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## Projet ROLL2RAIL: Deliverable D2.3 - State of the Art in Radio Technologies and Recommendation of Suitable Technologies

Christophe Gransart, Thomas Gallenkamp, Eneko Echeverria, Stephan Pfletschinger, Stephan Sand, Paul Unterhuber, Marion Berbineau, Inaki Val, Aitor Arriola, Cyril Adrian, et al.

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# NEW DEPENDABLE ROLLING STOCK FOR A MORE SUSTAINABLE, INTELLIGENT AND COMFORTABLE RAIL TRANSPORT IN EUROPE

## D2.3 – State of the Art in Radio Technologies and Recommendation of Suitable Technologies

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Luis Mesa	VOSSLOH (VOSS)	VOSS has written a summary from Marathon Project.

Finally, all partners have contributed in Appendix I – Main Characteristics of Each Technology.

## EXECUTIVE SUMMARY

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The Roll2Rail project aims to develop key technologies and to remove already identified blocking points for radical innovation in the field of railway vehicles, as part of a longer term strategy to revolutionize the rolling stock for the future. The results will contribute to the increase of the operational reliability and to the reduction of the life cycle costs. This project started in May 2015 and it is supported by the Horizon 2020 program of the European Commission. Roll2Rail is one of the lighthouse projects of Shift2Rail and will contribute to Innovation Program 1. At the end of the project all the results will be further developed, leading to demonstration in real vehicles or relevant environments in Shift2Rail.

Going into detail, this Roll2Rail project covers different rolling stock topics such as Traction (WP1), TCMS (WP2), Car-Body-Shell (WP3), Running-Gear (WP4), Brakes (WP5), Vehicle Interiors (WP6) and transversal activities such as Noise (WP7) and Energy Management (WP8).

In that context, WP2 work package's concrete goal is to make research on technologies and architectures to allow new generation of train communication systems based on Wireless Transmission for Train Control and Monitoring System (TCMS), functions and Infotainment, CCTV applications, thus reducing or even completely eliminating, on board communication cables and simplifying the train coupling procedure.

The goal of this deliverable on state of the art in radio technologies (D2.3) is to have a snapshot of the main current technologies available and future trends to achieve data transmission in real time. The objective is to collect information of existing, promising or under development technologies and architectures from other fields like aeronautics, industrial, telecommunications or signaling. The report include an overview on hardware, protocols, frequencies, performance, simulators and tools, official institutions and bodies, standards, other research projects or initiatives.

This state of the art studied various technologies in the railway field and also into some others fields: aeronautics, industry and automotive with the hope to have cross-fertilization usage of some technologies.

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## 1. INTRODUCTION

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This Roll2Rail project covers different rolling stock topics such as Traction (WP1), TCMS (WP2), Car-Body-Shell (WP3), Running-Gear (WP4), Brakes (WP5), Vehicle Interiors (WP6) and transversal activities such as Noise (WP7) and Energy Management (WP8).

In that context, WP2 work package's concrete goal is to make research on technologies and architectures to allow new generation of train communication systems based on Wireless Transmission for Train Control and Monitoring System (TCMS), functions and Infotainment, CCTV applications, thus reducing or even completely eliminating, on board communication cables and simplifying the train coupling procedure.

The goal of this deliverable (D2.3 within WP2) is to have a snapshot of the main current technologies available and future trends to achieve data transmission in real time. The objective is to collect information of existing, promising or under development technologies and architectures from other fields like aeronautics, industrial, telecommunications or signaling.

Therefore, this State of the Art on Radio Technologies and Recommendation of Suitable Technologies presents the current state of the existing technologies to use wireless network for an intensive usage. In order to do that, different chapters have been allocated depending current sector of application.

Firstly, technologies used in the railway world are explained, such as TETRA, Ultra-Wide-Band or Cognitive Radio. Furthermore, reference to previous research projects such as Marathon has been included.

Secondly, aeronautics sector technologies (i.e: AeroMACs, ADS-B or LDACS) have been extensively described and their suitability for railway sector has been indicated technology by technology.

Thirdly, industrial environmental technologies have been described, such as WirelessHART, WiFi, DECT or LTE, and a summary of their suitability for railway domain has been also included.

Fourthly, a summary of automotive industry technologies has been executed, making a difference between car to car or car to infrastructure communications. Suitability against railway sector has been added in each sub-chapter.

Moreover, a conclusion chapter has been added to summarize different technologies described along the deliverable, focusing in their suitability for different type of communications that will be necessary to cover in order to achieve a complete wireless TCMS solution. These conclusions will be used by other tasks in order to define proper architectures (T2.5 and T2.6) and guarantee that all requirements (T2.1) can be provided by selected technologies (within T2.7).

Finally, it should be remarked that inputs are coming from the partners: DLR, IK, IFST, THA, USBG and VOSS. The inputs are based on current knowledge of the partners and also on experience in various previous projects. More details on the contributions from each partner can be seen in the REPORT CONTRIBUTIONS chapter of current deliverable.

## 2. STATE OF THE ART IN RAILWAYS

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### 2.1 RADIO TECHNOLOGIES BETWEEN TRAINS AND CONSISTS

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#### 2.1.1 TETRA

TETRA (TErrestrail Trunked RAdio) is a professional mobile communication system designed for use by government agencies, public safety networks and the military and provides robust and secured communication even under disaster conditions. TETRA uses TDMA and features two modes of operation:

- TMO (trunked-mode operation) for communication between TETRA terminals and a base station
- DMO (direct-mode operation) for infrastructure-less operation. DMO also allows operating one or more terminals as a relay.

While TETRA was designed to provide primarily voice communication in challenging scenarios, it also includes data communication based on a  $\pi/4$  DPSK (Differential Quadrature Phase Shift Keying) modulation scheme), which has a spectral efficiency comparable to the one of GSM, but is limited by the channel bandwidth of 25 kHz.

TETRA operates in the UHF band, which provides favourable propagation conditions compared to higher frequency bands. Although the primary objective of TETRA has been voice communication, it includes several types of data communication such as the Short Data Service (SDS) which can be used in DMO. This mode is particularly interesting for train-to-train communications since it allows infrastructure-less point-to-point and point-to-multipoint transmission, as well as a fast call setup.

The following characteristics of TETRA are relevant for direct train-to-train communication [2]:

- High spectral efficiency of up 28.8 kbit/s in a 25 kHz channel
- Operation possible at high relative velocities of over 400 km/h
- Mobile-to-mobile communication is implemented in the DMO. Point-to-point and point-to-multipoint transmissions are possible
- Low carrier frequencies in UHF band permit a communication range of several kilometres
- Very fast setup times of typically less than 250ms for a single node call
- The system contains mechanisms to ensure communication even during overload situations.

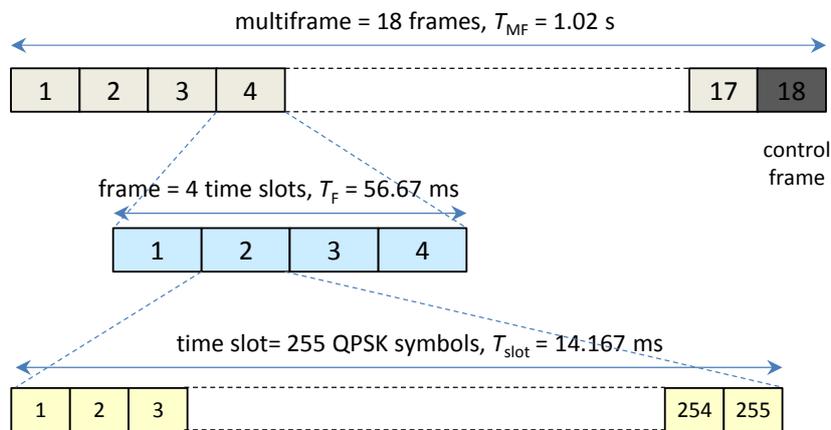
Access to the channel in the direct mode is managed by three defined channel states:

- Free: any mobile station may use it.
- Occupied: a call is in process
- Reserved: a reservation signal is present

In the absence of a base station, the node which initiates the communication will be the master, which is also the node which provides synchronization to all participating slaves. There are three types of bursts in DMO:

- DMO Linearization Burst (DLB): used to linearize the transmitters of the mobile stations. No data is transmitted
- DMO Normal Burst (DNB): two blocks of each 216 bits are transmitted
- DMO Synchronization Burst (DSB): used to synchronize the mobile stations which participate in the communication

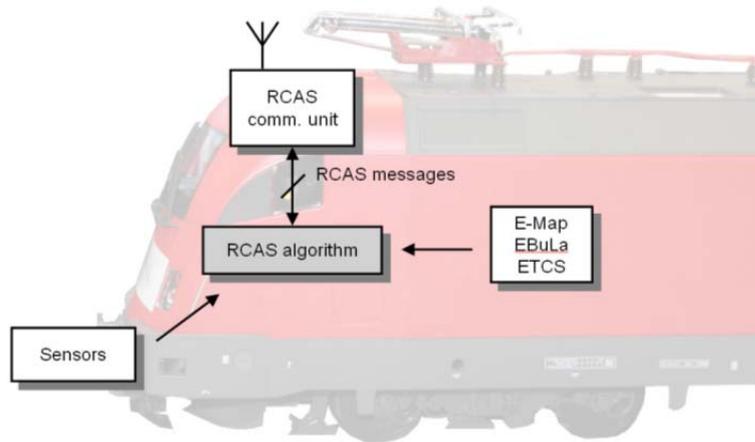
The frame and multi frame structure of TETRA DMO SDS is shown in Figure 1. The TDMA scheme provides 4 time slots per carrier, which are separated by 25 kHz. A more detailed description of the TETRA DMO SDS with respect to railway applications can be found in [2].



**Figure 1: Frame and multi frame structure of TETRA DMO**

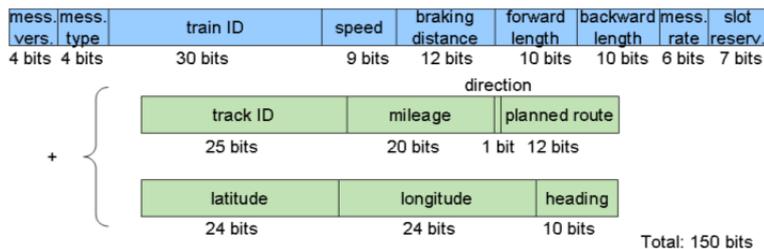
TETRA has also been used as a basic building block in the development of the infrastructure-less Railway Collision Avoidance System (RCAS) [3][4].

RCAS is defined as a safety overlay system and is providing information about position, velocity and time to the driver and to any other trains in the surrounding by broadcast. The RCAS unit analyses the received messages, generates a complete traffic scenario and warns the train driver in case of collision threats. As seen in Figure 2 the RCAS algorithm is based on train specific parameters (Sensors) and on the broadcasted RCAS messages from other trains. In addition ETCS (European Train Control System) information and train schedule information from the German EBUA (electronic schedule sheet and catalog of restricted speed zones) can be implemented to increase the reliability of collision detection [1].



**Figure 2:RCAS block diagram [1]**

The broadcast message is fixed in length with a size of 150 bit. The transmitted information is shown in Figure 3. The blue dyed bits are representing the train status information, the green blocks contain the Position and Route Information (PRI).



**Figure 3:Basic RCAS message [1]**

Bibliography of the paragraph

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- [4] Online: <https://www.youtube.com/watch?v=Fhz8MOy8cR0>

## 2.1.2 Project Marathon Experience in Distributed Power Long Trains

### Abstract

Project Marathon is a real example of application of radio technologies in railway between trains. Project was developed between 2011 and 2014 and the main goal was to prove the feasibility of long trains in Europe.

A survey of the different technologies available in the market was done at the beginning of the Marathon project. The survey included technologies like GSM, UMTS, LTE, WCDMA, HSPA, WMAN or WWAN. Many of the technologies analyzed at that moment have significantly progressed so results cannot be used although some results are still valid.

Due to budget and time restrictions three existent products in railways were proposed as alternatives: LOCOTROL from GE, a remote control system used for shunting locomotives and an End of Train Device (EoT).

LOCOTROL was the product more similar to what Marathon partners were searching for. It is used today in 6000 locomotives to allow distributed power in trains of more than 1 km but it has two main problems: the performances of the system were done for dedicated freight lines with low traffic and freight and the system does not fulfill the European safety standards like EN50126, EN50128 and EN50159-2.

In particular the reference standards requested are: **EN50126**, **EN50159**, **EN50239**, **EN50155**, and **EN300113**. Also the equipment used should be assessed by a notified body and approved by railway national authorities.

Finally a system based in a railway remote control system was chosen to be used as the radio system in the Marathon project.

The remote control system is SIL3 certified for 6 relay inputs and SIL2 certified through CANopen bus interface. It is capable to select up to 32 different radio channels and has two independent radio channels working simultaneously. It has been configured to allow 5 networks to work at the same time in the same geographical area thanks to an efficient STD channel allocation.

### Detailed Technical Work

Regarding the radio technology the main goal was to find a reliable data link to Exchange command-control data between 2 locomotives which can be used in all European countries.

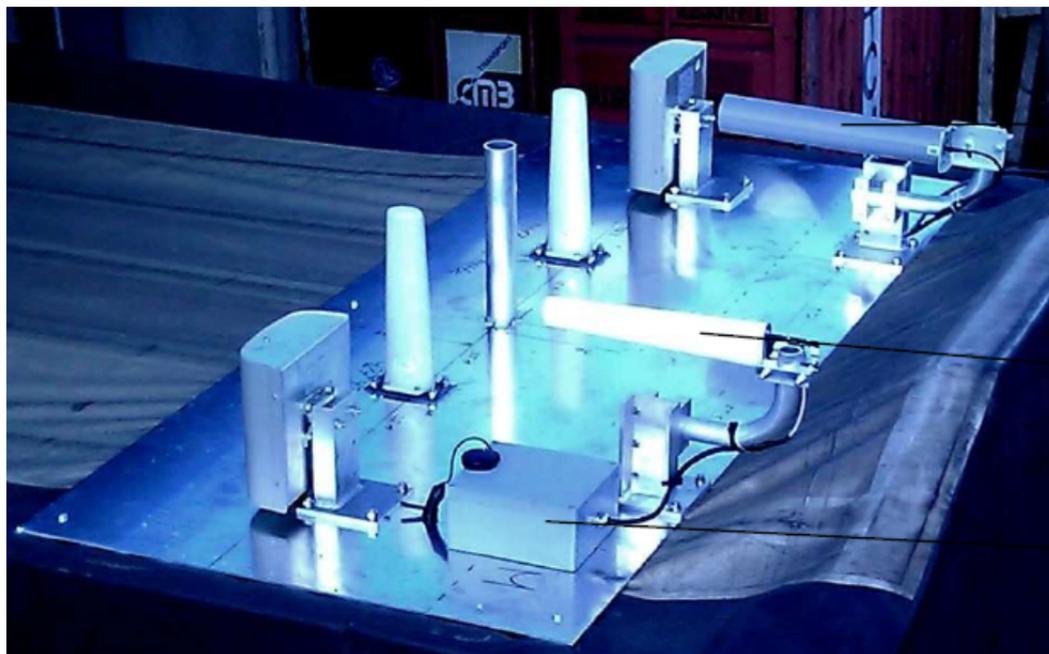
For the selection of the frequency band the whole spectrum was first divided in two main groups: frequencies below 1 GHz and above 1 GHz.

Frequencies below 1 GHz are commonly used in railways as the attenuation is relatively low but the data rate is smaller compare to higher frequencies. Also another problem of this frequency group is the low penetration due to the wavelength which causes communication losses in environments like tunnels or hills.

Two bands of each group were selected for testing purposes and a test was performed between Bettembourg (LUX) and Le Boulou (FRA) in the rolling highway as a first step to decide the frequencies for the final test of the project.

Bands selected for this first test were:

- Band of 400MHz: two channels at 427,4375MHz (500mW) and 417,435MHz (500mW)
- Band of 800 MHz: two channels at 869,4 and 869,625
- Band of 2.4 GHz with ten channels autochanging FHSS (100mW)
- Band of 5.4 GHz: one channel WLAN (100mW).



**Figure 4: Set of antennas used in the first radio test**

The operational /technical constraints of the Marathon radio system were:

1. Point to point bi-directional radio link. Maximal distance between the points: 750m.
2. Maximal speed of the vehicle: 120 km/h (freight locomotives). This is the speed between the train and ground and the propagation obstacles. The relative speed between the two points is 0 km/h.
3. System must be prepared to manage a situation with 5 simultaneous radio links working independently in the same geographical area at the same time without problems.
4. The technology chosen must be able to work under normal environmental situations found in railway applications such as tunnels, canyons, urban areas, vegetation, curves, slopes, weather conditions (rain, snow, fog, etc..). Summarizing the system must be suited for use in non line-of-sight and harsh environments.
5. Suited for railway constraints such as environmental (EN50155), operational, maintenance, mechanical and electrical like for instance in the type of antennas used, the antenna must be compatible for a railway vehicle roof and must allow the fulfillment of the clearance.

These constraints must be adapted for a wireless TCMS system, designed to be used in all kind of railway vehicles.

Ten runs were performed with radio equipment and antennas installed in two cars of commercial trains with separations between 300m and 660m.

Results with 400MHz, 800MHz and 2.4 GHz were satisfactory. 5.4 GHz band was not tested enough to have conclusions.

