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Flexibly Reconfigurable Fiber-Wireless Network using Wavelength Routing Techniques: The ACTS Project AC349 PRISMA

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Abstract. A dynamically reconfigurable fiber-wireless network using flexible wavelength routing techniques is proposed by the PRISMA project, which offers a ''forecast-tolerant'' solution for handling a wide variety of wireless services and capacity demands as may emerge in the fast evolving market of mobile communications. This approach can considerably increase the operation efficiency of wireless networks for broadband nomadic services (wireless LANs). It also supports the evolution from GSM and GPRS towards UMTS, and the entry of new operators and/or services into the liberalized mobile communications market. The system has been implemented in a field trial and has been operated successfully with real users and broadband nomadic services. The system concept is ready for further development into products.

Keywords: fiber-wireless networks, wavelength routing, dynamic capacity re-allocation

1 Introduction

The market for wireless services is evolving at an incredible pace. In Europe, the GSM market is even growing faster than Internet. New services are coming up quickly, such as mobile IP ones. Bandwidth demands are increasing (GSM 13 kbit/s, GPRS 115 kbit/s, UMTS 2 Mbit/s, ...), augmented by the entrance of new operators and the availability of new frequency bands. Starting in office environments, wireless LANs are being introduced, with growing bandwidth capabilities (2 Mbit/s in HIPERLAN2, 155 Mbit/s in HIPERLAN4). Fixed wireless drop systems (LMDS, MMDS) are delivering multi-Mbit/s capacities to residential users. These trends are leading to heavier traffic loads for the fixed network feeding the wireless base stations, and optical fiber is optimally suited to meet these demands. However, as illustrated by the recent market explosion, it is very hard to make reliable predictions about which types of services will emerge in the future, and how the user behavior will evolve. Fiber-wireless networks therefore need to be laid out in a ''forecast-tolerant'' way, such as to make capacity upgrades and flexible capacity re-allocation possible. The project AC349 PRISMA (Photonic Routing of Interactive Services for Mobile Applications) running from April 1998 to January 2000 [1,2] has been part of the European ACTS (Advanced Communications Technologies and Services) pre-competitive R&D program. It proposes to deploy flexible wavelength routing techniques in the fibre feeder network, fulfilling four key roles:

1. Increasing capacity of the network without extending the fiber plant.
2. Regional upgrading, by providing extra wavelengths locally.
3. Hosting independent services and/or operators (''wavelength -leasing'').
4. Providing capacity-on-demand (e.g., required by ''hot spots''), by dynamic capacity re-allocation.

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*The work was carried out while Ton Koonen was with Bell Laboratories, Lucent Technologies Nederland B.V. in Huizen, The Netherlands.

2 PRISMA's System Architecture

The system architecture adopted by the PRISMA project is shown in Fig. 1. At the local exchange (LEX) site, four optical line terminals (APON OLTs) are each feeding broadband interactive ATM-based services at 622 Mbit/s line speed to the amplified split fiber network, containing three local splitting centers (LSCs). Splitting factors typically are $N = 8$ and $P = 8$. In total $M = 8$ wavelengths are used; each OLT uses one wavelength for downstream signals, and another one for upstream signals. The four downstream wavelengths are positioned in the 1538–1541 nm range, spaced by 100 GHz, and the four upstream ones in the 1547–1550 nm range with the same spacing. The flexible wavelength router performs an adjustable routing of one or more wavelength channels from its inlet to one or more of its outlets (it thus provides uni-casting and multicasting). The wavelength routing is set by a network management and control (NM&C) agent, which is supervised by the master NM&C system at the LEX. Bi-directional optical fiber amplifiers (OAs) compensate for the network splitting losses. In the optical network unit (ONU) at the base transceiver station (BTS), the downstream wavelength channels are separated from the upstream ones by a coarse wavelength division multiplexer (WDM), and are fed to a photodiode for detection. In the upstream channels, the data are imposed by a reflective modulator on the continuous wave (CW) light that is injected by an array of four wavelength-specific laser diodes (LDs) at the router site. An NM&C agent at the BTS controls the time-slot access needed in the ATM TDMA protocol used; this agent is also supervised by the NM&C master at the LEX. The radio access point conveys the data on an ATM 20 Mbit/s shared basis to a number of portable PCs, deploying nomadic computing applications such as web access, file transfer, etc.

By locating the wavelength router function not at the BTS, but at a higher network split level, the costs of this function are shared by a number of BTSs. No wavelength-specific functions are needed at the BTS, which adds to the cost benefits; a universal ONU can be used, which offers economy of scale and less stock variety. On the other hand, the wavelength reconfiguration flexibility becomes coarser when moving the router to higher split levels. The optimum position of the router is therefore a compromise between costs and reconfiguration flexibility; system performance studies have shown that a good compromise is reached when positioning the router at LSC2.

