Radio-Over-Fiber Technology: a brief overview and the work at RDTL

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Abstract
Despite the remarkable growth in communication technologies, there is an increased requirement for integration of heterogeneous technologies, particularly mobile and wireless communications, into a backbone network being capable of providing mobile, broadband, reliable and ever-present services to end users. Radio-over-Fiber technology appears to be an emerging and efficient solution towards the seamless integration of optical and wireless networks for future broadband communications. This paper discusses the concept and the fundamental issues of radio over fiber technology and provides a brief survey on the current state of the art. Additionally, it presents an overview of the ongoing work at the Research and Development for Telecommunications Laboratory (RDTL) of the Technological Educational Institution (TEI) of Athens.

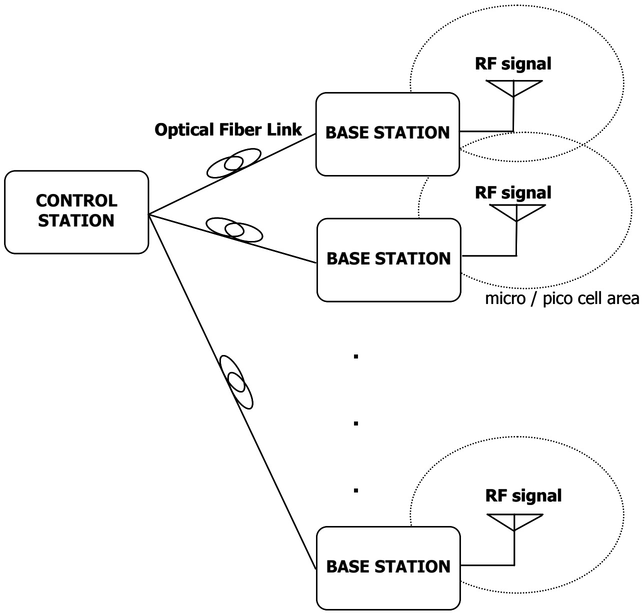
Keywords
Radio-over-Fiber, Distributed Feedback Laser, DFB, Wireless Networks, Optical Networks, Wireless Access, Microwave Photonics, Hybrid Fiber Radio.

1. Introduction

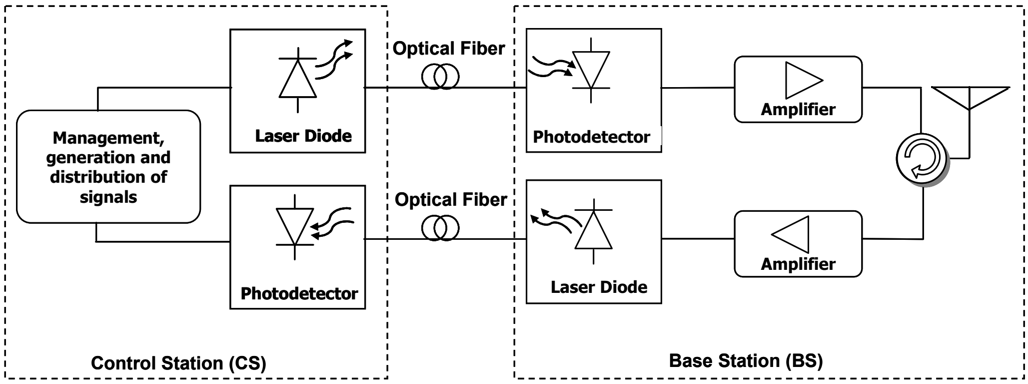
The tremendous evolution since the advent of wireless and mobile communications has boosted the transitions from second generation (2G) to third generation (3G) systems and, currently, beyond 3G or fourth (4G) generation. This development has further increased the requirement for the provision of mobile broadband and the necessity for network convergence and collaboration (Arroyo-Fernandez, 2003; Arroyo-Fernandez, 2004). The terms mobile and broadband, indicates the need for anytime-anywhere and multimedia high speed services respectively.