Conclusions of this first test were:

- Radio losses were mainly in tunnels and 75% of the losses lasted less than 5 seconds.
- The target for the radiated output power must be in minimum 5W
- Directive antennas according to railway standards must be used
- Radio equipment must be multichannel because it will be impossible to coordinate the frequencies between the different countries in Europe.
- As expected frequencies below 1GHz had poorer results in tunnels
- One single channel below 1GHz could assure Marathon functionality (Marathon system can handle without effect radio losses if they last less than 4 seconds) although for a wireless TCMS the better strategy could be to have a redundant channel above 1GHz in order to improve performances in tunnels and also to increase the non-safety data rate.
- Due to the high density of bands used in those frequencies, to the lower attenuation, to a higher sensitivity to side bands, the use of specific band pass filters is recommended for frequencies below 1GHz.

Final test of Marathon project was done with two channels: 400MHz and 2.4GHz applying some of the conclusions of the first test. Two locomotives separated 750m were connected via radio and the one in the head of the train (the master) controlled the second one.



Concerning the radio behavior conclusions were:

- 400 MHz channel had fewer disruptions than 2.4 GHz channel. The poor results of the 2.4 GHz band can be explained by the fact that there was a limitation of 100 mW of radiated power instead of the 2 W that the 400 MHz band had. This difference comes from the fact that for 2.4 GHz a public band was used. The recommendation is to use a reserved band above 1GHz which can have higher levels of radiated power.
- Only a few losses with impact in the behavior of the train were detected (losses of more than 3 seconds).
- Radio interruptions were always in tunnels or their surroundings.
- Disruptions did not happened in both channels at the same time, which demonstrate that frequency diversity is profitable although in some spots cut off happened for both channels at the same time.
- Integration on the locomotive lead to some degradation on the 2.4GHz behavior compared to the expected. Therefore some improvements can be expected in performance if the integration is better (type of antenna, filters, cables, etc.).
- The problem of having several networks working in the same geographical area at the same time must be handled carefully. In Marathon project the inauguration procedure of the network was pointed as a key feature.



**Figure 5: Marathon final test**

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### **Characteristics of the main radio link:**

The performances and behavior of the radio link are defined with regard of the needs of the locomotive control system. In this case for Marathon project the data rate needed is quite low compare to a wireless TCMS. As explained before a radio system based in a standard railway remote control system was chosen and its characteristics were:

- Frequency Range: 410/470 MHz (changes depending on the country)
- Bandwidth: 12.5 kHz
- STD (Synchronous Time Division)
- Maximal latency delay: 695 ms with 13 timeslots (for 5 trains in the same geographical area working at the same time).
- Maximal communication interruption duration: 4 seconds (5 messages loss)
- Power : 5W ERP
- 12 bytes exchanged via radio.

### 2.1.3 Ultra Wide Band

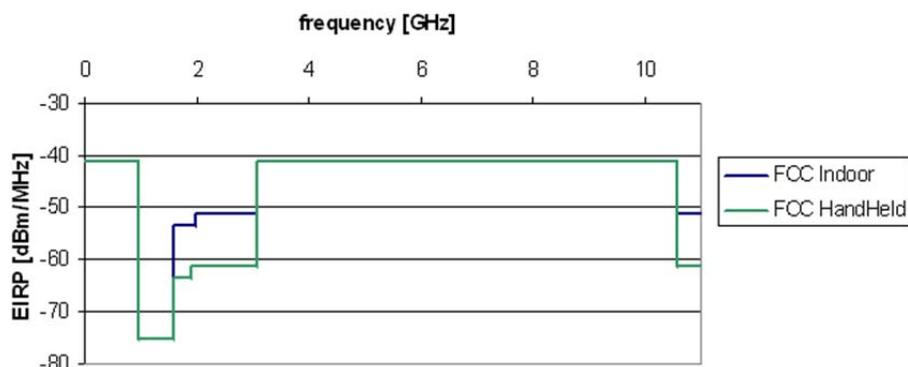
From [21] from FP6 InteGRail project :

#### Introduction

Historically, UWB systems have been developed as military applications and the main application were radar systems. Ultra-Wideband (UWB) has recently gained great interest in the research community for high speed short range communication (e.g. home networking kind of applications) as well as low speed long range communication (e.g. sensor network kind of applications).

In February 2002, the Federal Communication Commission, which regulates the radio spectrum utilization in the U.S., issued the FCC UWB rulings that provided the first radiation limitations for UWB, and also permitted the technology commercialization. UWB signals are of very short duration, typically of the order of nanoseconds and occupy the bandwidth from about DC to tens of GHz. They are also known as “base-band carrier-less short pulses”.

The FCC also granted the frequency range from 3.1 GHz to 10.6 GHz with very little emission power to UWB technology and provided two different spectral masks for UWB systems for handheld (outdoor) devices and indoor devices as shown in Figure 5.



**Figure 6: UWB Spectrum: FCC Indoor and Outdoor limits**

Recently the wireless application is growing much more rapidly than wireline services. According to the consulting firm Ernst & Young, wireless applications will surpass wire-line applications as the dominant telecommunication technology by 2008. Even though the cellular phones for voice calls have been the most popular wireless technology so far, the wireless local area network (WLAN) is getting more and more customer acceptance with the latest technological advancements. By the end of 2008, the UWB technology will generate \$1.39 billion revenues world wide according to the prediction of Allied Business Intelligence.

Because the potential market of UWB is huge, many industrial heavyweights, such as Intel, Texas Instrument (TI), Motorola, and Samsung, have been investing in UWB technology and UWB related devices. As many practical UWB devices are being designed, an industrial standard is expected to be made. Now a new high-speed wireless standard, IEEE 802.15.3a, is in the making, which will achieve up to 480 Mbps throughput. Two proposals, multi-band OFDM proposed by Intel and TI, and DS-CDMA proposed by Motorola, are competing in the IEEE802.15.3a working group. Final results are expected to come out in the near future.

## UWB Advantages and Disadvantages

Comparing to narrow band signals, UWB signal has the following four main advantages:

1. UWB signals have the capability to convey high-speed data. According to Shannon's communication theory, the information capacity increases linearly with frequency bandwidth, and decreases logarithmically with the signal to noise ratio. Since UWB has wide frequency bandwidth, it is inherently suited for high data rate communications. For instance the data rate of the IEEE 802.15.3a proposals can achieve up to 480Mbps. This is a giant leap from the existing 1 Mbps of Bluetooth, 11 Mbps of 802.11b, and 54 Mbps of 802.11a/g.
2. UWB signals have fine range resolution. This enables the use of RAKE receiver techniques in UWB systems. RAKE receiver improves system performance by equalizing signals from different paths. Objects between transmitter and receiver causes electromagnetic effects (e.g. reflection and diffraction) that make the signal travel by various paths to the receiver. A RAKE receiver includes many fingers collecting signal energy from the diverse paths similarly to how tines on a garden rake collect leaves. The RAKE receiver can enhance the performance of UWB systems in multi-path channel environments, especially in indoor environments. Due to its fine range resolution, UWB technology can also be applied to location-aware wireless networking such as E911 Wireless Services. In wall penetrating radar applications, UWB signal can precisely track the moving objects behind the wall.
3. UWB communication system is inherently secure. Since the power density of UWB signals is usually below environment noise, only a receiver that knows the schedule of the transmitter can decode the random pulses into a message. Other narrow band receivers cannot even tell the difference of UWB signals from the environment noise. This property of UWB is desirable in highly secure communication systems, such as in military walkie-talkie systems.
4. Impulse radio is carrier-less, so it only has base-band processing and no intermediate frequency (IF) processing is needed. This makes impulse radio devices much cheaper than other communication devices. Since the super-heterodyne architecture was invented by Edwin Armstrong in 1914, almost all communication systems thereafter adopted this technique, in which base-band signal is first up-converted to IF signal by multiplexing with a local oscillator (LO) frequency, then this IF signal is further up-converted to radio frequency (RF) signal. This super heterodyne technique can improve narrowband receivers' sensitivity. However, in the impulse radio devices, no LO is necessary, no up/down-converters are needed, therefore, impulse radio devices are simple and of low cost.

While it has all the above advantages, UWB technology also has four major disadvantages:

1. Since UWB signal uses a wide RF bandwidth, its interference with existing narrow band turns out to be a critical problem. This interference could be in two directions: one direction is that narrow band signals can interfere to UWB receivers, such as IEEE 802.11a that shares 5 GHz frequency band with UWB signals; the other direction is that UWB signals may interfere into narrow band receivers. For instance, GPS signals are usually of low power density, so it is vulnerable to UWB interference. However, without sacrificing much system performance, the interference of UWB to legacy systems can be mitigated through pulse shaping filter and different modulation scheme.



2. Since UWB pulses are very short in time domain, high-speed ADC (Analog to Digital Converter) and high-speed DSP are essential for UWB systems to digitize and process UWB signals.
3. UWB systems require wide-band antennas. Traditional frequency selective antennas could not keep constant amplitude and constant group delay for a wide frequency bandwidth. Instead, wide-band antennas, such as discone antenna, logarithmic antenna, etc., have to be adopted. However, wide-band antennas are bigger and more expensive than narrow-band antennas, designing a small and inexpensive antenna is crucial for UWB technology to be widely deployed.
4. UWB communication systems are limited in range. In order to make UWB interference to other radio systems insignificant, the transmission power of UWB signals has to be bounded under the emission mask set by the FCC. The low output power leads to smaller coverage area. In general, with high gain antenna, UWB signals may cover up to one kilometer. But with regular antennas, the range of UWB signals is usually from ten to twenty meters.

### Comparison of UWB with Existing Wireless Standards

Currently, four wireless standards, i.e. Bluetooth, IEEE802.11a, IEEE802.11b, and IEEE802.11g, are commonly used in North America. In Europe and Japan, HiperLan II is also widely used, whose physical layer is similar to IEEE802.11a. The main characteristics of these wireless technologies are reported in **Table 1**.

	Bluetooth	IEEE802.11b	IEEE802.11g	IEEE802.11a	UWB
Frequency Band	2.4 GHz	2.4 GHz	2.4 GHz	5 GHz	3-10 GHz
Max Data Rate	725 Kbps	11 Mbps	54 Mbps	54 Mbps	480 Mbps
Modulation	FHSS	DSSS	OFDM	OFDM	Multi-Band OFDM DS-CDMA

**Table 1 UWB and Wireless Technologies**

The Bluetooth radio employs frequency hopping spread spectrum (FHSS) with totally 79 hops. The frequency hopping range is from 2.402 GHz to 2.480 GHz. Its baseband modulation uses Gaussian Frequency Shift Keying (GFSK), where a binary one is carried out by a positive frequency deviation and a binary zero by a negative frequency deviation. The power control of Bluetooth devices is realized using 3 power classes. Power Class 1 is designed for long range (about 100 m) devices, with a max output power of 20 dBm. Power Class 2 is for ordinary range devices (about 10 m) devices, with a max output power of 4 dBm. Power Class 3 is for short-range devices (about 1m), with a max output power of 0 dBm.

802.11b employs direct sequence spread spectrum (DSSS) with complementary code keying (CCK) base-band modulation. Its RF spectrum occupies 83.5 MHz bandwidth (for North America) from 2.4 GHz to 2.4835 GHz. 802.11b has 11 channels, each of which is 22 MHz wide, and offers data speeds up to 11 Mbps.



802.11a adopts OFDM technology. Its frequency spectrum occupies two different bandwidths from 5.15 GHz to 5.35 GHz and from 5.47 GHz to 5.725 GHz. 802.11a provides 12 channels (8 for indoor applications and 4 for point-to-point applications) of 20MHz each and can offer data rate up to 54Mbps.

802.11g offers data speeds up to 54Mbps, and operates at radio frequency between 2.4 GHz and 2.4835 GHz. 802.11g uses 802.11b's Complementary Code Keying (CCK) to achieve bit transfer rates of 11 Mbps. In addition, 802.11g adopts 802.11a's Orthogonal Frequency Division Multiplexing (OFDM) modulation for data rate of 54Mbps. 802.11g is compatible with 802.11b, but not compatible with 802.11a since 802.11g and 802.11a operate at different frequency bands.

From the perspective of spatial capacity, UWB is also advantageous over other wireless standards. Spatial capacity is usually measured by data bits transmitted per cubic meter. However data bits per square meter are of more interest. So in the following study, bits per square meter are employed to calculate spatial capacity.

Bluetooth has a range of about 10 meters in free space. In a circle with a 10-meter radius, approximately 10 Bluetooth piconets can operate simultaneously, the aggregate over-the-air speed is about 7 Mbps. Divided by the area of the circle; this yields a spatial capacity of approximately 22Kbps/m<sup>2</sup>.

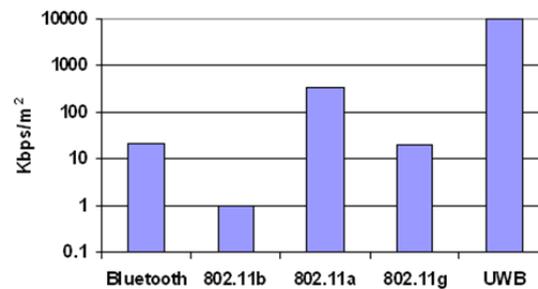
IEEE 802.11b devices have a range of about 100 meters in free space. In a circle with a 100-meter radius, three IEEE 802.11b systems can operate simultaneously, each offering a peak over-the-air speed of 11 Mbps. The total aggregate speed of 33Mbps, divided by the area of the circle, yields a spatial capacity of approximately 1Kbps/m<sup>2</sup>.

IEEE 802.11a has a range of about 20 meters in free space. In a circle with a 20-meter radius, eight IEEE 802.11a devices can operate simultaneously, each offering a peak over-the-air speed of 54 Mbps. The total data rate (432Mbps), divided by the area, yields a spatial capacity of approximately 343 kbps/m<sup>2</sup>.

IEEE 802.11g has a range of about 50 meters in free space. In a circle with a 50-meter radius, three IEEE 802.11g devices can operate simultaneously, each offering a peak over-the-air speed of 54 Mbps. The total data rate (162 Mbps), divided by the area, yields a spatial capacity of approximately 20 kbps/m<sup>2</sup>.

UWB has a projected range of about 15 meters in free space. In a circle with a 15-meter radius, 15 UWB systems can operate simultaneously, each offering a peak over-the-air speed of 480Mbps. The total data rate is 7200Mbps. The spatial capacity, i.e., data rate per square meter is approximately 10Mbps/m<sup>2</sup>.

Figure 7 summarizes the spatial capacity of these wireless standards.



**Figure 7: Spatial Capacity**

Power consumption is also an important perspective for wireless devices. The transmission power of Bluetooth Class 1 devices is 100 mW, 802.11b output power is about 20 mW, 802.11a output power is from 40 mW to 800 mW, and 802.11g transmission power is about 65mW. The transmission power of UWB devices is only 1 mW, which is significantly lower than those of Bluetooth (Class1), 802.11b/a/g.

Since UWB devices consume much lower power than other wireless products, some researchers are considering applying UWB devices in wireless sensor networks. The advantages of UWB devices in sensor networks are:

- UWB devices are easy to have precise distance information
- more nodes can be accommodated in the network
- good for real time control applications where response time is more important
- UWB devices consume lower power.

The disadvantages of UWB devices in sensor networks are overkill for low data rate, slow response applications and potential interferences to legacy devices.

## 2.1.4 Millimeter Communication

### WiGig or IEEE 802.11ad (from E. Masson)

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 [7], [13], [17]. 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 [13].

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 enables 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 4K 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 wave domains, a specific challenge to overcome is the severe path loss from transmitter to receiver [7]. 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 has 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 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 specification, 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 meters, 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 are an integral part of these specifications [13]. 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 [13]. In [10], 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  $5 \times 10^{-4}$  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 [5], 3D printing technology is used to develop innovating lens design and improve the gain of existing 60 GHz antenna solution. A 10 dBi improvement is achieved in the budget link. In [44], the authors developed a magneto-electric dipole antenna. In [9], a fully-integrated feature-rich 60 GHz SiGe BiCMOS antenna is developed and tested. In [11], a coplanar waveguide-fed broadband patch antenna is designed, microfabricated and characterized. A 15 % bandwidth and 5.5-7 dBi gain are obtained. In [12], 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 [13], a System-in-Package approach is used to address 60 GHz applications. A maximum gain value of 7.8 dBi is reached. In [14], [15] and [16], a CMOS transceiver chipset is developed. Finally in [8], 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.

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## Some products

IEEE-Standard 802.11ac



Wilocity's wireless chips allow 4.6Gbps transmission over the 60GHz band.

 Wilocity

**Figure 8: Wilocity's wireless board**

<http://arstechnica.com/information-technology/2013/01/fastest-wi-fi-ever-is-almost-ready-for-real-world-use/>



**Marvell und Qualcomm wollen 60-GHz-Funk serienreif machen**

Noch 2012 könnten die ersten drahtlosen Docks für Notebooks mit mehreren Gigabit pro Sekunde drahtloser Übertragung auf den Markt kommen. Qualcomm liefert bereits erste Muster der Funkmodule aus - Marvell will bald folgen.

23.07.2012 11 Kommentare



**MICROSOFT**

**Drahtlose Netzwerke für Rechenzentren**

Drahtloser Datenfunk im Bereich von 60 GHz eignet sich zum Einsatz in Rechenzentren, zu diesem Schluss kommt eine Studie, die Forscher von Microsoft zusammen mit der Universität Washington durchgeführt haben.

