Radio-over-Fiber-Based Solution to Provide Broadband Internet Access to Train Passengers

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ABSTRACT

Nowadays, combining high-bandwidth connections (e.g., 5 Mb/s/user) and fast-moving users (e.g., on a train at 300 km/h) while keeping a sufficient level of QoS is still an unsolved bottleneck. In this article we propose a cellular trackside solution for providing broadband multimedia services to train passengers. A Radio-over-Fiber network in combination with moving cells forms the base of this realization.

INTRODUCTION

To provide the present spectrum of multimedia services (e.g., Video-on-Demand, Online gaming, Voice-over-IP, etc.) to train passengers, an access network characterized by high bandwidth requirements and with a high level of quality of service (QoS) is desired. The challenge telecom operators are facing today is to examine how the required bandwidth and quality can be provided to the train carriages. Currently used cellular and satellite technologies cannot be considered as an appropriate solution because either they are limited in bandwidth or they suffer from an unacceptable delay.

Therefore, we designed a dedicated cellular wireless network along the rail tracks. However, most cellular networks in combination with fast moving users, such as train passengers, have one important drawback: the frequent handovers when hopping from one base station (BS) to another cause numerous packet losses strongly reducing the bandwidth. An attractive solution to solve this deficiency could be delivered by an optical access network using Radio-over-Fiber (RoF) to feed the base stations installed along the rail tracks, and this in combination with a "moving cell" concept. This work is also a part of our FAMOUS (FAst MOving Users) architecture to deliver broadband connections to moving users [1].

We motivate the need for this new network architecture and describe the shortcomings of the current solutions. We elaborate the optical access network and the moving cell concept, respectively. Some simulation results demonstrating the correct working of the moving cell concept are given. Finally, we present a first optical switching architecture to realize these moving cells in the optical domain.

MOTIVATION

BANDWIDTH REQUIREMENTS

We can assume the broadband connections in a train will approximately follow the connections available at home (nowadays, approximately 5 Mb/s) with a delay of some years (five years, for instance). To estimate the total bandwidth needed on the train, we have to put a value on the number of users. Recent high-speed and intercity trains can carry, for example, 750 to 1000 passengers, and some double-deck trains are equipped with even 1500 seats or more. During rush hour, the seating capacity of the train will be nearly completely occupied, and supposing 10 percent of the passengers want to have broadband access (for a more detailed user study, see [2]), we need a total bandwidth of 375 to 750 Mb/s, and almost 750 Mb/s for a double deck train. These figures take an individual bandwidth of 5 Mb/s into account. However, in general, a user will not need a dedicated connection of 5 Mb/s, and we may consider a certain form of statistical multiplexing. With a multiplexing factor of, for example, 20, we need 37.5 Mb/s for a double-deck train. In the distant future, bandwidths of 100 Mb/s or even 1 Gb/s will also be available at home. To offer this to train passengers while taking into account a train with 1000 passengers, a take rate of 10 percent, and a multiplexing factor of 20, a total bandwidth of, for example, 0.5 to 5 Gb/s/train will be desired.

CURRENT TECHNOLOGIES

In contrast with current cellular networks (e.g., GSM, GPRS, UMTS, etc.), we will not set up a direct connection between each train passenger and a ground base station. A direct link is too liable to high penetration losses because of the Faraday cage characteristics of a train carriage.

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To provide high-capacity services to high-speed train users a hierarchical approach will be required, consisting of a separate link between the railway and the train on the one hand and between the train and the users on the other hand. In the train carriages themselves, the Internet connection can be provided by the same technology as used by home users, e.g., WLAN IEEE 802.11 technology (or its successors). With the help of one (or more) access point per carriage, all passengers can have wireless Internet access. Next to the distribution in the carriages, the connection between the train and the fixed network is definitely the most challenging one. Nowadays, the most used technologies are cellular-based (trackside) and satellite solutions.

Satellite has some specific limitations such as a considerable inherent delay (approximately 500 to 600 ms), which makes them less suitable for real time applications. It is also limited in bandwidth, an important demerit when a large number of train passengers (possibly spread over several trains) are using Internet access. Finally, line of sight is required: there is poor satellite coverage in dense urban and hilly areas, and in tunnels there is totally no coverage. As a result, satellite will not be able to cover all future requirements for broadband multimedia services. However on some specific long-distance lines (e.g., in very rural areas), satellite may have its place in the near future.