Following the trend for convergence and seamless integration of broadband wired and wireless access networks, the effective combination of both optical and wireless access networks seems to be promising solution for the practical deployment of future broadband networks (IEEE, 2007). An efficient way to accomplish this goal is through the so-called Hybrid Fiber Radio (HFR) or Radio-over-Fiber (RoF) technology. The RoF technology may also serve as the proper interface infrastructure for the employment of optical networks as a backhaul for current and emerging mobile/wireless access schemes (Al-Raweshidy, 2002; Lee, 2007; IEEE, 2007).

Although the concept and the advantages of RoF are not new (Ogawa, 1992), recent advances in the fields of both optical and wireless communications and the ever increasing demand for more capacity, have further enhanced the interest for its exploitation in current and next generation communication systems (Al-Raweshidy, 2002; Pinter, 2005; Koonen, 2006; Liu, 2006). The fundamental idea and principal advantage behind Radio-over-Fiber systems is the centralized concept of central/control stations (CS) that consequently lead to the minimization of the required baseband and RF signal processing in base stations (BS) or remote antenna units (RAUs).



(a)



(b)

Figure 1 – Basic RoF architecture, (a) the interface between the CS and several BSs via optical fiber, (b) typical RoF uplink and downlink configuration.

The central stations are connected to base stations via optical fibers, making the latter simple, flexible and cost-effective.

This work discusses the concept and the fundamental issues of radio over fiber technology and provides a brief survey on the current state of the art. Additionally, it presents an overview of the ongoing work at the Research and Development for Telecommunications Laboratory (RDTL) of the Technological Educational Institution (TEI) of Athens. The rest of the paper is organized as follows: Section 2, covers the model and the components of RoF technology and depicts its

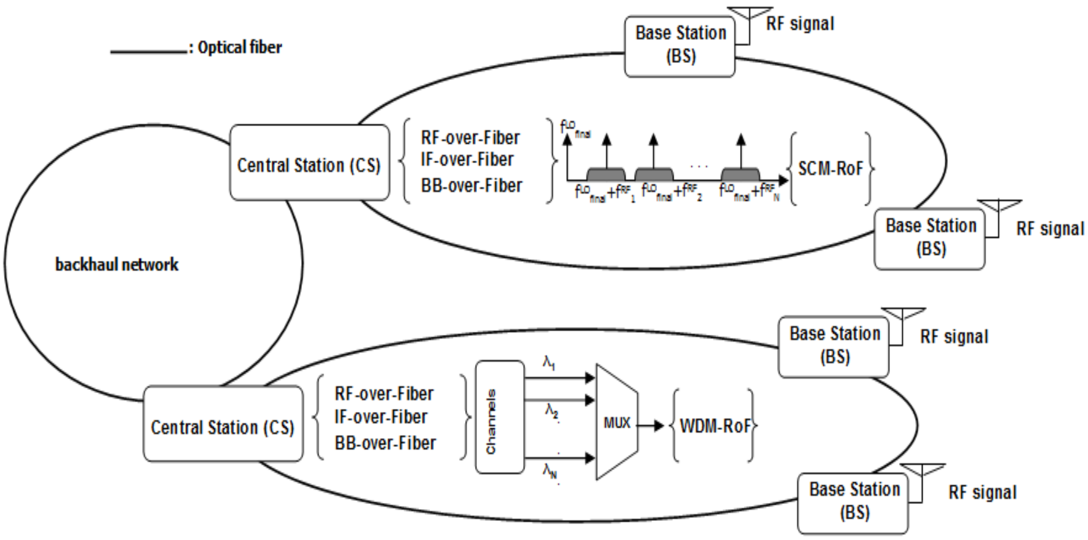


Figure 2 – RoF architectural configurations: The CS distributes the mm-wave signal using either RF-over-Fiber or IF-over-Fiber or BB-over-Fiber and possibly employing SCM. The same arrangement using WDM is also shown.

common techniques and architectural deployments. In addition, the relative merits and disadvantages of RoF are also discussed. Section 3, provides an overview of the research work in RDTL and section 4 summarizes this work.