18.01.2012 18 Kommentare



**WIGIG**

**CES als Startschuss für drahtloses HDMI und PCI-Express**

Die Entwicklung des Standards 802.11ad alias Wigig für drahtlose Gigabit-Netze macht Fortschritte. Auf der CES 2012 soll es erste Produkte zu sehen geben, die inzwischen auch untereinander funktionieren.

22.11.2011 7 Kommentare

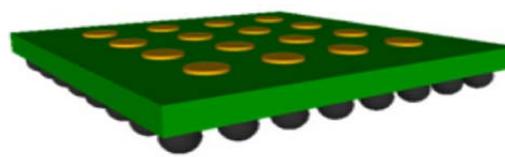
**Figure 9: WiGig products from Golem**

<http://www.golem.de/specials/wigig>

IEEE-Standard 802.11ad

SYSTEM SPECIFICATION SUMMARY				
CHANNEL	57 GHz to 66 GHz			
SCAN RANGE AZIMUTH	45 degrees			
SCAN RANGE ELEVATION	35 degrees			
CHANNEL TYPE	LOS, point to point			
DATA RATES	QPSK 1.5 Gbps		QAM16 3 Gbps	
RANGE	150m	300m	150m	300m
RX RF POWER CONSUMPTION @ MAX SPEED	1W	2W	1W	2W
RX RF POWER CONSUMPTION @ MAX SPEED	1.8W	3.8W	1.8W	3.8W

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IMEC 60 GHz SMALL CELL BACKHAUL MODULE (ARTIST IMPRESSION)

**Figure 10: IMEC products**

<http://www2.imec.be/content/user/File/NEW/Research/Wireless%20Communication/60%20Ghz/60Ghz%20SMALL%20CELL%20TECHNOLOGY%20.pdf>

IEEE-Standard 802.11ad

USB "dongle"



Figure 11: Mr LOOP products

<http://www.siantenna.com/products-5/products-wigigdongle.html>

IEEE-Standard 802.11ad.

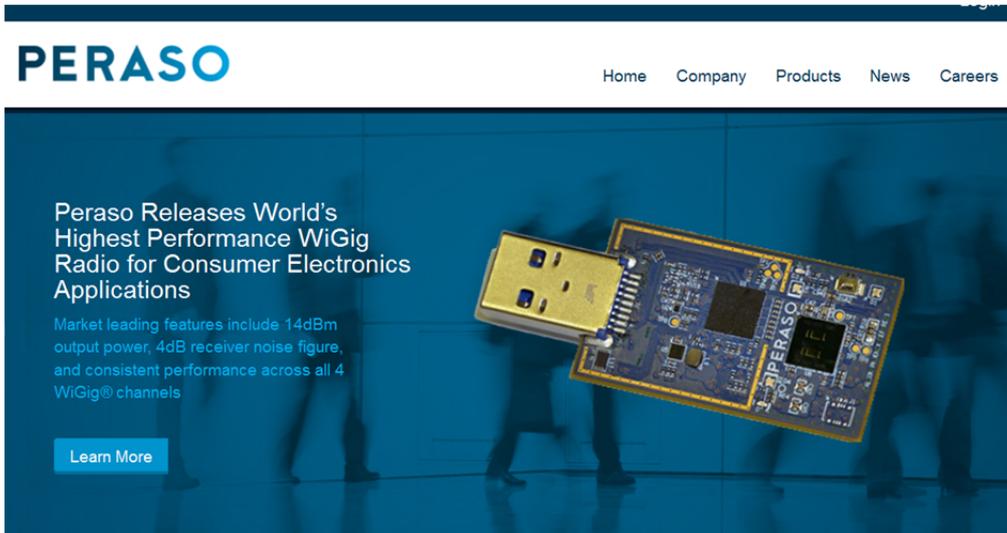


Figure 12: PERASO dongle

If you would like additional information about Peraso's 60 GHz band products, please contact [sales@perasotech.com](mailto:sales@perasotech.com).



Figure 13: PERASO components

<http://www.perasotech.com/>

TENSORCOM



Tensorcom  
Extreme Wireless

Product Brief  
TC-60G-USB3-EVB  
An 802.11ad/WiGig USB 3.0 Evaluation Board

## TC-60G-USB3-EVB

### Product Overview

The Tensorcom TC-60G-USB3-EVB is an 802.11ad/WiGig USB 3.0 dongle solution enabling Gigabit/s communications. The TC-60G-USB3-EVB is comprised of a highly integrated, ultra-low power, 802.11ad/WiGig 60 GHz CMOS system in package (SiP) with embedded antennas and a separate USB3.0 PHY and connector to form a complete WiGig USB 3.0 dongle for ultra-low power, high data rate connectivity.

We designed the TC-60G-USB3-EVB evaluation board to achieve low power without sacrificing performance. Using advanced RF design techniques we produced a highly efficient radio solution that provides excellent performance in both line of sight (LOS) and non-line of sight (NLOS) environments.

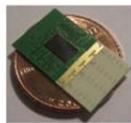


Figure 1: TC-60G-1115GE SiP on Module



Figure 2: TC-60G-USB3-EVB evaluation board

### The TC-60G-USB3-EVB Includes:

An 11mm x 15 mm Module that consists of:

- An AES-128 hardware engine that supports

### Figure 14: Tensorcom products

<http://www.tensorcom.com/files/TC-60G-USB3-EVB-1pg-pb-v01.pdf>

## 60GHz Wireless



### Figure 15: Bridgewave products

[http://www.bridgewave.com/products/60\\_ghz.cfm](http://www.bridgewave.com/products/60_ghz.cfm)

Spectrum Efficient using 64QAM in 250, 500, and 750 MHz wide channels  
Full Duplex providing up to 3000 Mbps Upstream and downstream  
Hitless Adaptive Rate and Modulation QPSK/8PSK/16/32/64QAM  
Link distances up to 5 miles/8 km at 99.995%

## 2.1.5 Research Works in the Railway Domain Using UWB, Millimeter Waves and 10 GHz Systems and Cognitive Radio Systems

Specifically in the railway domain we can mention several published research works and experimentations using:

- UWB systems for V2I communications and localization purposes,
- 10 GHz communicating systems for V2V communications
- millimeter waves systems for V2V and V2I communications.
- Cognitive radio based systems

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## Cognitive radio based systems

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## **2.1.6 Cognitive Radio**

### **Railway background**

To increase the quality, reliability, safety and security of railway transport systems while increasing their accessibility and productivity; railway exploitation is based on ever increasing information flows between the various stakeholders, centralized databases, but also equipment deployed onboard trains and along the tracks.

Generally, there are two main families of wireless communications: for control and command and for train operations. The vital transmissions for control and command are generally low throughput and very demanding in terms of robustness and availability. Non-critical transmissions generally require very high data rates. They mainly concern the embedded video monitoring, remote diagnosis, multimedia applications or CCTV (Close Circuit Television) and applications such as Internet for passengers onboard.

There is still no sufficiently powerful technology on the market capable of replacing all other telecommunications systems in rail domain and to respond to the multitude of uses and needs. As a result, many wireless communication devices operating at different frequencies are still widely deployed. The integration of all the heterogeneous wireless communication networks is now a major technical challenge if one wants to improve the overall efficiency of the railway system.

Emerging Cognitive Radio systems are now able to meet the railway needs such as interoperability, robustness, reliability, spectral efficiency, while being less expensive to deploy and maintain. UIC (International Union of Railways) and ERA (European Railway Agency) today strongly mobilized to set the radio of the future for the rail system. High-speed trains are not the only ones affected. The issues also affect conventional lines, regional and urban guided transport.

### What is cognitive radio

The concept of cognitive radio was highlighted as an attractive solution to the problem of congestion of the radio spectrum occupied by licensed users [Mitola99, FCC05, Palicot10]. "Cognitive Radio is a radio or a system capable of analyzing its electromagnetic environment and adjust dynamically and independently operational radio parameters to modify the operation of the system, ie throughput, interference cancellation, the interoperability, access to other radio networks". The diagram below shows the concept of intelligent radio.

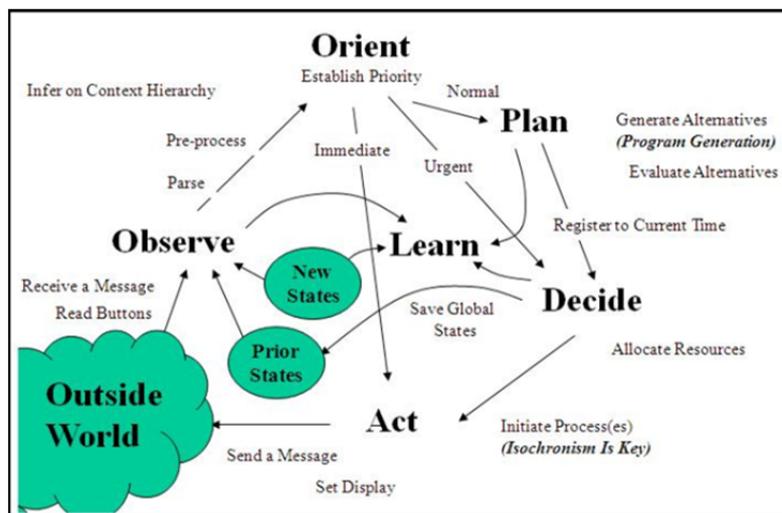


Figure 16: Cognitive Radio Concept

The corridor project is the first basic research project in Europe, paving the way for the development of Intelligent radio technologies (RI) for railway applications. The project objectives were to design, develop and evaluate fundamental bricks of a RI system adapted to the requirements and constraints of HSR (high speed, electromagnetic interference, poor coverage systems in rural areas).

### Current works on Cognitive Radio (CR)

The literature on CR is very abundant in the various fields of telecommunications considered. There are also several European projects on the subject of CR. However, the context of the railway is not treated today and the publications from the CORRIDOR project were the first to consider the characteristics of high speed trains.

- In the European Project FP6, InteGRail [<http://www.integrail.info/>], an intelligent communications architecture, ICOM, has been developed and allows, with solutions based on middleware, integration of several technologies wireless telecommunications in the railway sector. This implies that the mobile terminal is equipped with multiple communication modems [ICOM, Billion08].

- There are also solutions with mobile routers allowing choosing the best network available according to different criteria and particularly QoS [Attar08, Ishibashi08, Kassab08, Zouari09].
- SACRA (Spectrum and Energy efficiency through multi-band cognitive radio – ICT FP7- on going); the major outcome of SACRA is the proof-of-concept for a joint and cognitive communication in separate frequency bands.
- SENDORA (Sensor Network for Dynamic and Cognitive Radio Access), for which the challenge is the detection and use of spectrum holes without significant interfering with the licensed system (ICT-FP7-on going).
- LOLA (FP7 - Call 4) is on access-layer technologies targeting low latency robust and spectrally-efficient transmission in a set of emerging application scenarios based on long-range LTE-Advanced Cellular Networks and medium-range rapidly-deployable mesh networks.
- SAMURAI (FP7- Call 4) project will propose innovative techniques in the area of Multi User –Multiple Input Multiple Output (\*MU-MIMO\*) and \*Spectrum Aggregation\* (SA).
- @CROPOLIS (FP7 - Call 5) Network of Excellence aims to enhance system performance and cater for the services and applications of the future and demonstrate the need for cooperative and cognitive communications paradigms that support advanced coexistence technologies for radio optimization.
- SYMPA – (DGE FUI 8) project aims to develop a reconfigurable MODEM prototype for future terminals, based on the Idromel and PFMM architecture.
- E3 (End-to-End Efficiency Cognitive Wireless Networks Technologies). This project aims to transform current wireless system infrastructures into an integrated, scalable and efficiently managed beyond 3rd Generation cognitive system framework. The main issue is to introduce the cognitive systems in the wireless world, while contributing to the standardization of IEEE P1900.4.
- TEROPP (Technologies for TERminals in OPPortunistic radio applications) dealing among others with to implement cooperative spectrum management systems.
- The **Phidias** project (<http://www.ict-phydyas.org/>) focused on the development of a new PHY tailored for dynamic allocation of spectrum in the context of smart radio.
- The project **Qosmos** (<http://www.ict-qosmos.eu/>) focused on QoS and mobility for intelligent radio.
- The **Cogeu** project (<http://www.ict-cogeu.eu/>) deals with the effective sharing of TV white space bands in the European context;
- The **Emphatic** project (Enhanced Multicarrier Techniques for Professional Ad-Hoc and Cell-Based Communications) is close enough to the issues addressed in CORRIDOR. It addresses the issue of Cognitive radio for PMR (<http://www.ict-emphatic.eu/>).



- Some standards already exist and have been used as a basis in the CORRIDOR project: IEEE 802.22, IEEE P1900.

We have also to mention the COST actions IC9002, TERRA and WINEMO dealing with the CR concepts. CR features are also under standardization as part of the 5G standards.

The CORRIDOR (COgnitive Radio for Railway through Dynamic and Opportunistic spectrum Reuse) project is the first basic research project in Europe, paving the way for the development of Cognitive Radio technologies for railway applications. The project objectives were to design, develop and evaluate fundamental bricks of a CR system adapted to the requirements and constraints of HSR (high speed, electromagnetic interference, poor coverage systems in rural areas...). More details and publications can be found on [www.corridor.ifsttar.fr](http://www.corridor.ifsttar.fr). Generally, a Cognitive radio system requires the cooperation between an intelligent mobile terminal, an intelligent infrastructure and mechanisms to manage QoS and mobility transparently over heterogeneous networks.

The corridor project ended on 31/07/2015 and 20 journal publications and a demonstration have highlighted the results. All the results are available on the website.

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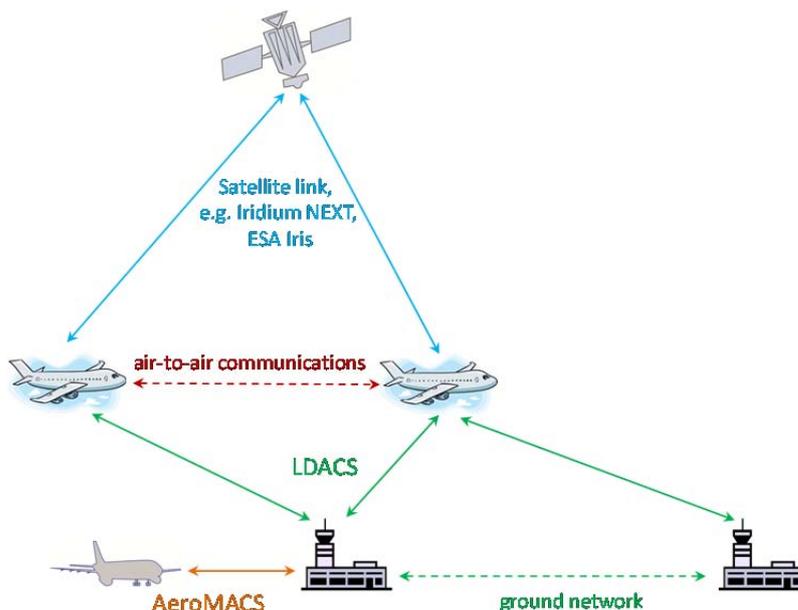
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### 3. STATE OF THE ART IN AERONAUTICS

#### 3.1 FUTURE AERONAUTICAL COMMUNICATIONS FOR AIR-TRAFFIC MANAGEMENT

In air traffic management for civil aviation, there is currently a major modernization process ongoing with the objective to meet the requirements of growing air traffic, particularly in dense areas like central Europe and parts of the United States. The current system, the globally standardized air traffic management (ATM) system ensures efficient traffic flows and safety of flight for all aircrafts in controlled airspace. While the current ATM system works properly, it is foreseen that it will reach its capacity limits in a few years in the regions of highest air traffic density.

It has been widely recognized in the International Civil Aviation Organization (ICAO) that a single data link technology is not well suited to cover the needs for all phases of flight and for this reason, the *future communications infrastructure (FCI)* has been defined, which serves as a basis for the development of future aeronautical communications within the main two initiatives, SESAR (Single European Sky ATM Research) in Europe and NextGen (Next Generation National Airspace System) in the US. As depicted in Figure 17, the FCI comprises LDACS (L-band Digital Aeronautical Communication System), AeroMACS (Aeronautical Mobile Airport Communications System), as well as future air-to-air communication and satellite links.



**Figure 17: The Future Communications Infrastructure (FCI) for aeronautical communications, including LDACS for air-to-ground communication and AeroMACS for communication between airplanes and the tower at large airports**

The satellite component is particularly important for maintaining communications in remote areas and over oceans, and it will serve as a complement for air-to-ground communication. The development of a direct air-to-air link is outside the current scope of SESAR and NextGen but will be addressed in the near future. This direct link between airplanes enables two important applications: a future ADS-B (Automatic Dependent Surveillance - Broadcast) system will be based on this data link, and it will provide the core technology for setting up ad-hoc networks in the sky. The former application has an interesting parallel for railway application and has been realized in the form of a Railway Collision Avoidance System (RCAS).

## 3.2 RADIO TECHNOLOGIES BETWEEN AIRCRAFTS

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### 3.2.1 Aeronautic MANet

An aeronautical mobile ad hoc network (MANet) is a concept for a system, where each aircraft acts as a router, relaying network traffic to its surrounding aircrafts, ground-stations and satellites. The benefit of such a system would be a reduced or no satellite traffic usage in areas where no ground based communication is possible as well as possible load balancing and fault tolerance. These come at the cost of complex routing algorithms and additional networking hardware for each aircraft.