Cellular technologies, on the other hand, are not liable to such high delays, but mostly there is a trade off between mobility and available bandwidth (Fig. 1). At a typical train speed (e.g., 160 km/h for an intercity train or even 300 km/h for a high-speed train), most present standards have a much lower data rate than the desired figures. However, in the long term, we believe high-speed Internet connections have to be brought to the train by cellular trackside networks and, as a consequence, the technology has to be adapted in that manner. The reduction of the cell size (e.g., 100 m cell diameter) and the adaptation to a one-dimensional cell pattern are two important aspects to succeed in the challenges described above. An increasing handover rate is an important consequence of reducing the cell size. A high-speed train of 300 km/h in combination with a cell size of 100 m corresponds to one handover every 1.2 s. With current handover times in the order of, for example, 0.1 to 1 s, this is intolerable. Thus, the most important challenge will be to minimize the handover times.

WIRELESS AND OPTICAL ACCESS NETWORK

WIRELESS NETWORK

As stated above, to offer future bandwidth-consuming (real-time) applications to train passengers, a cellular-based trackside technology will be most appropriate. Reducing the cell size, implementing a one-dimensional cell pattern and using frequencies from the microwave (300 MHz to 300 GHz) and especially the millimeter-wave band (30–300 GHz, i.e., the highest frequency range in the microwave band) will be necessary to get a real broadband Internet connection on the train. With frequencies out of the millimeter-wave band, the cell size has to be very limited, since the transmitted waves suffer highly from atmospheric attenuation, which causes increased radio propagation losses. As a consequence, these systems require a high density of micro (500 m) or even pico (100 m) cells.

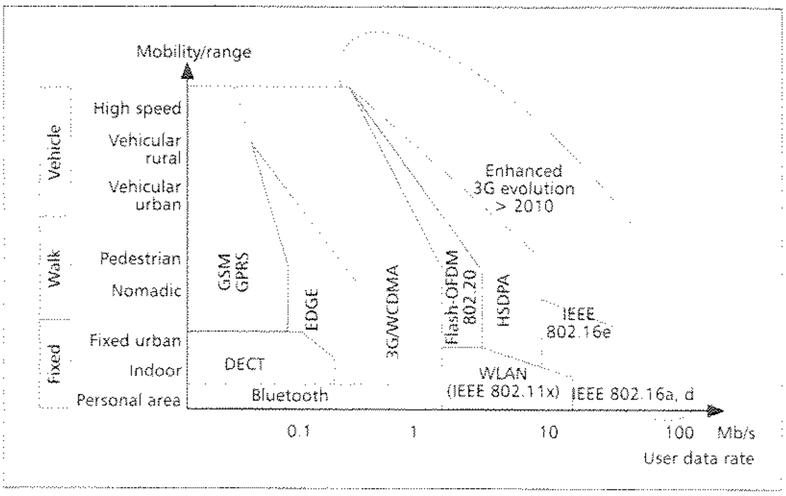

Figure 1. *Cellular technologies: trade-off between user speed and bandwidth (source: UMTS Forum [3]).*

Pico-cell networks offer operational benefits as well. The small cell sizes enhance efficient frequency spectrum reutilization, which makes it possible for them to offer integrated broadband wireless services to a large number of users per given area. Mainly the 60 GHz frequency band has unique properties when it comes to short-range communication. The unique scientific properties of this band and how it operates in our atmosphere makes it an ideal choice for short-range, high-bandwidth telecom applications. One of the greatest strengths of 60 GHz band is its performance in atmospheric oxygen. Oxygen absorbs frequencies around 60 GHz, and thus limits its communications range [4].

OPTICAL ACCESS NETWORK

From the previous paragraph, it turns out a huge number of base stations are required along the railways and combined with, for example, the 60 GHz frequencies, such a dedicated cellular network could be quite expensive. To reduce the associated costs, it would be very interesting to build the base stations along the tracks as cheap as possible. In this case, an RoF network can offer an appropriate solution [5]. An RoF system is a fiber-fed distributed antenna network. Its goal is to transfer complicated signal processing functions from the base stations along the railway (in an RoF network indicated as Remote Antenna Units or RAUs) to a centralized control station. The expensive signal processing equipment, such as (de)modulation, synchronization, multiplexing, spread spectrum techniques, error control, and so forth, at the control station can then be shared among several RAUs. To efficiently manage the proposed network, the RAUs are grouped over a distance of, for example, 5 km and then supervised by one control station that feeds all these RAUs via an optical

