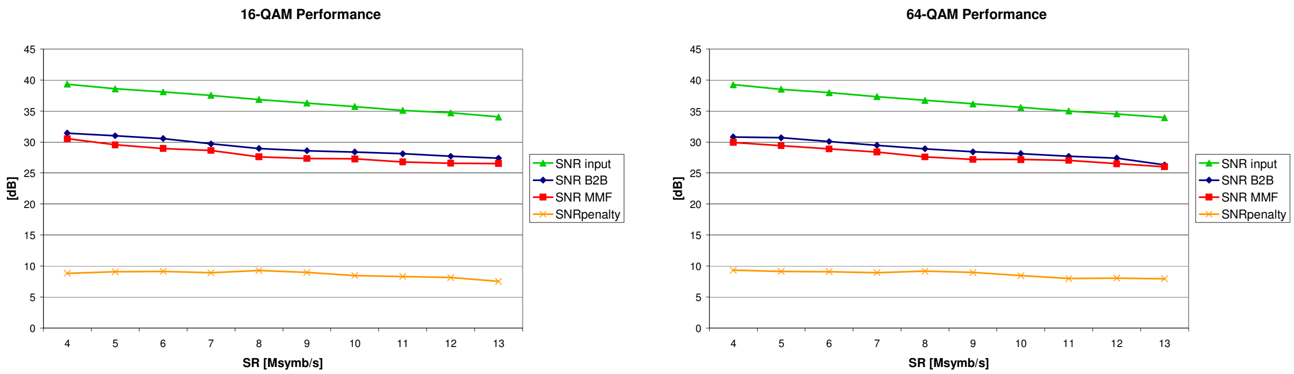


Fig. 6: Performance evaluation of the 16-QAM and 64-QAM signals obtained at 17.8GHz (SNR: signal-to-noise ratio; SR: symbol rate)

Accordingly to the previous EVM estimation, the SNR of the input signals at 1 GHz is practically the same for both 16-QAM and 64-QAM modulations and decreases with the symbol rate from 39.3dB to 34dB for 4Msymb/s to 13Msymb/s, respectively. As it can be observed, the SNR of the recovered signals at 17.8GHz before and after MMF transmission is independent of the modulation employed, and decreases with the symbol rate in accordance with the SNR of the input signals. This yields a SNR penalty of approximately 7.6dB in the back-to-back system; an additional SNR reduction of around 1dB is observed due to fibre attenuation after the MMF transmission, resulting in a total SNR penalty of 8.6dB after 4.4km of MMF transmission.

Thus, based on the similar performance of the two complex constellations investigated, the OFM radio-over-fibre link can be considered transparent and independent of the radio signal modulations transmitted.

Additional Propagation Delay

When inserting a RoF distribution antenna system to support the current and emerging wireless standards, the multiple radio access mechanisms as well as the radio duplexing schemes become a key requirement for the design of the RoF distribution system. This is because the additional propagation delay introduced by the fibre link might outrun the timing boundaries of the medium access protocols and the round trip delay.

Centrally scheduled MAC schemes, such as the one defined by IEEE 802.16 for fixed wireless access, allow flexibility for the insertion of an optical system between the CS and the AS, and for dynamically controlling the propagation delay. For example, IEEE 802.16 defines a time division duplex (TDD) mode of operation in which the uplink and downlink transmissions occur at different times and usually share the same frequency. The TDD frame has a fixed duration and contains one downlink and one uplink subframe (Fig. 7). The frame is divided into an integer number of physical slots (PSs)[1], which help to partition the bandwidth flexibly. The TDD framing is adaptive in the sense that the bandwidth allocated to the downlink versus the uplink can vary. The available bandwidth in the downlink direction is defined with a granularity of one PS. The available bandwidth in the uplink direction is defined with a granularity of one minislot[2].

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[1] One PS is the duration of 4 modulation symbols at the symbol rate of the downlink transmission.
[2] The minislot length is 2^m PSs, m ranging from 0 through 7.

The number of PSs within each frame is a function of the symbol rate. The symbol rate is selected in order to obtain an integral number of PSs within each frame. For example, with a 12Msymb/s symbol rate, there are 3000 PSs within a 1ms frame.

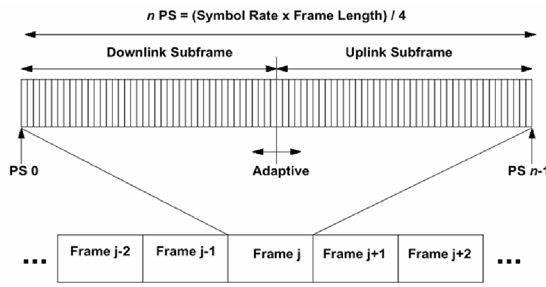

Fig. 7: IEEE 802.16 TDD frame structure

The split between uplink and downlink is a system parameter and is controlled at higher layers within the system. The Tx/Rx Transition Gap (TTG) is a gap between the downlink burst and the subsequent uplink burst. This gap allows the base station (BS) time to switch from transmit to receive mode and the terminals (SSs) to switch from receive to transmit mode. During this gap, the BS and SSs are not transmitting modulated data but simply allowing the BS transmitter carrier to ramp down, the Tx/Rx antenna switch to actuate, and the BS receiver section to activate. After the gap, the BS receiver shall look for the first symbols of the uplink burst. This gap is an integer number of physical slots (PSs) durations and starts on a PS boundary. Similarly, the Rx/Tx Transition Gap (RTG) is a gap between the uplink burst and the subsequent downlink burst. This gap allows the BS time to switch from receive to transmit mode and the SSs to switch from transmit to receive mode. This gap is also an integer number of PSs durations and starts on a PS boundary. The minimum SS receiver performance defines a maximum time from Tx to Rx and from Rx to Tx of *2µs*. This specifies the minimum number of PSs to assign for the TTG and RTG parameters.

