Experimental study of Bluetooth, ZigBee and IEEE 802.15.4 technologies on board high-speed trains

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Abstract— **This paper studies the feasibility of using low-power wireless technologies such as Bluetooth, IEEE 802.15.4 and ZigBee in high-speed railway scenarios that involve bidirectional ground-to-train communication. The presented results have been obtained through experimental tests conducted at the Madrid-Barcelona high-speed rail line. A multiplatform communication system has been installed in a high-speed train, circulating at velocities up to 300 km/h, whereas autonomous devices have been disseminated along of the railway path to communicate with the onboard devices. The conclusions drawn from this work will be used as guidelines for the future implementation of autonomous communication platforms for high-speed rail connectivity.**

Keywords— ***Bluetooth, IEEE 802.15.4, ZigBee, high-speed railway applications.***

I. INTRODUCTION

The use of wired and wireless elements for sensing and railway communications in European railway lines has been faced with many challenges, especially in the context of high-speed train applications. The main cause of the problem has been the lack of standardization, resulting to vendor-defined sensing devices that were often incompatible and hard to integrate to a single practical system. However, at the end of the nineties, the European Rail Traffic Management System (ERTMS) [1] has been implemented to improve the interoperability of systems by creating a single European standard for train control and command systems. Based on the success of the ERTMS for the European railway industry, the main objective of this work is to investigate the feasibility of using short-range and low cost wireless technologies such as Bluetooth [2], IEEE 802.15.4 [3] and ZigBee [4] for high-speed train communication scenarios and their future integration in the ERTMS system.

The ERTMS mainly includes two components. The first component is the GSM-R wireless communication system [5] for the exchange of information between train and ground. The second component is the Train Control System (ETCS) [6], a computer based system for signaling, control and train protection system that includes a trackside and an onboard module. The ETCS is divided into four levels. The first level is the ETCS level 0. In level 0 the onboard equipment monitors the maximum speed based on beacons along the path and is used on a non-ETCS route. The level 1 ETCS is a computer system for train signaling. This system is allowed onboard the train and includes an additional layer in the existing signaling system. Level 1 uses standard beacons to transmit data to the train from fixed points. The system continuously monitors and calculates the speed based on data received by devices on the trackside. In level 2, the ETCS uses the GSM-R wireless technology to forward the position that is detected by the ETCS system. In this level, trackside signals are not necessary, thus saving costs related to maintenance of sensors along the path. Finally, in the level 3 ETCS, the train itself sends its instantaneous location to optimize the line capacity and further reduce additional trackside equipments.

Due to the different components of the ERTMS infrastructure, our efforts are oriented towards the design of intelligent and autonomous trackside points that employ standard low-power wireless technologies for bidirectional communications between train and ground. These communication links have multiple practical applications for monitoring a diversity of conditions along the path, such as changes in environmental conditions, the operation of the pantograph, temperature of the wheels and detection of fallen objects, among others. The tests described in the paper have been carried out to determine the real limits of standards, such as IEEE 802.15.4 and proprietary open wireless technologies such as Bluetooth, and ZigBee and determine whether it is feasible to employ them in the context of the Spanish high-speed railway system. The performed experiments involve measurements of the connectivity time, throughput and the Received Signal Strength Indication (RSSI) for the link established between autonomous devices installed along the railway infrastructure and devices onboard a high-speed train.

The remaining of this paper is organized into five different sections. Section 2 provides a brief overview of the specifications of three employed technologies, namely Bluetooth, IEEE 802.15.4 and ZigBee. Section 3 explains the experimental setup and methodology that have been considered in this work. Results on the performance evaluation of each wireless technology are presented and discussed in Section 4. Finally, the last section is dedicated to conclusions and lessons learned in this work that will be used to determine the most efficient and feasible configuration that will eventually be employed to establish a link between high-speed trains and ground infrastructure for monitoring and control applications.

II. LOW POWER WIRELESS TECHNOLOGIES

In this section, the three employed low power and short-range wireless communication technologies are presented to compare the main tradeoffs for railways applications.