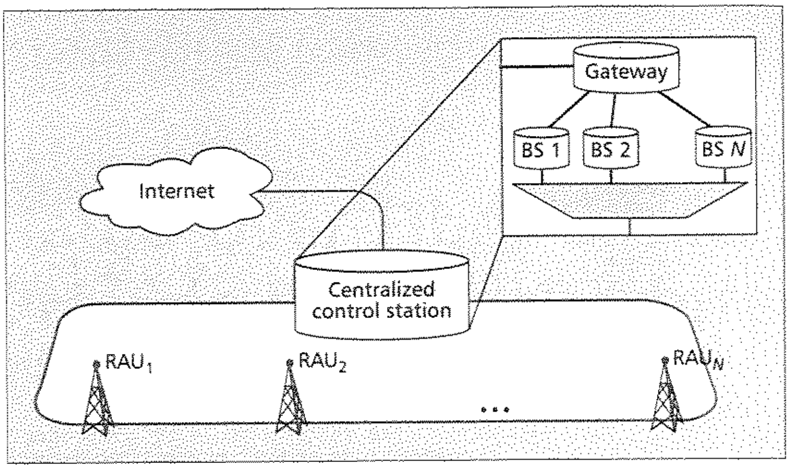

Figure 2. *Radio over fiber network providing Internet on the train, including centralized control station containing the different base stations, remote antenna units (RAUs) along the rail track, and an optical ring network connecting them all.*

network. As is explained in more detail below, a promising candidate topology to connect all RAUs in the range of one control station is a ring network.

Figure 2 shows an example of a RoF-based cellular network. Several RAUs (RAU$_1$ to RAU$_N$) are located along the rail tracks, and an optical ring network interconnects them. All RAUs within the same ring are under supervision of a centralized control station, where all processing is performed. We can also depict this as if the base stations themselves are located in the control station, and then connected to each RAU via the RoF network (Fig. 2). This means the wireless signals transmitted by a base station are not immediately broadcasted into the ether, but firstly, they are carried by an optical fiber to the RAUs, and there they are put into the ether. Commonly, each RAU is linked with a fixed base station in the control station, and will also have its fixed radio frequency. In the next section it is shown that it can be useful to abandon this last property.

TRAFFIC ROUTING

In the downstream direction, the data traffic will be modulated at the right radio frequency in the control station. Then these radio signals will be converted to the optical domain, and next transmitted by an optical fiber to the RAUs. The latter ones only have to recover the radio signals, which can be immediately transmitted to the train antennas without any further processing. In the upstream direction, the RAUs will capture the whole used frequency band, and this band is transmitted to the control station, where the desired frequencies are filtered out, and further processed.

To get the downstream packets at the right RAU, the control station has to keep track of the train location. This can easily be done by monitoring the upstream packets coming from the train. The RAU capturing the upstream packets is likely the one situated closest to the train. When the train is moving and the signals are captured by a new RAU, this RAU will soon be the only RAU communicating with the train. The control station can switch the downstream packets to the new RAU almost as soon as when the first packet reaches the control station by using this new RAU. Of course, the control station needs to remember the previous RAU in order to avoid switching back again in the overlap area.

COMPARISON WITH A CLASSICAL SOLUTION

Finally, we also stress the difference with a classical cellular wireless network (e.g., the current GSM, UMTS networks), where, on one hand, a base station (Base Transceiver Station or BTS in case of GSM, Node B in case of UMTS) transmits/receives the RF signals to/from the mobile users, and on the other hand, it also processes the RF signals. Now, both functionalities are split up between the RAU and the control station. All intelligence from the base station will be situated at the control station and the RAU can merely be considered as a passive device, and thus becomes significantly simplified, which is a critical issue in these high-frequency systems. Without the simplification of the RAUs, the deployment of micro- or pico-cell networks remains impractical in terms of system installation, operational and maintenance costs. On top of this, system upgrade and adaptation is also made much easier, since the critical equipment is centralized.

MOVING CELL CONCEPT

HANDOVERS

Each time a train antenna exceeds the cell boundary of the RAU to which it is connected at that moment, it has to reconnect to the next RAU, which means a handover has to take place. As mentioned above, the handover rate will drastically increase when the cell size is reduced to a diameter of, for example, 100 m. It is extremely important to keep the handover times as short as possible (i.e., implementing a fast handover), and handover times in the order of, for example, 100 ms to 1 s are absolutely impermissible. As described in the previous section, all intelligence is concentrated in the control station, and it is our intention to fully exploit this feature to implement the handovers.

