

# RoFnet – Reconfigurable Radio over Fiber Network Architecture Overview

Maria C. R. Medeiros, Ricardo Avó, Paula Laurêncio, Noélia S. Correia, Alvaro Barradas, Henrique J. A. da Silva, Izzat Darwazeh, John E. Mitchell, and Paulo M. N. Monteiro

**Abstract**—This paper introduces the basic operational concepts of the RoFnet – reconfigurable radio over fiber network, which is a project supported by the Portuguese Foundation for Science and Technology. This project proposes an innovative radio over fiber optical access network architecture, which combines a low cost base station (BS) design, incorporating reflective semiconductor optical amplifiers, with fiber dispersion mitigation provided by optical single sideband modulation techniques. Optical wavelength division multiplexing (WDM) techniques are used to simplify the access network architecture allowing for different BSs to be fed by a common fiber. Different wavelength channels can be allocated to different BSs depending on user requirements. Additionally, in order to improve radio coverage within a cell, it is considered a sectorized antenna interface. The combination of subcarrier multiplexing with WDM, further simplifies the network architecture, by using a specific wavelength channel to feed an individual BS and different subcarriers to drive the individual antenna sectors within the BS.

**Keywords**—optical access networks, optical single sideband, radio over fiber, reflective semiconductor optical amplifiers, wavelength division multiplexing.

## 1. Introduction

Internet technologies are now considered as the universal communication platform. Broadband access communication is rapidly becoming widely available, e.g., asymmetric digital subscriber line (ADSL) is now available in almost all parts of Europe. In parallel to the growth of the Internet, wireless and mobile network technologies have witnessed a great development. Mobile phone penetration exceeds that of fixed phones in most developed countries.

Wireless communications are entering a new phase where the focus is shifting from voice to multimedia services. Present mobile network users want to be able to use their mobile terminals and enjoy the same user experience as they do while connected to their fixed network either at work or at home. Wireless local area network (WLAN) hotspots based on IEEE 802.11 are a reality, and many consumer devices (Laptop PCs, mobile telephones, PDAs, etc.) have Bluetooth enabling them to establish a wireless personal area network. In this context, third generation (3G) of wireless networks have already adopted IP as the core network protocol in their data subsystems, as well as promising guaranteed quality for multimedia service, in both access and core networks. However, the services offered by wired local area network (LAN) connections require a broadband network with capacity even higher than 7 Mbit/s per radio

channel. Unfortunately, the actual wireless telecommunication network only provides narrowband communications when compared to wired LAN connections and thus a radio interface capable of supporting very high data rates, has to be developed. Over the last decade the millimeter-wave frequency band (26 to 100 GHz) has been pointed out as the best spectral region to provide broadband access to wireless networks [1]. However, the limited propagation characteristics of these high frequencies lead to small cell sizes. As a consequence, a large number of remote antenna base stations (BSs) is necessary to cover an operational geographical area. The multiple BSs providing wireless connectivity to users via millimeter-wave radio links are connected with a central office (CO) via an optical fiber access network. The CO performs the switching and routing functionalities.

The RoFnet – reconfigurable radio over fiber network project, introduced here, uses optical wavelength division multiplexing (WDM) techniques to simplify the network architecture allowing different BSs to be fed by a common fiber, with different WDM channels feeding different BSs. Additionally, in order to improve radio coverage within a cell, utilization of sectorized antenna interfaces is considered. Each antenna sector should be driven by an individual signal. The combination of subcarrier multiplexing (SCM) with WDM, simplifies the network architecture, since a specific WDM channel is fed to an individual BS and different SCM channels carried on the WDM wavelength channel are used to drive the individual antenna sectors within the BS.

For the downlink the millimeter-wave signals are transmitted directly over the fiber. This approach has the advantage of a simplified BS design but is susceptible to fiber chromatic dispersion that severely limits the transmission distance [2]. The RoFnet will employ optical single sideband (OSSB) modulation techniques to overcome fiber dispersion effects.