978-1-4673-0990-5/12/$31.00 ©2012 IEEE

A. *Bluetooth*

Bluetooth is a very popular wireless technology intended for short-range communications in the 2.4 GHz ISM band. It is often employed in mobile phones due to its coexistence with other 2.4 GHz devices. Bluetooth offers improved data rates compared to other short-range technologies and provides techniques to reduce interference based on Frequency Hopping Spread Spectrum (FHSS) [7] by avoiding the occupied channels of wireless devices near to the coverage area.

Bluetooth 2.0 + Enhanced Data Rate (EDR) class 1 devices can attain a coverage range of up to 300 meters and a maximum experimental data throughput rate of 2.1 Mbps using a transmission power of 100mW (20dBm). The working distance can be further extended with the optional use of external dipole or directive antennas. Newer Bluetooth devices (version 3.0 and class 3) achieve the same maximum experimental data throughput rate of 2.1 Mbps with a lower transmission power of 1mW (0dBm) in a range of a few meters. In 2010, Bluetooth Core Specification v4.0 was introduced for ultra low power short-range applications and this version establishes a new device profile of low cost and wireless connectivity in ranges below 100 m with a transmission power between 0.01 mW to 0.5 mW and a maximum experimental application throughput rate of 0.26Mbps. Nevertheless, this new Bluetooth version is intended mainly for applications such as health care, sports and fitness, security and home entertainment at indoor locations.

B. *IEEE 802.15.4-2011*

IEEE 802.15.4-2011 is mainly targeted to autonomous smart sensor applications. It employs a protocol stack divided in layers based on the Open System Interconnection (OSI) model, including the Physical layer (PHY), the Data Link Layer (DLL), and the application layer. The PHY layer is responsible for transmitting bit sequences and receiving messages from the wireless medium. Other important functions of the PHY layer available in commercial transceivers are frequency channel selection, transmission power, modulation, data frame synchronization, Cyclic Redundancy Checksum (CRC) and data encryption. Additional functions of wireless transceivers include the RSSI of the power level and Link Quality Indication (LQI) of a received message. The DLL layer consists of the Medium Access Control (MAC) and the Logical Link Control (LLC) sub-layers. The MAC regulates the access to the wireless medium, shared among multiple nodes, and employs PHY layer functions to achieve energy efficiency. On the other hand, LLC sub-layer is responsible for encapsulating each message segment using frames with headers that contain information such as destination node, the source address node, sequence information number and CRC calculation to detect errors in encoded byte values.

The IEEE 802.15.4-2011 standard employs techniques such as Direct Sequence Spread Spectrum (DSSS) and Offset Quadrature Phase-Shift Keying digital modulation (O-QPSK) and achieves a throughput rate up to than 250 Kbps in the 2.4 GHz band. The coverage range can be extended to a few hundreds of meters with a transmission power between 0 dBm to 20 dBm for wireless sensor networks (WSN).

The IEEE 802.15.4a-2007 [8] is a new standard that coexists with IEEE 802.15.4-2011 and uses a physical layer based on Ultra Wide Band (UWB) that supports additional digital modulation techniques such as Pulse Position Modulation (PPM), Pulse Amplitude Modulation (PAM), Burst Position Modulation (BPM) and Binary Phase Shift Keying (BPSK). This standard uses three different frequency bands, namely the 3-5 GHz band, the 6-10 GHz band and frequencies below 1 GHz. UWB specifies a mandatory data transfer speed of 851 Kbps, but also supports additional optional speeds of 110 Kbps, 6.81 Mbps and 27.24 Mbps. Furthermore, IEEE 802.15.4a employs the spread spectrum technique to modulate chirp pulses named Chirp Spread Spectrum (CSS) that was included as a rival to UWB. CSS offers a throughput between 250 kbps and 1 Mbps in the 2.4 GHz band and is used in applications that require ultra low power and short range in indoor environments.

C. *ZigBee*

In many situations, it is important to have a common syntax and semantics among heterogeneous sensor nodes, in order to achieve an effective communication and an accurate and secure exchange of information. To address this need, global standards are now beginning to be incorporated in the physical layer and higher level layers of WSN. At present, de facto industry association standards, such as ZigBee, ISA100 or WirelessHART are routed to commercial market objectives, whereas other open initiatives are tending towards standards that use the Internet Protocol (IP), such as 6LoWPAN.