When the train crosses the cell boundary of a RAU, some typical handover actions, briefly summarized below, have to be performed. The purpose of the handover procedure is to move data and control channels of the connection from the RAU and corresponding BS currently communicating with the train (what we call the "old" RAU/BS) to another RAU (located in another cell) and BS (the "new" RAU/BS). Usually, by evaluating received measurements from the train, the control station has to decide which cell and related BS/RAU is best suited to keep the connection. Luckily, in the proposed (one-dimensional) network, there is no doubt about the choice of the new RAU: it is simply the next RAU (and associated BS) in the direction the train is moving. The old BS detects the necessity of a handover from the measurements last received from the train. A message containing the "handover request" is sent to the control station, which prepares the new BS for establishing a connection to the train. Then, the new BS initiates the handover by transmitting the "handover command" message to the train through the old BS. This step permits the train to locate the radio channel of the new BS/RAU. Upon receipt of the "handover command" message, the train initiates the establishment of lower-layer connections in the new radio channels. In order to establish these connections, the train sends a "handover burst" message to the new BS and, when successful, transmission is established between the train and the new BS through its RAU. Finally, the train sends the "handover complete" message to the old BS through the new BS. Upon receiving this message, the old BS releases the old radio channels.

After determining the need for a handover, two important actions have to be executed:

- Preparing the new BS for establishing a connection with the train, so that the data flow has to be processed by this new BS in the control station.
- Establishing lower-layer connections in a new radio channel between the train and RAU.

However, in the proposed network architecture, all base stations are grouped in the control station, and normally, only one train will simultaneously be within range of a certain RAU (the case of crossing trains will be addressed further in this section). Keeping in mind these two features, we have proposed the moving cell concept to reduce the handover times.

MOVING CELLS

Instead of the train moving along a fixed repeated cell pattern, we consider a cell pattern that moves together with the train, so that the latter can communicate on the same frequency during the whole connection, also avoiding most (cumbersome) handovers. The idea of moving cells is not completely new; in [6], there was a proposal with physically moving cells. The idea was rather futuristic, and the operation and maintenance of such a network is also a point of discussion. However, the same principle, now with frequencies moving together with the train, can offer us the opportunity to reduce the handover times. Thanks to the central control system, we can implement these moving cells by reconfiguring the optical network feeding the RAUs. In this way, the speed of the cells can rather easily be synchronized with that of the train, and by means of current optical switching technology, the required reconfiguration time should be kept minimal. Finally, we want to stress the moving cell concept is extremely attractive in a train scenario, where a "burst of users" moves all together at the same speed.

By applying the moving cell concept, the actions that have to be performed after determining the need for a handover, will seriously change. The BS before and after the handover remains unchanged, only the used RAU will change. This also means that each BS is no longer associated with a fixed RAU and, besides, the number of BSs can be a lot smaller than the number of RAUs. It is sufficient to equip the control station with as many BSs as train antennas within range of the control station. Furthermore, the same radio channel will also be used, so no new lower-layer connections have to be established between the RAU and the train. The only action that has to be executed is that the output of a base station has to be transmitted to another RAU. Simply by an optical switch, it should be possible to complete the handover. So, no synchronization between the preparation of the new base station and the shift of the radio channel in the connection between the RAU and the train is needed. It is exactly this synchronization that can be very time-consuming, and which is responsible for the fact classical handover times often have an order of magnitude of 1 s and the proposed moving cell concept will offer an efficient solution.

NUMBER OF BASE STATIONS

So far, we have considered the basic situation with only one antenna on the train. For capacity reasons, we can also install two or more antennas, using different radio frequencies, on the roof of a train. In this case, each train is connected to more than one BS at the same time and we have to equip the control station with an adapted switching architecture, so all antennas on the train can stay connected with a fixed BS. Several implementations are possible: all antennas connected to their own fixed BS via the same RAU (e.g., a separate antenna for down- and upstream traffic), several antennas spread over the length of the train and connected with their fixed BSs via different RAUs (e.g., each antenna installed on a different carriage) or a combination of both. If one or more BSs are connected to the same RAU, this RAU will transmit several noninterfering frequencies.

Finally, the case with several trains within range of the same control station can be compared with a capacity extension on one train. However, here, we have to make a distinction between trains passing a different RAU and trains simultaneously passing the same RAU. The first situation is very similar to this one with several antennas installed on one train. The biggest difference is that the antennas on different trains will generally not move at the same speed. So, the implementation in the control station will become slightly more difficult. In the other case, where two trains pass each other in the same direction (passing trains) or in the opposite direction (crossing trains), two different BSs have to be connected with the same RAU, again transmitting noninterfering frequencies.