The PRISMA network architecture allows both the

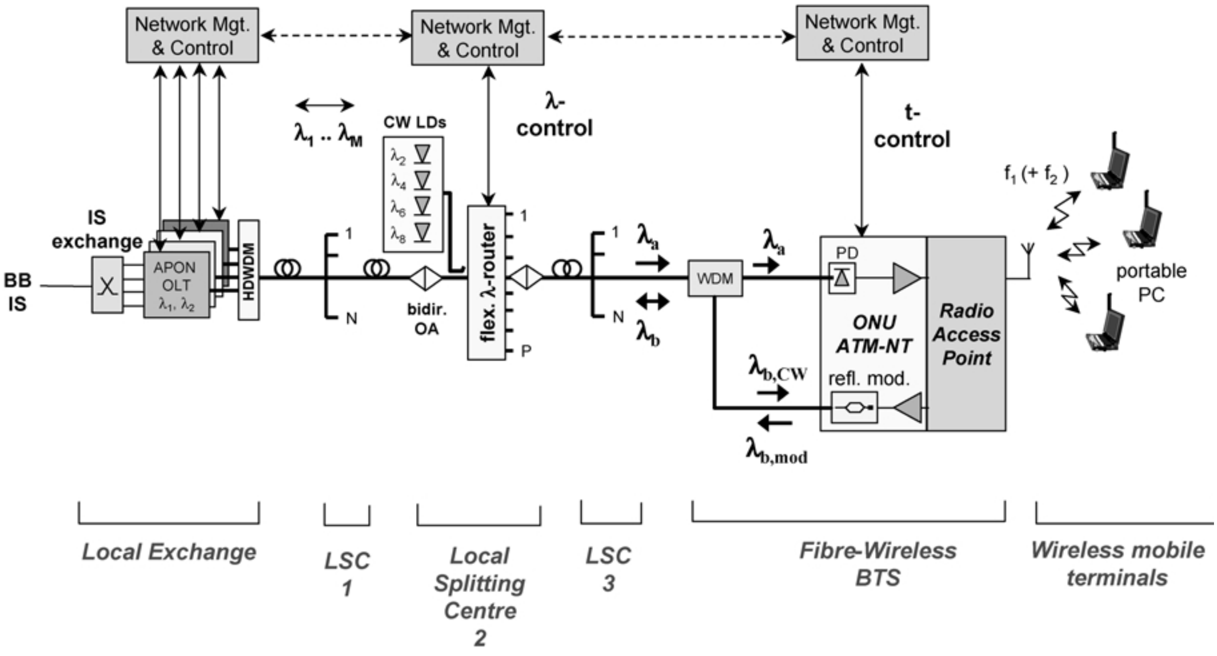

Fig. 1. PRISMA's system architecture.

access to the various wavelength channels and the access to the time slots to be controlled from the LEX. Thus, the network operator is in control of the virtual topology of the network, and can assign capacity on demand as needed to the BTSs. For instance, when suddenly in a network cell there is a high demand for capacity (a ''hot spot''), an extra microwave carrier is added in this cell, and the extra feeder capacity is offered by re-arranging the wavelength channel distribution among the BTSs.

The mapping relations between the microwave channels in the wireless cells and the wavelength channels in the fiber network are visualized in Fig. 2. By deploying flexible wavelength routing, these relations are not fixed, but can be adapted according to the operator's needs.

Fig. 3 shows the schematics of the implementation of the wavelength router. Thermo-optic Mach-Zehnder 1×8 switches were developed; insertion losses were around 13 dB with a polarization dependency of less than 1 dB, and an extinction ratio of better than 20 dB. Switching times are around 1 msec; with semiconductor optical gates, these may be reduced to nanoseconds. Bi-directional optical amplifiers (OAs) with gains of 23 to 25 dB deploying erbium-doped fiber were used at both sides of the router, which together with a 10 dB gain amplifier at the OLT site provide adequate system power margin. Fig. 4 shows the schematics of the reflective optical modulator at the ONU. By separating the TE- and TM-polarizations of the downstream CW light, and by deploying TM/TE polarization conversion, the polarization dependence of the lithium-niobate modulator can be circumvented. The remaining polarization dependence of the reflective modulator is less than 0.2 dB, and its insertion loss is about 6 dB.