2. Overview of RoF technology

2.1 RoF architectures and deployments

The architectural arrangement of RoF is illustrated in figure 1a. The CS is responsible of managing, generating and distributing the RF or millimeter wave (mm-wave) signals to several BSs via optical fibers. In turn, the BSs convert the signal back to electrical and transmit it to the end users. The reverse operation entails the conversion of the electrical signal into optical and transmission to the CS via the optical fiber. A typical link between the CS and one BS is shown in figure 1b. The principal infrastructure of a BS involves mainly optical to electrical conversion and vice versa along with amplification and antenna equipment. That is, the BS configuration is kept as simple as possible. This arrangement is also called RF-over-Fiber since the RF or mm-wave signal is distributed by the CS. Although this configuration is very cost effective, it is prone to fiber dispersion and phase noise. Alternatively, there are two more possible configurations namely, IF-over-Fiber and baseband (BB)-over-Fiber (Kitayama, 2000; Novak, 2007). In the former case, the CS transmits the signal in an intermediate frequency (IF) and the final up-conversion is done at the BS. In the latter one, the CS transmits the baseband signal and the final up-conversions are performed at the BS. These configurations alleviate the drawbacks of RF-over-Fiber in the expense of increased BS costs.

Similarly to mainstream wireless communications, in order to fully exploit the optical fiber's bandwidth and to bear for independent multi-service communications, multiplexing techniques are often employed. The most typical ones are sub-carrier multiplexing (SCM) (Hui, 2002) and wavelength division multiplexing (WDM) (Bakaul, 2006). In SCM, a number of individual carriers (or subcarriers) modulate the optical carrier, while in WDM each individual mm-wave carrier is assigned to a specific optical channel.

The centralized RoF architecture is beneficial and flexible since it offers the ability to achieve micro/pico cellular coverage, thus offering the benefits of mobile communications plus the high bandwidth of the optical fiber. Additionally, it takes advantage of the high frequency propagation phenomena and is capable of realizing efficient frequency reuse and allocation plans. This is significant since future high-speed networks are tailored to push mm-wave carrier frequencies beyond 60GHz. Overall, the merits of RoF, to name a few, are better coverage and increased capacity, centralized upgrading, adaptation and dynamic configuration of radio resources, higher reliability and lower maintenance costs, support for future broadband applications, and economic access to mobile broadband communications.

The most common techniques for generating and distributing the mm-wave signals are the Intensity Modulation / Direct Detection (IM/DD), which can be further categorized as Direct and External Modulation, and the Remote Heterodyning Detection (RHD). In IM/DD the intensity of the light source is directly modulated with the RF signal and a photodetector is used for direct detection in order to recover it. In direct modulation, the mm-wave signal is directly applied to the laser source while in the case of the external modulation the mm-wave signal is applied to an external modulator (e.g. a Mach-Zehnder Modulator (MZM)) (Stephens, 1987; Cox, 1997). In the RHD, a similar procedure to standard heterodyne telecommunications is performed so as to generate the mm-wave signal through the mixing of two light sources, and a coherent mixing at the photodetector so as to recover it. Other recent techniques include Optical Frequency Modulation (OFM) to generate and recover the mm-wave signal (Koonen, 2006).

Although RoF technology appears with many advantages, there are several critical issues that have to be alleviated or compensated for successful deployments. The most limiting factors are the nonlinearity of not only the laser transmitter but also the optical fiber, both of which directly relate to the linearity and the dynamic range of the optical link (Ackerman, 2001; Cox, 2006). Nonlinear behavior leads to harmonic and intermodulation distortion. In addition, the hybrid environment of the optical and wireless domain imposes several challenging tasks such as the multimode fiber (MMF) modal dispersion. Other issues are the frequency response of the optical transmitter and the relative intensity noise (RIN) that depends on the modulation index (Fernando, 2006).

Nowadays, there is a raised interest in the exploitation of RoF technology for mobile/wireless access networks (IEEE, 2007; Liu, 2006; Koonen, 2006). This is also true for the case of current WLAN and Mobile standards and especially those utilizing OFDM and WCDMA (Kurt, 2006; Fernando, 2006; IEEE, 2007). To this end, many European funded research projects and networks of excellence aim, among other issues, to elaborate RoF topologies and appropriate modulation schemes. Some of these are, *ISIS*, *e-Photon/ONe*, *Gandalf* etc.

