Radio-over-Fibre Transmission of Multiple Wireless Standards for Digital Cities: Exploiting the New Tramway Infrastructure

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Abstract — **The present paper aims at the specific application of Radio-over-Fibre to provide dedicated Wi-Fi access to tramway passengers. The challenge here is to provide wireless services in densely populated city areas based on a real-case scenario targeting public transport. The proposed system targets 2.4 GHz Wi-Fi access at 1 Mbps per user inside a tram, with a wireless bridge at 5 GHz along the track. A chosen design will finally be implemented and evaluated in terms of WiFi coverage, BER and power consumption. Lessons learned will be interpolated for 60 GHz RoF for Wi-Fi access. Replacing the 5-GHz track site solution by a 60 GHz wireless link will bring a significant increase in data throughput (>1 Gbps). We report here performances of running experiments on 2.4 and 5 GHz RoF systems and results on photonic 60 GHz generation for existing fibre backbone between the stations.**

Keywords - radio-over-fibre applications; multiple standards; running experiments.

I. INTRODUCTION

There is a growing demand for high-speed wireless access by the end users while they are on the move using trains, buses, planes, ships, etc [1-3]. Yet, train operators offer limited radiofrequency-based wireless network solutions to passengers on their intercity high-speed trains. Such solutions are mainly based on mobile (UMTS, LTE-4G) and/or satellite communications but are limited in terms of bandwidth, resulting in slow access even under the best conditions. One attractive way to overcome these limitations is to employ Radio-over-Fibre (RoF) transmissions to transport data-carrying radio-frequency (RF) signals optically to/from a set of wireless access points distributed along the track. Ongoing project CapilRTram (2011-2012) aims at developing a fibre-supported wireless system to provide high speed and seamless Wi-Fi connectivity along the new tramway line (under deployment) in Brest (France). One key advantage is that all stations are interconnected by an optical distribution network.

Section II of this paper presents the general system architecture of the Tram infrastructure. As will be shown, this system deals with different frequencies: Section III deals with the frequency 2,4 GHz to provide Wi-Fi for the passengers waiting in the tram station. In section IV, we focus on the frequency of 5 GHz to provide Wi-Fi connectivity between the Tram station and passengers inside the tram. Finally, Section V deals with the mm wave generation as 60 GHz band is an alternative to the 5 GHz link discussed in Section IV.

II. OVERALL SYSTEM ARCHITECTURE

Figure 1. General system architecture

As depicted in Fig. 1, the proposed system comprises, at each station, an optical node (5) including a bidirectional optoelectronic transceiver (O/E; E/O) adapted to convert RF signals into the optical domain and vice-versa. This transceiver is coupled to a first wireless module (3) which is adapted to communicate with at least one RF transceiver (1; 2) installed on top of each tramway carriage, thereby forming a high-speed wireless bridge between the tram and the stations. For that purpose, the antennas are selected and positioned to ensure continuous link availability between the station and the tram. A second wireless module (4) coupled to the optical node (5) provides wireless coverage to passengers waiting on the station platform. The first and second modules (3; 4) may be combined in a single module. The proposed system is Wi-Fi compliant (IEEE 802.11 a/g/b) and adapted to operate simultaneously on two distinct RF bands (i.e. 2.4 GHz and 5 or 60 GHz). Microwave links (e.g. 5 GHz) or millimetre-wave links (e.g. 60 GHz) will be deployed using commercially available equipment all along the tramway line to connect tram carriages to stations. Inside the tram, Wi-Fi coverage is provided at the conventional 2.4 GHz band by a commercially available wireless access point (1). Wi-Fi access points (4) at 2.4 GHz

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will also be provided to passengers on the station platform. The proposed solution is a flexible (easily upgradeable) and low-cost for a dedicated wireless access with high speed connections based on mature technology (IEEE 802.11a, 54 Mbps for 5 GHz). Thanks to its fibre base, it is transparent to wireless protocols and future-proof. There will be no need to replace the whole infrastructure in case higher throughputs are needed or other frequency bands need to be used. Replacing the 5-GHz link by a 60 GHz wireless link will bring a significant increase in data throughput [4] using existing standards at 57-66 GHz (ECMA-387, IEEE 802.15.3c or IEEE 802.11ad).