For the realization of the uplink of a radio over fiber (RoF) system using WDM, the BSs must incorporate an optical source, which is modulated by the millimeter-wave uplink radio signals. This approach suffers from several disadvantages. Namely, each BSs requires a WDM optical sources and a high-speed external modulator, resulting in a high cost BS. The RoFnet proposes a novel low cost uplink configuration, which eliminates the need for an expensive WDM source and the optical external modulator at the BS. This is accomplished by using a reflective semiconductor optical amplifier (RSOA) in the BS which replaces the high

cost WDM source and the high-speed external modulator. This approach offers several advantages. First, it avoids the need of stabilized a laser at each BS. Second, the RSOA can be used as a modulator which accomplishes both modulation and amplification functions. Moreover, this amplification function gives additional gain enabling the possibility of avoiding the use of an erbium-doped fiber amplifier (EDFA) in the system. For the first time, this uplink configuration exploits the capabilities of using RSOAs in RoF systems and this alternative may be applied to other wireless networks such as 3G mobile communication systems.

The remainder of this paper is organized as follows. Section 2, the network architecture is presented, emphasizing both the uplink and downlink operation. Section 3 discusses the fiber transmission limitations due to the fiber chromatic dispersion and how they can be minimized by the use of optical single sideband. The advantages of using WDM technology in radio over fiber systems are considered in Section 4 and finally Section 5 concludes the paper.

## 2. Network Description

Figure 1 shows the schematic of the RoFnet architecture concept, where  $N$  base stations provide the wireless connectivity to users via millimeter-wave radio links. The BSs are connected with a central office via an optical fiber access network employing WDM technology. Each BS is connected to the fiber access network by two fibers, one for uplink transmission and another for downlink transmission.

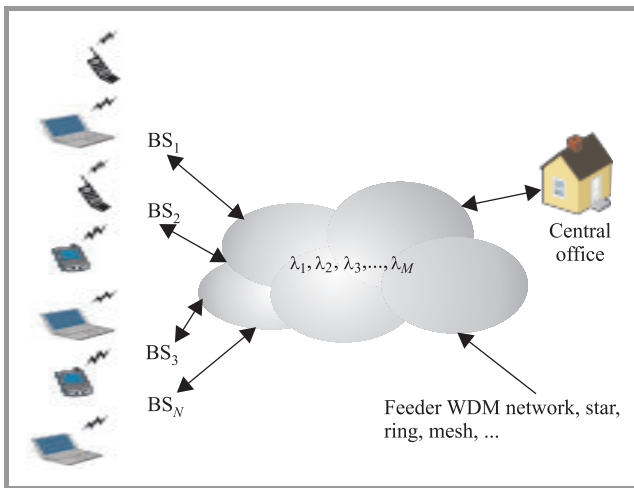


Fig. 1. Overall RoFnet architecture.

Each BS incorporates an antenna with  $L$  sectors. Each antenna sector is fed by an SCM channel. The use of WDM provides a simple topology, leading to easier network management and increases the capacity by allocating different wavelengths to individual remote nodes [3]. This solution is widely accepted and the necessary WDM technology is available. However, if this approach is to be implemented a cost effective implementation needs to be found.

A dynamic wavelength allocation scheme for WDM RoF systems using a novel add-drop multiplexer was demonstrated in [4]. An important feature of this scheme is the possibility of dynamic network reconfiguration when needed, namely through the wavelength reassignment to different base stations. Flexible wavelength allocation is an elegant strategy for dealing with traffic fluctuations since it allows efficient allocation of network resources by adaptively adjusting to the offered load. However, the implementation presented in [4] requires a new expensive device. The RoFnet architecture, by using a RSOA in the BS, eliminates the need of expensive devices. RSOAs are presently considered key devices for the future high-speed passive access optical networks (PONs) [5]. A RSOA can be used with both modulation and amplification functions. Moreover, a RSOA operated in the gain saturation region can reduce the intensity noise of the optical signal. The 3 dB electrical bandwidth of commercially available devices is up to 1.5 GHz in the long wavelength bands in the range of 50 to 100 nm. The wavelength range mainly depends on the RSOA manufacturing process.