SIMULATION

By simulations, we could demonstrate a correct operation of the moving cell concept. In first instance, we focused on a future technology with millimeter-wave frequencies, but current standards can also be adapted to implement moving cells (see also [7]). In our simulation, we have made use of the IEEE 802.11b technology, which is a cheap and easily available technology nowadays. To approach the concept of capturing a whole frequency band, we have installed a number of wireless network cards in the nodes that act as RAU so we can capture a small selection of that frequency band. There is one network

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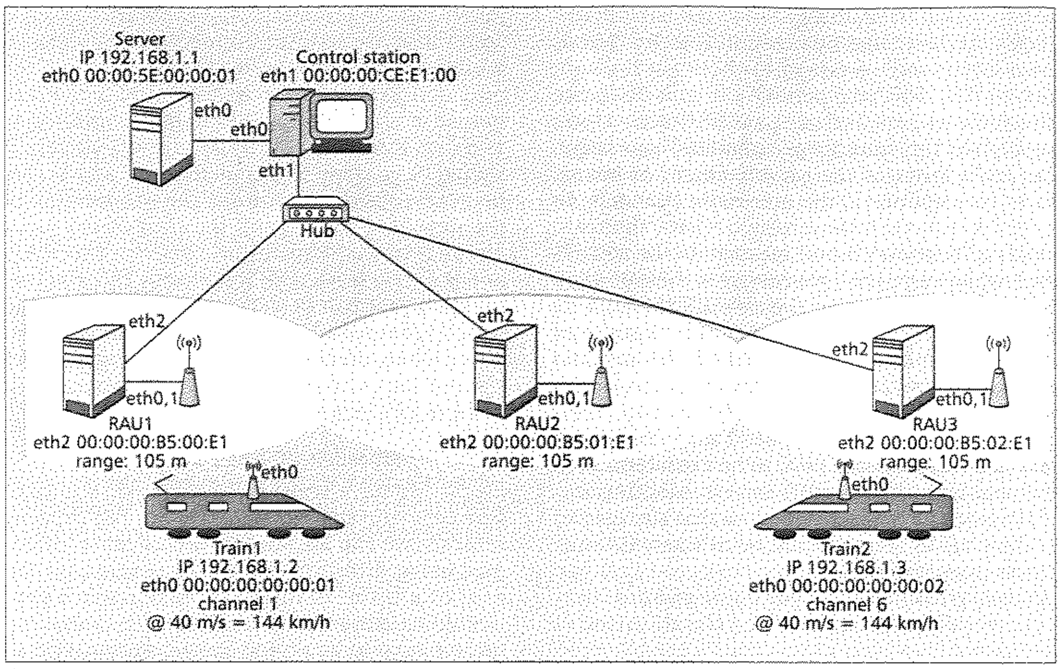


Figure 3. *Simulation setup to demonstrate the moving cell concept.*

To approach the concept of capturing a whole frequency band, we have installed a number of wireless network cards in the nodes that act as RAU so we can capture a small selection of that frequency band. There is one network card needed in each RAU for each train/channel we want to support.

card needed in each RAU for each train/channel we want to support.

Instead of an optical network, we have fallen back on Ethernet in the simulation environment (Fig. 3). By connecting the control station and the RAUs with a hub or switch and give all nodes a dedicated MAC address, we could simulate the optical fiber, by which the control station sends packets to each RAU separately. To model an RoF network, the RAUs encapsulate the whole captured packet, including extra information like signal/noise ratio and received power into a new Ethernet packet and send it to the control station. The RAUs only forward these packets, so they really act like dumb antennas.

To give a first indication of the correct working of the moving-cell concept, we have considered the following scenario. We have placed three RAUs at a distance of 200 m from each other. Each of them has a coverage range of 105 m so there is an overlap area of 10 m. We have used two trains, moving in the opposite direction and this at a speed of 40 m/s (~144 km/h). The first one starts at RAU_1 and moves towards RAU_3 while the second one makes the opposite movement. A User Datagram Protocol (UDP) test stream is sent in downstream as well as upstream direction. The UDP throughput is shown in Fig. 4. It is clear the network connection is not broken when changing to a new antenna. We can remark upon the two peaks where both trains are in an overlap area, and where their traffic is captured by two RAUs and sent to the control station together. We can also clearly see the traffic from the control station to RAU_1 stops as soon as the first packet from RAU_2 is received. When both trains are in the area of RAU_2, the traffic is twice as high. These simulation results show a correct operation of the moving cell concept, by which the traditional handover problem can be avoided.