2.2 RoF optical components

The main optical components employed in RoF technology are the laser transmitter, the photodetectors and the optical fiber. The types of laser transmitters are the Fabry-Perot (FP) laser, the Distributed Feedback (DFB) laser and the Vertical-Cavity Surface Emitting Laser (VCSEL) (Wake, 2004). Among them, currently the DFB lasers are the proper light sources for analog transmission, operating both at 1300 and 1550 nm carrier frequencies, due to their spectral purity, enabling thus low relative intensity noise (RIN) values. The most important deterioration factor of the DFB laser is the intrinsic nonlinear interaction between carriers and photons, which drastically increases the harmonic or intermodulation distortion as the modulation frequency approaches the laser's resonance frequency. Commercially available DFB lasers achieve a resonance frequency in the order of 10GHz although research efforts have reported prototypes of up to 40GHz (Radziunas, 2007). On the other hand, FP lasers are less considered for RoF deployments due to increased RIN. Moreover, until recently the use of VCSELs was prohibited for analogue links, but recent advances in research prototypes VCSELs indicate their potential impact for utilization in RoF installations (Wake, 2004).

Different types of photodetectors include p-i-n photodiodes and avalanche photodiodes (APDs) based on Si or InGaAs, depending on the required operating wavelength. Commercially available photodetectors are much more linear than typical laser diodes, so little distortion is added to a RoF system by the photodiode. Nonlinearity can be a problem only in the case of very high received power (Al-Raweshidy, 2002). A typical bandwidth of a photodetector is in the order of 25 GHz or even greater.

The role of the optical fiber is critical for the effective deployment of RoF links, where both single mode (SMF) and multi mode fibers are employed (Al-Raweshidy, 2002). Silica (SiO_2)-based single mode fibers (SMF) enable optimum performance and diminished pulse spreading. Dispersion in SMF occurs due to the wavelength dependent refractive index, thus pulse broadening diminishes for relatively small fiber lengths, as it is the case of typical RoF systems. However, the already mass installation of MMF and the increased cost of SMF have turned the interest towards efficient utilization of MMF (Kurt, 2006). The most important deterioration factor of MMF is the modal dispersion. As mentioned, the recent technique of OFM has shown to offer immunity to this impairment (Koonen, 2006).

3. Research approaches in RoF technology

As mentioned, the characterization of laser transmitters in terms of frequency response and nonlinearity is of great concern, especially when modern modulation formats (e.g. OFDM) are employed. The work at RDTL deals with laser model development, simulation and characterization for both analogue (AM, FM) and digital (M-QAM, OFDM) schemes. In particular, characterization of a DFB laser is performed by numerically solving the rate equations (Mikroulis, 2006a; Mikroulis 2006b). The use of the rate equations provides a precise and efficient approach in modeling the laser's behavior. Moreover, modeling and simulation is performed by integrating the models using modern system level design tools (e.g. *Matlab Simulink* from *Mathworks Inc.*) An example of such modeling is depicted in figure 3, where a RoF link is developed. The model utilizes OFDM in which every subcarrier is modulated by M-