III. Bi-directional RoF/ DAS link at 2.4 GHz (IEEE 802.11b/g)

Radio-over-fibre techniques used to interconnect optically wireless access points over Distributed Antenna Systems (DAS) could provide sustainable solutions for delivering high data rates to mobile end-users in public transport. In RoF systems, both the carrier and the data signals are transmitted from a central office via an optical fibre feed network to the remote antenna units from where they are distributed to the mobile end-users via wireless links. With RoF DAS, the transmitted signals can be easily shared amongst a large set of cells to provide improved coverage with reduced power levels. DAS was shown to be a flexible, bandwidth-efficient and cost-effective option for fibre-radio access infrastructure [5-6]. The use of RoF in moving vehicles is a novel application of RoF and more particularly for trains.

A Wi-Fi DAS demonstrator adapted to operate at 2.4 GHz will provide wireless coverage for mobile users, waiting for the tramway on the station platform. With reference to the overall system architecture illustrated in Fig. 1, the optical node at each station is connected to the optical distribution network by means of silica single-mode fibres (SMF) that transport the data-carrying RF signals on an optical carrier up to the individual roadside antenna units. As depicted in Fig. 2, the proposed DAS demonstrator comprises a conventional wireless router adapted to distribute Wi-Fi signals (IEEE 802.11b/g) to a set of four wideband omni-directional antennas, through a wired infrastructure based on fibre and coaxial cable. A circulator is used at each end of the loop to isolate the signals on the uplink and on the downlink. The circulators with an isolation of 23 dB could be replaced by switches showing an isolation level of 30-40 dB. An optical transmission link was introduced between the router and the antennas by means of two bidirectional RoF transceivers (E/O; O/E) with an output optical power of - 4.56 dBm and connected to each other by a 500-m single-mode fibre span. This length of fibre corresponds to the average distance between two adjacent stations in Brest.

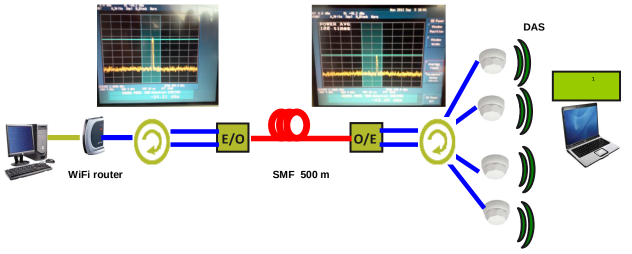


Figure 2. Bi-directional RoF-DAS demonstrator based on commercially-available components (Buffalo Wi-Fi router Model WHR-HP-G54) at 2.4 GHz; 2 RF Circulators; 2 FiberSpan bidirectional Transceivers (O/E; E/O) for 2.4 - 2.5 GHz with 1.5µm and 1.3µm optical sources; 1 Power supply for the two FiberSpan modules (HAMEG HM8040-3 (12V) – not shown here; 500m SMF (Corning); 4 Omni-directional Antennas 2.4/5 GHz (Hyperlink HG2458CU)

Power measurements (see Fig. 2) showed an attenuation of 18 dB between the RF output of the router and the output of the 2nd circulator. The optical link composed of the two RoF transceivers and the optical fibre span was characterised in terms of gain (-25 dB), non-linearity (Input Interception Point Order 3: 0 dBm <IIP3< 25 dBm), noise performance (Noise Figure: 50 dB <NF<55 dB) and frequency response (bandwidth: 2.4 GHz). Due to the low optical IIP3 and high NF of the optical link, the dynamic range (DR) of the RF signals must be reduced in order to meet the SNR requirements (minimum level of output signal power > noise + SNR) and to avoid the nonlinearities (maximum level of output signal power < OIP3 – 20 dB). DR is an important parameter for mobile cellular communications because the power received by the antenna from the endpoint varies widely (e.g. DR = 52 dB: -82 dBm to -30 dBm for WLAN 802.11g,). Automatic Gain Control techniques can be used to adapt the RoF system to various signal levels as described in the Wi-Fi standard.

