Internet access on fast trains: 802.11-based on-board wireless distribution network alternatives

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ABSTRACT

This paper discusses and compares different architectural solutions for the implementation of a wireless distribution network based on IEEE 802.11 to be used on a moving train. This framework is considered in the IST "FIFTH" (Fast Internet for Fast Train Hosts) project scenario. The "FIFTH" on-board network architecture envisions a number of 802.11b (Wi-Fi) access networks, each placed into a different train coach. Since wired interconnection of different coaches may be inconvenient, access networks are interconnected via a suitable wireless distribution network whose architectural design principles are tackled in the present paper. The goal of the distribution network is to enable users to reach on-board servers offering advanced service facilities to the customers of the train operator, as well as Internet access through an on-board gateway connected via a satellite link to the outer (Internet) world. The solutions discussed in this paper are in the process of being assessed also via a measurement campaign, aimed at exploring how interference and propagation issues affect the overall performances and even the very feasibility of the proposed architectures.

I. INTRODUCTION

We have recently seen a tremendous deployment of Wireless LAN technologies (specifically, IEEE 802.11 [1]) in small, highly-populated, public spaces (frequently referred to as "hotspots") such as hotels, convention centers, airports, malls, university campuses, etc. Cheap and easy-to-install components; unlicensed spectrum; broadband capabilities; interoperability granted by adherence to standards and to certifications (such as Wi-Fi): these are a few of the key factors that are driving the evolution of WLAN from niche technology to public access mean.

Moving trains are a very appealing application scenario for WLAN technologies. Train passengers need to spend up to several hours for a trip, which would be more appealing if working and entertainment opportunities were provided. This scenario has been object of a recent IST project called "FIFTH" (Fast Internet for Fast Train Hosts). The idea is that of a customer which is made available to access a number of services by means of their own terminals (personal computer or Palmtop) equipped with an 802.11b (Wi-Fi compliant) network interface card. Access to the Internet is provided via a satellite link, complemented by alternative technologies to be used in specific situations when the satellite is not in visibility (e.g., while crossing through tunnels) or when cheaper means of access are available (e.g., within stations).

The FIFTH service model may be considered as composed of three main types of *services*:

(1) Services offered by the train operator, divided into:
   a. data services (e.g., train timetables, train and hotels reservations,...).
   b. audio and video distribution services: they include services such as Digital and Web-TV and news and audio distribution.

(2) Services administratively hosted and provided by third parties but delivered on-board the train by the train operator with specific QoS guarantees (e.g., stock exchanges infos and transactions).

(3) Internet Access: this is the basic Internet access. It can be used for web surfing, receiving and sending e-mail, etc. As a possible extension, the service could be split into two subtypes: premium and best effort.

Besides the market appeal and the widespread deployment, there are technical reasons behind the introduction of an IEEE 802.11 based on-board network in a moving train scenario. Cabling train coaches may be a serious problem, and thus wired-based solutions, such as an Ethernet LAN, may be precluded.

This paper proposes and critically discusses a number of solutions for the implementation of an 802.11 wireless network on a scenario composed of independent train coaches. While wireless coverage within a single coach is easily achieved via an Access Point (AP), an open issue, tackled in this paper, is the design of a wireless distribution network able to interconnect different APs in different coaches, and, most important, able to provide connectivity to the satellite gateway (or to other external infrastructures) in order to access the Internet. Hence, this paper is aimed at providing a discussion of architectural solutions concerning the on-board wireless distribution network, and to describe the problems arising in this context. In order to compare the different solutions, we will follow these basic criteria:

1. achievable performance;
2. ease of deployment, related to the problem of the physical coaches inter-connection;
3. fairness, intended as an equal sharing of network resources among all customers, regardless of the coach the customer is connected to; customers traveling in coaches nearer to the satellite gateway may perceive better performance since they have to "cross" less coaches to reach the gateway;

"crossing" a coach, wirelessly, may imply competing with transmissions originated in that coach and thus observe a worsening of performance figures;

4. capability to provide differentiated QoS support for different users/applications: traffic class differentiation mechanisms may be introduced both at a MAC level – e.g., by relying on the IEEE 802.11e draft standard – or at a higher layer, as will be illustrated in the following paragraphs.

