BROADBAND INTERNET IN TRAINS

Kamlesh Kumar Singh
Principal,
Patna Saheb Group of institutions,
Hazipur, Patna, Bihar

ABSTRACT

Combining high-bandwidth connections (e.g. 2 Mb/s/user) and fast-moving users (e.g. on a train at 200 km/h) while keeping a sufficient level of Quality of Service is a major challenge for providing Broadband Internet access in Trains. This is due to the frequent handoffs which greatly reduces the bandwidth available to fast moving users. This paper proposes a moveable cell concept featuring fast handover and dynamic bandwidth allocation using the ability of centralized control of radio over fiber networks to support high data rate access in trains.

Keywords- Radio-over-fiber; Moving Extended Cell; Remote Antenna Units

I. INTRODUCTION

WITH the explosion in growth of the Internet in the last 20 years, people have a much higher expectation of being able to get on the Internet independent of location. Until recently trains and airplanes have been two locations where passengers have not necessarily been able to achieve high speed Internet connections. In the particular case of trains, providing Internet access to passengers on board trains makes good business sense: Internet access for passengers can provide a revenue stream for the train company while attracting more travellers. In the case of freight trains, Internet access can allow for real-time or near-real-time tracking of freight-related events on board the train, potentially resulting in a decrease in insurance charges to the freight carrier. In addition to these benefits, broadband Internet access on trains can also enhance the safety of the train by allowing an operations center to monitor, in real-time, train-related data.
To realize such a connection, we will have a need for a wireless network which provides a lot of these services to fast moving users and simultaneously also at high data rates. Up till now, the combination of high bandwidth and fast moving users is not very evident. On one hand, there exist a lot of wireless networks which offer a high bandwidth to stationary users (e.g. in some cities, there are so-called hotspots which already provide wireless broadband access).

On the other hand, mobile users at high speed can also set up a connection (e.g. GSM, UMTS) to a network such as internet, but the corresponding bandwidth will be insufficient to make use of the current broadband applications.

The main intention is to design a wireless network that can offer high data rates to mobile users at high speed. The network will contain a central control station, which is connected to a number of Remote Antenna Units (RAUs) via an optical fiber using Radio-over-Fiber (RoF) technology. In this paper, we demonstrate a novel concept for seamless communication supporting high end-user mobility in broadband Radio-over-Fiber networks irrespective of the user’s mobility pattern. The scheme relies on a capacity reallocation mechanism for reconfiguring the Extended Cells so as to form user-centric Moving Extended Cell (MEC) structures that follow the user’s mobility pattern. In this way, the end-user is always surrounded by a certain number of grouped cells transmitting concurrently the same user-specific data over the same radio frequency enabling in this way seamless communication conditions for truly random mobility and velocity patterns. The MEC scheme is mathematically formulated and results from the performance evaluation reveal zero packet loss and call dropping probabilities for user velocities up to 40 m/sec irrespective of the overlapping region between neighbouring cells. We also present the physical layer network architecture for the realization of 2.5 Gb/s downlink connection over a single 60 GHz radio frequency using the MEC approach.

The entire paper is organized as follows. Section II deals with the sustaining difficulties and opportunities in the current cellular architecture and serves as the statement of problem for this paper. Section III is about existing architectures (i.e Radio over Fiber technology) in the present train environment scenario and this also provides a firm base to improve upon to the next level of architecture (i.e Moveable Extended Cell concept). Section IV describes the concept of moveable extended cell concept and presents its mathematical analysis. Section V involves the performance evaluation of a RoF network when MEC is employed and compares its results with the simple case of inter-cellular handover.

II. DIFFICULTIES AND OPPORTUNITIES

A. Difficulties

Communications on board trains are complicated by several factors. Lannoo et al. [1] state that railcars have Faraday cagelike characteristics which can lead to high penetration losses for signals. Beeby [6] adds that other complicating factors include:

- A “high vibration environment” that may require mechanical isolation of communication devices.
- A “thermally challenging” environment, since heat may be a significant issue in certain parts of the train.
• A harsh electrical environment due to:
  – The proximity of high voltages, as in electrical trains.
  – High magnetic fields, as in magnetic levitation (Maglev) trains.
  – Trains are not designed to provide a “clean” electrical supply for computers.
• The need to have equipment with minimal maintenance schedules—this may result in equipment with near military-grade specifications.
• The presence of trackside features, such as railway signalling equipment.