#### **Maturity**

Currently aeronautical MANETs exist only as a concept.

#### **Applications**

Depending on the implementation, an aeronautical MANet can be used for non-real-time and real-time applications.

#### **Suitability for the rail domain**

Such MANET concepts would be also applicable for the rail domain in case that direct "line-of-sight" connections between neighbouring trains or consists can be granted. Detailed simulations modelling train movements and related communications would be required – taking into account appropriate radio channel propagation and terrain models – to evaluate the suitability of MANET concepts for the "Roll2Rail" domain.

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### 3.2.2 ADS-B

ADS-B stands for Automatic Dependent Surveillance – Broadcast. It provides an "ADS-B Out" service, which enables an aircraft (it needs to be aware of its position usually through satellite navigation) to broadcast its identification, speed and position information. Also provided is an "ADS-B In" service, allowing each aircraft to receive the broadcast information from other ADS-B enabled aircraft. There are two competing data link standards, Universal Access Transceiver (UAT) and 1090 MHz Extended Squitter (1090ES).

#### **Main characteristics**

- Aeronautical surveillance system
- Dependent on on-board position determining system
- Possible replacement for secondary surveillance radar (SSR)
- Two competing data link standards, Universal Access Transceiver (UAT) and 1090 MHz Extended Squitter (1090ES).

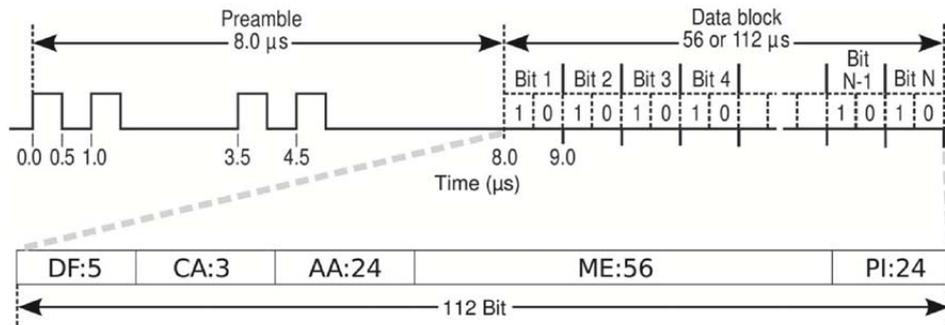
#### **Maturity**

ADS-B is part of the American Next Generation Air Transportation System (NextGen) as well as the European Single European Sky ATM Research (SESAR) and is planned to be introduced in 2017 in the EU. It is already mandatory for flights in Australia above FL300 (30,000 ft).

**Physical & Data Link Layer**

a. *1090 MHz Extended Squitter (1090ES)*

The 1090ES data link is based on the SSR Mode S and therefore existing SSR equipment can be used. It uses the 1090 MHz frequency. It uses two synchronization pulses and pulse position modulation (PPM) for the data (see Figure 1).

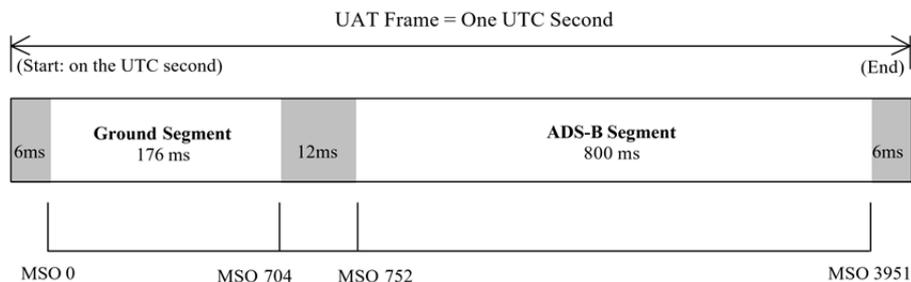


**Figure 18: ADS-B 1090ES Frame [45]**

The used message length for ADS-B 1090ES is 112 bit.

b. *Universal Access Transceiver (UAT)*

The Universal Access Transceiver uses frequency shift keying (FSK), with 978MHz ± 312.5 kHz for 1 and 0 and 0.96 μs per bit. The data rate is further limited by the fact that each participant is allowed a transmission only once per second, which is the time for one UAT messaging frame. Inside each frame there is a dedicated time segment reserved for uplink messages (ground to air) and one for downlink (air to ground). The whole messaging frame is split into message start opportunities (MSO) of 250ms. The size of an uplink message is 4448 bits and for downlink the message size can be 144 bits (short) or 272 bits (long).



**Figure 19: ADS-B UAT Frame [44]**

**Applications**

Used for automated surveillance and as a possible replacement for second surveillance radar (SSR).

**Suitability for the rail domain**

It should be noted that ADS-B systems use a frequency range which is explicitly reserved for aeronautical applications. Such ADS-B concepts would however be also applicable for the rail domain in case that another frequency range is used and that direct "line-of-sight" connections between neighbouring trains or consists and – for specific applications - with infrastructure ground stations can be granted. Please refer to [47], for a detailed description of possible applications and adaptations for the train domain. Detailed simulations modelling train movements and related communications would be required – taking into account appropriate radio channel propagation and terrain models – to evaluate the suitability of ADS-B for the rail domain.

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### 3.3 RADIO TECHNOLOGIES FOR PLANE TO INFRASTRUCTURE COMMUNICATION

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#### 3.3.1 ICAO VDL Mode 2

VDL Mode 2 stands for VHF Data Link Mode 2. It is the main version of all VDL standards and has been implemented inside the Eurocontrol Link 2000+ program. It is also the only mode currently operationally which supports Controller Pilot Data Link Communications (CPDLC) [48].

##### Main Characteristics

- Air-Ground Communication for Air Traffic Services (ATS) and Aeronautical Operational Control (AOC) services
- Broadcast radio system with CSMA (Carrier Sense Multiple Access)
- Deployed in the VHF-Band with 25 kHz wide channels; currently the following frequencies are allocated for VDL Mode 2: 136.975 MHz (Common Signaling Channel (CSC) + data); 136.875 MHz, 136.825 MHz, 136.725 MHz; refer to [3] below).
- D8PSK (Differential 8-Phase-shift keying modulation), raw data rate is 31.5 kbit/s
- VDL Mode 2 Communication Service Provider: ARINC and SITA
- Used for CPDLC (Controller Pilot Data Link Communications) and the data exchange between airline / airport personnel and aircraft crew (AOC)

##### Maturity

VDL Mode 2 is an operational and implemented standard. A detailed performance evaluation of VDL Mode 2 has been carried out recently by simulating accurately the European air traffic (today's traffic and future expectations up to the year 2040), related ATS and AOC data messages and the VDL Mode 2 data link layer protocol behavior in detail (refer to [50] below).

##### Physical Layer

The VDL Mode 2 physical layer uses Differential 8-Phase-shift keying (D8PSK) modulation and operates in the aeronautical VHF-Band (117.95 – 137 MHz). The channel width is 25 kHz with 10,500 symbols per second, resulting in a physical layer bit rate of 31.5 kbit/s. For forward error correction, interleaving and Reed Solomon coding is used.

##### Data Link Layer

The VDL Mode 2 data link layer consists of the medium access control (MAC) sub-layer, the data link service (DLS) sub-layer and the link management entity (LME) which controls the link establishment and maintenance between DLS sub-layers.

##### Applications

In principle, VDL Mode 2 supports data exchange between:

- *Air Traffic Services (ATS)*: communications between an air traffic controller (ATCO) and the pilot of an aircraft (known as "Controller-Pilot Data Link Communications (CPDLC)")
- *Aeronautical Operational Control (AOC)*: communications between the crew of an aircraft and an airport (e.g. destination aerodrome) or between the crew and its corresponding airline (home base).

Each phase of a flight (e.g. communications at the departure gate, communications during taxiing to the departure runway, during takeoff, during flying on standard instrument departure route (SID), during en-route, during flying on standard arrival route (STAR); during approach, final approach and landing, communications during taxiing to the destination gate, finally communications at the destination gate) requires the data exchange of specific ATS and/or AOC messages. Examples of such messages, the triggering event and the estimated amount of such messages – which is important for the overall performance of the VDL Mode 2 link - are described and evaluated in [51] below.

VDL Mode 2 is the only currently operational standard for controller-pilot data link communications (CPDLC).

### **Suitability for the rail domain**

It should be noted that VDL Mode 2 systems use a frequency range (e.g. around 130 to 137 MHz) which is explicitly reserved for aeronautical applications. The applicability of VDL Mode 2 concepts to the rail domain is limited, due to the specific characteristics of train-ground communications: shadowing due to obstacles and terrain, hidden station problem, etc. Furthermore, VDL Mode 2 uses a complete decentralized approach, whereas for ground communication systems usually a master/slave principle is used to allocate and assign available communication resources dynamically.

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### 3.3.2 LDACS

LDACS stands for L-Band Digital Aeronautics Communication System. It is a candidate technology for a future air traffic management air-ground communications standard. It was developed for communication concerning the safety and regularity of the flight.

LDACS is a cellular broadband system sharing many technical features with 3G and 4G wireless communication systems. It is specified in [52][53][54] and discussed in detail in [55][56] [55] [56] [57]..

#### Main Characteristics

- Air-Ground communication for the safety and regularity of the flight.
- Support for very high mobility which results in high Doppler shifts of up to 2 kHz. On the other hand, only small Doppler spreads are expected due to the presence of a strong LoS path.
- Cellular radio system. Multiple cells may be organized into larger networks.
- Up to 512 users per cell.
- Maximum cell radius 200 nautical miles (370km), which leads to propagation delays of up to 1.2 ms.
- Deployed in the L-Band (960 – 1164 MHz) on two separate channels.
- Coexistence with other services within the L-Band.
- Full duplex. Separate channels for forward link (ground-to-air) and reverse link (air-to-ground).
- OFDM (orthogonal frequency-division multiplexing) with several coding and modulation schemes. Small message sizes which require sufficient granularity for framing and channel coding. Data rates go from 291.2 kbit/s to 1318.4 kbit/s on the forward link and from 220.3 kbit/s to 1038.4 kbit/s on the reverse link.
- Designed to provide strong quality of service guarantees on delay, security and robustness with deterministic medium access.

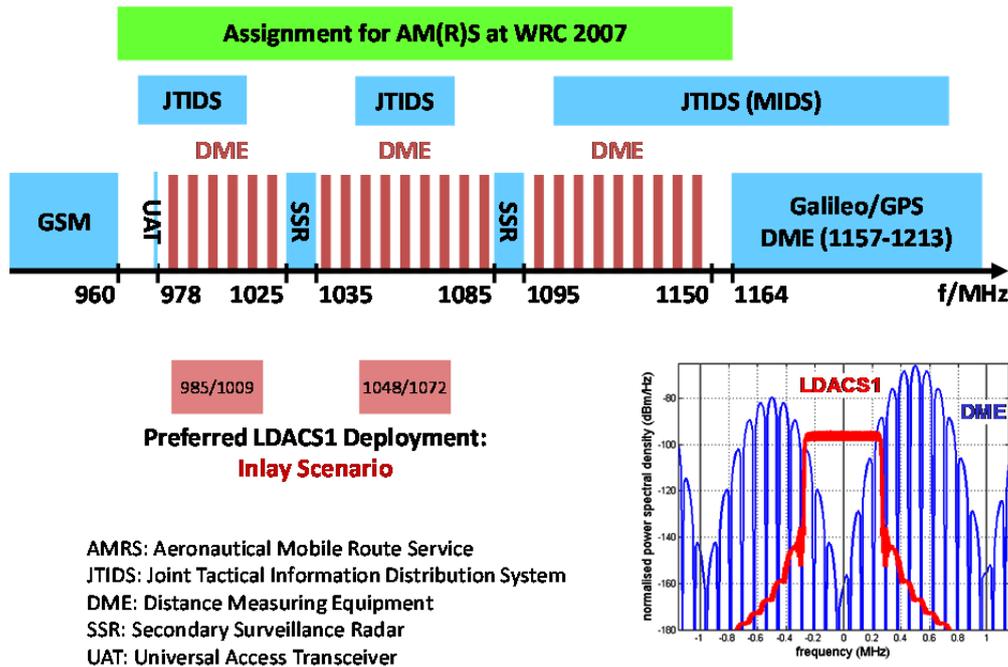
#### Maturity

The Single European Sky Air traffic management Research program (SESAR) considers LDACS to be at the transition point between maturity level V2 (feasibility) and V3 (pre-industrial development & integration) in the “SESAR2020 Multi Annual Work Programme”.

#### Physical Layer

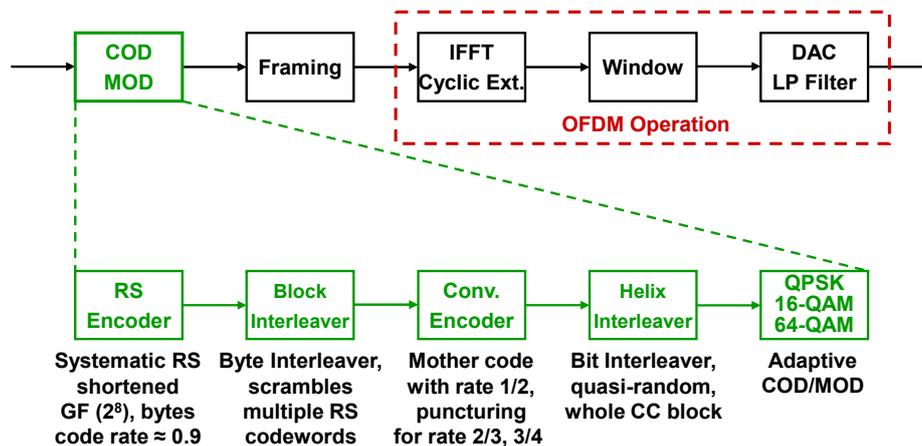
The LDACS physical layer uses OFDM with various coding and modulation schemes and operates in the aeronautical L-band (960 – 1164 MHz). It can either be deployed as inlay system, using the frequency spectrum between DME (distance measuring equipment) frequencies with a channel separation of 1MHz, or as non-inlay system.

One of the major challenges for LDACS is illustrated in and consists of the coexistence with already deployed services like DME (distance measurement equipment). To avoid interference into legacy systems, low out-of-band radiation is mandatory. This is achieved by a properly designed OFDM system which includes transmit windowing.



**Figure 20: Spectrum assignments in the L-band and preferred deployment for LDACS**

The block diagram of an LDACS transmitter is given in and we can observe that it contains the typical ingredients of a modern communication system: adaptive coding and modulation followed by OFDM implemented with an IFFT and a cyclic prefix. Concatenated Reed-Solomon and convolutional coding might not make for the most modern channel coding scheme, but it provides very reasonable performance at moderate complexity and it is routinely implemented in many communication devices like e.g. DVB receivers.



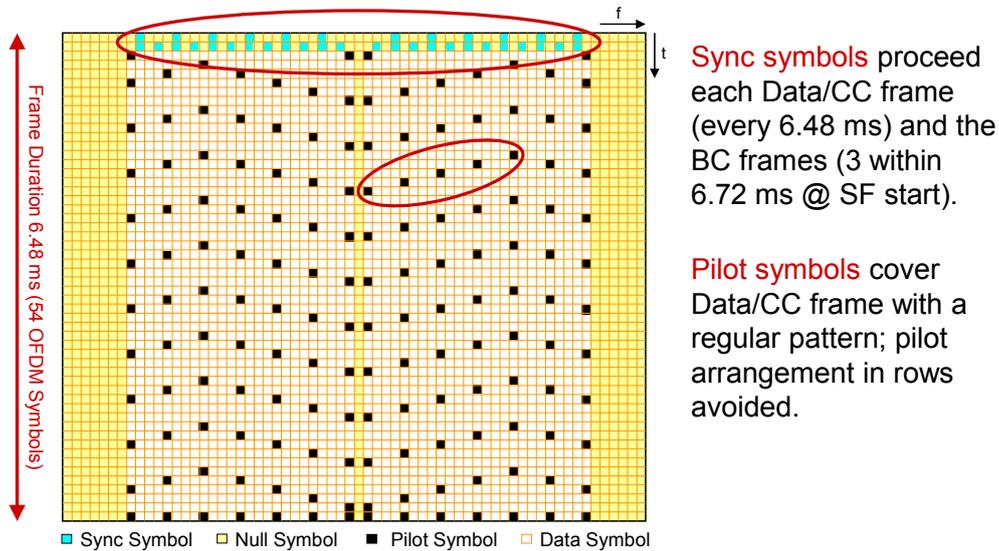
**Figure 18: Block diagram of an LDACS transmitter**

The OFDM system parameters of LDACS are summarized in . Adaptive coding and modulation allows adjusting the data rate to the quality of the link. A further measure to increase the robustness is interference mitigation at the receiver [60], which has been extensively researched in recent years and shows very promising results.