The rest of this paper is organized as follows. In section II, we describe the on-board wireless network architecture considered in the frame of the IST "FIFTH" project. In sections III and IV we discuss a number of solutions for the implementation of an on-board wireless distribution network, where wireless connectivity between different coaches is achieved. Conclusions are drawn in Section V.

II. ON-BOARD DISTRIBUTION NETWORK

Train customers are connected to the outer world via a satellite gateway, which resides at a unique site in the train called "Train Server" (TS) – see Figure 1. The TS plays the role of Inter Working Unit, and allows to offer a number of services, including Internet browsing and retrieval of multimedia information, to the customers traveling on the train. The TS is equipped with several additional functionalities, which include i) caching and pre-fetching capabilities, to minimize the outage in presence of disconnection periods, and ii) gateways functions to other networking technologies envisioned in special scenarios. These alternative technologies can be used because of technical reasons, such as satellite link outage (occurring, e.g., while crossing through tunnels), or because of convenience or economical reasons (e.g., while standing in a train station, an 802.11 connection might result more convenient). The 802.11 technology has then a threefold role: 1) to connect mobile end-users (i.e., laptops) to the "coach network"; 2) to connect several coaches between themselves and to the Train Server; 3) to connect the Train Server to the outer world, when the satellite is not available or is more expensive.

The Train Network in the FIFTH architecture is illustrated in Figure 1. It is made up of a set of devices allowing users terminals to send data to and receive data from the Train Server (TS). As shown in the Figure, it consists of a number of Access Networks (ANs) and of a Distribution Network (DN). The AN is composed of an Access Point (AP), located inside each train coach, to which user terminals (stations-STA) connect by means of the IEEE 802.11b (Wi-Fi) standard. Wi-Fi has been selected as technology because of its widespread market distribution: as of today, most of the portable computers come with an internal or external Wi-Fi card – we remark that customers should be able to use their own equipments to enjoy communications services while traveling on the train.

The DN is devised to grant the communication among the APs and the Train Server, which is in charge of distributing on-board information to the clients, and to provide inter-working with external world via the satellite link, or via other alternative means. For instance, the Train Server could even be connected to external servers via wired means, when inside stations, to "refill" or refresh and update on-board distribution servers (think to movies or updated timetables).

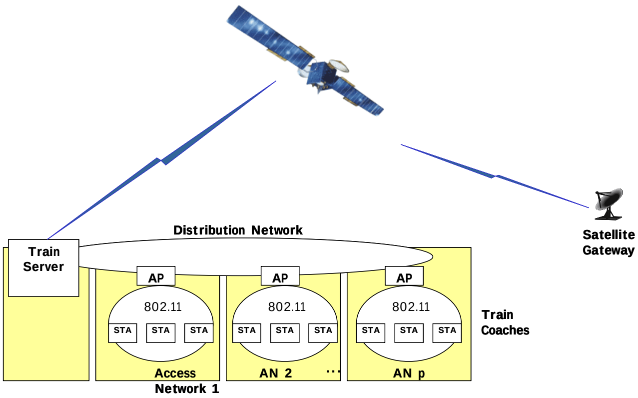

Figure 1 - On-Board Network Architecture.

The simplest, and most convenient, implementation solution for the DN is to use an Ethernet LAN. However, cabling the train coaches could be expensive and a manual connection of the different segments of the network would be required in case of train configuration changes. So, a wireless DN has been considered. In the following two sections, we propose and discuss two basic alternative architectures for the implementation of the wireless distribution network:

a. Wireless links Distribution Network: the Distribution network is achieved by using separate wireless links connecting adjacent coaches. As discussed in section III, these wireless links can rely on 802.11b or they can be based on more advanced and performing technologies (e.g., 802.11a).
b. Access Networks used also as a Distribution Network: in this case, a particular STA in a coach, connected by means of an Ethernet interface with the resident AP, becomes also a client of the previous coach AP.

Within each considered architecture, a number of possible implementation alternatives is also outlined.

III. WIRELESS LINKS DISTRIBUTION NETWORK

In this section, we discuss a number of possible solutions, which share the idea of connecting adjacent coaches by means of wireless links. In order to avoid the signal attenuation due to the coaches infrastructure, the antennas should be located outside the carriages and they should be chosen in a suitable way, depending on the wireless link technology.