ZigBee maintains the PHY and MAC layers of the IEEE 802.15.4 but, in addition, defines upper layers for networking, security and application control. As a result, the ZigBee specification introduces more control overhead and complexity compared to the IEEE 802.15.4, but also provides enhanced reliability and interoperability and supports more complicated network topologies. ZigBee defines three physical device types, depending on the hardware requirements: the Full Function Device (FFD) gateway, other FFD that can function in any topology and have network coordination or routing capabilities and the lower complexity Reduced Function Devices (RFD), which can only operate in a star topology, connected to a FFD. Depending on its logical role within the ZigBee network, a device can be characterized as Coordinator (ZC), ZigBee Gateway (ZG), a FFD device responsible for setting up the network, Router (ZR), and End Device (ZED). End Devices are usually autonomous RFD that employ energy harvesting techniques and rechargeable batteries and operate under ultra low duty cycles to save energy. On the contrary, the ZigBee Coordinator node cannot enter a sleep mode and is in many cases powered by a USB bus attached to a PC.

III. EXPERIMENTAL SETUP

The set of experimental measurements has been carried out in the location of Anchuelo (Alcala de Henares, at approximately 35 km northeast of Madrid) (lat. 40°27'22.04"N., long. 3°18'50.59"O) on the Madrid-Barcelona high-speed rail line, as shown in Figure 1.

Figure 1. Location of measurements along the railway infrastructure

Three sensor nodes, one for each considered wireless technology, were installed on a communication post at 15m of altitude, as shown in Figure 2.

In particular, the following devices have been installed:

- A Meshlium Linux router from Libelium [9] with a Bluetooth radio interface (Bluetooth 1.1 - IEEE 802.15.1). The transmission power has been set to 17 dBm and an omnidirectional dipole antenna of 5 dBi has been employed. The Bluetooth router was powered by Power on Ethernet (PoE).
- A WaspMote sensor platform of Libelium [10] with a ZigBee radio transceiver (XBee-ZB-Pro), configured as a ZigBee Coordinator (ZC).
- A WaspMote sensor platform of Libelium [10] with an IEEE 802.15.4 radio transceiver (XBee-802.15.4-Pro).

Figure 2. Autonomous nodes located in a post at 15 m of altitude next to the railway infrastructure

The ZigBee and IEEE 802.15.4 nodes were operating on a low duty cycle of 1% to save energy. Each device was attached to a 2 dBi omnidirectional antenna and the transmission power was configured at 10 dBm. The power to operate the devices was supplied by solar panels and stored in Li-ion batteries.

Similarly, devices of the three technologies have been included in a communication multiplatform, installed on a high-speed train laboratory. The setup included a Parani UD-100 Bluetooth module, a WaspMote module with a ZigBee radio transceiver configured as ZigBee Router (ZR) and a Waspmote module with an IEEE 802.15.4 radio transceiver.

The communication modules have been connected to an industrial PC, for recording and calculating statistics. A GPS device has also been included in order to provide information on the train location and speed throughout the experiment. The onboard multiplatform setup is shown in Figure 3. A group of automated scripts was programmed to be executed in a Linux Ubuntu PC in order to save the measurements for the analysis.

Figure 3. Wireless Communication Multiplatform installed onboard the high- speed train laboratory Seneca

All communication devices, including the GPS, were connected to two aerodynamic multiband antennas Huber+Suhner Sencity Rail SWA 0859/360/4/0/DFRX30 [11], installed in the roof of the train, as shown Figure 4. Two diplexers Microlab/FXR model BK-26N were used to connect the different communication modules to the antennas [12].