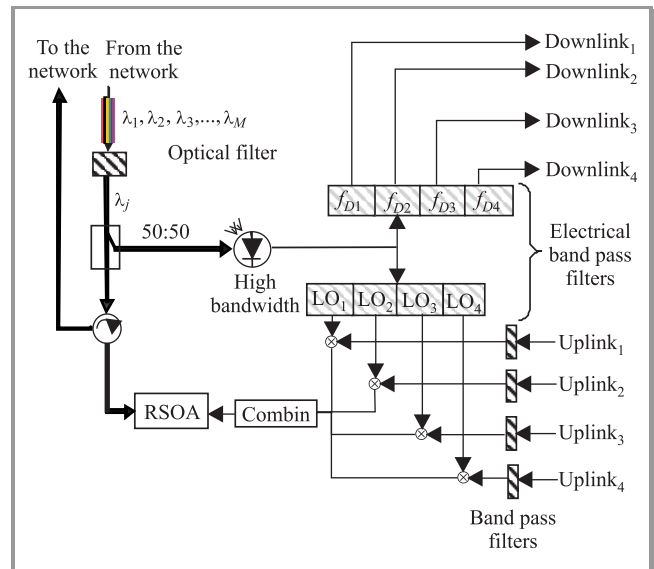


Fig. 2. Schematic diagram of a base station.

In the RoFnet architecture, the CO, as well as performing all the switching, routing and frequency management, also generates the  $M$  optical WDM carriers required for uplink operation of the  $N$  BSs of the RoF network.

Each BS, as represented in Fig. 2, is equipped with a fixed optical filter, and thus operates only with a unique specific wavelength  $\lambda_j$ .

### 2.1. Downlink Operation

Base station  $j$  receives the downlink millimeter-wave signal on wavelength channel  $\lambda_j$ . The downlink millimeter-wave signal is composed by  $L$  multiplexed subcarriers combined with a set of unmodulated RF carriers, as shown in Fig. 3.

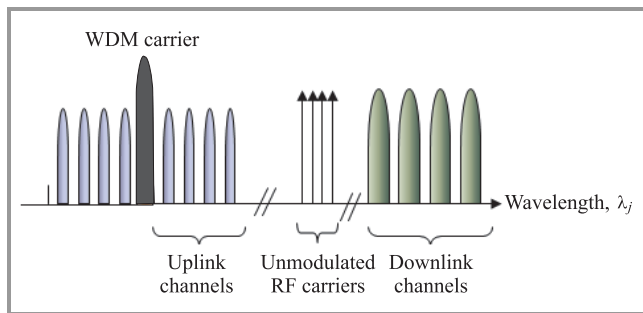


Fig. 3. Optical spectrum around wavelength carrier.

The  $L$  SCM channels feed the  $L$  antenna sectors, and the set of unmodulated RF carriers are used in the uplink operation. The unmodulated RF carriers and the downlink signals are generated at the CO and modulate an optical carrier using optical single sideband modulation. The OSSB modulation is used in order to minimize the fiber dispersion effects and to improve spectral efficiency.

We note that OSSB modulation is required only at the CO, and thus it does not increase the cost of the BS. At the BS, the downlink optical signal in wavelength channel  $\lambda_j$  is split by a fiber coupler. One part is directed to the RSOA, and the other part is detected by a high bandwidth receiver. The detected signal consists of the downlink millimeter-wave signal and the unmodulated RF carriers.

### 2.2. Uplink Operation

The downlink optical carrier travels through the RSOA, where it is amplified and modulated by the uplink data, which has been down converted to an intermediate frequency (IF). The unmodulated RF carriers act as local oscillators (LO) and are used to down-convert the uplink data to an IF, within the electrical bandwidth of the RSOA (1.2 GHz). The RSOA is directly modulated by the SCM uplink signals, and thus the optical carrier is double sideband modulated, as represented in Fig. 3.

Using this technique, the uplink optical signal is generated by recovering a portion of the optical carrier used in the downlink transmission. Although optical frequency reuse techniques previously used eliminate the need for a WDM optical source at each BS, they require a high-speed external modulator at the BS. However, the necessary bandwidth of the external optical modulator can be reduced if the uplink signal is down converted by mixing it with a local oscillator. The generation of a LO at the BS increases its complexity and therefore should be avoided. The solution adopted in RoFnet is the remote delivery of the LO, as implemented in [6].

## 3. Transmission Limitation in Radio over Fiber Networks

The performance of RoF systems may be severely impaired by fiber chromatic dispersion [2]. This effect can be over-

come by using optical single sideband modulation. The benefits of OSSB modulation have been demonstrated both for radio frequency carriers modulated onto optical carriers and baseband systems. The OSSB improves immunity to chromatic dispersion relative to transmission using conventional optical double sideband (ODSB) modulation, as well as enhancing spectral efficiency.

