Chapter 2
Railway Applications Requiring Broadband Wireless Communications

This chapter is dedicated to all the railway applications requiring broadband wireless communications. The works focus especially on the way to provide Internet access on board trains. The different technologies are reviewed, regarding initial research projects, architectures and existing deployed solutions.

Providing Internet access on board trains ensure broadband links between train and ground, which allows railway operators and infrastructure managers to ensure other applications. Thus, operational applications requiring high throughputs, relying on video transmission for instance, such as predictive maintenance and video surveillance, could be also considered. They are presented in the second part of the chapter.

2.1 Broadband Internet Access on Board Trains

Providing an Internet access on board trains became an important objective for railway operators in a more and more competitive domain. Several technologies and strategies can be implemented, relying globally on the same basic architecture presented in Sect. 1.1.5. A selected survey of the studies, projects and solutions deployed all around the world is presented.

Two issues have to be solved:

- How users access Internet on board (from the train access terminal)?
- How to connect the train (via the train access terminal) to the Internet backbone?

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2.1.1 How Users Access Internet on Board?

2.1.1.1 Wi-Fi

Deploying a WLAN such as Wi-Fi within the train is the approach chosen unanimously by all deployed solutions [1, 2]. The deployment of a wired Ethernet network could be considered. However, it causes very high installation costs, especially since it requires equipment of all "connected trains" [3]. Rewiring may also be needed every time the train is reconfigured. In addition, it is generally accepted that replication concept of Wi-Fi access points within the train is not only the best technical solution to create "connected trains", but also the ideal client interface [1]. Wi-Fi is a well-known technology with unlicensed bands, easy to roll out and cost effective. The different standards of Wi-Fi IEEE 802.11 are reminded in the Table 2.1.

IEEE 802.11n allows achieving theoretical throughput up to 450 Mbps on each available band (2.4 and 5 GHz). It improves the previous standards: IEEE 802.11a on the 5 GHz band, and IEEE 802.11b and IEEE 802.11g on the 2.4 GHz band by the following enhancements:

- The standard relies on the Multiple Input Multiple Output (MIMO) technology;
- The aggregation of channels allows increasing the bandwidth to 40 MHz, instead of 20 MHz for previous standards.

In [3], two different topologies are studied in order to construct the network on board train using Wi-Fi technology. The wireless coverage in a single carriage is easily achieved via an Access Point (AP) by using IEEE 802.11a. The issue is the wireless distribution network, whose goal is to interconnect the different carriages. The first topology consists in linking the different cars with IEEE 802.11b via external directive antennas. The second topology is based on the assumption that the access network (IEEE 802.11a in each carriage) is also used as a distribution network between the different carriages. The paper concludes that these propositions still have to be tested by real experiments.

Finally, the last Wi-Fi standard developed from 2011 to 2013 was approved in January 2014, the so-called IEEE 802.11ac. It uses the 5 GHz band exclusively. Theoretical throughput of 500 Mbps can be reached and up to 7 Gbps by using multiplexing and MIMO techniques. The main drawback of this new standard is

Table 2.1 Main standards of the Wi-Fi IEEE 802.11

Standard	Standardization	Frequency	Theoretical throughput
IEEE 802.11a	1999	5 GHz	54 Mbps
IEEE 802.11b	1999	2.4 GHz	11 Mbps
IEEE 802.11g	2003	2.4 GHz	54 Mbps
IEEE 802.11n	2009	2.4/5 GHz	450 Mbps
IEEE 802.11p	2010	5.85–5.925 GHz	/

that terminals have to be specifically designed for this new technology. However, equipped terminals can support 802.11n standard (but not a, b and g ones).

Some researches investigate also very recent technologies, such as the new IEEE 802.11ad, or WiGig (at 60 GHz), and the Li-Fi. They are presented in the following.

2.1.1.2 WiGig or IEEE 802.11ad

The WiGig (Wireless Gigabit—also known as 802.11ad) is a new wireless technology operating at the unlicensed 60 GHz band (9 GHz bandwidth from 57 to 66 GHz in Europe) that will able broadband communications and very high throughput up to 7 Gbps [4–6]. It allows high-speed, low latency, and security-protected connectivity between nearby devices. WiGig technology has a limited transmission distance around several decades of meters. Recent advances of using SiGe and CMOS to build inexpensive 60 GHz transceiver components lead to a growing interest to the 60 GHz radio [5].

WiGig was developed by the WiGig Alliance, which was formed to promote the IEEE 802.11ad protocol in May 2009. The Wi-Fi Alliance subsumed the WiGig Alliance in March 2013. WiGig will then extend the Wi-Fi Alliance vision for seamless connectivity and enable new use cases that complement traditional Wi-Fi. Popular use cases for WiGig include cable replacement for popular Input/Output (I/O) and display extensions, wireless docking between devices like laptops and tablets, instant synchronization and backup and simultaneous streaming of multiple ultra-high definition and 4 K videos.

With WiGig technology now under the wing of Wi-Fi Alliance, the forthcoming WiGig CERTIFIED program will ensure devices provide a great user experience, the latest security protections, and multi-vendor interoperability. Many WiGig CERTIFIED products are expected to be Wi-Fi CERTIFIED as well, and products implementing both WiGig and Wi-Fi will include mechanisms to facilitate seamless handover between the two technologies.

WiGig operating in millimeter waves domain, a specific challenge to overcome is the severe path loss from transmitter to receiver [4]. Typically, WiGig systems will suffer a loss of about 21 to 28 dB relative to the IEEE 802.11n (operating at 2.4 and 5 GHz), because of the shorter wavelength at 60 GHz. Thus, the distance between the transmitter and the receiver have to be reduced and the remained loss has to be compensated by increasing the antenna gain. Increasing antenna gain leads to a narrower beamwidth of the antenna, which requires automated antenna pointing or beamforming. This was not an issue for the IEEE 802.11a/b/g/n standards that use omnidirectional antennas.

The PHY and MAC layers specifications of the WiGig [7] provide similar functionality to the IEEE 802.11a/b/g/n standards, incorporating enhanced operations in the 60 GHz band. The WiGig MAC and PHY specifications, version 1.1, includes the following capabilities:

- Data transmission rates up to 7 Gbps are supported, more than ten times faster than the highest 802.11n rate;
- The 802.11 MAC layer is supplemented and extended, it is backward compatible with the IEEE 802.11 standard;
- PHY layer enables low power and high performance WiGig devices, guaranteeing interoperability and communication at gigabit rates;
- Protocol adaptation layers are being developed to support specific system interfaces including data buses for PC peripherals and display interfaces for HDTVs, monitors and projectors;
- Support for beamforming, enabling robust communication at distances beyond 10 m, is implemented. The beams can move within the coverage area through modification of the transmission phase of individual antenna elements, which is called phase array antenna beamforming;
- Advanced security and power management are widely used for WiGig devices.

Beamforming techniques is an integral part of these specifications [5]. Beamforming utilizes multiple antennas to form a beam toward a certain direction to increase the signal strength. This beamforming gain is achieved by transmitting phase-shifted signals from multiple antenna elements, which are added coherently. Beamforming at 60 GHz can be easier performed compared to the 2.4 or 5 GHz bands. Indeed, antenna sizes are reduced and multiple antennas can be packed in a very small area [5]. In [8], an extra codebook is proposed in order to avoid the signal loss introduced at the intersection of two adjacent beams when employing original beamforming codebook of the IEEE 802.11ad standard. It is based on Maximal Ratio Combining. Performed simulations showed a significant decrease of BER by using the new codebook; a decrease of the BER from 5×10^{-4} to 10^{-4} is for example obtained with a codebook using three antenna elements.

A final point that can be addressed on the WiGig technology is that a large recent literature can be found on the development of antennas for WiGig applications at 60 GHz. In [9], 3D printing technology is used to develop innovating lens design and improve the gain of existing 60 GHz antenna solution. A 10 dB improvement is achieved in the budget link. In [10], the authors developed a magneto-electric dipole antenna. In [11], a fully-integrated feature-rich 60 GHz SiGe BiCMOS antenna is developed and tested. In [12], a coplanar waveguide-fed broadband patch antenna is designed, microfabricated and characterized. A 15 % bandwidth and 5.5–7 dB gain are obtained. In [13], a new differentially-fed planar complementary antenna array is proposed relying on a low cost process. 25 % impedance bandwidth and 11.5 dBi average gain are achieved. In [14], a System-in-Package approach is used to address 60 GHz applications. A maximum gain value of 7.8 dBi is reached. In [15–17], a CMOS transceiver chipset is developed. Finally in [18], a 60 GHz monopole antenna with slot defected ground structure is presented.

As presented in this part, the WiGig technology is extensively explored in different researches, especially concerning the inherent beamforming techniques that have to be implemented to arise antenna gain at 60 GHz.

2.1.1.3 Li-Fi

Some recent works showed the possibility to make a connection by the Light Fidelity (Li-Fi) technology. Li-Fi is a “post-Wi-Fi” wireless technology based on the use of Visible Light Communication (VLC) (instead of radio frequency waves for Wi-Fi). Li-Fi is a 5G VLC system that uses light from Light-Emitting Diodes (LEDs) as a medium to deliver networked, mobile and high-speed communications. Li-Fi principle relies on the data transmission by amplitude modulation of light sources, according to a well-defined and standardized protocol. VLC works by switching bulbs on and off within nanoseconds which is too quickly to be noticed by the human eye. Li-Fi is different from laser, fiber optic or infrared communications by its protocol layers. The light waves cannot penetrate walls which makes a much shorter range (about a decade of meters, a few more than Bluetooth technology), though more secure from hacking, relative to Wi-Fi. A complete solution includes a standardization process, established by the IEEE 802 workgroup. Indeed, the Li-Fi relies on the IEEE 802.15 standard.

All big companies in electronics, such as Philips, Siemens or General Electric, work on this new communication technology [19, 20]. The French start-up Company, Oledcomm, is the most advanced on the subject. Two researchers of Versailles University, working on the technology since 2005, founded the Oledcomm Company in 2012. The start of the Li-Fi technology is a direct consequence of the migration of the light to the LED lamps, electronic devices that are suitable for high-frequency modulation. This technology allows throughput of several hundreds of Mbps and even up to several Gbps. As all new technology, Li-Fi has some drawbacks. The communication requires obviously a light on during the transmission. Furthermore, no mobility is possible.

SNCF takes an interest in the Li-Fi since several years [21]. Studies on geolocalization products in railway stations and transmission of information in trains via the reading lights were performed. The tennis competition of Roland Garros presented a connected TV via Li-Fi in June 2014. In a museum, when approaching a work, visitors can have access to an informative multimedia content. In a supermarket, the trolleys connected to the lighting system via a tablet can provide a range of services to clients. A large number of applications can be based on the Li-Fi technology, the different recent applications can be found on the site and blog on Li-Fi [19, 20]. However, one of the drawback is the fact that use cases are mostly unidirectional. For example in Museum, only downlink is possible and for supermarket the up-link is complicated, and is done via Wi-Fi. This one-way link is common for many use cases involving mass-market devices like computers.

Currently, a project between Luciom Company (people from Philips NXP) and the CEA-Leti is investigating a bidirectional Li-Fi modem allowing wireless Internet access up to 20 Mbps [19]. To our knowledge, there is no studies performed in the context of an Internet access on board trains via Li-Fi transmission in trains. However, the announced evolution by Oledcomm is to provide Internet access via Li-Fi. There is no doubt that it is a topic to investigate on board trains by performing transmission via individual lights of passengers.