Some other factors hindering communications on trains include:
• Railway companies constantly add or remove rail cars from trains. As a result, it is necessary for the communications network to discover these changes automatically[5].
• Poor coupler contacts on rail vehicles, which may introduce communications failures [5].
• Tunnels may limit visibility to wireless communication infrastructure.
• Frequent handoffs in the cellular network. These handoffs can result in packet loss and packet reordering.
• The train’s mobility complicates the provision of quality of service to different traffic flows [11].

In spite of these difficulties, there are several opportunities to provide Internet access on trains using a variety of technologies, including Wi-Fi, WiMax, satellite technologies, and radio-over-fiber. In Section II-B we discuss some of these opportunities.

B. Opportunities

The growth in wireless communication technologies over the last two decades opens up several opportunities for supporting communication on board trains. For example, customers in a stationary train can have Internet access through the existing cellular infrastructure without many modifications, except for an antenna on the outside of the train. Issues arise only when the train begins to move, particularly at high speeds, and requires several handoffs in a short period of time. Beeby [6] argues that communications capabilities on mobile terminals is constantly improving, with some phones now having multiband and Wi-Fi capabilities. Currently it is standard to have Wi-Fi integrated on laptops, and eventually WiMax might also be commonly available. These factors, especially the latter, have the potential to drive Internet usage higher, particularly because as connectivity becomes more prevalent, usage increases [6]. Beeby [6] goes on to argue that there are significant opportunities available for Internet access on trains if access to the technology can be made: simple, ubiquitous (as in not requiring any special software or terminal), and useable (that is, acceptable throughput and delay with few service interruptions). In this respect, Fourth Generation (4G) communications technologies, such as WiMax, IEEE 802.16m, or LTE [9] may be good solutions for offering Internet access on trains. We expect further growth in broadband Internet access availability on trains as more train operators are convinced of the business viability of negotiating for wireless coverage along their tracks using WiMax or some other 4G technology. Another application for broadband communication on trains is railway signaling. Aguado et al. [10] note that standards based communications systems such as IEEE 802.16 and IEEE 802.20 (Mobile Broadband Wireless Access) can be used for railway signaling instead of the cable-based systems currently in use.
III. RADIO-OVER-FIBER TECHNOLOGY

In 2005 and 2007 Lannoo et al. ([1], [2]) proposed extensions to Gavrilovich’s [3] moving base stations model. Lannoo et al. [1] argue, that frequent handoffs greatly reduce the bandwidth available to fast moving users. Consequently, they propose using radio-over-fiber, to feed base stations along the rail track. Unlike in Gavrilovich’s model there are no moving base stations, instead there is a fiber-fed distributed antenna network. These distributed antennas are located along the railroad tracks, and they are called remote antenna units (RAU) (These correspond to the base stations in Fig. 1.). The remote antenna units are supervised by one control station via an optical ring network. For communications from the access network to the train, data is modulated at the control station and sent optically to each remote antenna unit using wavelength division multiplexing, i.e., each RAU has a unique wavelength for communications. The remote antenna unit will convert the optical signal to radio waves and transmit to the train. For communications from the train to the access network, the data will typically be captured by the remote antenna unit closest to the train. In order to reduce handoff times for the train access terminal, Lannoo et al. propose using “moving cells,” i.e., a cell pattern that is constantly reconfigured at the same speed as the train so that the train access terminal communicates on the same frequency during a trip. Fig. 1 presents a reference architecture for the radio-over-fiber deployment.

IV. MOVING EXTENDED CELL CONCEPT

Fig. 2 provides a schematic representation of the MEC concept depicting a MU in a picocellular network configuration. Each cell corresponds to a specific RAU and the gray area indicates the group of cells that comprise an Extended Cell transmitting the same user-specific data content over the same radio frequency.

![Fig 1: Reference Architecture for Internet Access on Trains using Radio-over-Fiber](image-url)
As shown in Fig. 2(a), the Extended Cell involves the user’s cell and the six surrounding cells ensuring connectivity for all possible directions when the user leaves his/her current cell #4. However, in the case of user’s entry in a new cell, the Extended Cell is recomposed so as to form a new user-centric seven-cell group following the user’s motion. This is clearly illustrated in Fig. 2(b), where the MU leaves cell #4 and moves into cell #7. Upon receiving the beacon signal of cell #7, the initial Extended Cell is reconfigured so that cell #7 becomes the new central cell, resulting to a new Extended Cell formation that consists of cells #3, #4, #6, #7, #8, #9 and #10, releasing the capacity of cells #1, #2 and #5. To this end, the Extended Cell is always formed around user’s current location and is adaptively restructured when the user enters a new cell. As a result, the end-user is continuously surrounded by cells that transmit the same data content, offering in this way seamless communication conditions for all possible subsequent movements.