FFT size	64
Number of used subcarriers	50
Total OFDM bandwidth	625 kHz
Effective bandwidth	498 kHz
Subcarrier spacing	9.77 kHz
OFDM symbol duration	102.4 $\mu$ s
OFDM guard interval duration	4.8 $\mu$ s
Transmit window duration	12.8 $\mu$ s
Sampling interval	1.6 ms
Minimum data rate (QPSK, code rate 0.45)	561 kbit/s
Maximum data rate (64-QAM, code rate 0.68)	2.6 Mbit/s

**Table 2: LDACS system parameters**

Each OFDM frame contains, as illustrated in , a number of pilots which are distributed over the entire frame, in addition to the sync symbols at the beginning of the frame. These pilots facilitate channel estimation and account for the high mobility of the aircraft.



**Figure 22: Frame structure and pilot pattern of LDACS forward link**

LDACS uses FDD (frequency division multiplex) for forward and reverse link separation. Reverse link and forward link use a 500 kHz channel each. On forward link a continuous OFDM symbol stream is sent, while reverse link transmissions are based on OFDMA/TDMA bursts which are assigned to different users by the ground station.

The OFDM symbols are organized as frames with hierarchical arrangement. The forward link uses data, common control (CC) and broadcast (BC) frames. The reverse link uses data, dedicated control (DC) and random access (RA) frames. These frames are grouped into multi-frames of 60ms duration and super-frames of 240ms duration (see Figure 19).

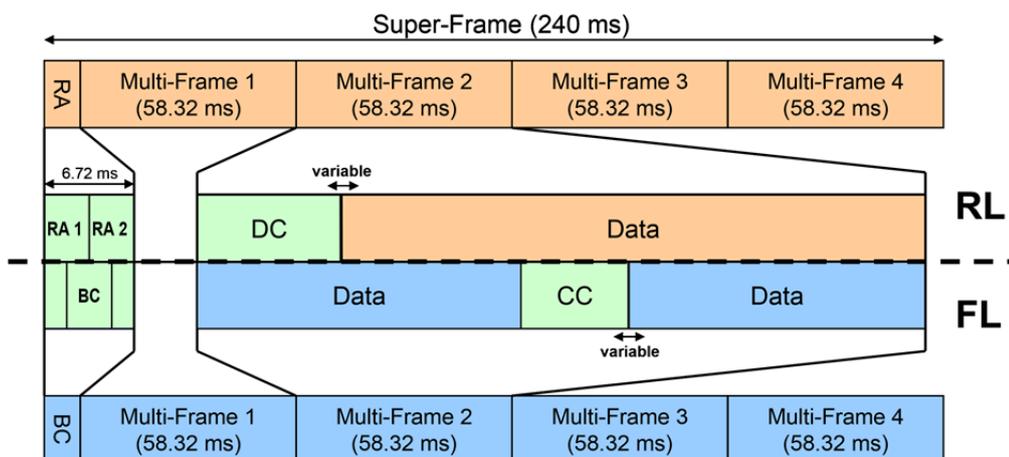


Figure 19: LDACS Super-Frame Structure [52].

The achievable data rate depends on the coding, modulation, and control channel configuration used. It ranges from from 291.2 kbit/s to 1318.4 kbit/s on the forward link and from 220.3 kbit/s to 1038.4 kbit/s on the reverse link.

### Data Link Layer

The LDACS data link layer provides the necessary protocols to facilitate concurrent and reliable data transfer for multiple users. The functional blocks are organized in two sub-layers, the medium access control (MAC) and the logical link control (LLC) sub-layers (see Figure 20).

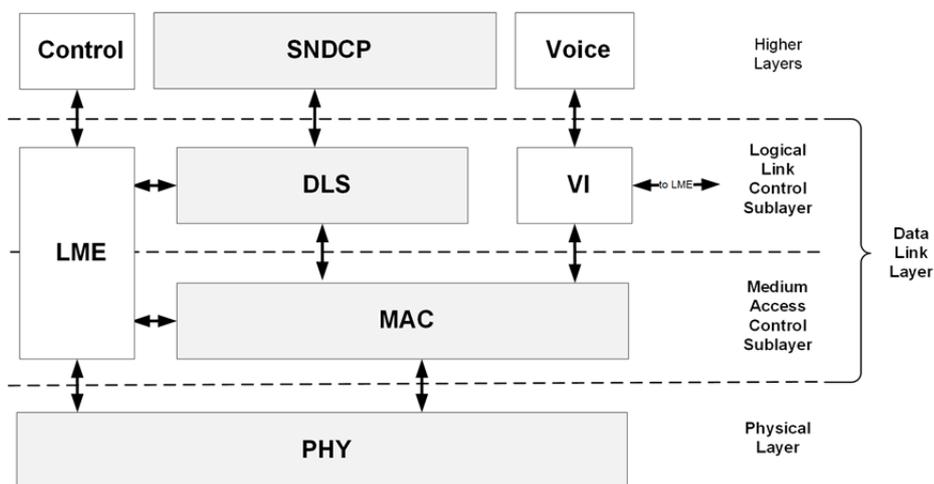
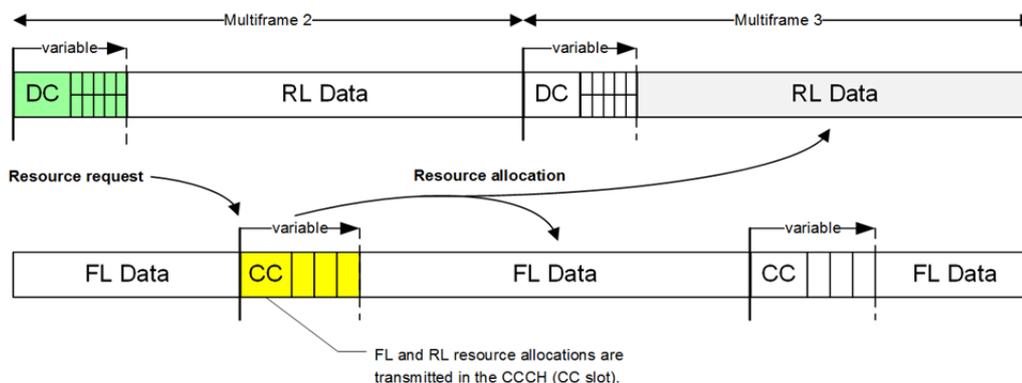


Figure 20: LDACS Data Link Layer

The medium access sub-layer manages the organization of transmission opportunities in slots of time and frequency. The logical link control sub-layer provides reliable and acknowledged point-to-point logical channels between the aircraft and the ground-station using an automatic repeat request protocol [59].

Forward link packets are locally scheduled by the ground-station based on its transmission queue and the priority of the packet.

Reverse link transmissions are initialized by a resource request sent to the ground-station. The ground-station then allocates data slots in the following multi-frame(s) according to the priorities of all received resource requests (see Figure 21).



**Figure 21: LDACS RL Resource Allocation**

### Applications

LDACS was designed for communication related to the safety and regularity of the flight. It shall therefore become a part of the Aeronautical Telecommunications Network (ATN) and support air traffic management, and airline operational control applications. Support for digital voice is optional.

### Suitability for the rail domain

In summary, LDACS can be seen as a good example for the design of communication system which is tailored to the requirements of the aeronautic environment. An excellent overview of LDACS is provided in [[52], while more detailed information can be found on the website [53].

It should be noted that LDACS system concepts are designed for co-existence with the currently used distance measurement equipment (DME) ground stations in the L-Band (962 MHz to 1213 MHz), which is reserved exclusively for aeronautical applications.

Such LDACS concepts could however be also applicable to the rail domain in case that another frequency range is used and that direct "line-of-sight" connections between trains and LDACS infrastructure ground stations can be granted. Detailed simulations modelling train movements and related communications would be required – taking into account appropriate radio channel propagation and terrain models – to evaluate the suitability of LDACS concepts for the rail domain.

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### 3.3.3 AeroMACS

AeroMACS stands for Aeronautical Mobile Airport Communication System. It is a broadband wireless communication system, implemented as a profile for the IEEE 802.16e standard and a subset of the WiMAX Forum™ Mobile System Profile specification. It was developed to upgrade the current airport surface communication systems.

It is specified in [61] and [62], and further discussed in [63].

AeroMACS is based on the IEEE 802.16-2009 standard, Part 16: Air Interface for Broadband Wireless Access Systems.<sup>3</sup> This standard is well suited for implementation below 11-GHz. The amendment for mobility uses 512 sub-carrier (in 5-MHz channel) scalable orthogonal frequency division multiple access (S-OFDMA) modulation and supports multiple channel bandwidths from 1.25- to 20-MHz, with peak duplex data rates above 50-Mbps. Some of the features of the IEEE 802.16 mobile standard that makes it attractive for use on the airport surface are highlighted in below.

Mobility	Supports vehicle speeds of up to 120 km/hr , sufficient for aircraft taxiing and emergency surface vehicle speeds
Range	Covers up to ~10 km in line-of-sight (LOS) communications, sufficient to cover most airports
Link obstruction Tolerance	Exploits multipath to enable non line-of-sight (NLOS) communications
Quality of Service (QoS)	Enables QoS based on throughput rate, packet error rate deletion, scheduling, time delay and jitter, resource management
Scalability	Includes flexible bandwidth and channelization options to enables network growth on demand
Security	Includes mechanisms for authentication, authorization, encryption, digital certificates, and fast handovers
Privacy	Supports private Virtual Local Area Networks (VLANs)
Open Sourced	Leverages modern communications technologies and supports modern Internet-based network protocols
Cost Efficiency	Via commercial standards and components, industry capabilities, and reduced physical infrastructure

**Table 3: Features of IEEE 802.16 desirable for implementation of AeroMACS networks**

Since AeroMACS is based on a specific WiMAX Forum® profile of the IEEE 802.16 standard. This enables the aviation community to leverage extensive international standards collaboration and commercially-provided components and services. The AeroMACS profile closely follows the format and substance of profiles developed by the WiMAX Forum® for commercial and industrial use. The WiMAX Forum® is an industry consortium whose primary technical function is to develop the technical specifications underlying WiMAX Forum Certified™ products. An ad-hoc joint committee was established between RTCA SC-223 and the WiMAX Forum® in August, 2010, to facilitate development of an AeroMACS profile. The profile is expected to be incorporated as one of several WiMAX Forum Certified™ profiles.

In the U.S., an RTCA Special Committee on Airport Surface Wireless Communications, SC-223, was established in July 2009 to develop the AeroMACS profile and MOPS. The U.S. final draft profile was completed at the end of 2010. The AeroMACS profile and MOPS are developed in close coordination with EUROCAE Working Group WG-82 in Europe. Common AeroMACS standards in the U.S. and Europe are requested by ICAO in part to be responsive to the recommendation of ANC-11 for global interoperability and to help expedite ICAO approval of international AeroMACS standards



An AeroMACS based on the WiMAX™ standard for local area networks can potentially support a wide variety of data, video, and voice communications and information exchanges among mobile users at the airport. The airport Communications, Navigation, and Surveillance (CNS) infrastructure that supports Air Traffic Management (ATM) and Air Traffic Control (ATC) on the airport surface can also benefit from secure wireless communications with improved availability and diversity. A wideband communications network can enable sharing of graphical data and near real-time video to significantly increase situational awareness, improve surface traffic movement to reduce congestion and delays, and help prevent runway incursions. AeroMACS can provide temporary communications capabilities during construction or outages, and reduce the cost of connectivity. A broadband wireless communications system like AeroMACS can enhance collaborative decision making, ease updating of large databases, provide up-to-date weather graphics and aeronautical information (Aeronautical Information and Meteorological Services), and enable aircraft access to System Wide Information Management (SWIM) services and delivery of time-critical advisory information to the cockpit.

## Operational Application

The community of potential AeroMACS users in an airport environment varies with the size of the airport facility. Airport Authority, Airlines and Civil Aviation Authority are principal airport tenants that deliver services and have a need to transport application information over a wireless network. User applications for transport over AeroMACS have been classified in 5 different functional domain categories. The functional domains are:

- Air Traffic Management/Air Traffic Control
- Aeronautical Information Services and Meteorological Data (AIS/MET)
- Aircraft Owner / Operator
- Airport Authority
- Airport Infrastructure

Applications identified and categorized in these 5 domains may have different performance characteristics, security needs, and quality of service requirements. The type of information content for each application ranges from live video streaming to low throughput system monitoring data exchanges. Several applications belonging to different functional domains have been identified for consideration. Following is a sample of potential applications that can be transported over AeroMACS. Digital Notice to Airmen (D-NOTAM), the next generation NOTAM, are created and transmitted by government agencies to alert pilots of hazards in the NAS. D-NOTAM has been identified as a strong candidate application for transport over AeroMACS. Digital Taxi-Graphical and digital Air Traffic Information System (D-ATIS) are applications that are currently transported using ACARS. Both D\_Taxi and D-ATIS have been noted as candidates for implementation over AeroMACS. Future applications such as 4D Trajectory Data Link (4DTRAD) leverage advanced avionics to manage the end-to-end aircraft trajectory. 4DTRAD for surface movement application is under consideration for transport over the AeroMACS network. Airport Infrastructure equipment such Airport Surface Detection Equipment (ASDE-X) has long been identified as an application that could benefit from a wireless communications technology.

Mobile stations support both mobile and stationary applications on the airport surface. The following sections describe some potential examples of each. Operation in the RF Physical domain will be identical for all mobile stations.

### *Mobile Applications Examples*

- ATC Communications with any aircraft anywhere on the airport surface.
  - ATC communications with any vehicle in the airport movement area (runway and taxiways)
  - Tower Data Link System (TDLS) for flight clearances
  - Loading FMS via CMU with 4D trajectories and modifications
- AOC, Advisory, and non-ATS voice/data between airlines and pilot
  - Collaborative decision making and 4D trajectory negotiations
  - EFB data, GPS and AIS updates; hazards advisories; NOTAMS
  - Surface management, gate and ramp control
  - Graphical weather corresponding to 4D trajectory
- Mobile SWIM and airport surface users 31
  - Publish and subscribe; receive/“listen” only
  - Fire, safety, snow removal, de-icing (in movement area)
  - Airport operations security; security video from cockpit and cabin

### **Operational Goals**

The operational goal of the AeroMACS system is to provide advanced data communication means to augment the current existing capabilities on the airport surface

### **Main Characteristics**

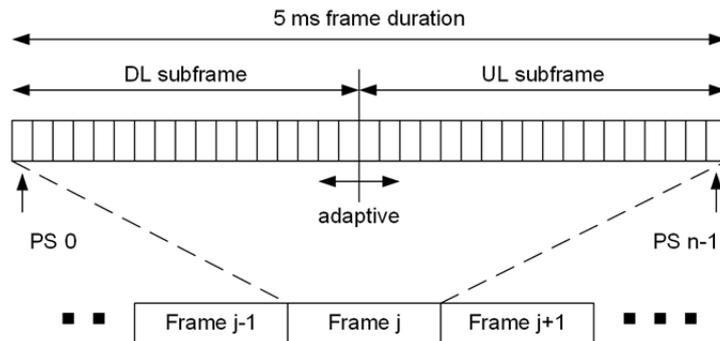
- Air-Ground and Ground-Ground communication within close proximity of an airport
- Subset of the WiMAX Forum™ Mobile System Profile specification which is a profile based on the IEEE 802.16e standard.
- Deployed in the protected aviation spectrum band from 5000 MHz to 5150 MHz with 5 MHz wide channels and a reference channel at 5145 MHz.
- Orthogonal Frequency-Division Multiple Access (OFDMA) digital modulation with Time Division Duplexing (TDD).

### **Maturity**

AeroMACS is based on the mature WiMAX standard and the AeroMACS minimum operational performance standards (MOPS) as well as the AeroMACS profile document have been jointly developed by the Radio Technical Commission for Aeronautics (RTCA) and the European organization for Civil Aviation Equipment (EUROCAE). The International Civil Aviation Organization (ICAO) has approved the standards and recommended practices (SARPS) as well.

### Physical Layer

The AeroMACS physical layer is based on the orthogonal frequency-division multiple access (OFDMA) physical layer specification of the IEEE 802.16 standard with a channel bandwidth of 5 MHz. As time division multiplexing (TDD) is used, base station to mobile station (uplink: UL) and mobile station to base station (downlink: DL) resources can be allocated dynamically (see Figure 28).

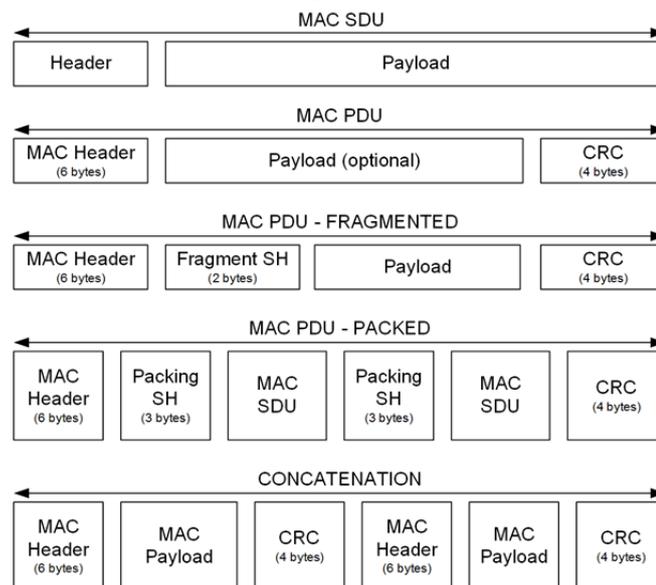


**Figure 22: AeroMACS frame with adaptive DL/UL subframe width [62]**

The 802.16 standard supports several coding and modulation schemes which determine throughput and robustness of the radio link. Combined with the dynamic DL/UL resource allocation, various bandwidths can be achieved.