2.1.2 Classification of Technologies to Connect the Train to Internet

Several technologies can be used to link the train to the Internet backbone. As mentioned in Chap. 1, a set of technologies are embedded in the TAT. Each technology can connect opportunistically. The criteria to select a particular technology among the available ones are typically the quality of the connection (signal strength), the delays, the throughput or the costs. The point of divergence between the different existing solutions that will be presented relies on the different technologies employed by the TAT and how it integrates them in order to provide a continuous connection.

We can consider two major families of technologies: satellite and terrestrial technologies. Satellite solutions can be based on different types of satellites (GEO, MEO, LEO), they can use different frequency bands and can be unidirectional or bidirectional. The following section gives all the details on the use of these technologies. The terrestrial solutions can be divided into two subcategories:

- Technologies relying on existing networks, so-called public cellular networks solutions;
- Technologies requiring the deployment of a specific ground-infrastructure: the dedicated train-to-infrastructure solutions. Among these are, in particular:
  - Leaky coaxial cables;
  - Solutions based on Wi-Fi or WiMAX;
  - Radio-over-Fiber;
  - All-optical solutions.

Several thesis and reports achieved a State-of-the-Art of existing systems to provide Internet on board trains [2, 22, 23]. Several papers detail specific systems developed to provide Internet access on board trains. The website of the railway operators were also used to find information. An annual conference dedicated to "Wi-Fi on Trains" takes place every year in London, the "TrainComms conference". The papers presented at the conference helped to update the information about existing systems. The state of the art presented in this chapter relies on all of these studies and documents.

2.2 Satellite Solutions

2.2.1 Description of the Technology

Communication satellites represent a first solution to enable broadband Internet access on board trains. The main advantages of such solutions are [22]:

- The easy coverage of a large geographical area (one geostationary satellite can cover a quarter of the earth surface);

- The well adapted broadband connectivity for connection and aggregation of the traffic of a large number of mobile terminals;
- The resistance to high velocity;
- The low CAPital EXpenditure (CAPEX) due to the absence of installation of a dedicated infrastructure on track.

Nevertheless, the use of satellites leads to several constraints on systems design, which have to be taken into account [22]:

- Use of satellite requires satellite in Line-Of-Sight (LOS) in order to obtain broadband connectivity. Any obstacle between the satellite and the receiving antenna (catenary, bridge, high buildings) generates fadings or total loss of signal;
- Antennas require high antenna gain and a very thin beamwidth. It is then necessary to implement a precise tracking of the satellite. Moreover, train suffers of several movements, tracking solution of the satellite have to be even more precise in order to avoid interferences with other satellites;
- NLOS areas, such as tunnels, urban areas or stations, can lead to signal cut-off of several minutes and require the combination with other technologies, so-called "gap-filler". Two main solutions can be considered:
  - Satellite repeaters: one antenna is installed on the ground in order to recover the satellite signal and to redistribute it in the non-visibility areas. This kind of solution requires the deployment of an infrastructure along the track. Furthermore, specific authorizations have to be asked to railway infrastructure owner and to telecommunications regulator;
  - Vertical handover: allowing switching to other technologies, such as Wi-Fi, WiMAX or cellular networks (3G/4G).
- Railway constraints have to be obviously taken into account: Electromagnetic Compatibility with existing systems, installation, maintenance and space to install the antennas. Furthermore, satellite solutions can provide high throughput by using large antennas. Railway constraints force the railway operators to limit the size of the antennas, limiting then the delivered throughput, especially in the case of double deck trains.

Different kinds of satellites exist (cf. Appendix B.4): Geostationary Earth Orbit (GEO) satellites, Medium Earth Orbit (MEO) satellites and Low Earth Orbit (LEO) satellites. GEO satellites are generally very attractive because they use a geosynchronous orbit located at 36,000 km from the surface of the Earth, at equator level, which allows them to be seen as a fixed point in the sky. Moreover, GEO satellites cover a large geographical area and they are the only ones capable of providing broadband connectivity for mobile users. Thus, they are largely used in several existing communication and broadcasting systems. Satellites may have still some drawbacks. The use of GEO satellites leads to important propagation delays (around 400 ms) compared to MEO or LEO ones. This propagation delay may become a problem in the case of highly interactive applications. Modifications and optimizations are then necessary to accelerate the TCP/IP flow. Furthermore, GEO satellites being at equator level, north latitudes are then at weak elevation angles. This conducts to a reduced availability of satellite in case of obstacles. Finally, bandwidth has high costs (more than 1.5 M euros in Europe for a 36 MHz transponder per year).

Despite all these inconveniences, all connectivity solutions on board trains using satellite technology rely on GEO satellites. That can be explained by the fact that GEO satellites guarantee a large choice of products, constructors and satellite operators, together with a high capacity. Indeed, MEO and LEO are not able to provide broadband connectivity.

Another problem of satellite systems is a high OPerational EXpenditure (OPEX) due to the satellite capacity. Available throughput depends on satellite capacity; generated costs have to be taken into account in the business model. Nonetheless, clients desire more and more throughput, which arises bandwidth costs. An increase of the number of clients can generate an increase of incomes, but not an increase of throughput. Business model causes some big problems.

Satellites in Ka band can represent a solution to this problem because of their high capacity, which induces a reduction of bandwidth costs (3 to 5 less expensive than the Ku band). Moreover, satellites in Ka band operate at higher frequencies, which allows reducing the size of the antenna. The use of these satellites causes some problems yet. First of all, equipments in Ku band are not compatible with Ka band, which requires the development of new equipment fitting railway constraints. Moreover, signals in Ka band suffer of high attenuation in the case of bad atmospheric conditions (fog, snow, rain). These attenuations can reach 15 dB in worst cases. Finally, existing satellites in Ka band have a coverage area of about 250–500 km in order to allow a geographical reuse of frequency bands (and then optimize satellite capacity). A dynamic frequency allocation and a horizontal handover have to be implemented to assure connectivity of train from a cell to another. Global system will then be more complex. A complete study on Ka band still have to be performed, such as investigation on mobility effects and cell changes. These issues will be seen in the Chap. 3.

It is also important to notice that there have been recent developments regarding billing of bandwidth. Only bandwidth actually used is now charged, a "billing per us". Furthermore, the future is to use flat antennas that can be much more easily installed on trains.

2.2.2 Existing Studies, Projects and Solutions

2.2.2.1 Studies and Projects

Several studies and projects have been performed from satellite technologies. A survey on mobile satellite systems is presented in [24]. The report details the existing standards (such as S-UMTS, DVB-S2, DVB-SH) and the existing mobile satellite systems (such as Inmarsat, Globalstar, Thuraya). The different systems are then compared based on a number of criteria (frequency bands, PHY layer characteristics, multiple access techniques, satellite characteristics). A tutorial on satellite systems for Internet access is presented in [25]. More details of these two reports are given in Appendix B.4.

As presented above, when the satellite link is blocked, the TAT switch to a terrestrial network. This solution of "gap-filler" was first introduced in the ROSIN (Railway Open System Interconnection Network) project in 1999 [26], which intended to develop a system allowing supervising equipments on board trains thanks to a GSM connection between the train and the control center. The ROSIN project aimed to validate a complete and open platform, which represented the basis for a new generation of vehicles, consisting of an on board network that interconnects all various on board systems and subsystems. Works were pursued with the TRAINCOM [27] and the FIFTH [28] projects.

TRAINCOM [29] is a European project finished in 2003. 13 partners worked on the project, such as Siemens, Bombardier, Alstom, DB, and Trenitalia. During project life, two important railway operators, SNCF (France) and SBB (Switzerland), joined the TRAINCOM project as Observer Participants. The project aimed to develop a reliable communication system between the train and the ground, offering access to on board equipments and integration of all new available technologies (GSM or GSM-R links, protocols and language of Internet such as TCP/IP). The train was then connected to the ground with several wireless connections, and it could switch between them according to required bandwidth for a given application.

FIFTH (Fast Internet for Fast Train Hosts) project proposed a new network solution able to provide a broadband Internet access to passengers on board HST via satellite solutions. A new satellite technology was studied and a prototype was designed and developed in order to implement a practical demonstrator. The prototype was based on two subsystems: the railway mobile terminal and the network access infrastructure. The railway terminal was composed of the satellite network access interface and all the subnetworks in the train for passengers (servers and users terminals). Tracking and pointing techniques were based on a GPS navigation system and an inertial technique (gyroscope). A bidirectional satellite solution used in "classical trains" (non high speed) provided a communication with throughputs of about 2 Mbps/512 kbps (download and upload respectively).

The solution was then integrated under the INTEGRAIL project [30, 31], in the context of an intelligent integration of railway information system. Other works evaluate the TCP flows of satellite systems [32]. Finally, the TRAINIPSAT project [33] aimed to define, specify and test a technical solution to provide connectivity services for HST, both for individuals and professionals. The objective of the project was to demonstrate the feasibility and relevance of a solution combining a bidirectional satellite link and a terrestrial link, and a seamless connectivity on board train via a network such as Wi-Fi. The terrestrial link, based on the WiMAX technology, was specifically designed to take into account technical constraints due to fast mobility. The satellite link was explored with the development of a predictive model of availability of satellites, relying on Markov models. Mobility management and handover mechanisms were also investigated.

Some experiments were performed in Spain in the AVE trains (High Speed Trains) of the RENFE with Indra. Indra [34] is a multinational located in Spain and Latin America. It provides solutions and services in different domains, such as transportation, traffic, energy or industry. Indra experimented a solution to provide broadband Internet access on board trains. The system is based on a bidirectional satellite connection using Demand Assigned Multiple Access (DAMA) access scheme in order to optimize the use of the frequency band. Frequency bands are then automatically assigned to mobile terminals, depending on their needs. Indra's system manages three satellite technologies: DVB-S for downlink, wide spectrum Code Division Multiple Access (CDMA) for uplink, and Single Channel Per Carrier (SCPC) for both links, coexisting with SCPC and/or CDMA. Test measurements were performed on the line between Barcelona and Madrid. No further information could be found on these trials.

2.2.2.2 Developed Solutions

Two main companies provide solutions based on satellite technologies: Icomera and 21Net.

Icomera

Established in 1999, Icomera is headquartered in Sweden with office in the United Kingdom and channel partners worldwide. Icomera's products are deployed on rail, road and sea. Icomera developed a multi-technology platform using satellite technology for the downlink and cellular technology for the uplink, in order to provide broadband Internet access in trains with Wi-Fi deployed in the carriages. For the railway context, Icomera's solution relies on the X6 platform. In 2014, Icomera system was enhanced to be able to access LTE technology. The system comes with four LTE modems and Wi-Fi capability plus an additional modem or Wi-Fi slot for future expansion. Each modem slot has two SIM card slots and supports geo-fencing SIM card selection allowing operators to reduce costs in cross-border scenarios [35]. Throughputs can then reach 40 Mbps [36].

First tests of broadband on board trains in the world were performed in Sweden in September 2002, with the first deployment in January 2003 with Scandinavian rail operator Linx (owned by the Swedish Company SJ and the Norwegian Company NSB), between Gothenburg and Copenhagen, using Icomera platform. Since 2005, SJ offers Internet on board the whole network of Intercity and commuter trains [37].

The Icomera platform is also used since 2004 by Intercity East Coast Railway franchise in UK running from London to Scotland (operated by GNER, then National Express East Coast and currently East Coast Railway companies). East Coast trains carry up to 500 passengers at speeds up to 200 km/h through 400 miles of urban, suburban and rural areas. A single antenna is installed on the roof of the train and the different carriages are linked using the train lighting circuit. The main used technology is the satellite; system switches on cellular technologies in case of non-visibility [2]. Initially, the system was based on the combination of a satellite link and a GSM link, allowing average throughputs of 0.5 Mbps. Then to arise performance, several cellular 3G/High Speed Packet Access (HSPA) networks can be used at the same time (until 8). East Coast fleet is currently being upgraded with the new Icomera system.