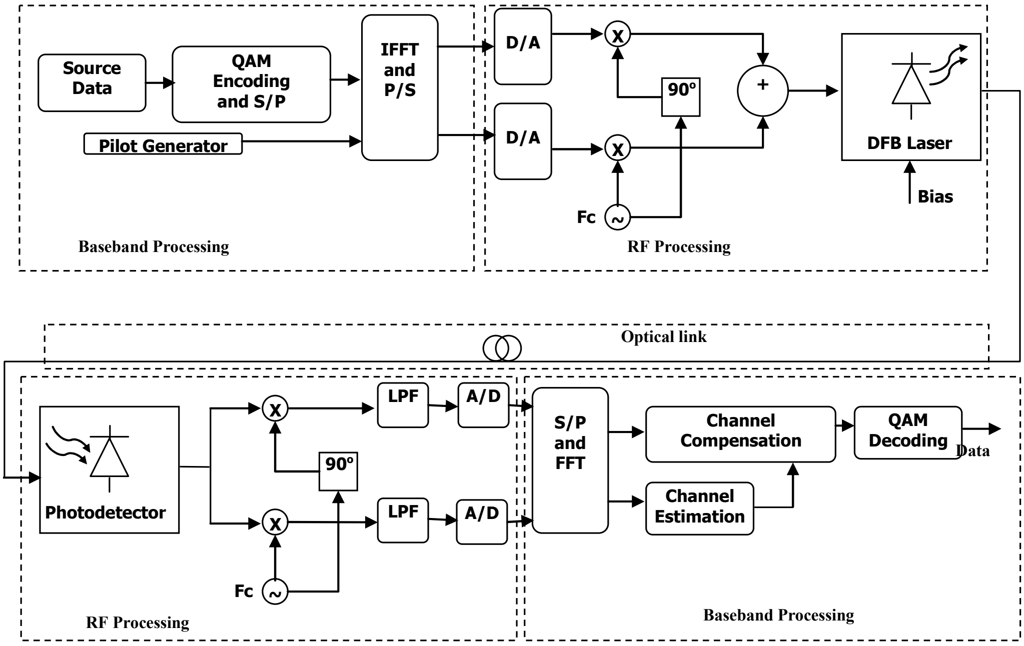


Figure 3 – RoF link model using OFDM.

QAM. The signal is up-converted to an RF band with tunable RF carriers, also covering the 2.4GHz and 5.8GHz bands that are of particular interest due to respective WLAN standards. The link is evaluated in terms of dynamic range, L-I curves (linearity), SNR and constellation diagrams. Furthermore, the model offers the ability to include channel models (e.g. MMF, wireless), to test several algorithms (e.g. channel compensation) and to add further techniques, such as injection locking, so as to study its effects on the laser's resonance frequency and how this in turn influences the underlying (electrical) modulation scheme (e.g. OFDM).

Besides modeling and simulation, practical RoF experiments are also under preparation using off the self equipment. In particular, RoF link experiments are planned, utilizing commercial DFB laser, DSP boards and wireless interface modules. In particular, the design is performed using the TMS320C6713 development kits from Texas Instruments Inc. Notice that the latter DSP boards can be effectively used in combination with the model development tools (Matlab, Simulink), since the latter offer the ability for direct code generation and downloading from the developed model, thus providing the means to easily build complex communication systems and test using real laboratory apparatus. In addition, FPGA equipment, through the Xilinx development tools, is also available for the design of more specialized and dedicated modules.

4. Conclusions

In summary, the necessity for high capacity mobile networks has increased the efforts for seamless integration of both optical and wireless access networks in order to efficiently combine their advantages in terms of high bandwidth and mobility. In this paper, we have provided a short overview of RoF technology and identified that its role is to serve as the proper interface infrastructure not only for current and emerging mobile/wireless access schemes but also for the employment of optical networks as a backhaul network for these schemes. Furthermore, we have reported on research issues that are currently under development in the RDTL laboratory.

6. References

Ackerman, E. I., & Cox, C. H. (2001). RF Fiber-Optic Link Performance. *IEEE Microwave*, December 2001, 50-58.

Al-Raweshidy, H. & Komaki, S. (2002). *Radio over Fiber Technologies for Mobile Communications Networks*. Artech House.

Arroyo-Fernandez B., Fernandes, J., & Prasad R. (2003). Composite Reconfigurable Wireless Networks: The EU R&D Path Toward 4G. *IEEE Communications Magazine*, July 2003, Part I.

Arroyo-Fernandez, B., Fernandes, J. & Prasad R. (2004). Composite Reconfigurable Wireless Networks: The EU R&D Path Toward 4G. *IEEE Communications Magazine*, May 2004, Part II.