### Data Link Layer

The IEEE 802.16 standard allows for implementing quality of service (QoS) at MAC level as well as several ways of fragmenting and reassembling MAC Service Data Units (SDUs). Within the AeroMACS profile, a variable length of MAC SDUs are allowed (see Figure 23).



**Figure 23: AeroMACS MAC PDU formats [63]**

## Applications

AeroMACS was designed for airport surface communication systems including air traffic control (ATC), air traffic management (ATM), airline operations applications such as aeronautical operational control (AOC) messages and airport infrastructure applications.

## Suitability for the rail domain

It should be noted that AeroMACS is a specific profile adaptation to the aeronautical domain for communications between ground infrastructure and mobile stations (e.g. aircraft), especially at airports, but the underlying WiMax communication standard (IEEE 802.16) could be also adapted to support train/ground communications in the area of railway stations or even for usage on-board of trains.

Detailed simulations modelling train movements and related communications would be required – taking into account appropriate radio channel propagation and terrain/obstacle models – to evaluate the suitability of WiMax / IEEE 802.16 standard for the rail domain.

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### 3.3.4 Satellite Communication

The European Space Agency (ESA) has a program called ‘ARTES 10 – IRIS’, with the goal to provide future satellite-based communication for European air traffic management (ATM). The main goal of this program is to enable 4D trajectory management via satellite for oceanic and continental airspaces. It is developed in close collaboration with the Single European Sky ATM Research Programme (SESAR), led by the European Union and EUROCONTROL.

#### Main Characteristics

- Satellite-based air traffic management
- Under development for future air traffic management (ATM)
- Enhances management of continental as well as oceanic airspaces

#### Maturity

The deployment of a first precursor is planned for 2018.

#### Applications

Future air traffic management (ATM), 4D trajectory management and complementary communication links.

### Suitability for the rail domain

It should be noted that the ESA/Iris Precursor is a specific adaptation of satellite communications to the aeronautical domain for communications between ground infrastructure and mobile stations (e.g. aircraft), especially in oceanic, remote and polar (ORP) regions, but also as a redundancy / back-up network in case of network congestion and/or temporary failures of the terrestrial networks (e.g. VDL Mode 2, LDACS, AeroMACS, etc.).

Due to its expected general availability and coverage, satellite communication is assumed to be a very suitable technology – both for ground-to-train as well as for train-to-train communications.

Detailed simulations modelling train movements and related communications would be required – taking into account appropriate radio channel propagation and terrain models – to evaluate the suitability of satellite communication for the rail domain.

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## **3.4 SUITABILITY FOR THE RAILWAY DOMAIN**

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In difference to chapter 4, for aeronautics sector, suitability for railway domain has been indicated in each technology.

## 4. STATE OF THE ART IN INDUSTRY

In the last decade, Ethernet-based solutions have been generally adopted and standardized for real-time and even safety-critical applications in industrial environments (e.g. automotive industry and IEEE 802.1 TSN/AVG standard for driver assistance). Moreover, the introduction of Wide Area Network (WAN) and Personal Area Network (PAN)-based wireless technologies, stand-alone networks, and hybrid wireline-wireless solutions have been remarkable developments affecting factory automation and control. It has been in fact the control and automation sector that has witnessed the introduction and deployment of sophisticated large-scale Wireless Sensor Networks (WSN) on the factory floor, such as WISA, ABB’s proprietary solution. The industrial control and automation sector has also invested in the development and standardization of new wireless solutions, such as WirelessHART, ISA 100.11a or WIA-PA, aiming at process automation to support non-critical monitoring and control functions with the prospect of addressing safety-critical applications in future releases.

### 4.1 RADIO TECHNOLOGIES FOR EMBEDDED SYSTEMS INTO THE FACTORY

Wireless communication systems in factories have been used mainly for Industrial Automation Applications (IAA) [66][67]. This type of applications can be subdivided in two main areas (although very often a combination of both is needed):

- *Process Automation:* refers to continuous production processes (e.g. chemical industry, oil and gas, paper, etc), where analog signals are mainly used for controlling the process. They require deterministic behaviour, but latencies can be in the range of a second (soft real time). This would be the application area for standards such as WirelessHART and ISA 100.11a.
- *Factory Automation:* this refers to discrete manufacturing processes (i.e. products that are made in many discrete steps, such as automotive assembly lines, food and medical industries, etc). In this case, digital signals are used for controlling the manufacturing process. They require determinism and low latency, and they include hard real time, closed-loop control applications, and even isochronous real time (hard real time with jitter constraints). Standards such as WSA would fall into this area.

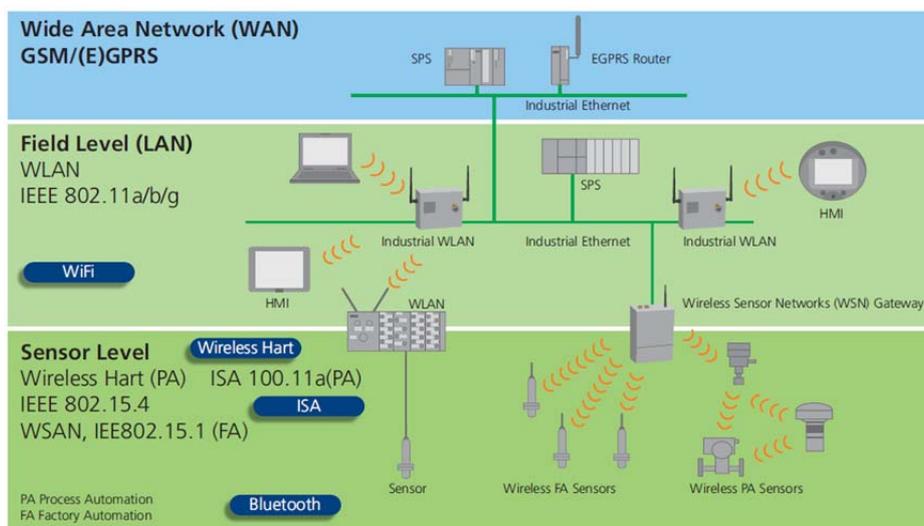
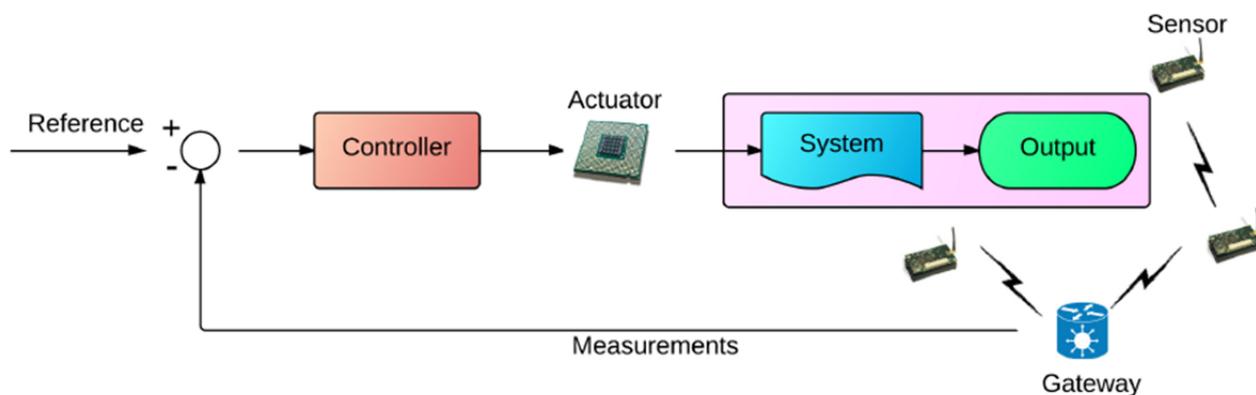


Figure 24: Wireless technologies in industrial applications [66]

According to the International Society of Automation (ISA), the industrial systems can be classified into six classes based on criticality of data and operational requirements. These classes range from critical control systems to monitoring systems, and their operational requirements and criticality vary accordingly. These six classes are:

1. *Safety systems.* Systems where immediate (in the order of ms or s) action on events is required in the order of seconds, belong to this class e.g. fire alarm systems. The WSN nodes are deployed uniformly throughout the area of concern to cover the entire area. The nodes are usually stationary.
2. *Closed loop regulatory systems.* Control system where feedbacks are used to regulate the system. WSN nodes are deployed in the area of concern in a desired topology. Periodically and based on events, measurements are sent to the controller. Periodic measurements are critical for the smooth operation of the system. These systems may have timing requirements that are stricter than safety systems. Based on these measurements, controller makes a decision and sends it to the actuators which act on this data. Due to its strict requirements, a new protocol suite is proposed for this class of systems. A simple control loop with wireless sensors and an actuator is shown in 29.
3. *Closed loop supervisory systems.* Similar to regulatory systems with the difference that feedbacks/measurements are not expected periodically but can be based on certain events. The feedbacks are non-critical e.g. a supervisory system that collects statistical data and reacts only when certain trends are observed, which can be related to an event.
4. *Open loop control systems.* Control systems operated by a human operator, where a WSN is responsible for data collection and relaying the collected data to the central database. The operator analyzes this data and undertakes any measures if required.
5. *Alerting systems.* Systems with regular/event-based alerting. An example is a WSN for continuous monitoring of temperature in a furnace and alerting at different stages, to indicate part of the work done.
6. *Information gathering systems.* System used for data collection and data forwarding to a server. An example could be WSN nodes deployed in a field to gather data about the area of interest, such as temperature and moisture, for a specific duration of time. This data gathered over a long period can then be used to decide on long term plans for managing temperature and moisture.



**Figure 29: Wireless closed loop control**



When classifying industrial applications with respect to their real-time characteristics, most applications in process automation are representatives of the class of soft real-time. Otherwise, closed-loop control applications belong to the class of hard real-time, i.e. given temporal deadlines have to be strictly met, or isochronous real-time, i.e. hard real-time plus additional constraints on the jitter.

The design of a hard real-time system, which always must produce the results at the correct instant, is fundamentally different from the design of a soft-real time or an on-line system, such as a transaction processing system. Table 4 compares the characteristics of hard real-time systems versus soft real-time systems.

Characteristic	Hard real-time	Soft real-time (on-line)
Response time	Hard-required	Soft-desired
Peak-load performance	Predictable	Degraded
Control of pace	Environment	Computer
Safety	Often critical	Non-critical
Size of data files	Small/medium	Large
Redundancy type	Active	Checkpoint-recovery
Data integrity	Short-term	Long-term
Error detection	Autonomous	User assisted

**Table 4: Hard real-time versus soft real-time systems [68]**

1. *Response Time.* The demanding response time requirements of hard real-time applications, often in the order of milliseconds or less, preclude direct human intervention during normal operation or in critical situations. A hard real-time system must be highly autonomous to maintain safe operation of the process. In contrast, the response time requirements of soft real-time and on-line systems are often in the order of seconds. Furthermore, if a deadline is missed in a soft real-time system, no catastrophe can result.
2. *Peak-load Performance.* In a hard real-time system, the peak-load scenario must be well defined. It must be guaranteed by design that the computer system meets the specified deadlines in all situations, since the utility of many hard real-time applications depends on their predictable performance during rare event scenarios leading to a peak load. This is in contrast to the situation in a soft-real time system, where the average performance is important, and a degraded operation in a rarely occurring peak load case is tolerated for economic reasons.
3. *Control of Pace.* A hard real-time computer system is often paced by the state changes occurring in the environment. It must keep up with the state of the environment (the controlled object and the human operator) under all circumstances. This is in contrast to an on-line system, which can exercise some control over the environment in case it cannot process the offered load.
4. *Safety.* The safety criticality of many real-time applications has a number of consequences for the system designer. In particular, error detection and recovery must be autonomous such that the system can initiate appropriate recovery actions and arrive at a safe state within the time intervals dictated by the application without human intervention.
5. *Size of Data Files.* The real-time database that is composed of the temporally accurate images of the RT-entities is normally of small size. The key concern in hard real-time systems is on the short-term temporal accuracy of the real-time database that is invalidated by the flow of real-time. In contrast, in on-line transaction processing systems, the maintenance of the long-term integrity and availability of large data files is the key issue.
6. *Redundancy Type.* After an error has been detected in an on-line system, the computation is rolled back to a previously established checkpoint to initiate a recovery action. In hard real-time systems, roll-back/recovery is of limited utility.



The requirements for the communication infrastructure of a real-time system follow from the discussion about the properties of real-time data. These requirements are substantially different from the requirements of non-real-time communication services.

1. *Timeliness.* The most important difference between a real-time communication system and a non-real-time communication system is the requirement for short message-transport latency and minimal jitter. The communication system must provide accurate instants on a common timebase.
2. *Communication Reliability.* In real-time communication, the use of robust channel encoding, the use of error-correcting codes for forward error correction, or the deployment of diffusion based algorithms, where replicated copies of a message are sent on diverse channels (e.g., frequency hopping in wireless systems), possibly at different times, are the techniques of choice for improving the communication reliability. In many non-real-time communication systems, reliability is achieved by time redundancy, i.e., a lost message is retransmitted. This tradeoff between time and reliability increases the jitter significantly. The black-channel principle can be applied: the transmission channel is regarded as unsafe and must be supervised by a mechanism developed according to the procedures of IEC 61508. Packet Loss Rate  $<10^{-9}$  for field-level applications in factory automation.
3. *Temporal Fault Containment of Components.* It is impossible to maintain the communication among the correct components using a shared communication channel if the temporal errors caused by a faulty component are not contained. A shared communication channel must erect temporal firewalls that contain the temporal faults of a component, so that the communication among the components that are not directly affected by the faulty component is not compromised. This requires that the communication system holds information about the intended (permitted) temporal behavior of a component and can disconnect a component that violates its temporal specification. If this requirement is not met, a faulty component can block the communication among the correct components.
4. *Error Detection.* A message is an atomic unit that either arrives correctly or not at all. To detect if a message has been corrupted during transport, every message is required to contain a CRC field of redundant information so the receiver can validate the correctness of the data field. In a real-time system, the detection of a corrupted message or of message loss by the receiver is of particular concern.
5. *End-to-End Acknowledgment.* End-to-end acknowledgement about the success or failure of a distributed action is needed in any scenario where multiple nodes cooperate to achieve a desired result. In a real-time system, the definitive end-to-end acknowledgment about the ultimate success or failure of a communication action can come from a component that is different from the receiver of an outgoing message. An outgoing message to an actuator in the environment must cause some intended physical effect in the environment. A sensor component that is different from the actuator component monitors this intended physical effect. The result observed by this sensor component is the definite end-to-end acknowledgement of the outgoing message and the intended physical action.
6. *Determinism.* The behavior of the basic message transport service should be deterministic such that the order of messages is the same on all channels and the instants of message arrival of replicated messages that travel on redundant independent channels are close together. It can be defined as the capability of a system to provide guaranteed upper-bound deadlines for response time and transmission delay.
7. *Availability.* This requirement refers to the ability of a communication system to accomplish a dedicated data transmission regardless of channel conditions and unintended or interfering data traffic.

In order to ensure these requirements, there are supervision mechanism is a usually a so-called safety protocol (e.g. ProfiSafe, CIPSafety, OpenSafety, CANOpen Safety). The protocol checks constantly the already mentioned performance parameters of the transmission channel such as latency, synchronicity and reliability in form of packet loss and correct sequence numbering. If one of these performance rules is violated, the safety protocol detects it and switches the safety application into an unsafe or fail-safe state. However, when this happens, the availability of the application gets degraded. That means, when the transmission channel is unreliable, the safety application has a bad availability.

Sensor Network Applications	Delay	Range	Battery Lifetime	Update Frequency	Security level
<b>Monitoring and supervision</b>					
Vibration sensor	<i>s</i>	100 <i>m</i>	3 years	sec - days	low
Pressure sensor	<i>ms</i>	100 <i>m</i>	3 years	1 sec	low
Temperature sensor	<i>s</i>	100 <i>m</i>	3 years	5 sec	low
Gas detection sensor	<i>ms</i>	100 <i>m</i>	3 years	1 sec	low
<b>Closed loop control</b>					
Control valve	<i>ms</i>	100 <i>m</i>	> 5 years	10 – 500 <i>ms</i>	medium
Pressure sensor	<i>ms</i>	100 <i>m</i>	> 5 years	10 – 500 <i>ms</i>	medium
Temperature sensor	<i>ms</i>	100 <i>m</i>	> 5 years	500 <i>ms</i>	medium
Flow sensor	<i>ms</i>	100 <i>m</i>	> 5 years	10 – 500 <i>ms</i>	medium
Torque sensor	<i>ms</i>	100 <i>m</i>	> 5 years	10 – 500 <i>ms</i>	medium
Variable speed drive	<i>ms</i>	100 <i>m</i>	> 5 years	10 – 500 <i>ms</i>	medium
<b>Interlocking and Control</b>					
Proximity sensor	<i>ms</i>	100 <i>m</i>	> 5 years	10 – 250 <i>ms</i>	medium
Motor	<i>ms</i>	100 <i>m</i>	> 5 years	10 – 250 <i>ms</i>	medium
Valve	<i>ms</i>	100 <i>m</i>	> 5 years	10 – 250 <i>ms</i>	medium
Protection relays	<i>ms</i>	100 <i>m</i>	> 5 years	10 – 250 <i>ms</i>	medium

**Table 5: Typical Industrial wireless sensor and actuator network requirements [69]**

The Table 6 and Table 5 show communication requirements for different application groups.