From 2010, Icomera and Fleetconnect associated to install passengers Wi-Fi on board Irish Rail trains. Fleetconnect is an Irish provider of public transport Wi-Fi services. The system uses multiple 3G+ mobile broadband networks to deliver a fast availability connection. Icomera was awarded the contract to install Chiltern Railways mainline fleet in UK in early 2011. Fleet installation was completed for Chiltern mainline service, launched in September 2011. The Icomera mobile application router is at the heart of the Chiltern Railways Wi-Fi service, and uses multiple HSPA mobile broadband networks to deliver a fast availability. The system is ready to take advantage of new faster 4G services as these are rolled out in the UK [35].

In Czech Republic, the Czech Railway company contacted Icomera in the late 2011 in order to improve the level of services offered to its passengers on board its Pendolino trains between Prague and Ostrava. The aim was to provide connection to passengers via Wi-Fi and also to provide additional entertainment options via infotainment system. The solution is then based on the Icomera platform in partnership with Simac passenger infotainment system [35].

ScotRail, the national Scottish railway company, awarded Icomera to the contract to provide on-train Wi-Fi services on its trains running from Glasgow to Edinburgh. Initially announced on December 2012, the installation was completed in late 2013 [35].

Finally, a contract was won in October 2014 by Icomera to supply on-board Wi-Fi to the fleet of vehicles operated by Dutch transport Rotterdamse Elektrische Tram (RET). The installation of the complete information system and Internet on board was expected for December 2014 on the fleet composed of 113 trams and 145 metro trains.

It has to be noticed that Icomera got the contract to renew the Thalys connectivity, from satellite to cellular. Icomera is no more focused on satellite but also on cellular solutions.

21Net

21Net is a British Company founded in 2002. It received support and funding from the European Space Agency (ESA) and the British National Space Centre (BNSC). In 2004 in the context of ARTES project (2004–2006), 21Net set up trials with Spain's national rail operator RENFE demonstrating access to broadband Internet via a bidirectional antenna on a HST running at over 300 km/h, allowing throughputs up to 4 Mbps/2 Mbps (downlink/uplink) [38]. The satellite solution relies on the Hispasat satellite, DVB-S technology for the forward link and SCPC for the return link. The "gap-filler" relies on cellular solutions. An upgraded cellular solution is implemented since mid-2013 relying on a multi-operator and multi-SIM bonding that aggregates bandwidth across multiple channels simultaneously. The system is based on MIMO techniques, recent cellular technologies (LTE, HSPA) and standard 2 bonded SIMs per operator, ideally using all available networks [39]. The satellite solution was also upgraded in order to increase spectral efficiency and availability with Adaptive Code Modulation (ACM) [39]. An optimal usage of available bandwidth is also implemented, such as an advanced accelerator and proxy optimized for mobile environment, a fair bandwidth distribution among passengers and a blocking of services [40]. 21Net is currently working on new satellite flat antennas in Ka band [38]. The system is deployed in different railway contexts.

In 2005, 21Net, in collaboration with Nokia, runs a commercial pilot train on the Thalys network to deliver broadband Internet access in its HST, combining a satellite and a cellular links [41]. The overall fleet of 26 trains was equipped with the ThalysNet system in October 2008. With its mobile access router, the 21Net system combines and aggregates several cellular links and a satellite link thanks to a satellite antenna in Ku band set up on the train roof. A single DVB-RCS modem was developed to share bandwidth among all the trains in the network, and to allocate band on demand depending on needs. Throughputs up to 4 Mbps/0.5 Mbps are recorded [38]. In November 2014, Thalys launched a trend to update its Internet on board service. Specifications are to rise throughputs 5–8 times [42]. Icomera won the call for tenders and will equip the Thalys fleet for the end of 2015.

In 2009, NTV (Nuovo Trasporto Viaggiatori), an Italian railway Company chose 21Net to operate the entire Telematics system (Broadband Internet Multimedia Entertainment) in their HST. For this project, 21Net worked with Alstom in order to integrate the system in the design of the 25 AGV (Automotrice à Grande Vitesse). Satellite antennas were then perfectly integrated in the AGV trains. First equipped trains started in May 2012 and the entire fleet was equipped in February 2013. The system relies on the combination of a bidirectional satellite link and several cellular networks. The system is also equipped of a multimedia portal with touchscreens, live TV, VoD, newspapers, books, etc. Average throughputs than can be reached are 8 Mbps/0.5 Mbps [38]. Currently, NTV is migrating from a satellite solution to a cellular one. 21Net is responsible of the rollout, monitoring and integration of the new technology [40].

In January 2009, 21Net and Techno Sat Comm performed tests on the lines of the Indian Railway operator [43]. Three Radjani Express trains are then equipped in February 2013 on the line between Delhi and Calcutta. The system operates also from a bi-directional satellite link and several cellular networks. Seamless broadband connectivity of 9 Mbps at 180 km/h were recorded. The satellite solution is scalable to 3rd Generation Ka band systems that will allow throughputs up to 1.5 Gbps for the downlink.

Other Solutions

PointShot Wireless is a Canadian Company built in 2002. It provides a number of wireless solutions for broadband connectivity. The RailPoint solution was developed for the special case of broadband Internet access on board trains. This solution was deployed from 2006 in the Via Rail trains in Quebec. Connection between train and ground was established using satellite, cellular networks (GSM, GPRS or UMTS) or terrestrial links (Wi-Fi, WiMAX). To our knowledge, no further information are given about the precise technical solutions used and it seems that the PointShot Wireless Company went out of business. Current solutions in Via Rail trains are presented in the Sect. 2.3.

Temir Zholy, the national railway company of Kazakhstan, equipped its Tulpar HST with an Internet on board access in 2011. Gilat's Very Small Aperture Terminal (VSAT) platform was installed on the trains. Gilat Satellite Networks is a public company headquartered in Israel that develops and sells VSAT satellite ground stations and related equipment [44, 45]. The Gilat system relies on GEO satellites. Throughputs up to 2 Mbps can be obtained.

Zoom on SNCF Solution

The French railway Company SNCF performed several tests [22, 46, 47], in order to provide a broadband Internet access on board HST. Experiments on train-to-infrastructure solutions were performed and will be presented in the Sect. 2.3. Combined solutions with satellites for the downlink and cellular networks for the uplink were also tested. Radio cellular coverage being too weak in France (contrary to some countries as Sweden), works initially focused on bidirectional satellite solutions [47]. Two solutions were tested: the Thales Alenia Space and the 21Net ones. These two solutions are based on DVB-S technology for downlink and SCPC for uplink. However, Internet applications on board trains require flexible frequency allocation, together with multiple access techniques able to distribute the different operated trains at a given moment. SCPC solution remains too inflexible at this level. Researches interested at the DVB-RCS technology. A first Internet service on board trains was launched by SNCF in December 2010 on the TGV-East line, the "BoxTGV". The system relies on a bidirectional satellite solution on Ku band (frequencies of 11 and 14 GHz, for downlink and uplink respectively) with a Wi-Fi coverage and 3G for NLOS areas (the "gap-filler" solution). Orange Labs Company and Alstom (supplier of the on board hardware bearing Orange software) were involved in the research and development of this solution [48]. However, the system never found its profitability (expensive technical architecture in terms of CAPEX and OPEX). In addition, technology could not be deployed on "Euroduplex" with two levels for technical reasons (high railway constraints), which leads to a poor legibility of the offer (offer not available on all trains). The "BoxTGV" system was then stopped in December 2013. Other studies are currently on going at SNCF, as seen in Chap. 3.

2.2.3 Summary on Satellite Solutions

As presented in this section, several "Internet on board trains" solutions relying on satellite technologies are deployed in the world. It has to be noticed that all these solutions rely also on cellular solutions, acting as "gap-filler". Nevertheless, this kind of solutions remain expensive and provide limited throughputs, as illustrated in Table 2.2. Currently, the trend is globally to go towards less expensive solutions, such as public cellular networks solutions, as presented in the next section.

However, a solution to enhance the systems is to use Ka band, as presented at the beginning of this chapter. Indeed, Ka band provides higher satellite capacity,

Table 2.2 Summary of throughputs of existing satellite solutions

Deployed solution	Downlink throughput	Uplink throughput
East Coast Railway	40 Mbps (announced)	/
Thalys	4 Mbps	0.5 Mbps
NTV	8 Mbps	0.5 Mbps
Indian Railways	9 Mbps	/
Temir Zholy	2 Mbps	/

which reduces costs and increases performance. Nevertheless, studies on Ka band still have to be performed, such as investigation on mobility effects and cell changes. This solution is envisaged by Indian Railway, which announced throughputs up to 1.5 Gbps.

In the long term, other types of satellites could be investigated, such as nanosatellite, which belongs to miniaturized satellites. Some future satellite technologies are presented in Chap. 3.

2.3 Terrestrial Solutions

2.3.1 Public Cellular Networks Solutions

2.3.1.1 Studies and Project

The public cellular networks solutions are usually based on the use of several public cellular networks deployed over landmasses. The TAT integrates several links (up to 8 in some cases) with different Mobile Network Operators (MNOs). Thereby, the TAT can manage the lack of coverage of one operator by supplying it with another one with better coverage. In the case of no coverage at all, a "gap-filler" solution can be used, as for the case of satellite solutions. Several solutions were deployed using cellular solutions. In [49], some field measurements are performed with the MNO 02 in UK. The objective was to evaluate TCP performance. The results show an average throughput at TCP level of 30 kbps with GPRS and 340 kbps with HSDPA. The authors pointed out the huge contrast with the theoretical throughputs announced by the operator (56 Mbps for the downlink, 22 Mbps for the uplink). In [50], two mobile Internet Service Provider (ISP) are compared in Korea. Each operator is operating two networks: 3G and 3.5G. Two scenarios are considered: an HST at 300 km/h and a mobile car at 100 km/h. Throughputs around 500 kbps at UDP level and 1 Mbps at TCP level, both in downlink and for both 3G and 3.5G are observed.

Nomad Digital [51], a specialist in on-vehicle ICT, provides wireless solutions to the transportation sector: trains, metros, trams and buses. The Company developed a wide range of solutions based on a scalable on-board IP platform, allowing passenger Internet access on board via Wi-Fi, and local contents, such as passenger information, infotainment and displays. The main solution is the NDConnect mobile router used in many rolled out solutions in the railway domain. Nomad Digital provides solutions based on public cellular networks only, and solutions based on the combination of cellular and WiMAX technologies. They are presented in the following.

2.3.1.2 Solutions Based on Public Cellular Networks only

The East Midland trains in UK are equipped with an on-train Wi-Fi since 2011, relying on the Nomad Digital system [52]. The system was upgraded in 2014 in order to improve connectivity speed and reliability.

DSB, the state-owned Danish rail operator, decided to equip all its Metropolitan S-trains in Denmark's capital Copenhagen with wireless communications, after a study revealed that real-time traffic information was the number one request from its daily passengers. The survey revealed that even in the event of delay, complaints would be minimized and customer satisfaction raised by providing accurate, up-to-the-minute information on new times of arrival, connecting traffic and service alterations. Free Internet access using the same wireless communication system was built into the package to further increase customer satisfaction. The communications between train and ground are provided by an NDConnect Communications Control Unit (CCU) mobile router from Nomad Digital, aggregating two mobile networks. The solution was chosen to be scalable with a modular approach in order to support new technologies and standards, such as LTE. Access points in the carriages and dedicated portal and infotainment servers support the services.