The importance of OSSB has driven the development of multiple techniques for its implementation. They can be classified into optical heterodyning technique, filtering methods and OSSB modulators. In this project we will focus on OSSB modulators. The simplest design is based on a dual-electrode Mach-Zehnder electrooptic modulator driven by electrical signals with a  $90^\circ$  phase-shift (Hilbert transformed). Other designs also use Hilbert transformed electrical signals applied to either a series combination of intensity and phase modulator or other configurations [7], [8]. Recently, an optoelectrical filter for 40 GHz OSSB generation has been demonstrated [9].

Although, it has been demonstrated that optical single sideband when combined with subcarrier multiplexing techniques (named OSSB/SCM) can significantly improve the system immunity to chromatic dispersion, as well as being more spectrally efficient, increasing and understanding OSSB/SCM system performance continues deserving great interest [10]. As in conventional SCM systems, two important transmission limitations exist in OSSB/SCM systems: the relative intensity noise (RIN) and the intermodulation distortion. Optical carrier suppression has been shown experimentally to be a key issue affecting the performance of OSSB/SCM systems [8]. Chen and Way [10] have developed a powerful analysis which is able to quantify the composite second-order (CSO) and composite triple beat (CTB) of an OSSB/SCM system, however their analysis is restricted to the case where the optical carrier is not suppressed. The analysis presented in [11] removes this restriction and shows how the suppression of the optical carrier affects the intermodulation distortion in terms of CTB and CSO. Other important feature of OSSB/SCM is its combination with wavelength division multiplexing.

## 4. Dynamic Wavelength Allocation

Traffic in wireless networks is highly dynamic. Therefore the access network should be reconfigurable depending on the traffic scenario. The network architecture defined in the previous section is reconfigurable and therefore can dynamically change its state according to the traffic needs. The RoFnet network is operated with  $M$  optical WDM sources and  $N$  BSs. Each BS is equipped with a fixed optical filter and therefore operates only with a unique specific wavelength  $\lambda_j$ . We consider  $M < N$ , i.e., the number of optical carriers present in the network is less than the number of served BSs. Such assumption means that rather than providing fixed capacity tailored to the “busy-hour” across

the network, the optical carriers are allocated to BSs depending on their needs. The optical carriers are generated by fixed lasers as well as by tunable lasers. The fixed optical carriers are allocated to BSs which should be always on use and the tunable carriers are allocated to BSs that might be out of use during some time. Therefore, besides demonstrating the feasibility of the RoFnet architecture another objective is to exploit its capabilities namely by developing wavelength allocation algorithms able to allocate network resources depending on varying user demand and quality of service (QoS).

## 5. Conclusion

This paper introduces a novel network architectures suited for radio over fiber networks, combining low complexity with flexibility and cost effectiveness. Its two main characteristics are: low cost BS based on RSOAs and use of optical single sideband modulation to improve the system immunity to chromatic dispersion, as well as the spectral efficiency. Additionally, an important advantage of RoFnet is the generation and management of the optical carriers at the CO. As well as facilitating wavelength monitoring and control this approach provides flexible wavelength allocation for the BSs depending on user requirements.

## Acknowledgments

This work was supported by the Foundation for Science and Technology within the project PTDC/EEA-TEL/71678/2006.

## References

- [1] J. J. O'Reilly, P. M. Lane, J. Attard, and R. Griffin, "Broadband wireless systems and networks: an enabling role for radio-over-fibre", *Phil. Trans. Royal Soc.*, vol. 358, no. 1773, pp. 2297–2308, 2000.
- [2] H. Schmuck, "Comparison of optical millimeter-wave system concepts with regard to chromatic dispersion", *Electron. Lett.*, vol. 31, pp. 1848–1849, 1995.
- [3] H. Bolcskei, A. J. Paulraj, K. V. S. Hari, and R. U. Nabar, "Fixed broadband wireless access: state of the art, challenges, and future directions", *IEEE Commun. Mag.*, vol. 39, no. 1, pp. 100–108, 2001.
- [4] W.-P. Lin, "A robust fiber-radio architecture for wavelength-division-multiplexing ring-access network", *J. Lightw. Technol.*, vol. 23, no. 9, pp. 2610–2620, 2005.
- [5] A. Borghesani, "Optoelectronic components for WDM-PON", in *Proc. ICTON 2007*, Rome, Italy, 2007, pp. 305–308.
- [6] C. Lim, A. Nirmalathas, D. Novak, and R. Waterhouse, "Millimeter-wave broad-band fiber-wireless system incorporating baseband data transmission over fiber remote LO delivery", *J. Lightw. Technol.*, vol. 18, no. 10, pp. 1355–1363, 2004.
- [7] G. H. Smith, D. Novak, and Z. Ahmed, "Technique for optical SSB generation to overcome dispersion penalties in fiber-radio systems", *Electron. Lett.*, vol. 33, no. 1, pp. 74–75, 1997.