Fig. 3 shows the network configuration considered for the mathematical formulation of MEC. 300 picocells formed by respective RAUs are placed on a straight line and are connected to the Central Office (CO) via optical fibers that are assumed to have the same length $L$. It should be noted that the 7-cell EC structure can be easily adjusted when cells with less than six adjacent cells are considered by following a more generic MEC formulation that relies on EC structures encompassing $(m+1)$ cells, with $m$ denoting the number of neighbouring cells. To this end, the MEC formed for one user in a generic network topology can eventually incorporate a different number of cells depending on the user’s location and the associated number of neighbour-cells. This can be enabled by taking advantage of the
centralized network topology knowledge provided by the CO in order to allocate the required number of MEC cells in each MEC reconfiguration process.

Fig. 4 shows the network configuration considered for the mathematical formulation of MEC. 300 picocells formed by respective RAUs are placed on a straight line and are connected to the CO via optical fibers. When concentrating on a single MU transition between two neighbouring cells, the fiber links between the two adjacent RAUs can be assumed to have the same length L since the cell radius R is only a few tens of meters, whilst L is in the km-range and as such R << L. The axial length of the overlapping region between adjacent cells is denoted as x₂, whereas x₁ stands for the difference R – x₂.

Fig. 4: The network configuration used for the performance analysis of the MEC concept

The beacon signals are emitted periodically at time intervals of T_b and are considered synchronized among all RAUs taking advantage of the common control management enabled by the CO. The MU can move with a constant velocity V along the line formed by the cell centers and lies initially at the center of RAU#1 cell, implying an initial EC that includes RAU#1 and RAU#2 cells.

Let us assume that beacon signal transmission begins at t=t₀, the MU enters the overlapping area between RAU#1 and RAU#2 cells at the moment t₁, and RAU#2 emits its next beacon frame at the moment t₂. The MU will receive this beacon signal if it is still in the RAU#2 cell at the moment t₂, and it will respond via an ACK signal to RAU#2 announcing its presence and initiating the Extended Cell reconfiguration process. In this way, a new Extended Cell consisting of RAU#2 and RAU#3 cells will be formed. A call drop upon leaving RAU#2 cell will occur only if the end-user has transit RAU#2 cell before t₂, implying that he will have crossed a total distance of 2R in a time interval of t₂ – t₁. This results to a call drop velocity cut-off condition provided by

\[
V = \frac{2R}{(t_2 - t_1)} \tag{1}
\]

During user’s transition from RAU#1 to RAU#2 cell, no packet loss will be experienced since both cells transmit the same data content being part of the initial Extended Cell. The MU will exhibit packet losses only in the case of leaving RAU#2 cell and entering RAU#3 cell prior to the completion of the Extended Cell reconfiguration process, i.e., before
RAU#3 starts the emission of the user-specific data signal. The time $T_{total}$ needed for completing the Extended Cell reconfiguration procedure is provided by

$$T_{total} = T_{proc} + \Delta_{update} + \frac{L}{c/n} \quad (2)$$

where $T_{proc}$ is the processing time of the CO switch, $\Delta_{update}$ is the time required following the beacon reception for informing the CO about the Extended Cell reconfiguration request, and $L/(c/n)$ is the time needed for the data packets to propagate through the fiber link from the CO to RAU#3, with $c$ being the speed of light and $n$ denoting the fiber refractive index. The CO is updated about the user’s Extended Cell reconfiguration request via the ACK message sent by the MU through RAU#2, yielding a $\Delta_{update}$ that corresponds to the propagation delay of the ACK signal. This propagation delay includes the time needed to travel through the wireless link between the MU and RAU#2 and the time required to propagate through the fiber link between RAU#2 and the CO. If $\Delta_{#2}$ is the time required by the user for crossing the RAU#2 cell boundaries after receiving the RAU#2 beacon frame, packet loss will equal zero as long as $T_{total} < \Delta_{#2}$ since RAU#3 will start the data packet transmission while the user is still in the RAU#2 cell. However, if $T_{total} > \Delta_{#2}$ then packets that cross the CO during a total time $T_{loss}$ will be lost. The value of $T_{loss}$ depends on whether the CO becomes updated prior to the user’s exit from RAU#2 cell or not. If the user loses connection to RAU#2 before the CO becomes updated and data packets are routed to RAU#3, the packets contained in the link between the CO and the end-user by the time of exiting RAU#2 cell, as well as the subsequent packets that will cross the CO before its update, will not reach the MU. The succeeding packets crossing the CO before its update correspond to a time interval of $\Delta_{update} - \Delta_{#2}$. However, if the CO becomes updated before the user’s exit, data packets will already be in the link between CO and RAU#3 by the time of crossing the RAU#2 cell boundaries and as such they will be received by the MU through RAU#3. To this end $T_{loss}$, is provided by