NSB, the Norway's national rail company, has implemented wireless Internet access for passengers on its intercity train's fleet. The country is large and sparsely populated outside major cities, which implies that mobile broadband coverage is patchy and frequently blocked by tunnels. Nomad's multi-carrier aggregating NDConnect solution presented above is used. The system exploits all public networks in Norway and a particular requirement was to use the ICE CDMA network operating at 450 MHz. The solution is scalable and modular to fit with LTE standard, which was launched extensively in Norway.

The NDConnect system is also used to provide passenger information and Internet access in the intercity trains of the NS Dutch Railways, in Netherlands. NDConnect router uses national cellular networks. Recently, NS dutch Railways announced that the entire Dutch intercity fleet will be equipped with 4G mobile internet connections by the end of the summer of 2015. A fair usage policy will be also initiated to boost Wi-Fi speed for all passengers, by limiting the speed per user to 150 kbps.

Queensland Rail, one of Australia's largest train and transport companies, which operates around 200 commuter and regional services along 7000 km of track, is rolling out free Wi-Fi on its trains. Some parts of the country suffer of poor coverage, which means loss of communication. The developed system works then across multiple networks. Nomad's technology uses the three main MNO carriers, which guarantees a higher level of network coverage and better bandwidth availability.

In [53], the author announces that Eurostar aims to bring Wi-Fi on board its fleet. Nomad Digital won the contract to provide the on board technology. Indeed, Nomad Digital is able to aggregate bandwidth from different MNOs, as explained in this part. A crucial point is also that it enables cross-border connections, which is important given that Eurostar currently across three countries (France, Belgium and UK) and plans to extend its reach to Germany and to the Netherlands.

Other solutions, which do not use Nomad Digital system and based on public cellular solutions, were also rolled out in different countries.

In Canada, the Via Rail trains, formerly equipped with the PointShot Wireless system, are now providing Internet access on board from three different wireless providers [54]. Eight antennas are mounted on the front-most cars of each train set. Trains from Quebec to Windsor and Montreal to Halifax are equipped with this solution.

In Denmark, a cellular solution was deployed in the Arriva's train, relying on an Icomera solution [37].

In Latvia, Latvian Railway, in cooperation with the wireless telecommunications company Triatel, provides an Internet services on board its trains since 2009 [37].

In Switzerland, the Swiss Federal Railways, the national railway company, proposes modern signal amplifiers in their trains to ensure better reception for passengers on the train. The Company announced that all long-distance trains will be fitted with 3G/4G signal amplifiers by the end of 2014. The signals came directly from the mobile phone signal from outside and are amplified into the coach.

Initially, the RailNet service on board ICE trains in Germany integrated 3G networks with a Flarion FLASH-OFDM based network. The T-Mobile mobile phone operator deployed its network as a "gap-filler", but soon after it was demonstrated as a feasible solution, so the coverage was extended [55]. Currently, the Telekom Company is responsible for the on board system and the trackside network, and also for the ISP. Telekom gets the exclusiveness on Wi-Fi in ICE trains. DB Company buys then "online-minute". Telekom manages operational, mobile networks, server on train and connection between coaches.

In Hungary, the Gysev Railway Company equipped its trains from Budapest to Sopron with a free Wi-Fi Internet access on March 2011 [56]. The system relies on the Telenor Telecommunication Company system. It uses High Speed Uplink Packet Access (HSUPA)/HSDPA/(Wideband Code Division Multiple Access) W-CDMA networks. Announced throughputs are 7.2 Mbps for the downlink and 5.76 Mbps for the uplink. Recently, the Russian Railways' subsidiary Aeroexpress announced that free Wi-Fi services will be available on all its trains running between the city center of Moscow and the airports. The broadband wireless link is provided by RTD-Telecom using 3G and 4G networks belonging to the main Russian mobile operators: MegaFon, Beeline, MTS and Yota. 20 to 25 Mbps average throughputs are announced. Moscow's metro trains were previously equipped with Wi-Fi connection on board, with 90 Mbps announced throughputs.

2.3.1.3 Combination of Public Cellular Networks and Dedicated Infrastructure

Southern Railway is a train operating company along 80 km of track in the south of England. Nomad Digital developed an on train broadband switching solution incorporating both 3G and 802.16 (pre-WiMAX) technologies to cover the entire Brighton Mainline route. Nomad Digital worked with T-Mobile in order to develop the system. Throughputs up to 2 Mbps can be obtained. The service seems to have been stopped since 2011.

Heathrow Express is the service to and from Heathrow Airport in London. Nomad Digital took T-Mobile as a partner in order to offer passengers Wi-Fi connections on board trains up to 2 Mbps. T-Mobile built an optimized wireless network along the entire line. On the 15 min of the trip, 6 km are in tunnel. This area is then covered by WiMAX radios. Five WiMAX ground stations covers the entire tunnel. The train in then equipped with three antennas: two for WiMAX and one for HSPA. Passenger accesses are provided through IEEE 802.11g; links between cabins rely on IEEE 802.11a. Since 2013, the system is being upgraded with an updated WiMAX in tunnel and a Vodafone 4G connection bonding 6 SIMS. Currently, the link between on board Wi-Fi and available Wi-Fi in the different terminals of the airport is performed [57]. Future uses are planned by Heathrow Express, such as staff smartphone and tablet applications or enhanced ticketing [57].

As for the Southern Railway and the Heathrow Express, the Pendolino fleet of the Virgin Trains in UK were equipped with a system combining 3G and WiMAX technologies in order to provide on board broadband connectivity. Nomad Digital resigned a contract with Virgin in 2014 in order to boost the existing solution. 76 trains will be upgraded—56 Pendolinos and 20 Super Voyagers. The Pendolino trains will then be able to deliver service speeds of up to 12 Mbps, while the Super Voyager trains will be capped at 8 Mbps. Nomad's wireless routers will connect mainly to the 3G network, and they will be ready to take advantage of 4G connections when available.

Nomad Digital proposed its mobile router, able to switch between cellular solutions such as 3G and WiMAX technology deployed along the track to the UTA trains of Utah, in US. Recent news showed that the system encounters many problems such as harsh environment and very large number of potential users, leading to connection problems and low throughputs.

A partnership agreement between the telecommunication company Du and the RTA (Roads and Transport Authority) was established to provide Wireless Internet access on board the Dubai metro in the United Arab Emirates (UAE) from 3G networks and WiMAX technology, relying on Nomad Digital system. The NDConnect router aggregates both Du's network, HSPA and WiMAX (802.16e) at 2.5 GHz. Du is also responsible for the rolling out of an Internet access on board the soon-to-be-launched Dubai Tram service.

Today, Nomad Digital does not propose anymore solution based on WiMAX, but reversely is able to propose a solution based on a mix of cellular and satellite technologies (with partners).

Other solutions based on the combination of cellular and WiMAX solutions, but not based on Nomad Digital system, are also deployed, such as the Taiwan High Speed Rail (THSR), which equipped its trains with a system relying on WiMAX and 4G networks to provide connectivity on board since 2012. First studies are presented in [58]. The method uses a Distributed Antenna System (DAS) with Radio-Over-Fiber. Base stations can then cover wider areas with less interference. It is showed that the coverage can be extended from 3/4 to 17 km.

In US, Amtrak, the national Railway Company, equipped 85 % of its trains of an Internet access. Amtrak is composed of Intercity trains, such as the California fleet, the Amfleet Northeast Corridor, the Acela Express and the new Midwest service (since February 2014) [59]. The solution, based on cellular networks, was upgraded to 3.5G in 2011/2012 and to 4G in 2013, allowing throughputs up to 10 Mbps. On June 2014, Amtrak Company [60] announced an improvement of the existing service allowing throughputs up to 25 Mbps. To support very high speed application such as video streaming, VoIP, video conferencing, an average throughput superior to 3 Mbps per passenger is required. In order to achieve this goal, Amtrak is currently thinking of the roll out of a dedicated trackside network, based on the Fluidmesh system [59], detailed later in the section.

2.3.1.4 Summary on Cellular Solutions

As presented in this section, many rolled out solutions in the world rely on cellular solutions. Nomad Digital represents the most deployed solutions. It is also important to notice that Internet on board train is a very fast evolving subject. We perform a survey on cellular solutions, that can not be exhaustive because of new solutions appearing constantly. This kind of solutions can be deployed “alone” or combined with other solutions, such as WiMAX technologies. It can be noticed that it is quite difficult to obtain precise informations on the performance of the systems, in terms of throughputs especially. As presented in Annexe C, using actual public 4G, throughputs cannot exceed 30 Mbps. In [61], authors claim that throughputs cannot exceed 10 Mbps for Internet on board train solutions. However, at the TrainComms conference standing in London on June 2014, Icomera claimed that throughputs up to 250 Mbps can be reached relying on cellular-based solutions, depending on LTE deployment in the countries.

Cellular-based solutions are many deployed for Internet on board access because they allow low costs, relying on the use of existing infrastructures. However, cellular-based solutions lead to many drawbacks. Minimum capacity requires multiple cells management. Moreover, base stations are not often near the tracks, and antennas are not oriented for track coverage. Cellular-based solutions have then the main drawback of no control over Quality of Service, by depending on MNOs.

Joint works between railway and MNOs skateholders are currently used to implement strategy for better on train Wi-Fi services and better railtrack coverage. This is the case in Denmark and in France for instance.

2.3.2 *Dedicated Train-to-Infrastructure Solutions*

This kind of solutions consists of the rolling out of a dedicated infrastructure on the ground, allowing connectivity to the TAT. This connectivity can be obtained: with guided waves through leaky cables, with radio waves in free space via systems relying on Wi-Fi or WiMAX technologies, or Radio-over-Fiber technology, or with optical signals, such as full-optical systems based on lasers or diodes. All these solutions are described in this part.

The dedicated train-to-infrastructure solutions allow meeting growing demand in terms of throughputs. However, this kind of solutions rely on long, complex and expensive deployments of infrastructures along the track. In order to reduce costs, it is then essential to try to minimize the number of sites required to ensure radio coverage of the network. The radio coverage is thus one of the main features to be taken into account for the choice of the communication technology [62]. Furthermore, another key feature is the throughputs that the system allows to reach. These two features are closely related and the best tradeoff between range and throughput have to be found to optimize the system. Other features have to be considered also, such as reliability, security and need for licensed radio spectrum.

2.3.2.1 Radio-Based Solutions

In the early 2000s, Gavrilovich [63] and Lin [64] studied the problem of providing broadband communications to fast moving users. Gavrilovich [63] argued that a large number of small cells operating at high frequencies was the most economical and practical infrastructure for providing wireless broadband access to a large number of users. The model relies on moving base stations that travel along a track. These ones are then linked to fixed base stations via wireless links. The fixed base stations are uniformly deployed on the track. The combination of moving and fixed base stations allows broadband wireless communications with fewer handoffs. However, the moving base station concept may not be practical. In [64], another architecture is proposed for providing communications and entertainment on board high speed transport systems. An architectural design is discussed at the conceptual/functional level of communication and entertainment services on board high speed transport, such as HST, cruise ship or airplane.

Leaky Coaxial Cables (LCX)

In Japan, some authors [65] demonstrated a broadband Internet access on board trains from leaky coaxial cables (LCX). The system requires a cut-off management between the different segments of the leaky cable at high speed. Authors proposed a communication architecture for bullet trains (Shinkansen trains from Tokyo to Osaka), which consists of a base station with an Ethernet interface, and mobile devices. First test beds were performed and showed a throughput up to 768 kbps.