BASIC OPTICAL SWITCHING ARCHITECTURE

DESCRIPTION

In addition to the simulation with IEEE 802.11b technology and an Ethernet network, we also propose a first optical switching architecture to implement the moving cells in the control station. First of all, we emphasize that the reconfiguration, needed to implement these moving cells, takes place entirely in the optical domain. Thanks to a ring network, the same fiber can be used by all RAUs within range of the control station and by using Wavelength Division Multiplexing (WDM), each RAU can be associated with a dedicated wavelength. By assigning a fixed wavelength to each RAU, it is possible to efficiently switch the output of a certain BS to another RAU. In this section we immediately consider the general situation with several antennas within range of the same control station (whether spread over several trains or not). All RAUs within reach of an antenna could then be fed by another radio signal, with each delivered by a fixed wavelength.

A possible way to implement the moving cell concept is illustrated in Fig. 5. The intention is to accomplish the moving cells by switching a couple of optical switches in the control station. If, in each RAU, there is installed a fixed Optical Add Drop Multiplexer (OADM), then a fixed wavelength is terminated in each RAU. The idea is then to put the desired frequency for a certain RAU on the right wavelength. This can be done through the use of some optical switches in combination with a WDM laser.

The WDM laser will generate a beam of light containing the desired wavelengths. The entire beam is sent to an optical switch and the right wavelengths are passed to the different RF modulators (each generating another radio frequency). To modulate a certain wavelength with the

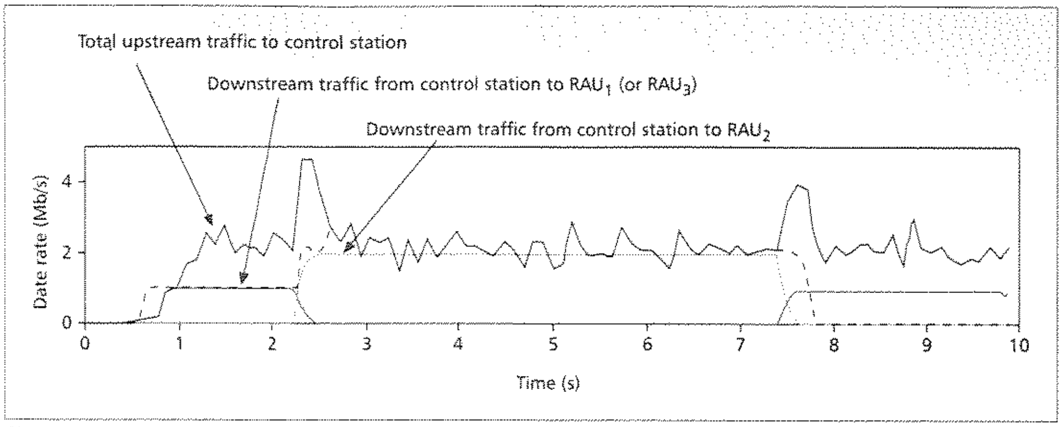


Figure 4. *Simulation results demonstrating the correct operation of the moving cell concept.*