Application area	Application	Max. transmission delay in ms	Update time in ms	Telegram loss rate or timeout*
Factory automation	Control** of machine and production cell „local“	10 .. 20	20 .. 30	< 10 <sup>-9</sup>
	Control in production hall „global“	20 .. 30	30 .. 100	< 10 <sup>-9</sup>
	Monitoring and diagnostics	> 100	> 500	10 <sup>-3</sup> - 10 <sup>-9</sup>
	Mobile operators, safety	10 .. 20	10 .. 30	< 10 <sup>-9</sup>
Process automation	Open-loop/ closed-loop control	50 .. 100	100 .. 5000	< 10 <sup>-4</sup>
	Operation „local“	> 100	< 1000	< 10 <sup>-3</sup>
	Monitoring and diagnostics	> 100	> 10000	< 10 <sup>-4</sup>

**Table 6: Time response requirements and packet loss rates [70]**



The MAC function is responsible for the medium access which controls most of the radio communication; hence it plays a vital role in increasing the energy efficiency and also in decreasing latency. Other functions like the routing function can considerably affect the energy efficiency, latency, and reliability. Transport protocols in WSNs are responsible for congestion control and loss recovery, with the aim of providing end-to-end packet delivery and hence increase reliability.

Medium Access Control (MAC) protocols are responsible for controlling the medium access and deciding the underlying schedule for communication among the sensor nodes. The schedule should be designed according to certain application specific requirements. The scheduling problem can be solved using numerous methods which can be classified into three main classes [71]: Fixed assignment, Demand assignment and Random access protocols.

Condition	TDMA	CSMA
Delay on High traffic load	Controllable	High (Owing to collisions)
Reliability	High	Low
Predictable performance	Yes	No
Throughput considering increasing traffic	Increases	Decreases for high traffic

**Table 7: Comparison of TDMA and CDMA performance [71]**

The main issues for industrial applications are reliability, predictability and delay sensitivity which can be addressed efficiently by TDMA schemes. TDMA with fixed slots is also more predictable than CSMA, which is a crucial element in selecting protocols for closed loop regulatory systems. TDMA has proved to achieve a high degree of reliability, since it is collision-free and predefined bandwidth allocation may be ensured. Although TDMA is energy efficient and collision-free, there are certain issues that require attention: synchronization and efficient slot allocation. Proper slot allocation techniques are required to ensure collision-free and interference-free channel access. TDMA also has issues in terms of scalability due to fixed time allocation and the requirement of time synchronization. In this context, we summarize the comparison between CSMA and TDMA in Table 7.

Name	WLAN	Bluetooth	WSAN-FA and WISA
max. gross system data rate	600 Mbps	3 Mbps	1 Mbps
network topology	star	star	star
nodes per network	(50)	7	120
min. cycle time $T_{cyc}$	(100 ms)	8.75 ms	10 ms

**Table 8: Comparison of wireless technologies in discrete factory automation [66]**

In order to give an insight into the performance of some wireless systems used in the discrete factory automation, the communication parameters of WLAN, Bluetooth, WSAF-FA and accordingly WISA are summarized in Table 8. In case specific values cannot be guaranteed by the wireless technology, estimations are given in parentheses. This table shows clearly, that WLAN provides very high data rates but can only support significantly large cycle times due to the CCA procedure. In contrast to this, Bluetooth achieves the shortest cycle times due to the TDMA medium access, but it offers only a very limited number of nodes per network. WSAF-FA supports a very low cycle time and a very high number of nodes per network, but can achieve only a low data rate. As a consequence, the discussed wireless technologies pose significant limitations for closed-loop control applications with very challenging requirements as listed in Table 6 and Table 5.

On the other hand, WirelessHART and ISA 100.11a adopt the complete IEEE 802.15.4 PHY layer, but they propose a new MAC layer which combines TDMA and channel hopping to control access to the network. Both WirelessHART and ISA 100.11a are mainly targeting applications such as condition monitoring which has quite relaxed requirements on latency. However, for more time critical applications it is likely that some improvements in current standards are needed.

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### 4.1.1 WIA-PA

Wireless Networks for Industrial Automation - Process automation (WIA-PA) is an industrial standard proposed by the Chinese Industrial Wireless Alliance. In 2011, the IEC approved the WIA-PA standard as a publicly available specification named IEC/PAS 62601. The aim was to design a high-reliability, energy efficient, and intelligent multi-hop WSN solution. It is fully compatible with the IEEE 802.15.4 standard and is designed to provide a self-organizing and self-healing mesh network that is reactive to dynamic change in network conditions. The MAC layer is IEEE 802.15.4 compatible and a mixed CSMA, TDMA, and FDMA technology is used for medium access. The network is composed by several routing devices (mesh topology), while the nodes around the routing device form an star topology network (see Figure 25).

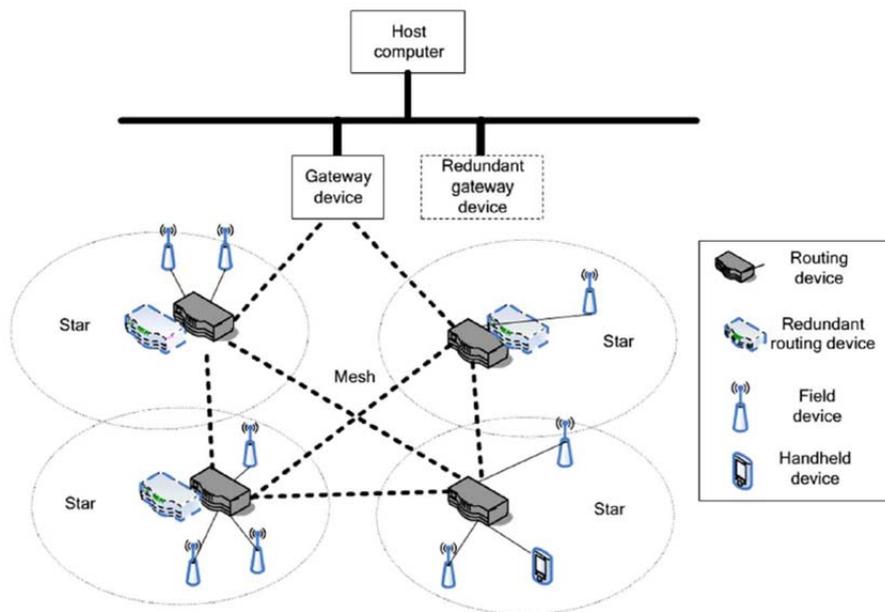


Figure 25: WIA-PA network topology

The frame structure is based on the beacon-enabled IEEE 802.15.4 superframe, as shown in the Figure 26. Devices that wish to communicate during the contention access period (CAP) must compete with other devices using a slotted CSMA-CA mechanism. On the other hand, a contention-free period (CFP) can be used for applications with restrictive requirements. Due to protocol limitations, the CFP has support for only seven timeslots. The WIA-PA superframe added other functions beyond the ones implemented in the IEEE standard. The joining process, intercluster management, and retransmissions occur in the CAP interval, where the MAC is based on CSMA-CA.

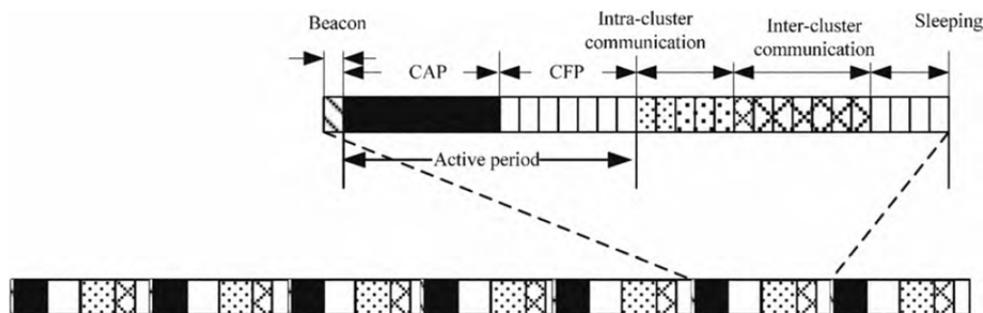


Figure 26: WIA-PA superframe structure



In order to improve the network reliability, it has 16 communication channels in the 2.4 GHz band and frequency hopping is supported. Three types of frequency hopping mechanisms are used: Adaptive Frequency Switch (AFS), Adaptive Frequency Hopping (AFH), and Timeslot hopping (TH). The hopping pattern AFS is used during the transmission of beacons, CAP and CFP. In the pattern, all the devices use the same communication channel. If the channel suffers some interference, the system configures the devices to use another channel.

The hopping pattern AFH is used during the intracluster communication, where the changes of channels occur irregularly depending on the actual channel condition. A channel is considered bad if the retry times in that channel reaches a threshold. When the sender device identifies that the current channel is bad, it chooses the next channel in the list. Thus, in the next retry timeslot, the sender notifies the receiver using the same bad channel. If the notification is not received, the receiver device will naturally increment its packet loss rate to that channel. After the threshold of packet loss rate is reached, the receiver device chooses the next channel in the list. On the other hand, if the receiver receives the notification (in the next retry timeslot), the channel is changed and an acknowledge packet (ACK) is sent to the sender device.

Finally, the hopping pattern TH is used during intercluster communication, where the channels are changed per timeslot. This is used to combat interference and fading. The jump sequence is not defined in the standard.

From the application point of view, the standard defines three application modes:

- P/S: used for periodic data
- R/S: used for aperiodic events
- C/S: used for aperiodic and dynamic unicast messages

In the P/S mode, the published sends data periodically according to its update rate. Alternatively, in the R/S mode, a report source sends aperiodic alarms or events to the gateway. It is mandatory to send an ACK to the report source. On the other hand, in the C/S mode, the client sends read or write requests to the server. The latter one should execute the request and send to the client the respective confirmation. The C/S is used for end-to-end retransmission, unicast messages in the intercluster communication, and during the CAP.

Being an industrial communication standard, the WIA-PA must guarantee the support for critical application. In general, such applications have stringent dependability requirements, as a system security failure may result in economic losses, put people in danger, or lead to environment damages. WIA-PA implements network security in the several levels. The data confidentiality is guaranteed using symmetric keys to encrypt and decrypt the payload of packets. Security keys are also adopted to guarantee device authentication, for example, during the join process.

### 4.1.2 WISA / WSAF

Wireless Interface for Sensors and Actuators (WISA) from ABB company, or Wireless Sensor-Actuator Network Factory Automation (WSAN-FA) as a Profibus-Profinet standard, has been designed for local use in control loops in factory automation. It is based on the physical layer of the IEEE 802.15.1 standard (Bluetooth), and also uses 79 hopping frequencies with a bandwidth of 1 MHz. WISA uses a frequency hopping spread spectrum with a time frame of 2 ms optimized for WLAN and ZigBee and also a large minimum hop width in order to hop reliably out of frequency bands which are already used or faulty. It provides improved synchronization by Frequency Hopping Multiple Access, which is a combination of TDMA and Frequency Hopping, but often imprecisely referred to as FHSS. In addition, the system implements a Frequency Division Duplex (FDD) mechanism in order to transmit in four simultaneous frequency channels (Figure 28). This system is especially designed for the need of factory automation on sensor actuator level and uses the data format according to the IO-Link standard[1].

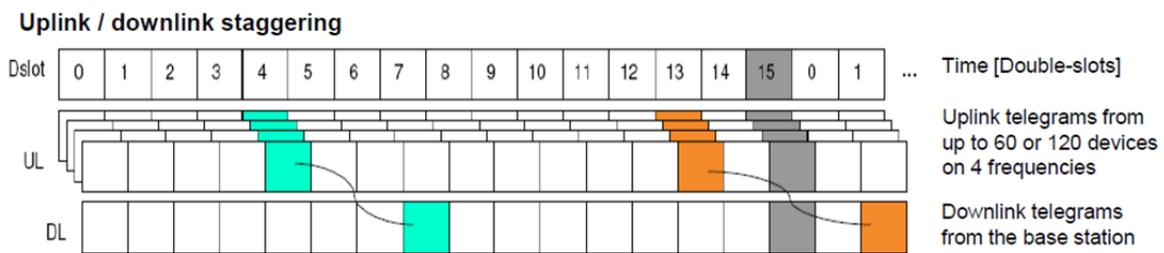


Figure 27: WISA/WSAN-FA frame definition

Up to 120 nodes, in star topology, can communicate in the 2:4 ms time frame without time overlapping. The Figure 28 shows the format of two different messages. To achieve a high reliability, four retransmissions on different frequencies are performed, which yields a system cycle time of  $T_{cyc} = 10$  ms. WSAF-FA provides blacklisting to exclude channels from frequency hopping to enable coexistence with other systems.

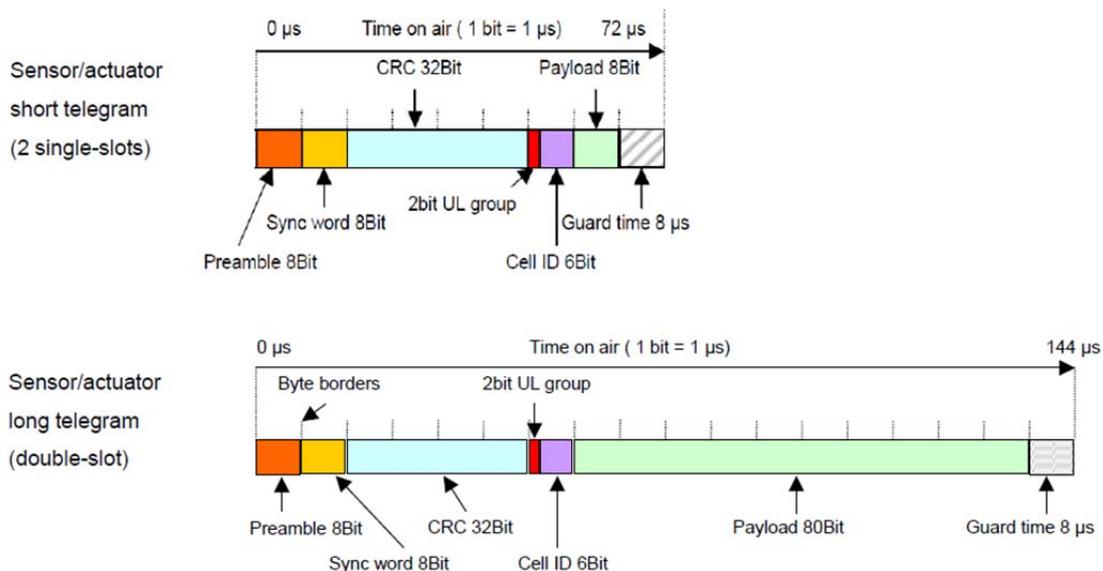


Figure 28: WISA/WSAN-FA telegram definition

Figure 29 summarizes the requirements and characteristics of a WISA/WSAN-FA network. WISA works with a fixed, small transmit power of 1 mW in order to apply many small radio cells to access any number of radio nodes in a factory hall. Characteristics of WISA are its low energy consumption and a rugged and deterministic response, independent of the number of nodes.

Requirement	Max.
Wireless devices per application per 1 WSAN System	300 (100*)
Overlapping WSAN Systems	5
Range	10 (30) m
Paket loss rate	< 10E-9
Delay max. [ms]	10 ms *

Figure 29: WISA/WSAN-FA characteristics

Currently, WSAN-FA is the only open standard optimized for the requirements of the sensor actuator level and seems to come close to the performance requirements for closed-loop applications. Beyond this, WSAN-FA has still some optimization potential regarding performance characteristics [1].