The Wi-Fi access on board “bullet train”, running on the Tokaido-Shinkansen line, is now available since March 2009, based on the LCX technology [66]. The

NTT Communications Company provides the service. Theoretical throughputs up to 2 Mbps can be reached for the downlink, and 1 Mbps for the uplink. The error rate is less than 10^{-5} with error correcting codes [67].

However, such solutions require the deployment of the cable along the track, which leads obviously to high CAPEX and OPEX. Furthermore, a LCX system is non scalable. Once a frequency is chosen, no modification can be brought.

WiMAX

IEEE 802.16 is a series of wireless broadband standards, known under the name "Worldwide Interoperability for Microwave Access" or WiMAX. The main standards are summarized in Table 2.3. WiMAX's bandwidths and range capabilities make it suitable for a variety of applications such as providing portable and mobile broadband connectivity. Its range capabilities also make it an alternative for cellular phone technologies. Furthermore, its bandwidth capacity makes it suitable for not only providing broadband Internet access but also providing additional services such as VoIP. Technical details on the Mobile WiMAX IEEE 802.16e can be found in [68].

All the solutions based on the combination of cellular technologies and WiMAX developed by Nomad Digital were already mentioned earlier in the part dedicated to the cellular solutions: the Southern Railway of Brighton, the Heathrow Express, the Virgin Trains in UK, and the UTA trains of Utah in US. In these solutions, the WiMAX base stations were connected to T-Mobile network through ADSL uplinks at 2 Mbps, which in fact represents a bottleneck for the users since the WiMAX technology can reach 48 Mbps. The implementation of WiMAX technologies in the railway context seems not to exploit all the capacities of the WiMAX technology [23]. Nevertheless, the major advantage is the large coverage, of about 5 km.

In the literature, few papers present experimental analysis using WiMAX technology in the railway domain. Aguado [69] present an architecture providing broadband wireless communication on trains, able to address the security, performance and communication needs. Enhancements in mobility management were introduced in the WiMAX network. In [70], the authors propose a mathematical model to estimate the bit error probability of a WiMAX system in order to offer the best chance to achieve improved throughput with the high mobility. In [71], a state of the art on handover mechanism for WiMAX is presented. It pointed out that while WiMAX is a promising technology (in terms of QoS, bandwidth and costs), there are still open issues about the handover management.

Table 2.3 Main standards of the IEEE 802.16

Standard	Standardization date	Frequency (GHz)	Theoretical throughput (km)	Range
IEEE 802.16d	2004	2–11	75 Mbps	7
IEEE 802.16e	2005	2–6	30 Mbps	3.5
IEEE 802.16m	2009	–	1 Gbps (fix)/100 Mbps (mobile)	–

A WiMAX solution is deployed in the Narita Express train connecting the Narita airport to the city center of Tokyo in Japan, which represents 90 km running in 55 min [66]. The service started in October 2009. It uses a WiMAX technology at 2.5 GHz bands. Maximum throughputs of 40 Mbps can be obtained for the downlink [72]. Since 2012, the same system equipped the Super Hitachi trains, which are limited express trains running from Tokyo to Iwaki (200 km, 2 h). Solutions based on WiMAX are also currently studied for the Caltrain of Silicon Valley in US, relying on a Nomad Digital solution. No further technical details were found on this system.

Wi-Fi

Wi-Fi was presented in the section dedicated to the way to connect users to the TAT. In this section, we present the opportunity to use the Wi-Fi standard to connect the TAT to the global Internet. Wi-Fi network has then to be deployed along the track. Wi-Fi technology is a very interesting candidate among terrestrial technologies. Indeed, it is an unlicensed and well known technology allowing good performance and resistance to the high velocity.

Some works present results on evaluation and testing of the applicability of Wi-Fi to provide connectivity to trains. These works were performed with the Federal Railroad Administration (FRA) office in US [73, 74]. In [73], the tests performed showed that the 802.11b technology is able to establish a communication with a train up to 144 km/h. A throughput of 6 Mbps is obtained, but with variations observed due to handover issues. The average delay observed from the train is 40 ms. In [74], a model is implemented to evaluate the performance of 802.11b in an underground scenario. In these two works, the main highlighted drawback is the difficult management of the handover mechanism, which decreases the overall throughput of the system.

In [75], Bit Error Rate (BER) analysis are presented, confirming the same conclusions, especially on handover issues. In [76], similar measurements were performed but on an architecture providing Internet access to mobile users in vehicle along the road. In [77], the authors present results on measurements of Wi-Fi connections between an in-motion vehicle and an access point located on the side of the road. In all these works, the common issue is the handover mechanism. Wi-Fi technology is not well suitable for train mobility scenario, using IEEE 802.11b standard. Furthermore, the deployment of such an architecture would induce high costs for large network of access points along a railway. Finally, in [78], experimental results on throughput, delay and coverage range of both the Wi-Fi (802.11b/g at 0.9 and 2.4 GHz) and the WiMAX (1.5 and 3.5 GHz) technologies in a tunnel. The measurements showed some good results for the Wi-Fi IEEE 802.11b/g at 0.9 GHz, closed to the results for WiMAX at 1.5 GHz. Throughputs up to 22 Mbps are obtained. However, WiMAX technology suffers of higher delays (around 35 ms) compared to the Wi-Fi one (around 25 ms).

SNCF, the French National Railway Company, performed, in collaboration with Orange Labs, some experimental tests relying on Wi-Fi IEEE 802.11b and g [47]. The tested network was based on 4 access points located on bridges and pylons, covering an area of 13 km in Vendome, near Tours in France. Connectivity performance tests were performed showing a network able to support a 2 Mbps traffic along the handover across the 4 access points. An extended network of 50 km was then deployed relying on 10 access points installed on 3G cellular sites. Results show some good performance in terms of data transmission throughputs. More recent experiments were performed in 2010 using the IEEE 802.11n standard [22, 62]. Two base stations were placed at 6.3 km from each other, close to the average distance between two consecutive GSM-R sites in France. Throughputs up to some tens of Mbps were achieved.

To our knowledge, only one real system was deployed. Indeed, the Tsukuba express in Japan provides Internet connectivity in its trains since 2006, based on the Wi-Fi technology [66, 67, 79]. Throughputs up to 54 Mbps are indicated but no further information could be found.

It has to be noticed that Even if the Wi-Fi technology was not designed for handover initially, several proprietary solution have been built by Signaling suppliers on the top of 802.11 standard, in order to provide efficient mobility. Wi-Fi train-to-ground connectivity is widely spread for metro segment bearing both CBTC and broadband services.

For instance, recently, Madrid metro starts experiment on Wi-Fi based solution with large fleet (around 2300 cars, 300 km of tunnel and 280 stations) with 8000 Wi-Fi Access Point deployed (4800 of them on board), 5000 IP HD-cameras, 800 train-to-wayside base stations...

Radio-Over-Fiber

"Classical" cellular networks have the main drawback in the case of high mobility: frequent handovers during the passage from a base station to another, which leads to a significant decrease of throughputs. One solution to this problem is to deploy a system based on Radio-over-Fiber (RoF).

In [80], authors argue that broadband connectivity can be obtained by reducing the size of the cells. However, it leads to the roll-out of a large number of base stations along the track. The authors propose then to use a RoF system, allowing feed base stations deployed along the track. Antennas fed by optical fiber are called Remote Antenna Units (RAU). The goal of a RoF system is to transfer complicated signal processing functions from the base stations along the railway to a centralized control station, and then to reduce costs deployment and frequency of handovers. For communications between the access network and the train, data are modulated at control station level and sent into optical format to each RAU, using multiplexing on wavelength, each RAU having a unique wavelength for communications. The antenna transforms the optical signal into a radio signal transmitted to the train. For communications from the train to the access network, the closest antenna captures data. To reduce handoff times at train access terminal, [80] propose to use the concept of "mobile cells". It consists of a cell reconfiguring constantly at the same speed than the train, so that the train access terminal communicates on the same frequency the entire ride.

The Radio-over-Fiber technology is used in the Shanghai Transrapid, which is a MAGLEV train running up to 500 km/h. This train runs between the Shanghai airport and the city center (around 30 km long). The system was implemented by the Telefunken RACOMS German Company and uses a communication system relying on fiber optic links and radio base stations deployed along the track of the train

[23]. Throughputs up to 4 Mbps can be obtained in full duplex at 3.5 GHz and up to 16 Mbps in full duplex at 5.8 GHz [81].

Other Proprietary Solutions

In addition to technologies, such as Wi-Fi or WiMAX, other solutions can be used to provide Internet on board trains, the proprietary solutions such as Fluidmesh, Luceor and Reicom.

Fluidmesh [82] was founded in 2005 by a team of researchers from the Massachusetts Institute of Technology (MIT) and the Polictecnico of Milan. Their goal was to reliably deliver fiber-like performance via unlicensed wireless spectrum, providing connectivity for transmission of video, voice, and data. Fluidmesh aims to bring broadband connectivity to sites and environments that are today too hard or large to connect, such as high speed moving vehicles and trains, large-scale industrial sites, distributed infrastructures and complex urban environment.

Fluidmesh developed a transmission protocol called FLUIDITY™ which is a license-free trackside wireless, operating in the 5 GHz band. They claimed to provide broadband up to 100 Mbps on a train running up to 350 km/h without service disruption. Furthermore, handoffs below 3 ms are announced. The system relies on a 2×2 MIMO-based radio technology and dual-polarized trackside and on board antennas. In fact, it consists of a modified Wi-Fi.

In June 2014, Amtrak announced its collaboration with the Fluidmesh Company to install dedicated trackside technology on its HST line connecting Boston to Washington, D.C.

Luceor [83] is a French Company founded in 2005. Luceor is a specialist in outdoor wireless networks developed for 3 main applications: emergency situations (natural disasters, industrial accident), events (political meetings, cultural or sporting events) and infrastructure (industrial sites, public transportations). The solution is based on the WiMESH technology. WiMESH is a routing and mesh technology based on IEEE 802.11n standard. It allows wireless devices to connect to the next, in a dynamic and instant way with no central hierarchy to form a "mesh" structure. Throughputs at UDP level up to 450 Mbps are announced, and mobility is supported until 350 km/h. Furthermore, coverage from 100 m to 10 km are announced.

RATP performed some tests in June 2014, based on the WiMESH technology. Experiments were in the context of tunneling emergency situations, needing new generations of wireless transmission of video streams and voice in mobility and very high speed, such as Luceor equipment.

Reicom [84] is an Italian Company established in 1999, that develops products for broadband radio and radar systems for telecommunications, industrial, automotive, railway, naval and defense markets. The Reicom competencies are:

- Software Defined Radio (SDR);
- Grid computing and cooperative computing;
- Audio and video streaming technologies;
- OFDM broadband radio;
- Ultra Wide Band (UWB) radio technology;
- Organic MESH Networks.

For the Railway market, the developed products are oriented to solve the problem of connectivity between the train and the ground and between coaches, and to bring real-time CCTV and Infotainment on board. Reicom developed the HSBRA™ (High Speed Broadband Radio Access) technology, relying on SDR for train to trackside broadband communications, tested over 300 km/h. HSBRA™ deals with the layer 1 and 2 of the OSI model, by implementing filtering, equalization, digital conditioning and management of the radio signal. HSBRA™ is designed to optimize and manage electromagnetic channel phenomena like fading, shadowing and Doppler effect. HSBRA™ is developed to be used in Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I) applications, addressing both safety and non safety critical applications. The technology relies on a Wi-Fi like technologies, dealing with IEEE 802.11 a/b/g/n and IEEE 802.11p standards, but also IEEE 802.20, IEEE 802.16 (WiMax) and 3G and LTE mobile networks.