The system performance has been assessed through bi-directional transmission of High Definition (HD) videos between two computers as shown in Fig. 2. Free software VLC 1.1.9 was used in broadcast mode to transmit 1360x768 HD video signals with an average data rate of 17.66 Mbps and maximum possible 20 Mbps.

IV. RoF link at 5 GHz (IEEE 802.11a/n)

According to the proposed system architecture, tram stations are interconnected by an optical distribution network and each station is connected to the tram by a 5 GHz Wi-Fi link.
For demonstration purposes, we tested the architecture as shown in Fig. 3 towards the 60 GHz RoF approach. This approach becomes essential to provide high data rates >10Gbps with high available bandwidth (7 GHz) to the end-user.

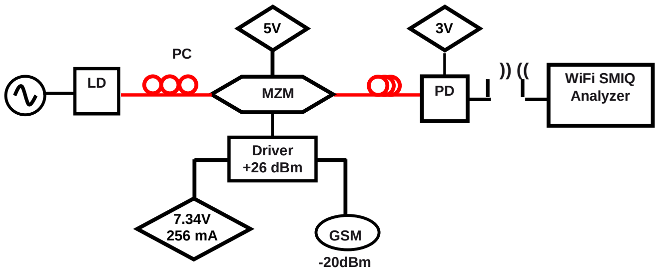


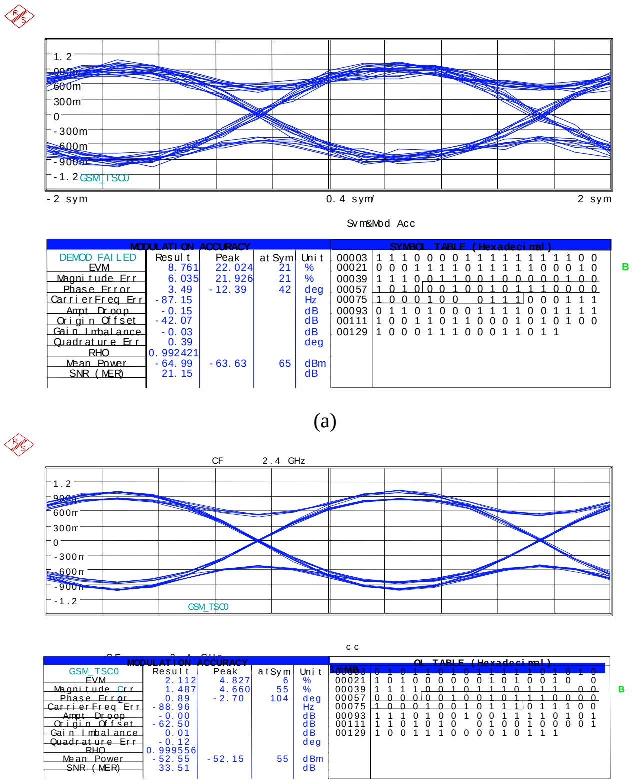
Figure 3. System setup showing the photonic mmw generation, data modulation, photonic wireless transmitter and SMIQ06 software as the wireless receiver. Laser Diode (LD): EMCORE [10341A] with FC/APC Optical Connector, Mach-Zehnder Modulator (MZM): LiNbO3 40 Gbps Photline MXAN-LN-40 at 1550 nm, 2.5 Gbps with FC/APC connectors; RF driver amplifier; Photodiode (PD): U2t 70 GHz photodetector, 0.57 A/W

Photonic RF generation was performed by means of a DFB Laser Diode (LD), operating at 1309 nm with an optical output power of 9.28 dBm directly modulated by 5 GHz RF signal at -10 dBm . Applying a direct modulated laser (DML) at frequency f_0 and a RF source with a frequency f_{RF}, the generated first-order sidebands are located at a frequencies $f_0 + f_{RF}$ and $f_0 - f_{RF}$. The same DSL technique can be applied at much higher frequencies in the millimetre-wave range.