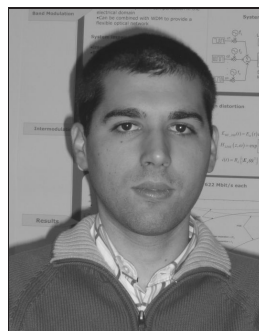
- [8] A. Loayssa, R. Hernandez, and B. Benito, "Optical single sideband modulators and their applications", *Fib. Integr. Opt.*, vol. 23, pp. 171–188, 2004.
- [9] D. Fonseca, A. V. T. Cartaxo, and P. Monteiro, "Opto-electrical filter for 40 Gb/s optical single sideband signal generation", in *Proc. OFC Conf.*, Anaheim, USA, 2006, Paper JThB14.
- [10] W. H. Chen and W. I. Way, "Multichannel single-sideband SCM/DWDM transmission systems", *J. Lightw. Technol.*, vol. 22, no. 7, pp. 1679–1693, 2004.
- [11] P. Laurencio, S. O. Simões, and M. C. R. Medeiros, "Impact of the combined effect of RIN and intermodulation distortion on OSSB/SCM systems", *J. Lightw. Technol.*, vol. 24, no. 11, pp. 4250–4260, 2006.



**Maria C. R. Medeiros** obtained the B.Sc. in electronics engineering from the University of Aveiro, Portugal, and the M.Sc. and Ph.D., both in electronic engineering, from the University of Wales, UK. Presently she is an Auxiliary Professor in telecommunications for the Faculty of Science and Technology at the University of Algarve, Portugal. She previously worked as a researcher at the University of Wales. Her research interests include modeling and optimization of optical WDM networks and radio over fiber techniques for access networks. She acted as the leader of several research projects namely the RoFnet project. Prof. Medeiros is the leader of the Center of Electronics, Optoelectronics and Telecommunications (CEOT).

e-mail: cmedeiro@ualg.pt

Center for Electronics, Optoelectronics and Telecommunications (CEOT)  
University of Algarve  
8000 Faro, Portugal



**Ricardo Avó** received the Licenciatura degree from the University of Algarve, Portugal, in 2006. Currently, he is a researcher at the Center of Electronics, Optoelectronics and Telecommunications conducting research towards his Ph.D. His research interests include optical networks and radio over fiber access networks.

e-mail: ricardoavo@ualg.pt

Center for Electronics, Optoelectronics and Telecommunications (CEOT)  
University of Algarve  
8000 Faro, Portugal



**Paula Laurêncio** received the Licenciatura degree in electrical engineering and the M.Sc. degree in telecommunications and computers from the Lisbon Technical University, Portugal. She obtained a Ph.D. degree in computing and electronics engineering in the University of Algarve, Faro, Portugal, in 2006. Her main current research interests

include characterization and modeling of single side-band fiber optic communications systems and subcarrier and radio over fiber techniques.

e-mail: plaurenc@ualg.pt

Center for Electronics, Optoelectronics and Telecommunications (CEOT)

University of Algarve  
8000 Faro, Portugal



**Noélia S. Correia** works as Professor at the Faculty of Science and Technology of the University of Algarve, Portugal. She received her B.Sc. and M.Sc. in computer science from the University of Algarve. The Ph.D. in survivable WDM networks, obtained at the University of Algarve, was done in collaboration with the University

College London, UK. Her research interests include throughput and network cost optimization, survivability, and other related optical network issues.

e-mail: ncorreia@ualg.pt

Center for Electronics, Optoelectronics and Telecommunications (CEOT)