Finally, some works are performed on millimeter-wave communication systems in order to solve the problem of degraded performance at high speed and growing traffic demand. In [85], the authors propose a Mobile Hotspot Network (MHN) of a millimeter-wave communication system as a mobile wireless backhaul. The solution proposes the physical layer design of the MHN uplink and downlink and the assessment of the performance of the two links.

Summary on Radio-Based Solutions

The section showed the different technologies that can be deployed as a dedicated track-to-wayside infrastructure, in order to provide broadband connectivity on board trains. The first observation is that there is just a few existing solutions. Most of them rely on WiMAX technology. However, as already mentioned, this kind of solutions allow an entire control of the Quality of Service, in terms of range and throughputs especially.

The Fluidmesh solution claims providing broadband connectivity up to 100 Mbps until 350 km/h. This solution is not yet largely deployed. To our knowledge, the first passenger service that aims to use it is the Amtrak trains.

The train-to-infrastructure solutions lead to high costs in terms of OPEX and CAPEX. A compromise has to be found between performance and costs (involved features are throughputs and coverage). This kind of solutions can be firstly used as a "gap-filler" solution.

2.3.2.2 Optical-Based Solutions

Optic Wireless Communications (OWC), also called Free Space Optics (FSO) represent an attractive technological solution in terms of throughput to obtain broadband Internet access on board trains. Indeed, FSO technologies offer large unregulated bandwidth allowing throughput up to Gbps, in addition to immunity to electromagnetic interferences and low Bit Error Rates (BER). Moreover, optical signals cannot penetrate walls and optical "print" being easily defined, transmission can be completely secured.

Studies in Japan

The Railway Technical Research Institute in Japan tested this technique, in collaboration with the Keio University [86–90]. Throughputs up to 700 Mbps are obtained at TCP level, for a speed of 130 km/h.

First works investigated a ground-to-train communication system using FSO technology [89]. Some BER experimental results using test train are given, showing that the proposed system is a promising candidate for train communication from the view point of BER characteristics. Works are then pursued by improving the system [87, 90]. Three different methods are tested:

- The leaky optical fiber method: this method requires installation of optical fiber along the track. It uses laser beam that flee through the fiber to establish a communication. The method allows to obtain continuous communication with the train;
- The "fan-shaped laser beam" method: this method uses a laser beam diffused with a concave lens. The lens radiates the laser beam in one horizontal direction. At reception, the laser beam is caught by the condenser lens. This is one of the characteristics of this method: laser transmitter can communicate with a wide area receiver;
- The "laser beam tracking" method: the transmitter consists of a laser transmission device and a mobile mirror. It transmits laser beams towards the receiver. This one is identified using an infrared beacon light. With the mobile mirror, the transmitter can follow the receiver and establish a continuous communication.

Preliminary tests were performed in order to compare the different methods. It follows that laser beam tracking method is the most efficient. It allows obtaining throughputs up to 400 Mbps (against 100 Mbps for the two other methods). Moreover, transmission distance is more important and dynamic mirror makes the solution much more flexible.

Authors detail the communication system by laser beam tracking adapted to the railway constraints. The communication device is embedded on board train (the mobile station) and its ground counterparts (base stations) send a laser signal in order to establish a bidirectional communication. Each of them transmits a light beacon signal, standing for an identifying signal, with a different wavelength from laser signal. To apply the laser beam tracking method to railway environment, it requires the deployment of many base stations in order to cover the entire railway line. Therefore, the system requires a handover mechanism between the different base stations. Problems to solve are then as following:

1. Connection has to be maintained whatever the speed of the train and the possible vibrations, for high speed. The mobile mirror has to operate in a very dynamical way;
2. Handover has to be performed rapidly and dynamically, even at high speed, connection being completely interrupted during the handover.

A developed prototype was able to record theoretical throughputs up to 1 Gbps. It consists of a mirror able to move in all 3D directions, which allows reducing size and weight of the device. Details of the development of the tracking mechanism and the optical equipment (lens, diodes and mobile mirror) are described in [88]. The minimization of the size and the weight of the lens is studied, in addition to the study of the beacon laser power and the types of lens to be used at reception (telephoto lens preferred to wide spectrum lens).

Handover mechanism between different base stations is also described. An optimized handover is implemented by improving standard protocol [86]. In this paper, measurement results in an emulated environment where a handover occurs every 5 s showed a packet loss rate of 2 % during the handover. The network is then divided in subnetworks because of its large size. Two types of handover have to be considered: the handover performed inside a same subnetwork, which is realized at layer 2 level, the link layer, and handover performed between two different subnetworks, realized at layer 3 level, the network layer. The system is based on the mobility protocol IPv6. Enhancements are performed from IPv6 at different steps of the handover, in order to minimize its duration.

Experiments are then realized in order to fix the “ideal” transmission distance depending on the number of base stations deployed along the track, which allow keeping a continuous communication during the entire trip. It follows that a distance between 300 and 400 m seems to be optimal.

Authors are interested in the influence of atmospheric conditions on the quality of the communication. The study is quite succinct and without numerical data. The given conclusion is that the quality of the communication depends on the visibility.

First tests of the entire system are set up. Initially, tests in static are performed. A first communication between two devices allows obtaining throughput at TCP level up to 923 Mbps. The transmission distance was tested until 360 m maintaining a communication. A glass was placed between two devices in order to simulate the train window. The transmission distance is reduced to 200 m, but without loss of throughput. A last test is implemented: a communication between a fixed base station and a mobile station put in a car moving at 100 km/h is realized; a maximal throughput of 656 Mbps is obtained.

After these preliminary tests, the system was tested on a train. Three bases stations are positioned along the track and connected to a control center. They are separated by 100 m from each other. At a speed of 130 km/h, throughputs between 500 and 700 Mbps are achieved. An important packet loss rate of about 20–30 % is observed, which represents a subject to improve. The handover time also remains high (about 0.4 s), which is due to the train vibrations causing instability of the infrared link. There is no significant observation regarding the influence of atmospheric conditions. A special effort is still to provide a protection of devices against condensation.

Finally, works conclude with HST trials on Shinkansen trains. The speed is about 240–270 km/h. A single base station could be installed. The handover mechanism could then not be tested. However, the communication between the mobile station on board train and the fixed base station was tested. The two stations could catch the beacon light for 0.7 s. A communication at PHY layer could be realized during 6 ms. However, no packets transmission could have been tested.

In [67], authors propose a collaboration of the Infrared Communication Device (IR-CD), presented above, and the LCX system deployed in the Shinkansen, presented earlier. The proposed system installs the IR at the upstream of the LCX system to keep the modification of the existing LCX system as small as possible. The LCX system and the IR system are not used at the same time; switch is performed when IR system is not available. The proposed system was implemented in Linux in order to evaluate the handover processing time (which is important in the case of the LCX system). It appears that handover time is short enough for passengers on Shinkansen (around 200 ms, near LCX handover time).

Studies in UK

Other works in UK were realized in order to evaluate performance of an OWC system to obtain a broadband Internet access on board trains. All the following papers are written by Paudel et al. from the Northumbria University of Newcastle.

In [91], the possibility to use MIMO optical systems is mentioned, in order to increase throughputs. However, the emphasis is placed on the description of a SISO optical system. Laser diodes are used and tests are performed on the size of the lens and the transmission power. The link budget of the developed system on short distances is computed. Nonetheless, no mobile experiments with higher distances (several hundreds of meters) were performed.

In [92], the communication protocol of the system is described. A base station is placed at a distance equivalent to two carriages of a train (around 42 m). Two receivers are placed for each carriage. Two types of applications are considered: the outdoor case and the indoor case (tunnel). In the first case, receivers are put on the roof of the train and base stations are deployed along the track, at the same height than receivers. In the second case, base stations are put on the ceiling of the tunnel, the configuration on train is the same. A system of control of switch on and off of the base stations with the passage of the train is presented. First tests on received power are realized. Optimizations on received power level with optical concentrators are presented.

In [93], the effect of turbulence on OWC is studied. Tests are performed in laboratory using an atmospheric chamber. The system is based on a transmission device using a LED, an infrared LED, an optical lens and a data source. The LED is modulated with a Non-Return-to-Zero (NRZ) and On-Off Keying (OOK) pseudo-random signal. Results show a high resistance of the developed system to the turbulence.

In [94], tests on throughputs depending on BER are performed in simulation, by varying the distance between two consecutive transmitters. The envisioned system is as follows. Transmitters consist of LED. They are put every 75 m on high voltage electric pylons located at about 1 m from the track. One transmit can cover three carriages (length of a carriage around 21 m). The receivers, consisting of photodetectors are positioned on the side or on the roof of the train at a height of 4 m approximately. A Lambertian model can represent this system. Simulations are performed with the Matlab tool in order to evaluate system performance. Thus, in order to obtain a BER of 10^{-6}, the optical coverage is around 75 m (3 carriages) for a throughput of 10 Mbps, 42 m (2 carriages) for a throughput of 100 Mbps, and 21 m (one carriage) for a throughput of 1 Gbps.

Finally, in [95], a model of the system specially designed for railway environment is presented. Laser are here used instead of LED, in order to obtain larger coverage area and more power. The system is then modeled by a Gaussian source, instead of a Lambertian source. A link budget analysis is performed showing a link margin of 17.75 dB for the worst atmospheric conditions. Simulation results with the Matlab tool are given in terms of BER performance of the system. It is showed that it is possible to have beam coverage up to 75 m for throughputs up to 50 Mbps.

Summary on Optical-Based Solutions

Works presented in this section highlighted different aspects. First of all, it appears that works performed in UK are largely dominated by simulations and no measurement in real sites, with railway constraints were performed yet. Conversely, works in Japan are quite advanced and promising for a new option for providing Internet on board trains. Very high throughputs can be obtained at very high speeds. Throughputs up to several hundred of Mbps were measured in a real site. However, the major drawback remains the cost of CAPEX and OPEX of optical-based solutions. Optical terminals have to be deployed at least every 400 m along the track, which leads to a very high investment. Furthermore, this rolling out leads to high cost of maintenance. Finally, optical solutions performance are very dependent on atmospheric conditions.

2.4 Summary on How to Provide Broadband Internet on Board Trains

2.4.1 General Remarks

There are several technological solutions that can be used to provide a broadband Internet access on board trains. The list of solutions presented in this chapter is not exhaustive, due to the constant evolution of the subject. Many new solutions are emerging regularly. Furthermore, each solution has its own advantages and drawbacks that will be summarized in this section. It appears that whatever the solution used, similar conclusions can be highlighted:

- Several Railway Companies establish a quota system on the used bandwidth in order to limit the required throughputs. For instance, Amtrak has implemented a rate limiting on all East coast and Midwest services in March 2014: passengers are allowed to consume up to 250 MB of date. Once exceeded, their data transfer rate is limited to 200 kbps to reduce data consumption [59]. Such a quota system is also used in Sweden and in the Netherlands, by limiting the speed per use to 150 kbps for the latter;
- A majority of the solutions were first rolled out in the 2000s. For the most part, they were, or are currently, upgraded, especially with the possible use of the Ka band for satellite solutions, and the deployment of the 4G cellular technology in the different countries for the cellular solutions.

2.4.2 Comparison of the Different Technologies

Table 2.4 presents a comparison and a summary on the different technologies, in terms of throughputs, latency and specific advantages and drawbacks. The table highlights that satellite solutions offer the advantage to be able to use the existing infrastructure. However, throughputs are limited and a “gap-filler” is necessary in presence of obstacles, such as tunnels.

Cellular-based solutions have the main advantage of having no infrastructure to deploy, by aggregating several public MNOs. However, it is not possible to manage the Quality of Service, in terms of throughputs, coverage, latency, etc.