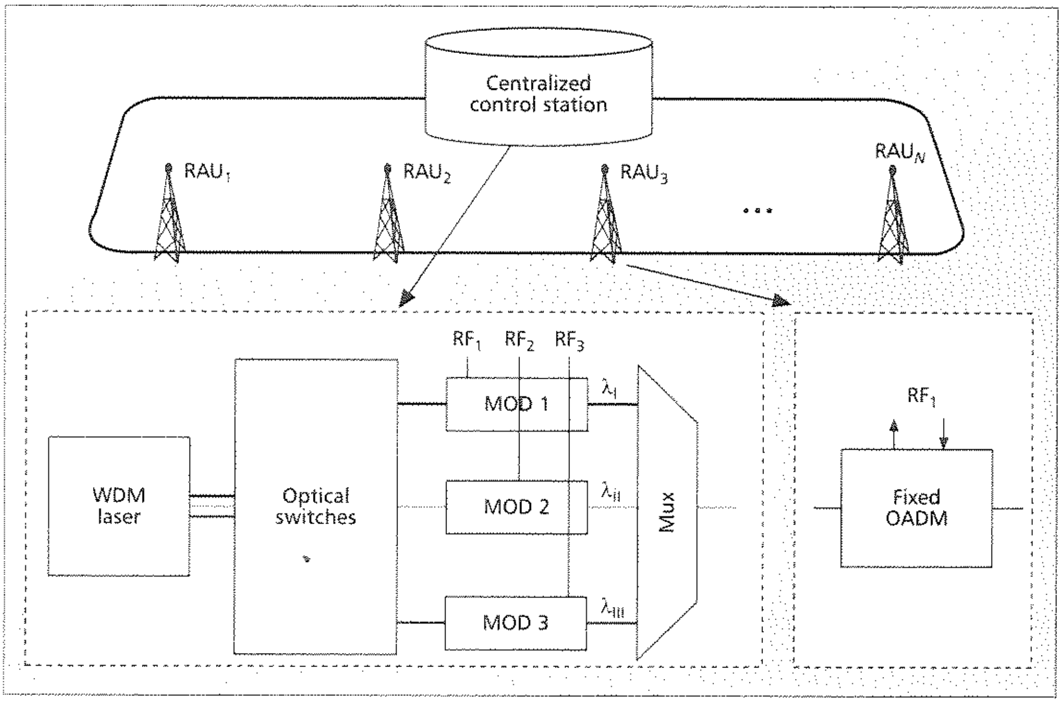


Figure 5. *Basic architecture in the control station to implement moving cells.*

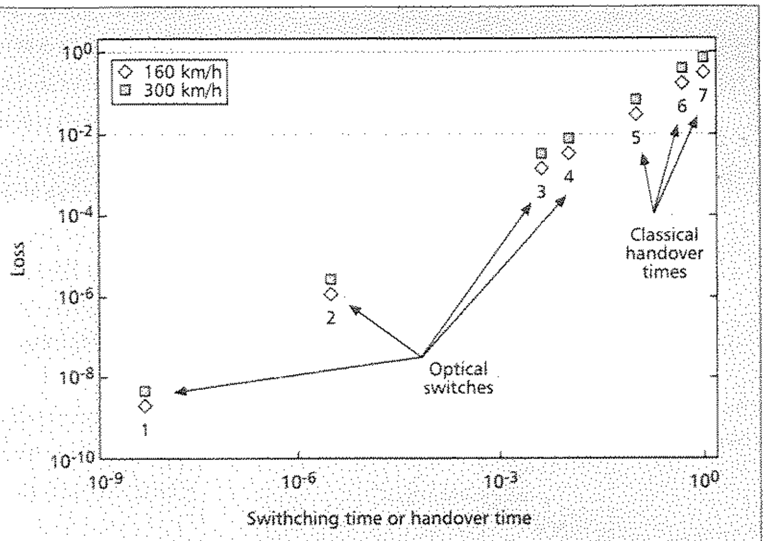
The WDM laser will generate a beam of light containing the desired wavelengths. The entire beam is sent to an optical switch and the right wavelengths are passed to the different RF modulators (each generating another radio frequency).

right RF signal, this wavelength has to leave the right output port of the optical switch. Based on the example of Fig. 5, $m = 3$, and the output order is, for example, λ_I, λ_{II}, λ_{III}. Consequently, λ_I is modulated with RF$_1$, and so on. The modulated wavelengths leaving the RF modulators are multiplexed, and transmitted through the optical fiber to the right RAU. The RAU equipped with the OADM dropping λ_I will transmit its information on RF1.

THEORETICAL EVALUATION

The switchover of only some optical switches in the control station will be much less time-consuming than classical handovers. Handover times of 100 ms, 500 ms, or 1 s are not an exception. On the other hand, optical switching times in the order of ns or µs (see table in Fig. 6 [8]) are already possible, and when these switching times correspond to the dominant factor in the handover time, the latter will reduce many orders.

That a handover time of 1 s is not sufficient was already proved above. A cell range of 100 m combined with a train speed of 300 km/h means a handover every 1.2 s, and in combination with a handover time of 1 s, we achieve a loss of 0.83 (no. 7 on the chart of Fig. 6), which is unacceptable. As shown in the chart of Fig. 6, this loss decreases a lot when using our architecture with optical switches. The numbers on the chart correspond with the numbers in the table, and a speed of 160 km/h as well as 300 km/h is depicted. It is obvious the influence of the speed is much smaller than this of the different switching times, which vary several orders of magnitude. Even with micro electromechanical systems (MEMS) (see no. 4), the loss is already decreased greatly, and the use of Semiconductor Optical Amplifiers (SOAs, used as switches), electro-optic switches, and acousto-optic switches shows great promise.



No	Switch	Switching time
1	SOA, electrooptic	5 ns
2	Acoustooptic	3 µs
3	Thermooptic, electromechanical, liquid crystal	4 ms
4	MEMS, bubble	10 ms

Figure 6. *Some optical switches with their switching times [8], and the corresponding losses.*

CONCLUSION

In this article we have proposed a cellular trackside solution to provide broadband Internet access to train passengers. The solution is based on a Radio-over-Fiber (RoF) network to reduce the costs of the remote antenna units along the tracks. Furthermore, we have proposed a moving cell concept to limit the handover times when a train moves form one cell to another one.