3 System Performance Analysis

The performance of wavelength routing strategies has been assessed assuming seven wavelengths, a Poisson distributed call arrival process, and a network of $7^3 = 343$ hexagonal cells in a honeycomb structure (a common model for homogeneous wireless networks) of which 49 are ''hot spots'' (i.e., having a traffic load four times that of a regular cell). The results are shown in Fig. 5. When all 49 hotspots are located at BTSs that share a single wavelength channel (curve 1 in Fig. 5), the blocking probability rises quickly with the normalized load on the system (i.e., the total actual load divided by the maximum available capacity, which is the number of wavelength channels times 622 Mbit/s). Contrary to this worst case is the situation

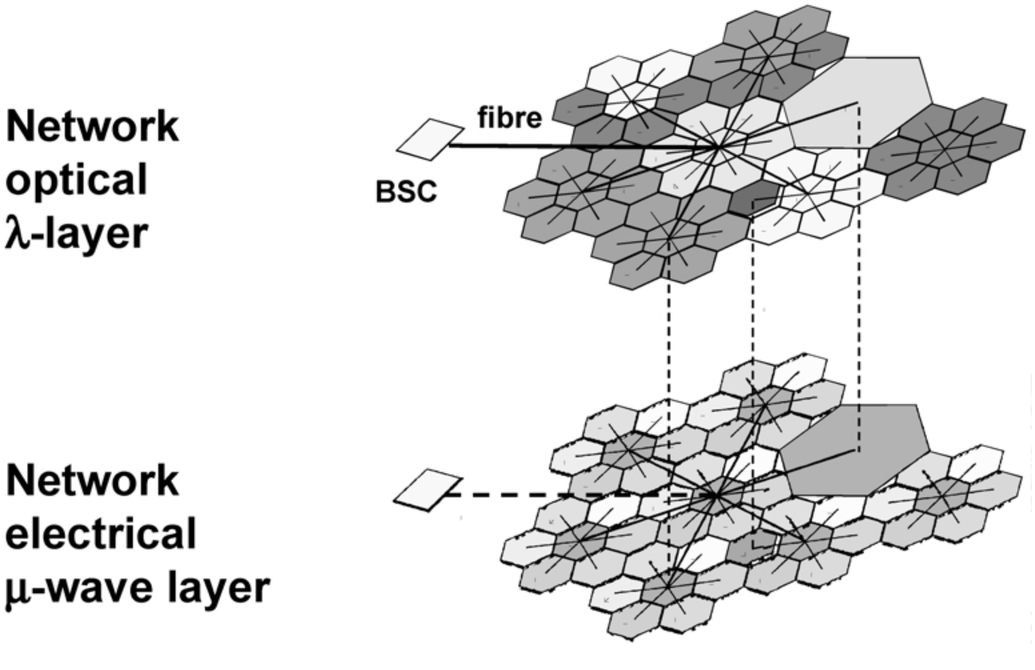

Fig. 2. Mapping microwaves to wavelengths.

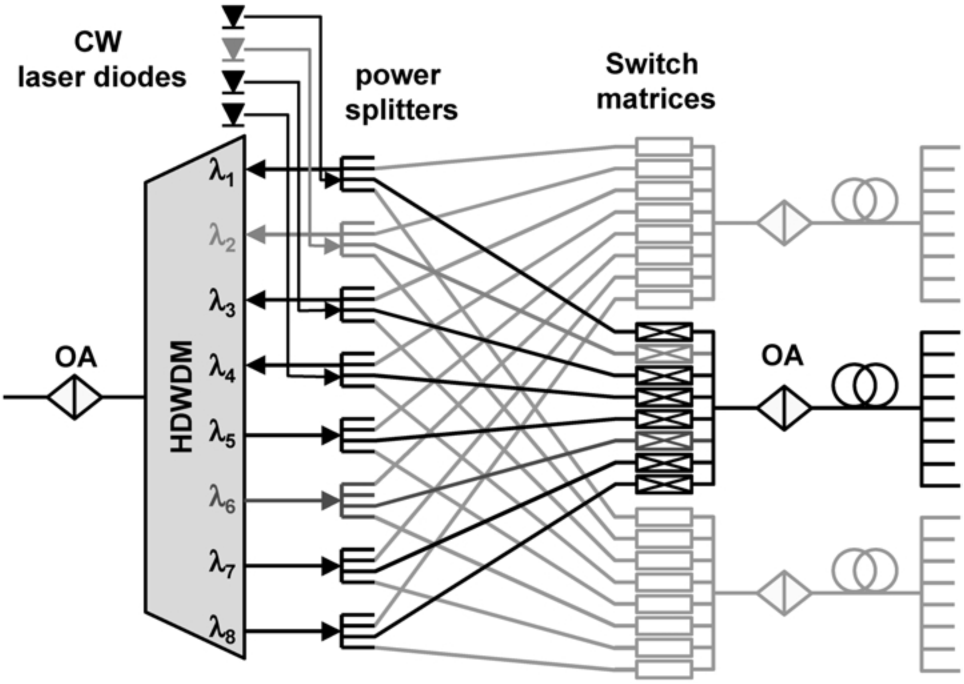

Fig. 3. Implementation of the flexible wavelength router, including continuous-wave emitting laser diodes.