Broadband modulation in the optical domain was carried out using a $LiNbO_3$ 40 Gbps Mach-Zehnder modulator (MZM). The modulator acts here as an optical mixer, multiplying the optical RF carrier with the data signal. As shown on Fig. 3 the transmitter is followed by a polarisation controller (PC) to adjust and maintain the polarisation state of the light for the MZM, which is extremely polarisation sensitive. The maximum RF power that can be possibly applied directly to the RF input port of the MZM is 28 dBm (i.e. 2 dBm delivered to the input of its driver amplifier which has a gain of 26 dB). We used -20 dBm GSM /IEEE 802.11.b signal at 5 GHz. The modulator is driven by a driver amplifier (bias 7.34 Volt corresponding to 256 mA) and biased at V_π, here 6.5 Volt and modulated first with a GSM data signal, generated by a R&S *vector signal generator* with a level of -20dBm maximum output power of 64 dBm for 2.4 GHz (GSM) with demodulation rate 270 kHz; symbol rate 270 ksym/s and GSM modulation 1bit/sym. The optical power measured at the output of MZM was -6 dBm.

The RoF unit is adapted to transmit the RF signal at 5 GHz in free space to the end user terminal. This RoF unit consists of a photodetector (PD) that converts the received optical signal to an electrical 5 GHz signal, a power amplifier that boosts this electrical signal and an antenna adapted to operate up to 5.8 GHz. The PD (U^2t Photonics XPDV3120R-FC-VF) has a bandwidth of 70 GHz and a responsivity of 0.57 A/W. The gain of the photodetector equals to -42 dB as measured by connecting it to the directly modulated laser diode LD (9.28 dBm optical LD output, -52 dBm electrical PD output).

The performance of the modulation procedure has been evaluated. The power of the optical signal measured at the output of the MZM was equal to -11.8 dBm with an input RF signal power level of -20 dBm. With a PD gain of -42 dB, the output signal should be -63.8 dBm as compared to its measured value: -64 dBm). Eye diagram for this signal is wide open with EVM = 6.5%, Peak EVM=15%, Mean Power = -62.3 dBm and SNR = 24 dB. Changing the level of the input signal up to -10 dBm shows corresponding results: satisfactory error-vector magnitude EVM = 2.5%, Peak EVM = 6%, Mean Power = -53.5 dBm, SNR = 32 dB.



(a)

(b)

Figure 4. Eye diagram characterisations, corresponding to GSM modulating signal with data rate of 30-40 Kbps with low noise amplification. GSM modulation is 1 bit/sym and demodulation rate is 270 ksym/sec (a) Signal at level -20 dBm, EVM = 6.5% (b) Signal at level -10dBm, EVM=2.5%

Clearly open eye diagrams were observed for GSM transmission experiment (Figs. 4a and 4b). It shows that the signal has little noise and the amplitude is sufficient to be clearly "recognized". Adding a low noise RF amplifier (MAXIM-MAX2649) with an electrically-controlled variable gain (not shown in Fig. 3) used as a Trans-

Impedance Amplifier (TIA) after the photodiode can improve corresponding values to EVM = 1%, Peak EVM = 2.5%, Mean Power = -45 dBm (compared to -62 dBm before), SNR = 40 dB (compared to 24 dB before).

To analyse the link performance, we have used *Rhode& Schwarz OFDM Software* working as a vector signal analyser. This Software synchronises and demodulates the modulated signal. For this purpose, we have chosen a standard WLAN A – 64 QAM demodulation and both cyclic and pilot aided synchronisations. EVM vs. Carrier diagram (showing peak, average, minimum performance) and selected constellation diagram, taken by choosing digital standard GSM-EDGE (GSM LNB) are displayed in Fig. 5 and Fig. 6. EVM analysis shows that multiple standard wireless access signals such as GSM and WLAN 802.11g can be successfully transmitted with no errors. With input Wi-Fi signal of -10 dBm, EVM is about 10% worse than with the GSM signal of the same power. In fact, as the envelope of Wi-Fi signals is no longer constant, it is possible that the peaks of signal exceed the maximum RF input level allowed by the MZM. In order to improve EVM and constellation, the input signal power of the driver should be less than – 20 dBm.