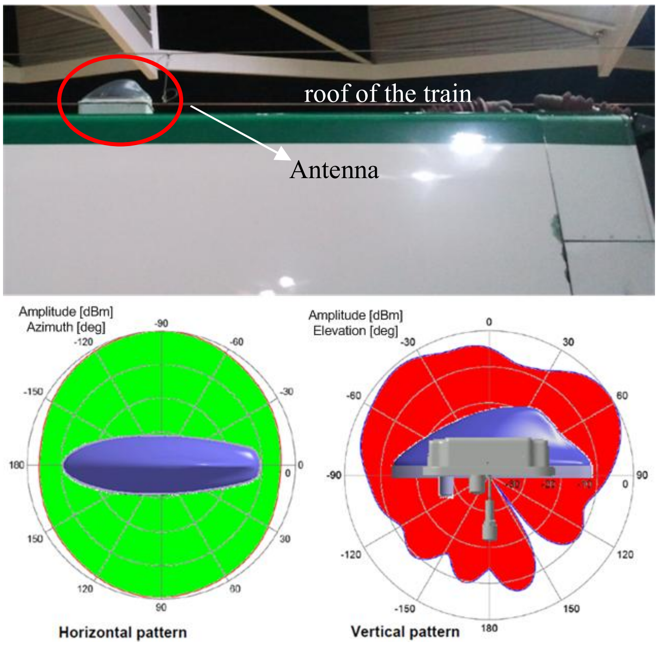

Figure 4. Aerodynamic multiband antennas mounted on the roof of the train and antenna radiation pattern [11].

The ZigBee and IEEE 802.15.4 tests included the transmission of small messages of 60 bytes every 800 ms, from the fixed ground devices to the onboard devices. The Bluetooth tests included an inquire procedure to receive metadata from the Bluetooth device located in ground.

IV. RESULTS

During the experiments, a point-to-point link was established between the communication modules installed in the railway infrastructure and the onboard devices. The communication links were established and maintained during the time the train was in the coverage range of the fixed devices installed in the railway infrastructure. This time was determined by the coverage range of the devices, which depended on the transmission power and antenna gains, and the rolling stock velocity, which varied from 240 Km/h to 305 Km/h. As soon as the train entered the coverage range of the infrastructure devices, a discovering and association phase was initiated. The duration of this phase was different for each technology and had a critical impact on the performance. Fast association processes meant that a longer time interval could be dedicated to data transmission (i.e., the connectivity time), thus increasing the volume of transmitted data. On the other hand, a long association phase would limit the connectivity time and could result to few or no transmitted data.

A. ZigBee and IEEE 802.15.4 results

The Zigbee protocol has a relatively lengthy and complicated discovery and association process that involves the upper layers defined in its protocol stack. In the conducted experiments, the onboard device (ZR) had to detect the beacon frames broadcasted periodically by the coordinator (ZC) installed at the infrastructure. After the beacon detection, a bidirectional association and authentication handshake of several steps had to take place. Once this process was successfully completed, the ZR could join the network set up by the ZC and receive the transmitted messages.

On the other hand, the IEEE 802.15.4 association phase is much simpler, since only the PHY and the MAC layer protocols are involved. In the conducted experiments, the node installed at the infrastructure would transmit unicast messages towards the onboard device. Once the train entered the coverage range, the onboard device would receive the transmitted messages and acknowledge them, without any further control information exchange.

Table 1 shows the connectivity times (i.e., the time dedicated to data transmissions) of ZigBee and IEEE 802.15.4 devices as a function of the train velocity at the time of connection. The data was collected from 26 trials (i.e., train passings in both directions, from Madrid to Barcelona and vice versa) train carried out in four days. In the case of IEEE 802.15.3, the connectivity time varied from 7 s to 31 s, depending on the train velocity. Nevertheless, connection was established successfully in all the conducted trials, even at a train velocity of 305 km/h. ZigBee devices, on the other hand, faced many connectivity problems. The connection between ground and train could not be established for speeds above 275 Km/h. Even for lower train velocities, connection was not guaranteed.

In order to explain the variations in the connectivity time of the ZigBee technology, the discovery and association time has been measured in a static scenario.