in which the 49 hot spots are equally spread over the seven wavelength channels (curve 2). In this best-case situation, the blocking probability is obviously much less. In practice, the hot spot distribution across the network is unknown, so the actual system performance for a fixed wavelength allocation to the BTSs can be anywhere between this worst case and best case. Using the dynamic wavelength allocation as proposed by the PRISMA project and positioning the wavelength router at LSC3, however, the system can widely adapt to any hot spot distribution, and the resulting blocking performance is given by curve 3. This performance is not only better than the best-case static one, but also holds for any distribution of the 49 hot spots across the network. Thus the dynamic wavelength allocation scheme enables the network operator to offer a guaranteed performance level to his customers. For cost reasons, locating the router at LSC2 is preferred; this only slightly deteriorates the blocking performance (see curve 3) [3].

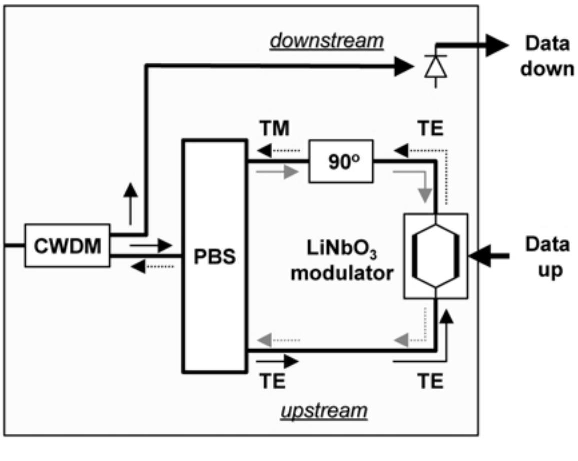

Fig. 4. Polarization-independent reflective optical modulator at the ONU (PBS: polarization beam splitter; 90°: TE/TM polarization converter; CWDM: coarse wavelength (de)multiplexer).

4 Cost Comparison with Alternative Architectures

The PRISMA architecture has been compared to a number of alternative architectures:

- Space division multiplexing (SDM), i.e., applying multiple fibers instead of multiple wavelength channels
- Power-splitting passive optical network (PS-PON), i.e., applying a single fiber from the

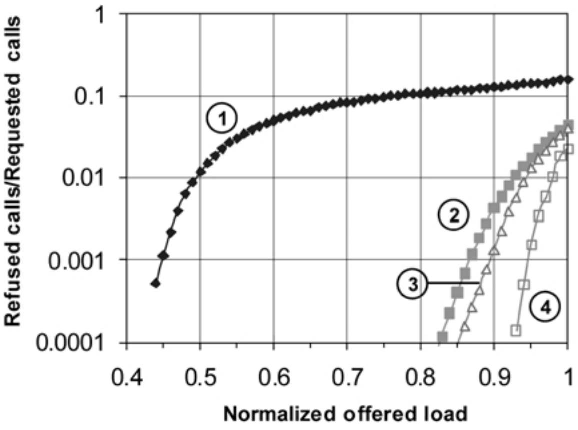

Fig. 5. System blocking performance when varying router location (1: at LSC1, worst case; 2: at LSC1, best case; 3: at LSC2; 4: at LSC3).

OLT fanned out to the ONUs with optical power splitters; the total capacity downstream (and upstream) is only 622 Mbit/s, however

- Nested WDM, i.e., applying multiple OLTs with individual wavelength channels, transported by a single fiber from the OLT, and fixed WDM (de)multiplexers at the network splitting centers to feed the ONUs with one wavelength per ONU
- Power-splitting passive optical network and fixed WDM (PS-PON + fixed WDM), i.e., the PRISMA architecture but with fixed wavelength routing at LSC2.