The simplest and most economical approach is to use 802.11b inter-coach wireless links. This solution is illustrated in Figure 2. To protect from interference, the antennas connecting two different coaches must be directive. Moreover, different frequencies should be used. We remark that the 802.11b PHY allows three non overlapping channels (e.g., Channel 1, Channel 7, Channel 13) (in selected countries). A convenient channel allocation pattern is depicted in Figure 2.

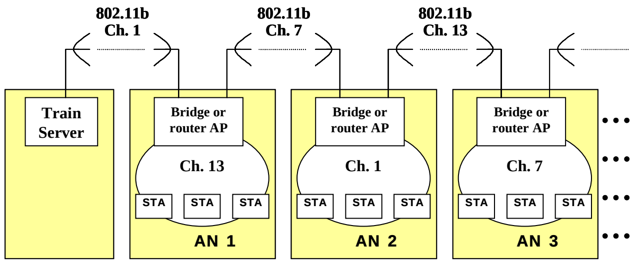

Figure 2 - Wireless links Distribution Network (with non overlapping 802.11b channels)

Inside each coach, the AP has the additional task of taking routing decisions, i.e., forward packets addressed to local customers inside the coach, while forward other packets, either addressed to the Train Server or to customers in other coaches, to the relevant antenna. This implies that the AP must provide bridging or IP routing functions or, alternatively, the AP must be wired to an external bridge or router placed in the same coach.
From an implementation point of view, these functions are already present in several commercial APs. In alternative, a prototype realization of either a bridging or an IP routing solution is possible by using a Linux PC. We recall that a Linux PC can be easily configured as a router. In the case of bridging, this solution is possible thanks to an Open Source driver (HostAP) and a bridging module in the Linux kernel. A number of implementation issues are discussed in [2],[3]

III.A. Performance Issues and Enhancements

From the analysis of Figure 2, it is evident that the link rate available on the wireless links interconnecting adjacent coaches may become a bottleneck. This is especially true if 802.11b is used as the wireless link technology of choice.
In a train scenario, we expect that the large majority of the traffic generated by the customers will be addressed to the Train Server. Hence, the link interconnecting the Train Server coach with the first adjacent coach will be the most loaded link (if the TS is located at one end of the train, as in Figure 2, otherwise if the TS is located in the middle of the train, the overload will fall on the two neighboring coaches). This would happen especially in downstream, because of the natural asymmetry of information retrieval traffic, such as web browsing or multimedia information retrieval. If 802.11b is the technology of choice, the maximum capacity of this link is 11 Mbps. Such a capacity value may significantly limit the type and quality of services provided to the customers, especially if the number of customers is fairly large; for example, it appears impossible to provide on-board video services.
To increase the capacity of the wireless links, it is necessary to adopt a different technology. A convenient choice is to use an 802.11a physical layer for the wireless communication between APs placed in adjacent coaches, while using 802.11b inside each coach (or, when available on the market, and widespread among customers, 802.11g, i.e., an up to 54 Mbps physical layer in the same 2.4 GHz band of 802.11b). This choice has two advantages. First, and most significant, the channel rate available is up to 54 Mpbs. Second, since 802.11a uses the 5 GHz band, transmission on the wireless links do not interfere with the transmission occurring inside the coaches.
Another specific problem of the considered train traffic scenario is fairness. Customers should be granted the same capacity regardless of the coach they are sitting into. Conversely, it is easy to realize that users placed in coaches closer to the Train Server are expected to receive better uplink performance than users far from the Train Server.
A solution to this problem can be achieved by enforcing traffic control functions at the AP, in order to treat in a differentiated manner traffic incoming from the wireless link connecting the downstream coach with respect to traffic collected in the considered coach. This is a very easy task to accomplish, if the AP provides IP routing functions, for example by configuring a suitable scheduling discipline such as Weighted Fair Queuing. However, this function could be performed also at the bridging layer, depending on the availability on the market of devices capable of flexible traffic control and scheduling functions.