All the solutions requiring a dedicated infrastructure have the main drawback to lead to high cost in terms of CAPEX and OPEX. However, Quality of Service can be managed and performance are quite better. First solution is to install radio terminals, relying on Wi-Fi or WiMAX technologies. Throughputs up to 100 Mbps can be obtained. The second solution consists in using fiber optic to connect the different base stations. As presented in the dedicated section, this system relies on low cost base stations allowing a reduction of handover times, a reduction of costs and an increase of performance in terms of throughputs. Finally, the third solution, the optical-based solutions, allows clearly obtaining the best performance in terms of throughput and latency. Nevertheless, it requires a heavy installation along the track (optical terminals put every 400 m), which leads to very high CAPEX and OPEX. Furthermore, optical-based solutions are dependent on atmospheric conditions, such as now, rain and fog.

Next section is dedicated to the broadband wireless communications that can be used for operational needs. Indeed, providing broadband links between train and

Table 2.4 Summary of the different technologies to provide internet on board trains

	Satellite	Cellular	Radio terminals	RoF	Optical
Throughput	>10 Mbps	>10 Mbps	>100 Mbps	/	>10 Gbps
Latency (ms)	>400	>200	>100	>100	>50
Advantages	Existing infrastructure	No infrastructure, low cost	Average throughput, seamless communications	Low cost base stations, seamless communications	Very high throughput, seamless communications
Drawbacks	Limited throughput, communication failures due to obstacles (tunnels, relief, etc.),	Possible limited coverage, limited throughput	High costs	High costs	Heavy infrastructure needed, influence of atmospheric conditions, very high costs

ground for Internet on board allows the railway operators to perform other operational applications requiring high throughputs, such as maintenance and video surveillance.

2.5 Broadband Wireless Communications for Operational Needs

Broadband wireless communications needs for railway applications are quite growing since several years, as presented in Chap. 1. Services to passengers are very demanding in terms of throughputs, as presented above. Other applications requiring broadband wireless communications are presented in this section. Among these applications, we studied maintenance activities, video surveillance applications and other applications, such as smart metering and freight. We decided to separate the maintenance and the video surveillance applications even if they are strongly related. On one hand, maintenance can be performed by using video techniques, but also other techniques, such as WSNs. On the other hand, the video surveillance can be used for maintenance purposes but also for other applications, such as security.

2.5.1 Maintenance

With the rapid innovations in computer science, an increase of amount of data, coming from many sources is observed in many domains, such as railway domain [96]. The traditional data-collecting methods rely on selected measurements over specific assets. Henceforth, it is now possible to perform continuous collection of information from several sources from the entire railway system. This phenomenon leads to an improvement of monitoring and maintaining of railway system by using real-time information.

Maintenance operations lead to accumulative delays, that can disturb railway traffic. Scheduling maintenance work is quite difficult due to the high occupancy. There is then a high demand for efficient and reliable maintenance operations based on frequent measurements of the different parts of the railway system. Thus, continuous data processing and high quality decision making are required. Video is one of the technology that can be used to monitor the systems leading to high required throughputs to transmit the data.

ERRAC targeted for the year 2020 to double passenger and freight traffic by rail. Taking into account this expected growth in passenger and freight volumes and the aging of existing infrastructure, maintenance needs and costs are likely to increase significantly in the coming years. It represents then a major objective to reduce the life-cycle cost of the railway transport. One way to reduce the cost of rail services is to limit expenditures linked to the operation of services, including energy consumption and maintenance.

Maintenance of rail network infrastructure has to be safe, reliable, cost-effective and sustainable. A significant part of the costs for reliable high capacity infrastructures is related to intensive maintenance, most of which is preventive. Thus, maintenance costs have to be reduced by especially simplifying procedures and automation. Better maintenance strategies can be based on risk-based or condition-based analytics, using more reliable sensor technology to detect real asset condition. Furthermore, enhanced maintenance procedures can be based on remote infrastructure condition monitoring and automated, self-inspecting, adjusting and correcting devices. The maintenance systems can be built on cutting edge measurement and monitoring tools that provide static and dynamic data from all relevant components of the rail infrastructure, using train-borne, wayside and remote sensing measurement and monitoring systems. Automation should be achieved for routine maintenance checks, as well as for repetitive tasks, such as track relaying, ballast renewal, tamping and alignment.

The amount of data that has to be raised from train to ground are then more and more important and requires high capacity wireless communications between train and wayside. An alternative could be that some pre-analysis on board the train is performed to reduce train-to-ground transfer. All the systems are presented in this section.

2.5.1.1 Definitions Related to Maintenance Systems

Three main types of maintenance can be identified [97]:

- The corrective maintenance: according to the definition of the standard NF EN 13306, the corrective maintenance is carried out after failure detection and aims to restore an asset to a condition in which it can perform its intended function. The corrective maintenance can be divided into two cases: the "immediate corrective maintenance" based on an immediate intervention after a failure, and the "deferred corrective maintenance" where the work is delayed in conformance to a given set of maintenance rules;
- The preventive maintenance: it aims to maintain equipment and facilities in satisfactory operating condition by providing inspection, detection and correction of failures, either before they occur, or before they develop into major defects. It can also represent the tests, measurements, adjustments, and parts replacement performed specifically to prevent faults from occurring. Two preventive maintenance can be identified: the planned maintenance and the condition-based maintenance. The two subgroups differ regarding the determination of maintenance time, or the determination of moment when the maintenance should be performed;
- The predictive maintenance: it goes further the preventive maintenance by predicting the moment the maintenance should be performed. The predictive maintenance allows reducing cost over routine or time-based preventive maintenance. Indeed, maintenance tasks are performed only when warranted. The predictive maintenance allows convenient scheduling of corrective maintenance and prevents unex-

pected equipment failures. These techniques lead to shorter and fewer "planned stops" and then to an increase of availability. Furthermore, an increase of equipment lifetime, plant safety and a decrease of accidents with negative impact on environment are the consequences of the use of predictive maintenance.

2.5.1.2 Optimization Models for Maintenance

Several works deal with the optimization of the railway maintenance system. Some models are developed to optimize maintenance scheduling and perform preventive works.

In [98], an optimization model is developed to improve rail maintenance decisions, relying on a dynamic schedule of preventive maintenance activities. Maintenance works are assigned to different time periods and different track segments. Approximation methods are introduced to deal with the large amount of instances and provide the best possible solutions.

In [99], different approaches are proposed to deal with the problems of the railway preventive maintenance scheduling. Different algorithms and techniques are tested, such as an hybrid genetic algorithm, ontology-based modeling. The paper also examines the different strategies applied all over the world for solving the maintenance scheduling problem. In US, the aim is to minimize the overall cost of all maintenance jobs while in Europe, the reduction of immobilization of the trains is a main concern.

In [100], a Markov technique is used to model a section of railway track in UK and aims to be extended to implement a global strategy of maintenance decision process for railway track.

In [101], an optimal maintenance model combined with maintenance activity is proposed for High Speed Railway Signaling System in China. In [102], the authors deal with predictive maintenance and management for Indian Railways, by introducing techniques of mining data, such as clustering approach.

In [103], the authors describe the works performed in the SURFER project (2010–2013) dealing with a discriminative model for online predictive diagnosis of train door system. The project proposed a system of diagnosis and detection of embedded failures to develop a predictive maintenance and increase availability of equipment. According to Bombardier, a partner of the project, the doors access represent 5 % of the cost and 30 % of failures in the case of Francilien. It is then really interesting and cost-effective to intervene before the failures occur. The data of selected indicators are transmitted in real-time to a distant terminal via 3G communication links.

2.5.1.3 Track Maintenance

Many works deals with the techniques dedicated to track maintenance. Rail inspection is a quite important task in railway maintenance domain. Inspection can be performed manually by human operator walking along the track and searching for visual anomalies. However, such method is slow and lack of objectivity, depending on the observation of the person in charged. Other automatic and intelligent system are developed.

In [104], the authors present a real-time Visual Inspection System for Railway (VISyR) maintenance, able to detect automatically the fastening bolts that fix the rails to the sleepers. Images acquisition is performed with a digital line-scan camera. In [105], a computer vision system is implemented to improve the track maintenance. The system relies on video acquisition and analysis. Algorithms are developed to perform detection, segmentation and defect assessment of track components. In [106], a video monitoring system is developed for high speed railway applications, relying on three parts. The first part is composed of ground condition collectors installed on track to collect railway conditions, encode, encapsulate and transmit information to wireless relay network through fiber cables. The second part of the system deal with the wireless relay network, that transmit information from track to vehicle. The third part consists of vehicles, that decode information and show the conditions to the driver. The objective is to provide a view for the driver beyond his LOS. Simulations are performed to evaluate the theoretical performance of the system in terms of throughput, outage probability and average delay.

In order to increase track lifetime, systems and methods still have to be developed and enhanced for measuring stress, degradation, stiffness, friction, defects or impacts from climatic changes on tracks. At the same time, damage prevention strategies can also be enhanced, using integrated health monitoring systems and innovative methods for on-site rail manipulation [107]. Thus, many studied systems rely on video acquisition and transmission to optimize the maintenance, such as the automatic track monitoring. Broadband wireless links are then required between train and ground to transmit the large amount of video data. Furthermore, the rolling stock can be used to monitor the track or install dedicated system on the track. The rolling stock already allows to monitor the track by analysing the accelerometer default and traction default for instance.

2.5.1.4 Cloud Computing and Big Data

The management of the huge amount of data required for the different railway applications, such as maintenance, can be performed by the new techniques of cloud computing and Big Data. Cloud computing is a computing term relying on the deployment of groups of remote servers and software networks to centralize data storage and online access to computer services or resources. Cloud computing aims to share resources over a network. The term "moving to cloud" can refer to an organization moving away from a traditional CAPEX model, relying on dedicated hardware with depreciation of it over a period of time, to the OPEX model, relying on the use of shared resources with a pay-per-use system. Cloud computing can be divided into three levels of services:

1. Software as a Service (SaaS): users can have access to application software and databases over Internet, without required installation of software. The cloud infrastructure and platform are not managed by the users in this case;
2. Platform as a Service (PaaS): users can have access to a computing platform, including typically operating system, programming language execution environment, database, and web server;
3. Infrastructure as a Service (IaaS): users can have access to a remote computer. The user can then install the needed operating system and put his applications.

Big Data is a broad term for data sets very large or complex, for which traditional data processing can not be applied. The challenges can then include analysis, capture, curation, search, sharing, storage, transfer, visualization, and information privacy. Big data can be described by the following characteristics (5Vs):

- Volume: the quantity of generated data is very important. The size of the data determines the value and the potential of the data under consideration and if it can be considered as Big Data;
- Variety: the category to which Big Data belongs is also a very essential point needed to be known for the data analysis;
- Velocity: it represents the speed of generation and processing of data;
- Variability: it refers to the inconsistency which can be shown by the data at times and leads to difficulty to handle and manage the data effectively;
- Veracity: accuracy of data analysis depends on the veracity of the source data, knowing that the quality of the data can strongly vary;
- Complexity: data management can become a very complex process, especially when large volumes of data come from multiple sources. Data need to be linked, connected and correlated in order to be able to grasp the information that is supposed to be conveyed by these data. This situation is therefore termed as the "complexity" of Big Data.