The results from comparative cost studies are shown in Fig. 6, giving a breakdown of the costs of the various key system parts when assuming 343 ONUs. Due to the extensive amount of WDM modules, the nested WDM architecture is the most costly. From a network evolution perspective, the most economic option is to start with the PS-PON architecture. As the capacity demand grows, it can be upgraded by introducing multiple wavelength channels, e.g., by evolving to the PS-PON + fixed WDM architecture. A more attractive upgrade is, however, an evolution to the PRISMA architecture, as this architecture provides more network flexibility at only a minor additional investment.

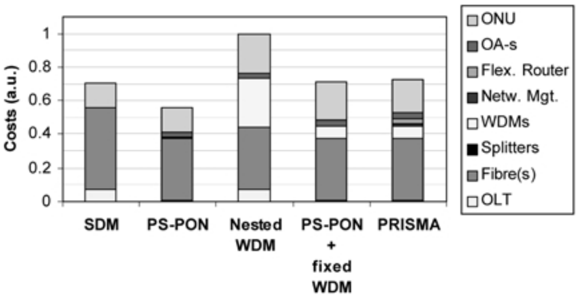

Fig. 6. Cost comparison of network architectures.

5 Field Trial

The PRISMA system has been validated in a field trial in Ghent, Belgium, where it operated from the beginning of October 1999 until the beginning of January 2000 [4]. The system has been installed in the Urbis building, shown in Fig. 7. It contained also multi-wavelength OLT equipment from the ACTS project AC028 TOBASCO, ATM-PON equipment from AC022 BONAPARTE, and ATM wireless equipment from AC085 WAND [5]. Furthermore, commercially available WaveLAN equipment from Lucent was used. On the ground floor, where many shops are located, a WaveLAN radio access point (RAP) was mounted providing 8 Mbit/s broadband wireless access to a computer shop and a job agency. On the third floor, the rest of the system equipment was located in the laboratories of the IMEC group, belonging to the University of Ghent. Here university staff members and students were provided with 20 Mbit/s wireless ATM-based access via the WAND equipment, and 8 Mbit/s via the WaveLAN RAP. The services provisioned were fast Internet access and electronic mail (via BELNET, the Belgian national research network), fast file transfer to and from the university servers, and video conferencing.

Fig. 8 gives a view of the setup of the major part of the field trial equipment in the laboratories of the IMEC group. The layout of the trial is shown in Fig. 9. At the OLT site, multiple 155 Mbit/s interfaces were used to the ATM switch. Permanent virtual circuits (PVCs) could be set up between the OLTs and the ONUs. Via the WAND base station (BS), the ATM connection is extended to the mobile terminal, i.c. a portable PC. To connect the WaveLAN BSs, an ATM-to-Ethernet bridge was deployed.

To assess the performance of the system, extensive measurements were made of the signal delay characteristics. The distributions of the round trip time (RTT) for a 64-byte packet without and with the wireless systems are shown in Figs. 10 and 11,

Fig. 7. The Urbis building in Ghent, Belgium.

respectively. For these measurements, ping techniques were used in a number of different system configurations where the ATM switch functioned as the source. The LAN emulation client (LEC) contributes 1.1 ms to the RTT, and the ATM PON on average about 1.4 ms. As evident from Fig. 11, the wireless systems add significantly more to the overall RTT, due to their more complex signal processing. Fig. 12 illustrates the contributions of the various system parts to the average RTT, as a function of the packet size. Obviously, the contribution from the wireless system gets even more dominant for larger packet sizes. Due to its more complex signal handling at one hand, but higher transfer speed at the other hand, the WAND system yields a higher RTT than the WaveLAN one for short packets, but a smaller RTT for long packets.

During the field trial period, the overall system showed a stable behaviour. Interviews were held among the users to obtain feedback. All users were quite satisfied with the speed and reliability of the system, and would like to have such a system in the future (at limited costs). Some users who had experience with a fast Ethernet (100 Mbit/s) connection to their desktop PC did not notice a degradation in the performance when wirelessly connected to the PRISMA system. New business opportunities for the shops connected were foreseen taking advantage of the broadband mobility offered.

6 Applicability of Flexible Wavelength Routing for Nomadic Applications

By means of flexible wavelength routing in fiber-wireless networks, the delivery of broadband nomadic services can be quickly adapted to meet