IV. ACCESS NETWORKS USED ALSO AS A DISTRIBUTION NETWORK

Within the frame of the FIFTH project, the architecture described in the previous section may be intended as a subsequent evolution stage of a simpler architecture which users the access network within a coach for distribution network purposes too. In other words, thinking to a demonstrator or to the first implementation of this scenario in a prototype train, an “homogeneous” solution may be easier to implement. Here, by homogeneous solution, we name the choice of using Access Networks as a Distribution Network too.
This alternative foresees that a given STA in a coach acts as AP for the coach, while becoming also a client of the previous coach AP, see Figure 3.
The illustrated solution assumes that a special station in the coach acts as an AP for the other stations within the coach, while acting as a normal station for the adjacent coach. This implies that i) the special station (referred to in the figure as STA-AP) must support two 802.11b cards operating on different channels, as well as elementary bridging functionalities, and ii) the STA-AP is in radio visibility of the corresponding STA-AP in the adjacent coach.

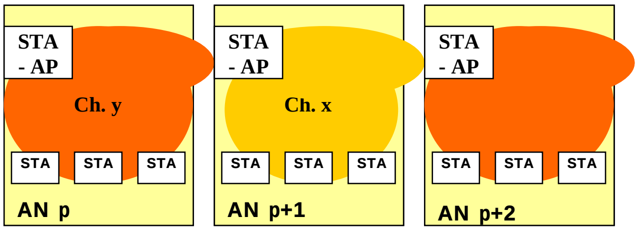

Figure 3 - Access Networks used also as a Distribution Network

This solution is simpler than that discussed in section III, and easier to install. In principle, no wires appear necessary at a first stage, although, as discussed in section IV.B, to improve radio coverage, the STA-AP antenna that receives and transmit signal to the adjacent coach might be split from the STA-AP device and placed outside the coach. This solution may be suited, as said above, both in a first stage of deployment and in smaller trains or even in buses and in other fixed scenarios. In addition, this way of operation would present also greater re-configurability capabilities to changes of topology: coaches may be positioned at will, with no need for any channel assignment planning (it suffices that channels adopted in adjacent cells are non-overlapping). Clearly, the price to pay for this increased simplicity is in terms of performance, as discussed in section IV.A.

IV.A. Performance Issues and Enhancements

The principal drawback of this solution is in terms of performance achieved and fairness. Regarding performance, it is immediate to realize that this solution shares the bottleneck link problem with the solution illustrated in section III. In fact, throughput performance within each coach is limited to the channel rate available, i.e., 11 Mbps for 802.11b. Thus, the capacity available in coach adjacent to the Train Server coach becomes the bottleneck.

Unlike the solution illustrated in section III, fairness in this case is a severe problem. As known, the IEEE 802.11 standard implements a CSMA/CA medium access mechanism ruled by the so-called Distributed Coordination Function (DCF). In the DCF mode, each station senses the medium, if it is idle for a DIFS (DCF Inter Frame Space), before to transmit, a back off procedure is started and the station has to wait for an additional pseudo-random time interval, that is an integer multiple of a “time slot”; if the medium is still idle, the station transmits, otherwise it senses again the medium in order to start again the procedure.

With this architecture, when DCF is used, a generic data unit (MSDU) sent by the TS to a station, or viceversa, has to compete *p* times for the access to the medium, to reach its destination, where *p* is the number of coaches between TS and destination. The MSDU delivery delay increases too when the number of APs to be passed through increases.

Besides, the capacity of an 802.11b channel is 11 Mbps (nominal), but this channel is shared among stations belonging to the same Basic Service Set (BSS). In our scenario, each AP is a client of the previous AP; the capacity available between any two interconnected APs is a fraction of the channel capacity, which in average is equal to $1/(n+1)$, where n is the number of stations connected to the AP of which the other AP is a client. Consider a customer sitting in coach p (being coaches numbered from 1 starting from the one adjacent to the Train Server coach), and let n_1, n_2, …, n_p be the number of end-users in each coach. If congestion is experienced in each WLAN, the capacity available between the generic station in the p-th coach and the TS is reduced to a fraction of the link capacity by a factor equal in average to:

$$\frac{1}{n_1+1}\cdot\frac{1}{n_2+1}\cdot\ldots\cdot\frac{1}{n_{p-1}+1}\cdot\frac{1}{n_p}$$

Note that this derivation is for UDP flows. In case of TCP flows different results are obtained due to the TCP congestion control mechanism. In any case, there will be unfairness in sharing resources between terminals in the different coaches.

Unlike the solution discussed in section III, this fairness problem cannot be resolved by applying a suitable scheduling discipline. However, possible solutions can be envisioned by operating at the MAC layer.