TABLE I. CONECTIVITY TIME FOR ZIGBEE AND IEEE 802.15.4

ZigBee			*IEEE 802.15.4*		
Speed Train (Km/h)	*Connectivity time (s)*	*Throughput (bps)*	*Speed Train (Km/h)*	*Connectivity time (s)*	*Throughput (bps)*
305	0.0	0.0	305	7.0	111.4
304	0.0	0.0	301	12.2	98.3
300	0.0	0.0	299	11.8	96.6
292	0.0	0.0	291	10.6	90.5
280	0.0	0.0	288	24.8	49.8
274	3.0	80.0	279	12.0	84.9
270	18.0	63.3	275	31.0	54.1
265	0.0	0.0	271	16.0	78.7
249	67.0	15.2	244	8.8	95.3

Table 2 shows the association times as a function of the parameter Scan Duration (SD) in a ZigBee network consisting of a ZC and a ZR. It can be observed that the association times exhibit a large variation with respect to the average value. Even in the case of SD = 4, which was the value adopted in the train experiments, the average association time varies between 4.6 to 7.5 s.

TABLE II. ASSOCIATION TIME FOR A ZIGBEE NETWORK IN A STATIC SCENARIO

Scan Duration (SD)	**Min (s)**	**Avg (s)**	**Max (s)**
1	5.5	24.5	159.5
2	5.8	13.1	72.7
3	5.8	8.1	37.1
4	4.6	6.7	7.5
5	5.8	6.7	7.4
6	4.5	6.7	7.5
7	5.8	6.7	7.5

B. Bluetooth results

With respect to the Bluetooth technology, we have studied the best mechanism for sending short messages (less than 248 bytes) by using the Remote Name Request procedure (RNR). The RNR procedure is used to discover Bluetooth nodes and to obtain the "user-friendly name" of another Bluetooth device in a scheme Master-Slave. This procedure is executed in a low level at the Bluetooth Host Controller Interface (HCI). The RNR procedure is encoded in 8-bit Unicode Transformation Format (UTF-8), containing a maximum length of 248 bytes sufficiently to send telemetry data from ground toward the train in movement. The RNR procedure includes two steps: inquiry and paging. The time to response any inquiry and paging may take several seconds depending on the hardware configuration.

Therefore, the parameters page scan window and page scan Interval (18-128) were adapted in accordance with the dynamic railway environment to reduce the time to discover the nodes. Further tests were carried to measure the throughput, the total time for each RNR procedure, and the maximum range of the Bluetooth connection. Figure 5 shows the Bluetooth percentage cumulative distribution function for a remote name request procedure in laboratory static environments and dynamic environments during the passage of a train that runs at high speed. The x-axis is the minimum time required to successfully complete a Bluetooth RNR procedure.

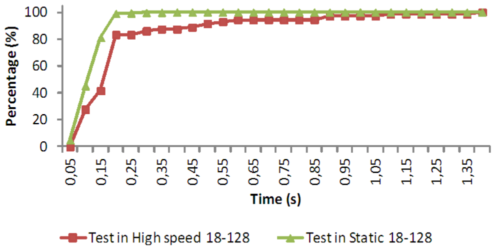

Figure 5. Bluetooth cumulative distribution function for a remote name request procedure for static and dynamic scenarios.

Experimental tests validate the most suitable configuration to determine a statistical confidence level of 95% related to node discovery. Figure 5 shows the values obtained for a static laboratory environment and a dynamic environment with a train traveling at high speed. The minimum time required to perform a RNR procedure with the confidence level of 95% in real dynamic environment was 0.85 s while in laboratory tests was only 0.6 s, taking into account the configuration of page scan window and page scan Interval (18-128). In both cases, this configuration was chosen because it provided the best results based on a real environment, given a point-to-point link and line of sight during different field trials at night. Figure 6 shows the profile associated with the level of RSSI received on the train from infrastructure nodes. The point 0 in the x-axis is the point where the nodes in ground are located. The signal strength is maximized when the train approaches the infrastructure installation. The maximum measured values were -50 dBm for ZigBee, -60 dBm for IEEE 802.15.4 and -45 dBm for Bluetooth (using the inquire procedure). In all cases Bluetooth had a better coverage range that ZigBee and IEEE 802.15.4, despite the fact that the Bluetooth transceiver had the minor maximum sensitivity (-88 dBm) than ZigBee (-102 dBm) or IEEE 802.15.4 (-100 dBm).