In [108], cloud computing concept is used to perform remote maintenance, such as remote switch and crossing monitoring, relying on the SURVAIG application specifically developed. Remote monitoring equipment combined with PC server rent on the Internet (IaaS) are used. All the applications are then installed on one SURVAIG platform (PaaS). The SURVAIG service is then accessible via the Internet (SaaS). The system is installed in parallel of the existing infrastructure. It performs data measurements and also analysis of data: Failure Mode, Effects and Criticality Analysis (FMECA). The SURVAIG application can then be rent monthly. The infrastructure managers can reduce their investments with the absence of the initial cost and the maintenance cost of a server. Thus, the SURVAIG system acquires wide range of data in real time, processes then locally, archives them in a deported station and performs immediate or deferred analysis, to predict maintenance works and anticipate failures or interventions. For railway applications, devices on track are connected to the cloud via local deployed cellular networks, such as 3G or 4G.

In [96], the authors study the possibility to use Big Data techniques to enhance maintenance decisions for railway tracks. The conditions of the 5 Vs of Big Data are discussed for railway monitoring systems. Indeed, several problems have to be overcome to collect and store the data. Efficient methods have to be implemented to analyze the Big Data for decision making. The authors present a case study of an embedded monitoring solution relying on Axle Box Acceleration (ABA) measurements, GPS and video of the track. Existing ABA systems can be based on ultrasonic and eddy current techniques or on video from cameras mounted below the train. It is showed that Big Data techniques present a great potential to enhance maintenance decisions. In the case study in Dutch railways, 1 terabyte of raw data per day have to be managed. Selective data processing is implemented, it is demonstrated that all parts of the track can be monitored.

Cloud computing and Big Data can thereby represent quite relevant means to deal with the huge and growing amount of data circulating between train and ground for different applications, such as maintenance and monitoring works. The digital transformation must come with the system evolution.

2.5.1.5 Wireless Sensor Networks (WSNs)

Wireless Sensor Networks (WSNs) and Internet of Things (IoT) are largely explored in many domains, relying on a large number of physical objects being connected to each other and/or to the Internet [109, 110].

In [111], it is showed that research in the field of WSNs is very dynamic, and there are high expectations regarding applications of sensor networks. A state of the art on recent developments in WSN technologies and their applications is performed. The obstacles in the application of WSN that should be addressed in order to push the technology further are identified. A taxonomy of WSN applications is presented, highlighting the particular case of ITS.

WSNs are particularly studied to perform railway monitoring. Distributed sensor technologies can be used to perform structural health monitoring of tracks, carriages and other equipment in the railway system. In recent years, sensing technologies grew up and a large range of sensors became cheaper. Furthermore, the cost of using public network has decreased significantly. Machine-to-Machine (M2M) SIM cards will then expand largely. It is less and less necessary to build dedicated private networks which represents a high sustaining cost. This phenomena lead to a rapid expansion of WSN systems. WSNs can be implemented for maintenance applications, such as condition monitoring of railway systems. WSNs rely on the deployment of several sensors and on networking technologies to couple the different sensors. Thus, recent advances in wireless telecommunications and adhoc networking also enable the development of these technologies. WSNs can be used for monitoring the railway infrastructure (bridges, rail tracks) and also perform vehicle health monitoring (chassis, bogies, wheels).

In [112], a survey of WSN systems for monitoring in the railway industry is performed. The paper deals with the engineering solutions developed, such as the types and different uses of sensor devices, and the identification of sensor configurations and networks. In [113], a monitoring system is developed to detect rail damage.

An integration of three different methods is realized: an optical fiber grating method, an optical imaging method, and a Lamb guided wave method.

Studies on decentralized control of remote trackside objects, such as level crossing are considered without using trackside cables [114]. To do this, locally-derived power supply and safe and secure radio communications have to be set up. We talk about “connected objects”. Sensors capabilities relying on self-adjustment can also be used for self-diagnosis and remote condition monitoring leading to a reduction of failure and maintenance costs for Switch and Crossing applications. Finally, Railway Integrated Measuring and Monitoring System (RIMMS) are being considered to measure relevant data, monitor the status of railways critical assets and then enhance the monitoring and maintenance applications [114].

The section presented the large domain of applications regarding the railway maintenance, diagnosis and monitoring. More and more data transit between train and ground because of the possibility to perform continuous collection of information from several sources from the entire railway system. All the collected data can then be used to optimize maintenance works by using real-time information. The interest of real time is mainly for decision making, it can then confirm a train mission or route the train towards a maintenance depot. The life-cycle cost of the global railway system can then be minimized because of the reduction of the cost of maintenance.

2.5.2 *Video Surveillance*

Nowadays, video surveillance systems are largely deployed in public spaces, including the transport domain. Many researches and studies are conducted in this thematic to help human operator in charge of analyzing the recorded images. The earliest systems were called Closed-Circuit TeleVision (CCTV) because the data were not transmitted outside of the environment being monitored. Currently, systems rely on IP cameras linked by an Ethernet network. The objective is to perform maximum interconnection and interoperability of all the video surveillance systems inside a specific environment, such as public places or transport environment. Strong constraints are required in terms of integration, maintenance and communication. Reliable wireless broadband communication systems have to be implemented to link the video surveillance systems on board vehicles and on the ground. Video surveillance can be used for surveillance of railway infrastructures (tracks, terminals and stations) or for surveillance on board vehicles [115].

2.5.2.1 Video Surveillance of Railway Infrastructures

Several projects were dedicated to surveillance of railway infrastructures. The first video devices were entirely managed manually. However, human operator can have difficulty to focus on a large number of video screens at once and over a long period of time. The CROMATICA and PRIMATICA research projects were the first collaborative projects dealing with the development of tools to aid the exploitation of video surveillance systems [115]. The projects elaborated a breakdown of the requirements in terms of automatic functions that systems of video surveillance in metro stations, train stations and airports could offer. The technical feasibility was demonstrated for some specific user cases, such as estimation of the density of passengers and crowd detection, detection of fallen objects on tracks, etc. The different user cases were then tested and a decentralized processing at camera level was implemented, in order to transform the centralized system to a distributed system, able to react more efficiently to rapid events. The CARETAKER project pursued the works by exploiting audio and video streams in metro stations. More recently, the VANAHEIM project worked on the automatic analysis of video and audio streams in a metro station.

The PANSAFER project aimed to improve the safety at level crossings. The project defined and performed a functional analysis of the different typical accident scenarios. The objective of the project was also to study the feasibility of an automatic system able to detect and alert road users in case of an accident scenario, relying on video perception tools and wireless communications, from IEEE 802.11p standard, which adds Wireless Access in Vehicular Environments (WAVE). The objective is to send the information of an abnormal situation occurring to the users, so they adapt their behavior to solve the incident. Other works can be also cited on the surveillance of level crossings, relying on video [116], but also Ultra Wide Band (UWB) technologies [117].

Video surveillance for railway infrastructure monitoring, such as railway stations and level crossings, does not require broadband wireless communications from train to ground. The following section deals with this subject.

2.5.2.2 Video Surveillance on Board Vehicles

Video surveillance systems were embedded in vehicles since the early 2000s in France to ensure the safety of users throughout their journey, including in a multimodal context (use of different modes of transport). Some research projects, such as TESS and EVAS projects, dealt with the video surveillance of buses. The objective of the TESS project was to develop new information and safety services, relying on satellite geolocalization and on the coupling of audio and video by equipping the bus of several cameras and microphones. The system allows then to compensate the difficulties encountered by the image interpretation methods. Works were pursued in the EVAS project, that developed a real-time system using smart audio and video surveillance and a wireless communication between the bus and the control center, relying on a MIMO-WiMAX wireless link.

In the railway domain, transport operators expressed the need of video surveillance systems, noting the lack of surveillance solution particularly because of the absence of efficient means of transmission between the trains and the control center. The two main axes of research in the railway domain are then to develop automatic audio and video systems and to implement broadband wireless communication systems between train and infrastructure. Several research projects worked on these topics. The SAMSIT project initiated the works in the context of railway environment.

The BOSS project [118] developed a system able to interconnect all the actors involved in the detection of abnormal events, such as the audio and video surveillance system, the conductors, the driver of the train and the control center. A communication system was developed, based on an IP gateway able to communicate both within the train itself and with the outside world, adapting the throughputs and the quality of the connection, and managing mobility of information both on board and to the ground. The system was tested in a Madrid suburban train. Finally, the SURTRAIN project allowed the integration of an audio and video surveillance system, designed in accordance to railway norms, in a railway vehicle. It was installed as a permanent fixture inside the vehicle.

Few works deal with the video surveillance in the railway domain. A lot of CCTV systems are deployed in metro, where wireless Wi-Fi like networks are easily deployed in the particular tunnel environment. In the case of conventional trains, such as suburban trains, few systems were studied. Finally, and to our knowledge, no systems are installed in the case of HST due to the absence of efficient wireless transmission link between train and ground.

2.5.3 Other Operational Applications

2.5.3.1 Smart Metering

One of the keys of innovation for the future of the railway is the enhancement of the energy efficiency. This objective can be reached by using methods of smart metering. Smart metering relies on a distributed energy resource management system, which aims to manage the different energy flows of the entire railway system [107]. A smart metering system allows to obtain a knowledge of all consumers and generators energy flows, which enable to set up energy savings, losses reduction and efficient energy management.

The WP11 of the In2Rail European project [119] aims to develop a Smart Metering for a Railway Distributed Energy Resource Management System (RDERMS). The main objectives of the works are to design an open system dedicated to the fine mapping of different energy flows within the whole Railway System on a synchronized time basis. The workflow methodology is defined around the design of the physical and software support, linking together measurements taken at different locations, subsystems, and temporal information. The smart metering aims to reduce the energy bill, optimise asset management and increase capacity. Such systems rely on sensors deployed in the railway system (on board and at trackside), communication between sensors and communication between the train and the ground.

Smart metering systems relies then in particular on sensor networks and communication protocols. Intelligent WSN have to be set up to guarantee successful collection of distributed sensor measurements. Then, trackside and on board devices can be installed. Wireless communication systems have then to be set up from train to ground to transmit the amount of different energy measurement data, requiring broadband links.

2.5.3.2 Freight

Rail freight generates low level of external costs and allows reducing the environmental impact. Indeed, rail is the most eco-friendly land transport mode for freight with much more energy consumption and CO2 emissions than road freight or transport by waterways. The key challenge for rail freight is then to offer an attractive, reliable, fast and cost-efficient alternative to road freight [107].

Rail freight suffers of a stagnation in the freight domain due to legal barriers and operational and technical problems, which impact the overall capacity and performance of the rail freight. The cost competitiveness and the reliability of freight services need then to be improved.

Two main challenges can then be identified:

- Acquisition of a new service-oriented profile for rail freight services, relying on on-time delivery and competitive prices;
- Increase of productivity by addressing current issues, such as interoperability and development of cost-effective solutions, by optimizing existing infrastructure and promoting transfer from other sectors to rail freight.

Freight trains has then to follow technological evolutions to improve operational performance, interoperability and increase capacity, such as [114]:

- Increase automation of marshalling yards and then reduce train setup;
- Improve dynamic train performances;
- Provide real time information, such as health monitoring, control and monitoring of dangerous goods;
- Enable interaction and exchange of information from train to ground.

Freight wagons has then to be equipped with mechatronic system with sensors, data processing and communication systems. In [120], The French Train-MD research project is presented, dealing with the transport of hazardous goods. The project aimed to design and develop an innovative system to better manage the hazardous goods traffic, relying on tracing facilities, such as GPS, GSM or GPRS balises. Remote real-time diagnosis is also performed with sensors embedded in the wagons. Finally in [121], wireless monitoring is performed in order to improve the safety of freight trains.

This section presented the large number of operational applications requiring broadband communication links between train and ground. These applications are more and more demanding in terms of throughputs, due to the quite growing data flow coming from the entire railway system. The next chapter is dedicated to the future challenges and opportunities of railway and points out the different emerging technologies and future trends in terms of railway communications.

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