The insertion of the optical link can be then adjusted by increasing the number of PS assigned to the TTG and RTG parameters according to the propagation delay added by the optical fibre. Thus, the longer the time gap between downlink/uplink subframes, the longer the optical fibre length between central station and antenna site, though the radio resource utilization decreases. The number of idle PSs necessary to accommodate an optical fibre link in a radio-over-fibre distribution antenna system is depicted in Fig. 8, for different symbol rates. The frame capacity reduction produced by the additional propagation delay has been calculated as the ratio of idle PSs to the total number of PSs in a frame, for the *0.5*, *1* and *2ms* frame types (as defined by IEEE802.16-TDD). It increases linearly with the fibre length L as $0.02{\cdot}L$, $0.01{\cdot}L$ and $0.005{\cdot}L$ for the *0.5*, *1* and *2ms* frame types, respectively. For fibre spans shorter than 500m, the frame capacity reduction is less than 1% for all frame types; with longer fibre spans, the radio resource utilization differences are more noticeable for the different frame types (e.g., 8.8%, 4.4% and 2.2% frame capacity reduction results for the *0.5*, *1* and *2ms* frame types, respectively, with the fibre span -4.4km- employed in the experiments).

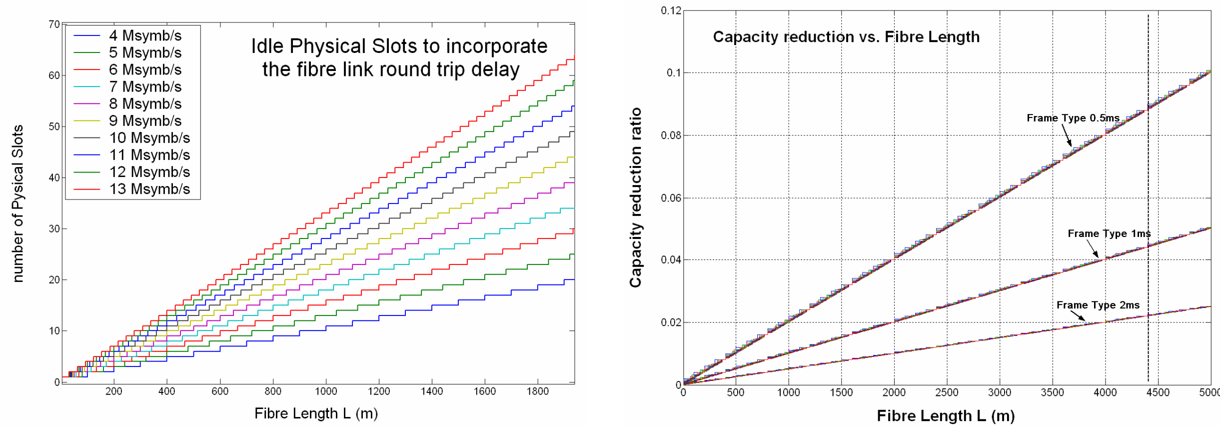

Fig. 8: IEEE 802.16 TDD frame capacity reduction for the accommodation of an optical fibre link between the CS and the AS

Therefore, it is advisable to use the longer frame format in distribution antenna systems with long fibre links in order to minimize the effects of the additional propagation delay inserted by the fibre link and maximize the radio resource utilization.

Conclusions

Radio-over-Fibre distribution antenna systems are becoming an interesting option for the access architecture of the emerging broadband wireless systems because they allow reduction of infrastructure cost and antenna site complexity. The inherent analogue nature of this approach establishes stringent link transparency requirement in order to transport the different modulation signals employed in the air interface. Moreover, flexible and dynamic control of the additional propagation delay inserted by the optical fibre has to be also provided.

The optical frequency multiplication (OFM) technique can generate very high frequency carriers ensuring transparent transport of the modulation formats employed by the wireless signals. The OFM link transparency has been evaluated experimentally by means of generating different wireless signals, namely 16-QAM and 64-QAM with symbol rates ranging from 4Msymb/s to 13Msymb/s, at 17.8GHz after 4.4km of multimode fibre. The results show that the OFM link introduces a total SNR penalty of around 8.6dB after multimode fibre transmission, independently of the modulation format employed. EVM values lower that 5% have been achieved for all the wireless signals obtained at 17.8GHz. Thus, it can be considered that the OFM link fulfils the link transparency requirement.

Centrally scheduled MAC schemes, e.g. the one defined by IEEE 802.16 for fixed wireless access, allow flexibility for the insertion of an optical system between the CS and the AS, and for dynamically controlling the additional propagation delay inserted by the fibre link. In TDD mode of operation, this additional propagation delay implies a frame capacity reduction, linearly increasing with the fibre length. For fibre spans shorter than 500m, this reduction is less than 1% for the three frame types defined by the standard. With longer fibre links, the 2ms frame type is more efficient in terms of radio resource utilization, since the ratio of idle physical slots to the total number of physical slots is lower than in the shorter frame types.

Acknowledgement

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