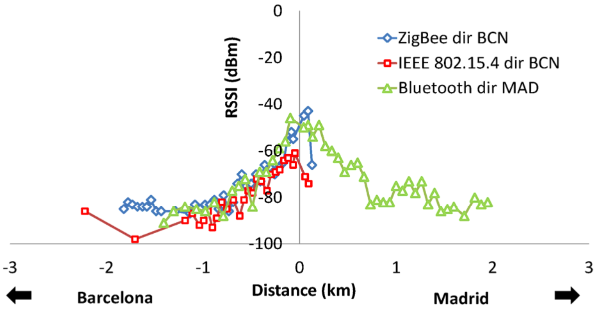

Figure 6. RSSI signal level with a train moving @ 300 Km/h

V. CONCLUSIONS

Field tests have demonstrated that short-range wireless communication technologies, such as Bluetooth and IEEE 802.15.4 are suitable for ground to train connectivity in high-speed train environments. Although the tests were performed in no hostile conditions such as Line of Sight (LOS), a straight section of the track and an appropriate location of the nodes, the feasibility can be assessed. Bluetooth and IEEE 802.15.4 devices worked properly at train speeds up to 305 km/h. An interesting finding has been that ZigBee devices using all protocol layers (not just PHY and MAC 802.15.4) failed to function properly at speeds above 250 km/h. All these measurements are a solid basement for the future implementation of autonomous communications platforms to provide bidirectional connectivity between train and ground in the context of the high-speed railway systems.

ACKNOWLEDGMENT

This work has been carried out within the ongoing project “P26/08”, funded by the Spanish Government. In addition, the work is partially supported by the project TEC2011-27723-C02-01 funded by the Spanish Government (MICINN) and FEDER.

REFERENCES

[1] S.K Abed, “European Rail Traffic Management System - An overview”. IEEE International Conference on Energy, Power and Control, 2010, pp.173-180.
[2] Bluetooth SIG, https://www.bluetooth.org/apps/content/.
[3] Std IEEE Standard for Local and metropolitan area networks--Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)," IEEE Std 802.15.4-2011 (Revision of IEEE Std 802.15.4-2006) ,2011, pp.1-314.
[4] ZigBee Alliance, http://www.zigbee.org/Standards/Overview.aspx
[5] H.Hofestadt, “GSM-R: global system for mobile radio communications for railways”. International Conference on Electric Railways in a United Europe, 1995, pp.111-115.
[6] I S. Dhahbi; A. Abbas-Turki; S. Hayat; A. El Moudni, "Study of the high-speed trains positioning system: European signaling system ERTMS / ETCS. 4th International Conference on Logistics (LOGISTIQUA), 2011, pp.468-473.
[7] L. Zan ; C. Yilin ; J. Lijun. "A novel family of frequency hopping sequences for multi-hop Bluetooth networks". IEEE Transactions on Consumer Electronics, 2003, vol.49, no.4, pp. 1084- 1089.
[8] E.Karapistoli; F.Pavlidou.; I. Gragopoulos; I. Tsetsinas. "An overview of the IEEE 802.15.4a Standard. IEEE Communications Magazine, 2010, vol.48, no.1, pp.47-53.
[9] Libelium. Meshlium AP. http://www.libelium.com/products/meshlium
[10] Libelium. Waspmote datasheet user guide manual. http://www.libelium.com/documentation/waspmote
[11] Huber+Suhner.http://www.hubersuhner.com/mozilla/products/hs-p-rf/hs-rf-antennas/hs-m-rail-ant-rail/hs-p-rf-ant-lightrail/
[12] J. Higuera, E. Kartsakli, C. Collado, José González-Arbesú, L. Alonso, José L. Valenzuela, et al. "An Experimental Study of Multi-radio Platform Coexistence in the 5 GHz Band for Railway Applications," in Lecture Notes in Computer Science LNCS, vol 6596, Strang et al, Eds. Springer-Verlag,2011, pp. 11–22.