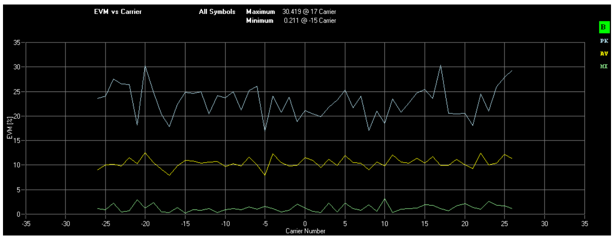


Figure 5. EVM vs carrier

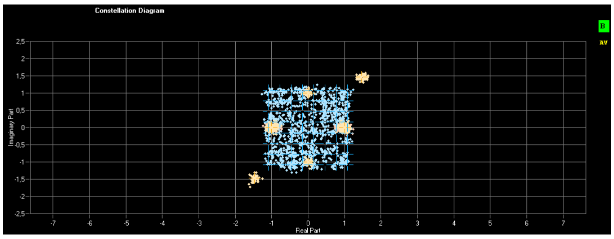


Figure 6. Constellation diagram

V. PHOTONIC 60 GHZ GENERATION (IEEE 802.11AD) BASED UPON EXTERNAL MODULATION

With the use of the IEEE 802.11ad standard, higher throughputs could be achieved - at least 3 Gbps within 4 m and 1 Gbps up to 25 m [7]. Such speed becomes mandatory to deliver future applications. The standard takes advantage of large continuous blocks of unlicensed spectrum at 60 GHz. As signal bandwidth and carrier frequencies keep on increasing, there is an urgent need to define the full potential of RoF technology for the transport of various wireless signals and protocols to meet the demand for new wireless services with enhanced data throughputs in moving vehicles. With the implementation of 60 GHz RoF, more than 1 Gbps could be delivered on wireless links between the tram carriages and the stations. Rather than generating the local oscillator signal electrically at each station, it is optically generated from a central point and distributed to the stations. Optical heterodyning was used to generate the 60 GHz carrier according to the schematics as shown in Fig.7. Some of the equipment listed in the previous paragraph was used in combination with a high power laser diode (ILX Lightwave). The DFB laser diode operating at 1550 nm was driven by a precision current source (LDX-3545B) and stabilised by a temperature controller (LDT-5412). The operating point was fixed at 18 dBm, corresponding to λ_0 = 1548 nm. The laserdiode is again followed by a polarisation controller, slightly reducing the optical power to 17.7 dBm.

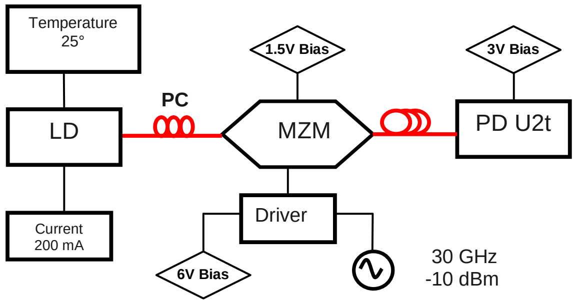


Figure 7. Photonic millimeter-wave generator based on external modulation. Components additional to Fig. 3: ILX Lightwave LDT-5412 temperature controller; Precision Current Source: ILX Lightwave LDX-3545B

Using the driver amplifier, the modulator (MZM) was biased at a minimum transmission point (MITP, here 1.5V), in order to suppress the optical carrier at central wavelength λ_0, and modulated with a millimetre-wave signal at a frequency of 30 GHz, provided by the signal generator Anritsu MG-364A. The power of the 30 GHz input signal was set to -10 dBm. If bias is set to MITP with respect to the optical carrier, the carrier is cancelled out as the phase shift between both arms is set to π. While applying an electrical signal at half the desired mm-wave frequency, i.e. 30 GHz (= 0.5 x f_{LO}) to the RF electrode of the modulator, the total frequency difference between both sidebands is now f_{LO} = 60 GHz. Two optical signals with a wavelength separation of 0.5 nm at 1550 nm generate the desired beat frequency upon detection by the photodiode: $\delta f = f_2 - f_1 = c/\lambda_2 - c/\lambda_1$ with $\lambda_1 =$ 1562.5 nm and $\lambda_2 =$ 1562 nm. Applied

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signal generation technique is called double-sideband with carrier-suppression (DSB-CS) (see [8-9]).