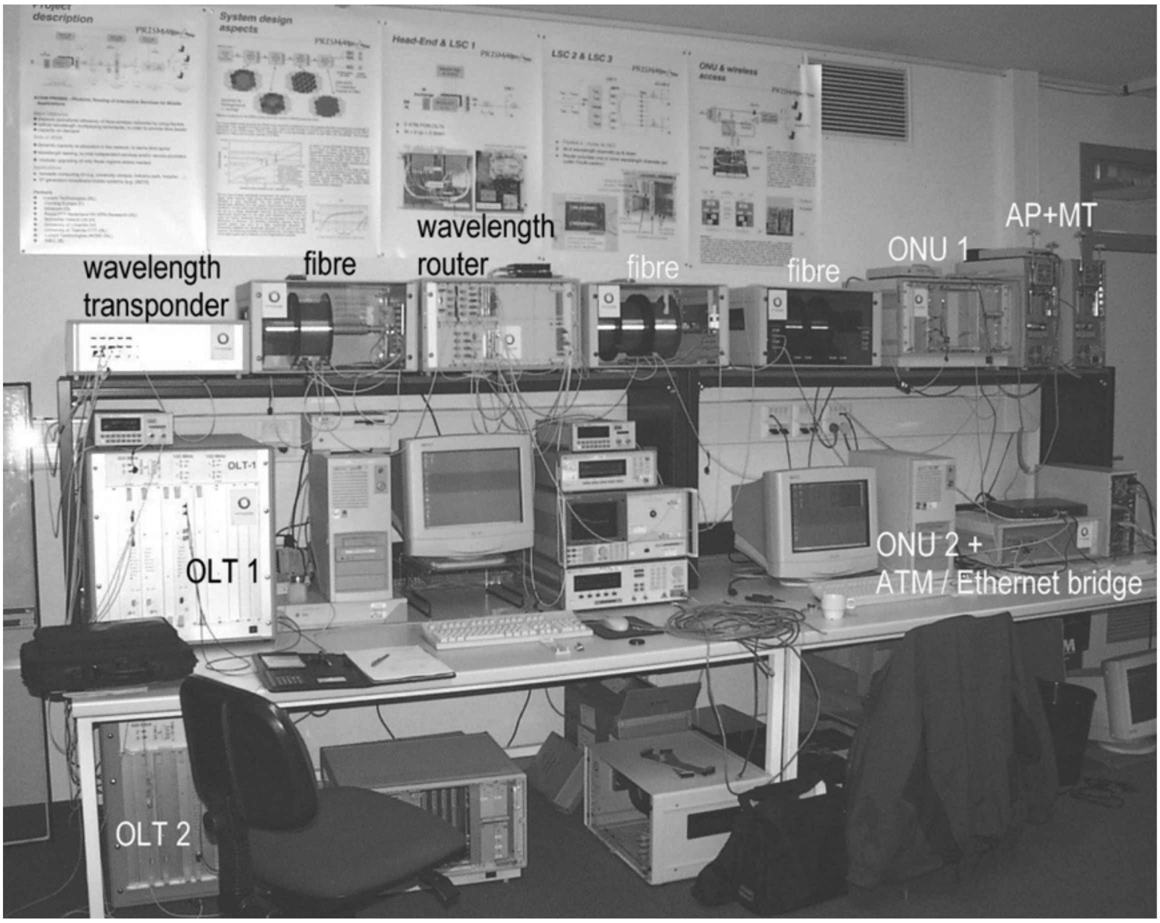

Fig. 8. Setup of the field trial equipment.

actual local traffic demands without cumbersome modifications of the network infrastructure. In particular, these network reconfiguration strategies are advantageous in environments where locally large variations in the number of users asking for broadband services occur, such as in university campuses, industrial parks, hospitals, downtown urban areas, shopping malls, entertainment parks, sport centers, etc.

Within the PRISMA project, a number of system modules for nomadic fiber-wireless networks have been developed and successfully evaluated: a flexible wavelength router, bi-directional multi-wavelength optical amplifiers, cost-effective optical network units deploying spectral slicing and deploying a reflective optical modulator. Also multiple transceivers per wireless access point and management systems for steering the network reconfiguration have been outlined. After having proven its technical feasibility in the field trial, the system concept is ready for further development into products.

7 Applicability of Flexible Wavelength Routing for Mobile Applications

In the near term, wavelength routing can be an attractive technique for flexibly provisioning parts of the network infrastructure to new operators and/or new services. By regional wavelength leasing, new entrants have their own independent transport pipes in the network, which can be laid out dynamically as the business grows. Thus they can roll out their services quickly in today’s liberalized mobile (GSM, GPRS) market. Several operators may share the same base station site, saving significantly on costs for real estate and reducing environmental visual ‘‘pollution’’. The speed with which the wavelength routing needs to be