Simulations in a simplified network demonstrated the correct operation of moving cells. More detailed simulations are still required in the future; however, these results are already very promising. Finally, a basic optical switching architecture for the control station was proposed. It is possible to implement the moving cells entirely in the optical domain, and this by some optical switches in the control station of the RoF network.

To provide real broadband access to train passengers, we believe our solution will become very promising in the future. Finally, we also want to remark that our solution is a standard independent one.

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BIOGRAPHIES

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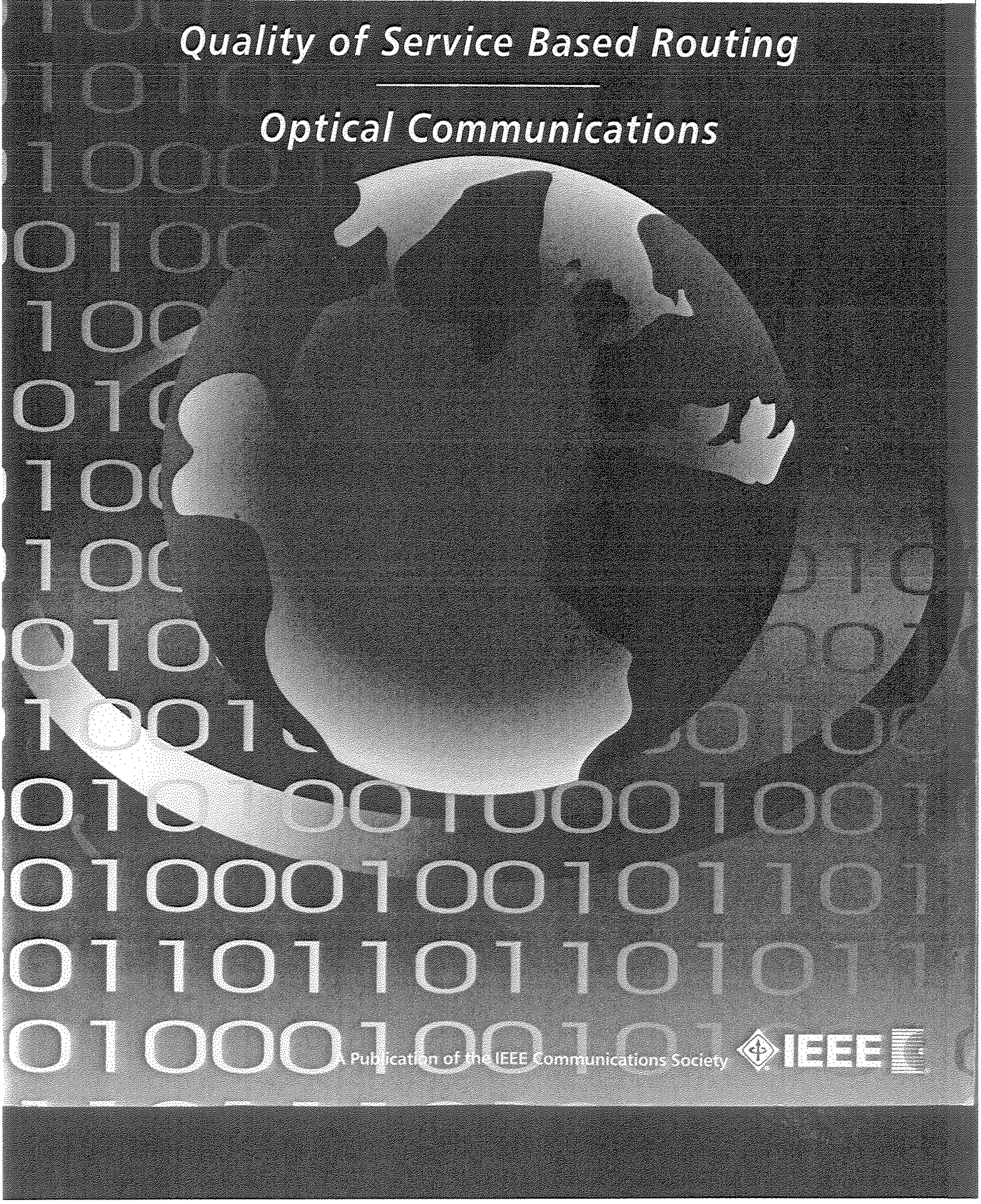
Quality of Service Based Routing

Optical Communications



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