Simulations under VPI Transmission Maker^{TM}, based on the schematics shown on Fig. 8 demonstrate that sidebands suppression contrast here is about 36 dB (see Fig. 9). The output optical field from the modulator consists now of the suppressed optical carrier and two optical sidebands (lower and upper sidebands). Additionally, Fig. 10a illustrates that the maximum output power at 60 GHz that can be obtained with this material is equal to -35 dBm. From Fig. 10b, it is also clear that -35 dBm is the highest measured power value for the discussed system.

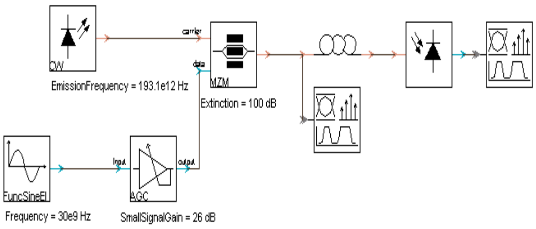


Figure 8. VPI scheme for setup, depicted on Fig. 7

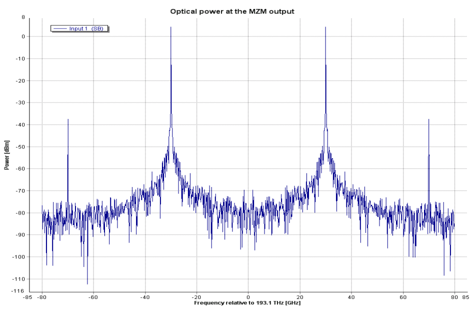
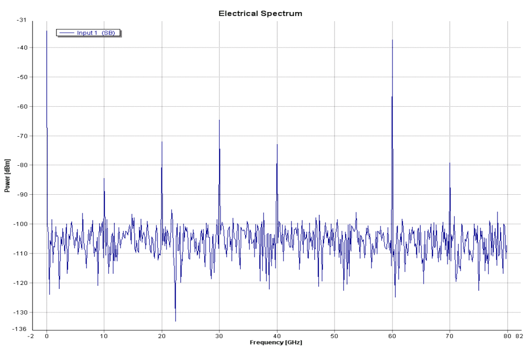
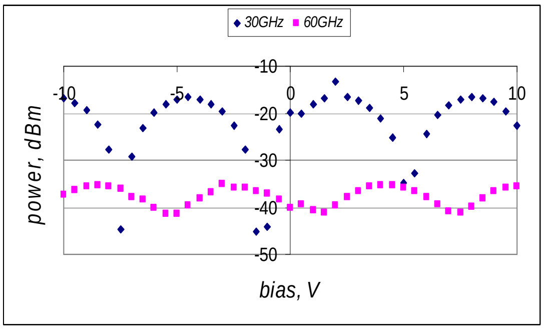


Figure 9. Optical spectrum while applying fLO/2 and biased at MITP



(a)



(b)

Figure 10. VPI simulations (a) and power measurements of 30 GHz and 60 GHz signals at the output of the PD (b)

VI. CONCLUSION AND FUTURE WORKS

In this paper, we have proposed track side solutions to provide Wi-Fi to tram passengers. Different scenarios, based on RoF were simulated and tested, in order to demonstrate their performance for tram installations and to make an insight into the limits of existing RoF components. Through careful application of bias, the linear and nonlinear domains of the MZM transfer function are successfully used for 60 GHz generation and for broadband modulation. VPI simulations were proved to be reliable and will be required in the future for the implementation of multiple standard solutions. Thanks to the broadband operation characteristics of the MZM and the PD, the proposed system can advantageously accommodate a large range of frequencies. System validations will follow by identification of critical components and optimization of energy consumption on 3 (out of 28) tramway stations in Brest and 2 carriages.

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