Bakaul, M. (2006). Technologies for DWDM Millimetre-Wave Fibre-Radio Networks. *Doctoral Dissertation*, University of Melbourne, Australia.

Cox, C. H. III, Ackerman, E. I., Betts, G. E., & Prince, J. L. (2006). Limits on the Performance of RF-Over-Fiber Links and Their Impact on Device Design. *IEEE Trans. Microwave Theory Techniques*. 54, 906- 920.

Cox, C., Ackerman, E., Helkey, R., & Betts, G. E. (1997). Techniques and performance of intensity-modulation direct-detection analogue optical links. *IEEE Trans. Microwave Theory* Techniques. 45(8), 1375–1383.

Fernando, X., (2006). Radio over Fiber in Multimedia Access Networks. *International Conference on Access Networks* (AccessNets'06). ACM.

Hui, R., Zhu, B., Huang, R., Allen, C.T. , Demarest, K.R., & Richards, D. (2002). Subcarrier multiplexing for high-speed optical transmission. *IEEE J. Lightwave Technology*, 20, 417–427.

IEEE, (2007). Special Section on Convergence of Optical and Wireless Access Networks. *IEEE J. Lightwave Technology*, 25(11).

Kitayama, K. (2000). Architectural Considerations of Fiber-Radio Millimeter-Wave Wireless Access Systems. *Fiber and Integrated Optics*, 19(2), 167-186.

Koonen, T. (2006). Fiber to the home/fiber to the premises: What, where and when?" *Proc. IEEE*, 94(5), 911–934.

Kurt, T., Abbas Yongacoglu, A., & Chouinard, J-Y. (2006). OFDM and Externally Modulated Multi-mode Fibers in Radio over Fiber Systems. *IEEE Trans. On Wireless Communications*, 5(10), 2669-2674.

Lee, Chi H. (Ed.). (2007). *Microwave Photonics*. CRC Press.

Liu, C. P., Ismail, T., & Seeds, A. J. (2006). Broadband access using wireless-over-fibre technologies. *BT Technology Journal*, 24(3), 130-143.

Mikroulis, S., Chipouras, A., Karabetsos, S. & Nassiopoulos, A. (2006). Evaluation of Distributed Feedback (DFB) Laser Operating Parameters for Direct Modulation Schemes in IM-DD RoF Links. *In Proc. of Communication Systems Networks and Digital Signal Processing (CSNDSP'06)*, Patras, Greece.

Mikroulis, S., Karabetsos, S., Pikasis, E., Chipouras, A., & Nassiopoulos, A. (2006). Evaluation of the performance of a Distributed Feedback Laser (DFB) for RF signals propagation and Radio-Over-Fiber Applications. *in Proc. TEMU 2006*, Crete, Greece, July 2006.

Novak, D., Nirmalathas, A., Lim, C., Waterhouse, R., Bakaul, M., & Kurniawan, T. (2007). Hybrid Fiber Radio – Concepts and Prospects. In Chi H. Lee (Ed.), *Microwave Photonics* (pp. 157-183). CRC Press.

Ogawa, H., Polifko, D., & Banba S. (1992). Millimeter-wave fiber optics systems for personal radio communication. *IEEE Trans. Microwave Theory and Techniques*, 40, 2285–2292.

Pinter, Z. S., & Fernando, N. X. (2005). Fiber-Wireless Solution for Broadband Multimedia Access. *IEEE Canadian Review*, First Quarter 2005, 6-9.

Radziunas M., Glitzky, A., Bandelow, U., Wolfrum, M., Troppenz, U., Kreissl, J., Rehbein, W. (2007). Improving the modulation bandwidth in semiconductor lasers by passive feedback. *IEEE J. Selected Topics in Quantum Electronics*, 13(1), 136-142.

Stephens, W. E. & Joseph T. R. (1987). System characteristics of direct modulated and externally modulated RF fiberoptic links. *IEEE J. Lightwave Technology*, LT-5, 380- 387.

Wake D., Webster M., Wimpenny G., Beacham K.and Crawford L. (2004). Radio over fiber for mobile communications. *IEEE Conference on Microwave Photonics*, invited paper.