University of Algarve  
8000 Faro, Portugal



**Alvaro Barradas** received his M.Sc. in computer science from the University of Algarve, Portugal, in 2004. Currently he is an assistant lecturer at the Faculty of Science and Technology and a Ph.D. student in the Center for Electronics, Optoelectronics and Telecommunications at the University of Algarve. His research area focuses

on provisioning of quality of service improvement mechanisms for optical burst switching networks based on contention avoidance schemes. His present research interests also include other optical network switching paradigms, their related communication protocols, and the object oriented approach to the simulation of communications systems. His previous professional experience includes 2 years

of work as a programmer/analyst for a large computer science and telecommunications consulting company, doing system test at the telecommunications branch. He is also a CCNA instructor at the local Cisco Academy.

e-mail: abarra@ualg.pt

Center for Electronics, Optoelectronics and Telecommunications (CEOT)

University of Algarve  
8000 Faro, Portugal



**Henrique J. A. da Silva** received his Ph.D. degree in communication systems engineering from the University of Wales, UK, in 1988. Since then he has been with the Department of Electrical and Computer Engineering at the University of Coimbra, Portugal, where he is now an Associate Professor. He is the leader of the Optical

Communications Group of the Institute of Telecommunications at the University of Coimbra, since 1992. His research interests include optical and mobile communication systems, with emphasis on enabling technologies and transmission techniques.

e-mail: hjas@ci.uc.pt

Institute of Telecommunications

Department of Electrical and Computer Engineering  
University of Coimbra

Pólo II, Pinhal de Marrocos  
P-3030-290 Coimbra, Portugal



**Izzat Darwazeh** holds the University of London Chair of Communications Engineering in the Department of Electronic and Electrical at the University College London (UCL), UK. Born in 1963, he obtained his first degree in electrical engineering from the University of Jordan in 1984 and the M.Sc. and Ph.D. degrees, from the

University of Manchester Institute of Science and Technology (UMIST), in 1986 and 1991, respectively. He worked in the Universities of Wales and Manchester before joining UCL in Oct. 2001, where he is currently the Head of the 80 strong Communications and Information System (CIS) Group and the Director of UCL Telecommunications for Industry Programme. He is a Fellow of the IET and a senior member of the IEEE. His research interests are mainly in the areas of wireless communication system design, modeling and implementation, high-speed optical communication systems and networks, microwave circuits and MMICs for optical fibre applications and in mobile and wireless

communication circuits and systems. He has authored/co-authored more than 130 research papers.

e-mail: I.darwazeh@ee.ucl.ac.uk

Telecommunications Research Group  
Department of Electronic and Electrical Engineering  
University College London (UCL)  
Torrington Place, London, WC1E 7JE, UK



**John E. Mitchell** received the Ph.D. degree in electronic engineering from the University College London (UCL), UK, in 2000. In 1999 he became a research fellow in the Department of Electronic and Electrical Engineering at UCL, becoming a lecturer and senior lecturer in 2000 and 2006, respectively. He has published over 40 papers in

the area of optical communications. His research interests include optical access technologies and the transport of millimeter-wave radio signals over optical fibre for communications, and noise relating to crosstalk in optical networks. He is a member of the Institute of Engineering and Technology (IET) and the IEEE Lasers and Electro-Optics Society (IEEE-LEOS).

e-mail: J.mitchell@ee.ucl.ac.uk

Telecommunications Research Group  
Department of Electronic and Electrical Engineering  
University College London (UCL)  
Torrington Place, London, WC1E 7JE, UK



**Paulo Monteiro** was born in Coimbra, Portugal, in 1964. He received the diploma and doctoral (Ph.D.) degrees in electronics and telecommunications from the University of Aveiro, Portugal, and the M.Sc. degree from the University of Wales, UK. He is Optical Networks Technology Manager at the Transport, Aggregation and

Fixed Access Department of Nokia Siemens Networks. He is also Associate Professor at the University of Aveiro and researcher at the Institute of Telecommunications. His main research interests include high speed communications for access and core optical networks, fixed-mobile convergence. He has acted as a reviewer of the IEEE Journal of Lightwave Technology, IEE Electronics Letters, ETRI Journal and OSA Journal of Optical Networking (JON), SPIE Optical Engineering. He has participated in several national and European projects and is currently the project coordinator of the large-scale integrating project FUTON. He has authored/co-authored more than 18 patent applications and over 200 refereed papers and conference contributions.

e-mail: Paulo.l.monteiro@nsn.com

Nokia Siemens Networks Portugal S.A.

R. Irmãos Siemens st 1  
2720-093 Amadora, Portugal

Institute of Telecommunications  
University of Aveiro  
3810-193 Aveiro, Portugal