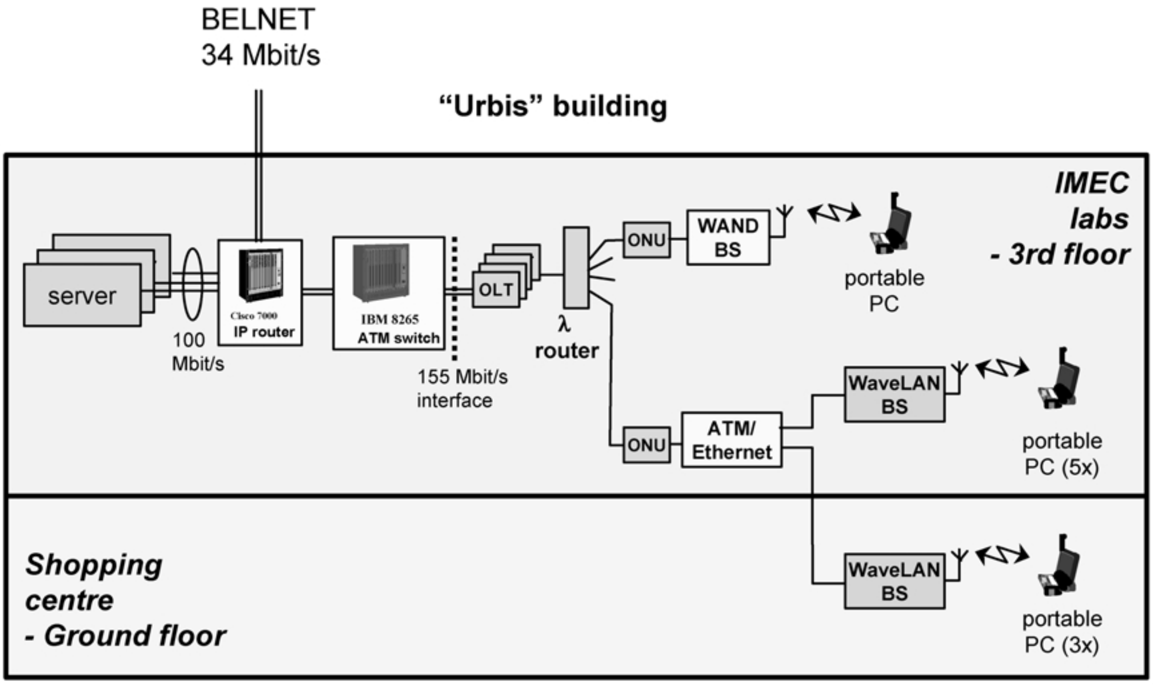

Fig. 9. Layout of the field trial in the Urbis building.

done is fairly low, thus putting relaxed requirements to the configuration management system and the wavelength router.

As a follow-up to the existing GSM 900, GSM 1800 and GPRS mobile systems, third generation mobile systems are foreseeing increased bandwidth demands (e.g., UMTS goal of 2 Mbit/s mobile connections). It is expected that for the provision of (medium) broadband UMTS services, large numbers of microcells are needed, especially at hot spot locations. The upcoming applications and network services for UMTS, of which the traffic load impact on the network is yet unknown, are expected to require ultimately the adoption of a flexible core network architecture. In this respect the PRISMA architecture, developed primarily for broadband nomadic computing applications, can be extended and adapted to support UMTS.

The UMTS high-mobility medium-bandwidth applications require the support by specific procedures such as seamless handover and macro-diversity (i.e., maintaining contact with more than one base station, and applying soft decoding). The UMTS radio interfaces will be based on wide-band CDMA (W-CDMA; probably also on TD-CDMA) technologies, where in comparison to GSM the frequency re-use factor is in principle 1 and the bandwidth per carrier is up to 5 MHz. Shifting the RF-radio/ATM interworking point to higher levels in the access network can bring significant advantages in optimizing the mobility functions and in simplifying the equipment at the antenna locations. In addition, PRISMA's dynamic reconfiguration strategies opens new approaches to capacity planning, for instance for handling hot spots.

Deployment of WDM technology in the fiber network feeding the antenna locations thus is an attractive option in order to ease mobility functions, to serve the high number of microcells, and to meet the

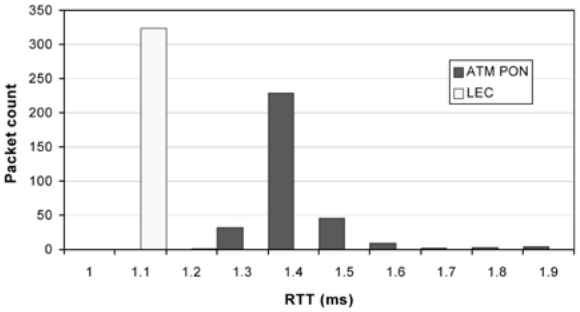

Fig. 10. RTT distribution for 64-bytes packets, without wireless system.