$$T_{loss} = \frac{L}{c/n} + \frac{R}{c \cdot \cos\phi} + T_{proc} + (\Delta_{update} - \Delta_{#2}), \quad \text{if } T_{update} > \Delta_{#2} \quad (3)$$

$$T_{loss} = \frac{L}{c/n} + \frac{R}{c \cdot \cos\phi} + T_{proc} + (\Delta_{#2} - \Delta_{update}), \quad \text{if } T_{update} < \Delta_{#2} \quad (4)$$

with $\phi$ denoting the angle formed between the MU and the RAU with respect to the horizontal plane. A detailed mathematical treatment for the call drop and packet loss expressions in MEC is provided. Taking into account that packets are transmitted at a packet rate $r = S/B$ with $B$ and $S$ denoting their Constant Bit Rate (CBR) and packet size, respectively, including any possible guard bands, then the total packet loss in number of packets can be easily calculated using the expression

$$\text{packetloss} = T_{loss} \cdot r - 1 \quad (5)$$
in case the MU has completed its last packet reception process when exiting RAU#2 cell, and by the relationship

$$\text{packetloss} = T_{loss} \cdot r + 1 \quad (6)$$

if the MU is within a reception process whilst crossing the cell boundaries.

IV. SIMULATION RESULTS

A C++ simulation model for the RoF network shown in Fig. 4 has been developed in order to evaluate the network’s performance when employing the MEC concept and compare it with the general simple case scenario that employs the conventional hard-handover approach for user transitions between single picocells. For the purposes of our analysis, the simple message exchange scheme involving two possible situations for the packet loss calculation has been considered: the first situation refers to the reception of the beacon frame by the MU before the data packet is sent by the RAU, and the second one corresponds to beacon reception after the RAU sends the data packet. The signal and network parameters used in the complete series of simulations carried out have the same values both for the MEC and the simple-case handover approach, being: $R=20\text{m}$, $T_b = 1 \text{ sec}$ and a continuous CBR data flow traffic profile with data packet size of 210 bytes. Average packet loss and call dropping probability values have been calculated as the average values of a set of more than 100 independent simulations, with each simulation run having a run-time of less than 30 sec using an Intel Core2 Duo CPU at 2.4 GHz with 3 GB RAM. Processing times of a few µsecs at the CO have been incorporated $T_{loss}$ in the expression. In order to avoid any correlation, the moments that the RAUs start sending beacons, the MU starts moving and the data traffic starts being sent, are randomly chosen within the interval $[0.0, 1.0] \text{ secs}$.

Fig 5: Average call dropping probability per user transition versus user velocity in the simple case and in the MEC approach for a cell radius of $R=20\text{m}$
Fig. 5 illustrates the average call dropping probability per user transition as a function of the user’s velocity for both cases of simple handover and MEC, considering five possible values for the axial overlapping distance $x_2$ within the range [1 m, 5.35 m]. The value $x_2 = 5.35$ m was chosen so as to correspond to the overlapping area among the circumscribed circles of hexagonal type cells given by $x_2 = (2 - \sqrt{3})R$. In the simple handover case, the call dropping probability is zero until the user’s velocity reaches the value. This suggests a maximum speed limit for retaining connectivity that depends on $x_2$ and is restricted to pedestrian velocities even for an overlapping distance of 5.35 m. When the user velocity becomes greater than its $x_2$-dependent upper limit, the call dropping probability increases very quickly, exceeding 20% for speed values greater than 10 m/sec. In the case of MEC, the call dropping probability is independent of $x_2$ and is zero for the complete range of user velocities below 40 m/sec. This is a result of dynamically rearranging the user-centric Extended Cell by establishing a new user connection in all possible next destination cells upon entering a new cell area, preparing seamless conditions for all possible subsequent movements. In this way, the time interval being available for initiating the Extended Cell reconfiguration equals the new cell’s transit time and is independent of the actual overlapping area between adjacent cells, resulting to enhanced flexibility in network planning and to seamless conditions even for vehicle speeds. Beyond 40 m/sec, call drops are gradually increasing at a slower rate than in the simple handover case, yielding values greater than 20% only for speeds beyond 50 m/sec, i.e., 180 km/h.