A very interesting possibility is to provide the STA-AP with prioritized access to the channel, while maintaining the other STAs with standard DCF channel access. This issue is being considered in the Task Group “e” of the Working Group IEEE 802.11. Unfortunately, the current version of the 802.11e standard is still draft [4], although a proposal for the implementation and deployment of a subset of the 802.11e functionalities has been considered (802.11 Wireless Multimedia Enhancements, WME – see [5]). This draft standard introduces a number (8 in [4], 4 in [5]) of Traffic Categories-TCs, differentiating the relevant performance by means of an Enhanced Distributed Coordination Function (EDCF). Data units (MSDUs) are delivered through multiple backoff instances, each one depending on the TC they belong to. Note that, in the considered scenario, only the STA-AP should be equipped with an 802.11e (or WME) wireless card, while all the other STAs may be based on 802.11b.

It is interesting to mention that prioritized channel access may be provided by relying on an already deployed solution, specifically the Point Coordination Function (PCF). In the PCF mode a “Point Coordinator (PC)” controls the access to the medium during the “Contention Free Period”; the PC can transmit after waiting only for a PIFS (PCF Inter Frame Space), which lasts less than a DIFS, without an additional backoff, thus it gets priority over other stations, and polls stations to give them the opportunity to transmit. In our considered scenario, it suffices that the AP acts as PC, and, in the contention-free period, it provides increased channel access possibility for the adjacent STA-AP.

IV.B. Radio Coverage Issues and Enhancements

By analyzing Figure 3, it appears that a possible problem of the considered architecture is that the STA-AP placed in the adjacent coach, say *p*+1, although in radio visibility with the STA-AP in coach *p*, may indeed be hidden from other STAs in coach *p*. This implies that the optional RTS/CTS mechanism standardized in [1], is instead mandatory in order to avoid transmission from the STA-AP while another STA is holding the channel.

Another possible problem of this selected configuration is the attenuation between APs due to the coach structure. Since, as shown in Figure 3, APs are located inside the coaches, it might result hard (at least for some coach types) to provide radio visibility between APs.

To mitigate the problem, hybrid wired/wireless solutions may be considered: the AP antenna could be split and a part could stay inside the coach for station communications, while the other part could stay outside for inter-AP communications, as shown in Figure 4. Note that, by proceeding along this direction, this solution becomes an hybrid between the one discussed in section IV and the wireless links one discussed in section III.

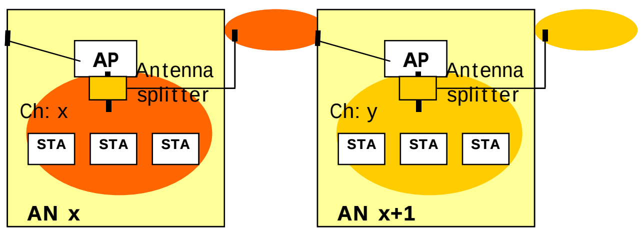

Figure 4 – Antenna Splitter

V. CONCLUSIONS

We have presented a number of architectural alternatives and solutions for a wireless Distribution Network aimed at providing distribution services over a train fleet by means of wireless LANs, based on 802.11. For each architecture envisioned, performance issues and possible enhancements have been discussed. On going work concerns also radio-coverage measurements on board the train, and the set-up of an experimental on-board wireless network. In other words, we stress that a real-world measurement campaign is essential to assess how interference and propagation issues affect the overall performances and even the very feasibility of the proposed architectures. In fact, the selection of the most suited solution to be implemented both in a prototype/near term perspective and in a longer term/target system perspective should/must take into account issues such as:

- interference generated by train systems toward wireless communications;
- interference generated by wireless communications towards train systems (with special reference to critical on-board system and operator's communications services);
- interference caused by neighboring trains (e.g., when in stations) and systems;
- within-train propagation issues (i.e., communications within a coach affect or not communications in neighboring coaches? Are inter-coach communications possible without relying devices?);
- can wired distribution systems be easily deployed on existing trains (e.g., by exploiting power lines, or existing audio distributions systems);
- are short-range infrared or radio links between neighboring coaches a viable solution as an alternative to 802.11 ones?

Answers to these questions may come only with the help of extensive measurements, such as those actually on-going in the framework of the FIFTH project.

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