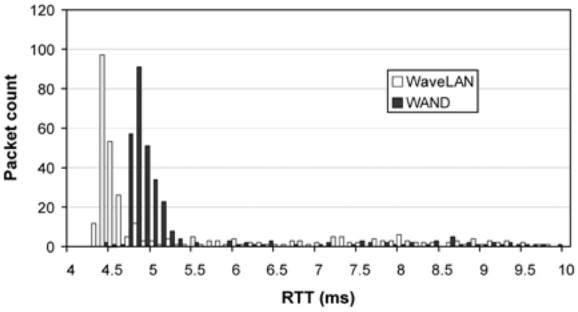

Fig. 11. RTT distribution for 64-bytes packets, with WAND or WaveLAN wireless system.

demand of high transport capacity. Basically, the concept explored is to centralize the UMTS base station transceivers (BTSs) in a single location, and to establish the link between the BTSs and the antenna locations by means of a WDM fibre network. This provides attractive installation and maintenance opportunities, since the OAM cost of the base station transceivers in a central location could be low and the nodes at the antenna locations can be implemented in a low-cost and compact manner.

8 Conclusions

A new approach for dynamically re-allocating capacity resources in fiber-wireless networks has been reported, offering a significant improvement of the network operation efficiency. The system setup developed within the PRISMA project deploys flexible wavelength routing, and has been successfully validated providing broadband nomadic services in a field trial in Ghent. The system concept is ready for starting product development. It offers an economically attractive solution for upgrading the capacity of power-splitting passive optical networks feeding wireless base stations. In the near term, flexible wavelength leasing may stimulate the entry of new independent services and/or operators in the liberalized mobile telecommunications market. The PRISMA approach may support significantly the evolution of wireless networks to provide future nomadic and mobile services with high bandwidth and (yet unknown) mobility demands.

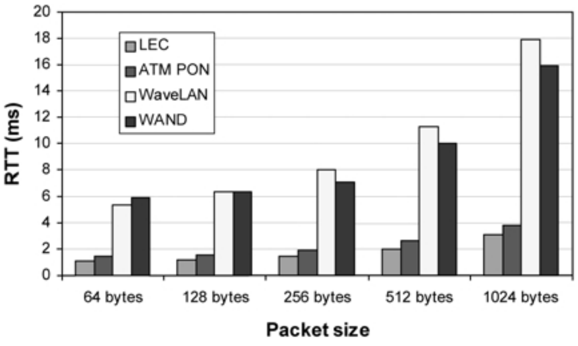

Fig. 12. Average RTT for different system setups and packet sizes.

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Ton Koonen received his M.Sc. degree (cum laude) in Electrical Engineering from Eindhoven University of Technology in 1979. He joined Philips' Telecommunicatie Industrie in 1979, part of which since 1984 has become Lucent Technologies Nederland. He has worked on various passive optical devices, wavelength-multiplexed networks, and high-speed long-haul fiber-optic systems. He was a Technical Manager of the Access Platforms group of the department Forward Looking Work, Bell Labs, Lucent Technologies, from 1987 to 2000. He has participated in various European R&D collaborative projects in the RACE and COST program. He was the Project Manager for ACTS project AC028 TOBASCO and AC349 PRISMA, and of the IST project HARMONICS; these projects dealt with broadband access in fiber-coax, fiber-wireless, and hybrid IP-based fiber networks based on flexible wavelength routing, respectively. He also has acted a number of times as a reviewer and auditor of European projects in RACE and ACTS. He has been appointed Bell Labs Fellow in June 1999. From 1991 to September 2000, he has worked as a part-time professor holding a chair on Photonic Networks at the University of Twente. Since September 2000, he is a part-time professor at the Technical University of Eindhoven, and from January 2001 onwards a full-time professor, holding a chair on Broadband Communication Networks. His current research interests are in high-speed multi-wavelength optical transmission and broadband access networks.

Kees Steenbergen received his M.Sc. degree in Applied Physics in 1992 from Delft University of Technology. In 1997, he received the Ph.D. degree on the topic ''High capacity integrated optical receivers'' at the Faculty of Electrical Engineering of the same university. In October 1996 he joined the Forward Looking Work department at Bell Labs, Lucent Technologies in Huizen, the Netherlands, where he has been working in the European ACTS projects AC028 TOBASCO and AC0349 PRISMA. Currently, he is managing the IST project HARMONICS. His main areas of research interest are network integration, optical access networks, integrated optics, optical and microwave measurement techniques and simulations.

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