![Fig 6: Average packet loss versus optical fiber link length for three different bit-rates in the simple case scenario](image)

Figs. 6 and 7 depict the packet loss values per user transition obtained in the simple handover case and in MEC, respectively, for various fiber link lengths $L = \{1, 2, 10, 30\}$ km and for three different packet bit rates $B = \{100, 144, 200\}$ Mb/s. As shown in Fig. 6, the packet loss in the simple handover case is independent of mobile speed and increases almost linearly with increasing fiber length and bit rate. For High-Definition TV services at 144 Mbps, an average packet loss of two packets is obtained when considering a fiber link of $L = 2$ km that could eventually correspond to a 60 GHz indoor RoF infrastructure for a small conference center or airport. In case the same service is delivered over an extended RoF network with 30 km fiber links, the exhibited packet loss increases significantly approaching a number of 25 lost data packets. The situation is greatly improved in the case of MEC. As
Fig. 7 reveals, packet loss will be zero irrespective of the data rate and the fiber link length between the CO and the RAU as long as the MU moves with a velocity lower than 40 m/sec. The packet loss increases beyond the zero level only when the user’s speed exceeds 40 m/sec.

**Fig.7.** Average packet loss versus optical fiber link length for three different bit-rates and different user velocities in the case of MEC

Beyond 40 m/sec, the average packet loss depends on MU’s velocity and is almost linearly related to L and B when comparing MT motions of the same velocity. However, average packet loss remains very low in all possible combinations of L, B and V and is almost always less than 0.3, reaching its 0.9 upper limit only in the case of $V = 40$ m/sec, $L=30$ km and $B = 200$ Mb/s. These low values are a result of triggering the MEC procedure prior to entering the new cell, indicating that the user will continue to listen to its current RAU after sending the ACK message. As such, data packets are lost only if the user leaves its current cell before the Extended Cell rearrangement has been completed. However, the total time required for the new RAU to start the data packet emission, as provided by (2), is below the msec range. Within this short time, the end-user moves only a few centimeters away, implying that the MU has to be located very close to the cell boundaries when requesting an EC reconfiguration in order to experience packet losses, severely limiting in this way the packet loss incidence possibilities. This is also the reason that the packet loss values are maximized when the user moves with a velocity of 40 m/sec, which corresponds to a propagation distance equal to the entire cell within a beacon time period. This speed value results to periodic pattern for the user’s intra-cell positions of higher repetition frequency than by other velocities, increasing the probabilities for user locations close to the cell boundaries when receiving the beacon signal.
VI. CONCLUSION

In this paper, we have proposed a network architecture to offer a broadband access connection to train passengers. Radio-over-Fiber technology as well as the moveable cell concept as two important parts of the network. Moveable cells are essential to avoid the high number of handovers in the wireless domain. The implementation of the moveable cell concept will be entirely done in the optical field, by reconfiguring the RoF network. The expected handover rates can then be supported, which is nowadays nearly impossible with the existing handover protocols. We have calculated the desired bandwidth and compared this with what would be achievable by the network. Both capacities match very well, which means that the proposed network should be able to provide sufficient bandwidth for a broadband connection in trains moving at high speed. We have demonstrated a handover scheme and its associated physical layer network architecture for providing seamless broadband wireless communication with high end-user mobility in 60 GHz RoF networks irrespective of the user’s mobility pattern. This scheme employs a single fiber network(SFN) radio frequency approach and a handover mechanism that is based on a novel Moving Extended Cell concept introducing reconfigurability in user-centric Extended Cell structures so that they can move together with the MU. The proposed MEC handover functionality is performed entirely by the optical switch located at the CO retaining in this way all scalability advantages arising by the centralized RoF network architectures. This scheme yields seamless communication regardless of the overlapping area size between adjacent cells and for mobile speeds up to 40 m/sec. To this end, it can effectively mitigate corner effect phenomena and high-mobility applications, rendering 60 GHz RoF networks suitable for both indoor pedestrian and outdoor vehicle wireless communications

REFERENCES