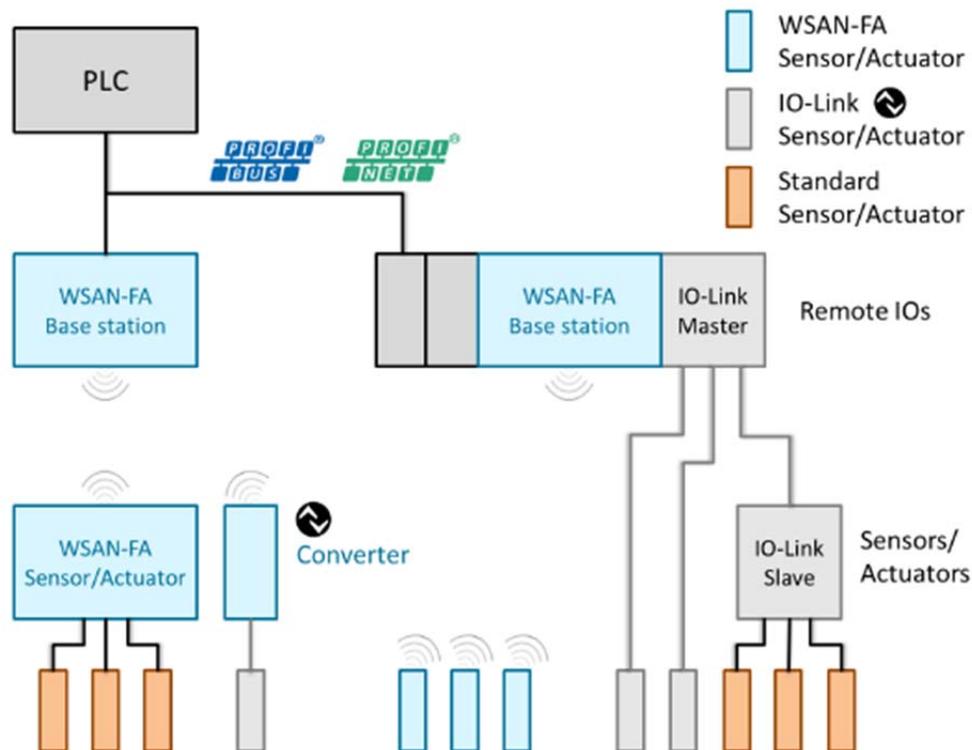
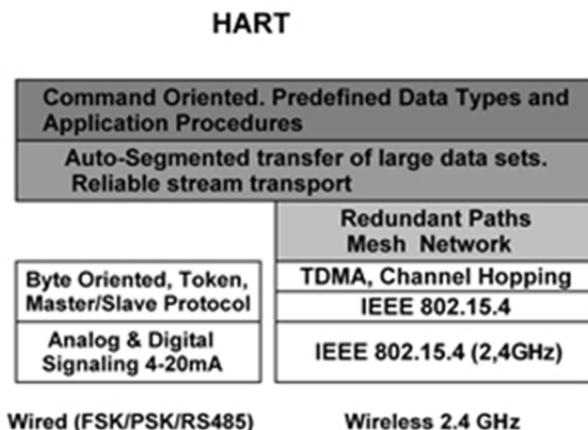


Figure 30: WISA/WSAN-FA network

### 4.1.3 WirelessHART

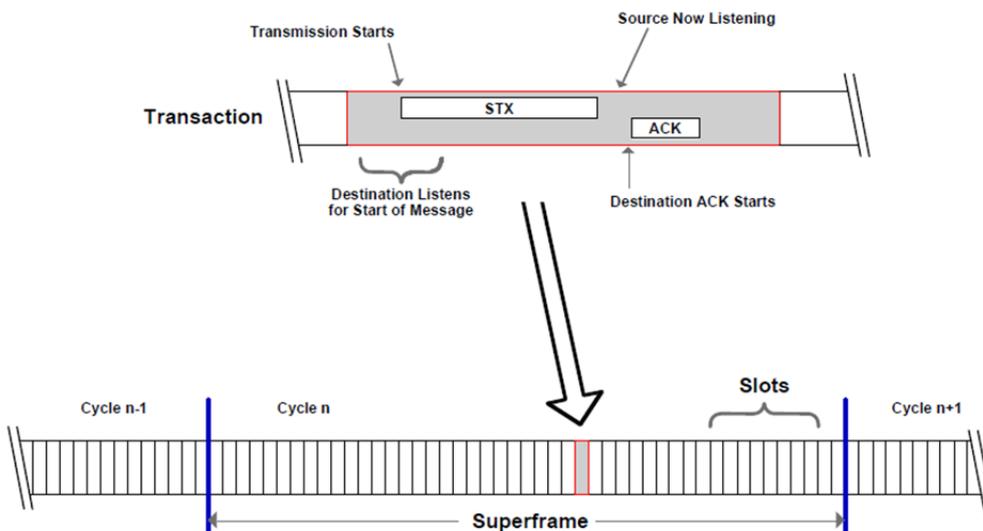
WirelessHART is based on the IEEE 802.15.4 physical layer, with an operation frequency of 2.4GHz, and uses 15 different channels. Figure 31 shows the OSI layers of WirelessHART.



**Figure 31: OSI layers of WirelessHART [72]**

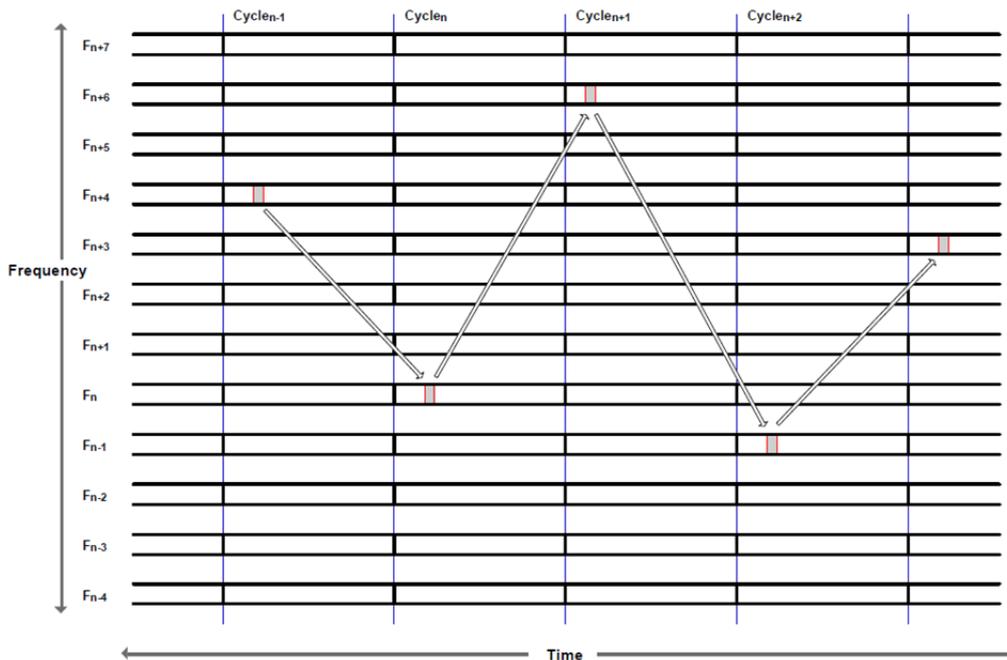
This standard uses the Time Synchronized Mesh Protocol (TSMP), which was developed by Dust Networks for medium access control and network layer functions. TSMP uses TDMA for channel access and allows channel hopping and channel blacklisting at the network layer:

- TDMA:** Figure 32 details the TDMA scheme used by WirelessHART. It is based on superframes divided in timeslots with a duration of 10 ms, where both data and acknowledgments are exchanged. Each timeslot can be allocated to a specific node or it can be shared by several nodes by means of a CSMA/CA mechanism. Whenever an acknowledgment is not received, the message is sent again through alternative paths, and always at a different frequency channel.



**Figure 32: TDMA scheme**

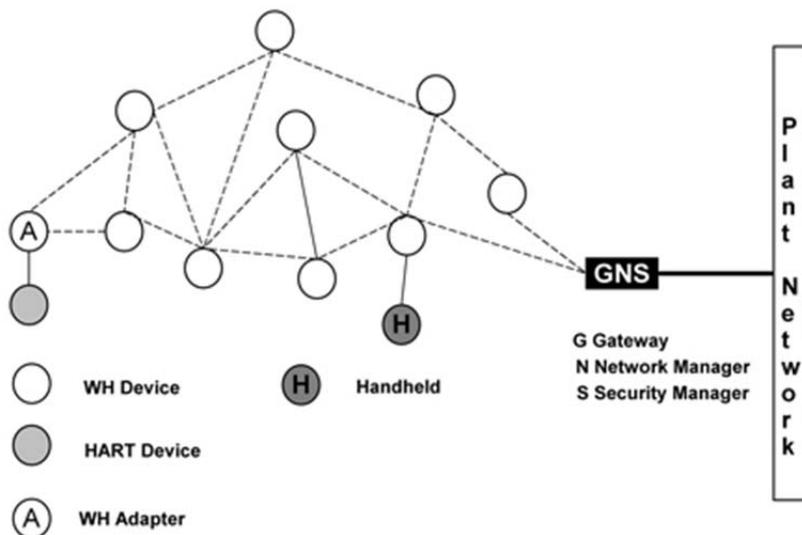
- Channel hopping** is a technique in which data transfer happens at different frequencies at different periods of time. WirelessHART standard supports up to 15 channels which are used in turns. Figure 33 shows an example of this hopping scheme.



**Figure 33: Frequency hopping scheme in WirelessHART**

- *Channel blacklisting* is a process of avoiding channels which exhibit large interference with the signals. The use of TDMA with channel hopping and channel blacklisting decreases the effect of interferences and noise.

Regarding network topologies, WirelessHART supports star and mesh topologies with redundant routing in order to enhance reliability. All nodes in a WirelessHART networks are routing devices. Figure 34 shows an example of this type of networks.



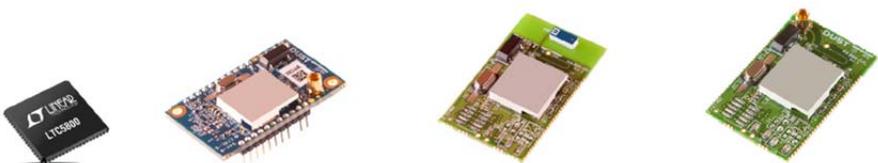
**Figure 34: WirelessHART network topology [72]**

WirelessHART is thus considered to be robust, energy efficient and reliable, but since this is still an emerging standard, there is a lot of scope for improvement. WirelessHART was designed, developed and standardized with industrial systems in mind and supports legacy systems built on wired HART.

Regarding implementations of WirelessHART, Nivis [73] provides a free and open-source WirelessHART implementation for their RF modules (Figure 35), while Witeck Consortium [74] offers a licensed implementation. There are also off-the-shelf WirelessHART RF modules, such as those provided by Linear Technology, formerly Dust Networks (see Figure 36) [75].



Figure 35: VersaNode 210 and VersaNode 310 modules by Nivis [73]



Part Number	Operating Temp Range <sup>1</sup>	Package (mm × mm)	Supply Voltage Range (V)	Antenna Connection	Radio Frequency (GHz)	RF Output Power (dBm)	Receive Sensitivity (dBm) <sup>2</sup>	RF Modular Certifications
LTC5800-WHM	I	QFN (10 × 10)	2.1 to 3.76	QFN Lead	2.4000 to 2.4835	8, 0 <sup>3</sup>	-93 <sup>3</sup>	NA
LTP5900-WHM (For Legacy Customers)	I	22-Pin PCBA (39 × 24.4)	2.75 to 3.76	MMCX Antenna Connector	2.4000 to 2.4835	8, 0 <sup>3</sup>	-93 <sup>3</sup>	USA, Canada, EU
LTP5901-WHM	I	Castellated PCBA (42 × 24)	2.1 to 3.76	Onboard Chip Antenna	2.4000 to 2.4835	10, 2 <sup>4</sup>	-95 <sup>4</sup>	USA, Canada, EU, Australia/New Zealand, India, Japan, Korea, Taiwan
LTP5902-WHM	I	Castellated PCBA (37.5 × 24)	2.1 to 3.76	MMCX Antenna Connector	2.4000 to 2.4835	8, 0 <sup>3</sup>	-93 <sup>3</sup>	USA, Canada, EU, Australia/New Zealand, India, Japan, Korea, Taiwan

Note 1: I Temperature Grade = -40 to 85°C  
 Note 2: PER = 1% per IEEE 802.15.4  
 Note 3: Conducted RF Output Power/Sensitivity  
 Note 4: Peak Radiated RF Output Power/Sensitivity via Integrated Antenna

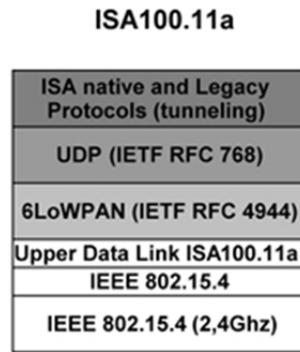
Figure 36: WirelessHART modules by Linear Technology [75]

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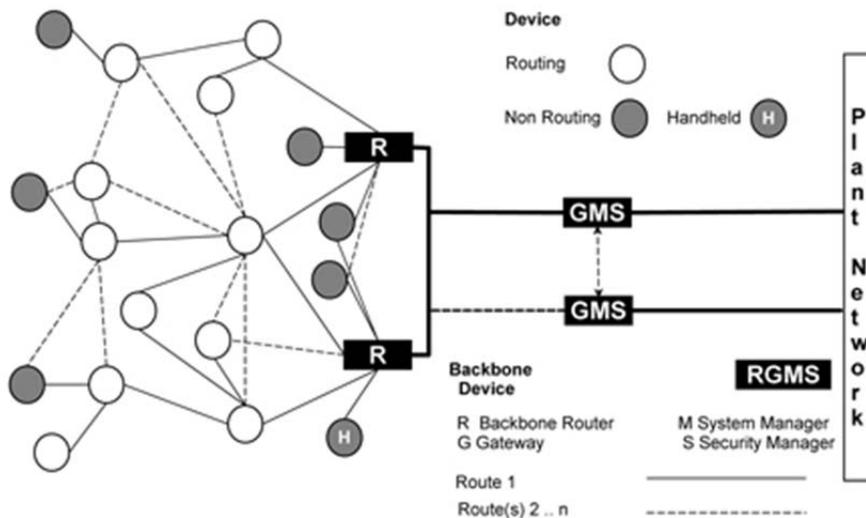
#### 4.1.4 ISA100.11a

The ISA100 working group developed the ISA 100.11a standard in order to provide robust and secure communications in process automation. Similarly to WirelessHART, the physical layer is based on the IEEE 802.15.4 standard. At the data link layer, it combines TDMA (with timeslots between 10 ms and 14 ms) and CSMA in order to capitalize on the advantages of both solutions. At the network layer, the compatibility with IPv6 gives opportunities for users to connect to the Internet, thus providing diverse possibilities. Figure 37 details the OSI layers of ISA 100.11a.



**Figure 37: OSI layers of ISA 100.11a [76]**

Similarly to WirelessHART, ISA100.11a uses channel hopping and channel blacklisting to reduce interference effects; however, ISA100.11a applies three different channel hopping methods: slow hopping, fast hopping, and mixed hopping. Regarding network topologies, as in WirelessHART, ISA100.11a supports Star and Mesh network topologies, and both routing and non-routing nodes can exist (Figure 38).



**Figure 38: ISA 100.11a network topology [76]**

Table 9 summarizes the main differences between ISA 100.11a and WirelessHART.



	WirelessHART	ISA 100 Wireless
Architecture	Access points Field devices (I/O and router, router)	Backbone router Field devices (I/O only, router, router and I/O) Multiple subnets
Physical layer	IEEE 802.15.4	IEEE 802.15.4
Data link layer	IEEE 802.15.4 + (TDMA, Channel hopping (1), mesh topology) Fixed time slot Priority levels (4)	IEEE 802.15.4 + (TDMA, Channel hopping (3), mesh topology) Configurable time slots Priority levels (2) subnets
Network layer	Based on HART 16- and 64-bits addressing	Based on IPv6 6LoWPAN (IETF RFC4944) 16-, 64- and 128-bits addressing
Transport layer	Auto-segmented transfer of large data sets, reliable stream transport	Connectionless service UDP (IETF RFC768) 6LoWPAN compatibility
Application layer	Command-oriented, Predefined data types, Support HART protocol	Object-oriented, Support legacy protocol (tunneling), QoS contracts
Real-time support	TDMA Priority levels (4)	TDMA Priority levels (2) QoS contracts

**Table 9: Differences between WirelessHART and ISA 100.11a**

Regarding implementations of ISA 100.11a, as with WirelessHART Nivis provides a free and open-source implementation of ISA 100.11a for their RF modules. On the other hand, Honeywell provides wireless solutions based on ISA 100.11a, known as *OneWireless* [77].

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**4.1.5 ISA100.12**

Based on the summary of state-of-the-art wireless standards we discuss some recent advances and current market share. Among all these standards, WirelessHART and ISA100.11a are the two major and dominating standards already in the market. GINSENG is relatively new and it has not yet been widely deployed. In spite of the competition, the Hart Communication Foundation (HCF) and International Society of Automation (ISA) have agreed to collaborate together to produce one single standard derived from WirelessHART and ISA100.11a. A subcommittee named ISA100.12 has been created to investigate the possibilities of convergence. The convergence could result in a global standard with positives of both these standards and improved IWSN solutions..

#### 4.1.6 WiFi

The IEEE 802.11 wireless LAN (WLAN) represents an interesting option for real-time industrial communication since, besides the known advantages of wireless networks, they can provide satisfactory performance for a wide range of applications. In particular, the IEEE 802.11n standard has proved to be an effective solution to the communication problems typical of industrial wireless networks where tight constraints in terms of both timeliness and reliability are often encountered. Furthermore, the recent IEEE 802.11n High Throughput (HT) amendment introduced several enhancements, at both the physical and MAC layers, which can be exploited to improve some significant performance figures for real-time networks, principally in terms of reliability and timeliness. The IEEE 802.11n amendment provides several improvements to the previous versions. In particular, it supports Multiple Input Multiple Output (MIMO) features, which allow for increased reliability, longer communication distances and higher transmission rates, while maintaining operations in the unlicensed 2.4 GHz and 5 GHz Instrumentation, Scientific and Medical (ISM) bands.

The IEEE 802.11n standard provides new and interesting features at the physical layer, which is a substantial re-design of the whole layer. Starting from the modulation and coding schemes (MCS), the set of available modulations has been slightly modified with respect to older versions of the standard, achieving an 11% increase in raw transmission rate, and also the number of subcarriers of the Orthogonal Frequency-Division Multiplexing (OFDM) modulation for 20 MHz channels has been increased from 48 to 52, yielding a further 8% rate improvement. Moreover, IEEE 802.11n makes available 40 MHz transmission channels, in both the 2.4 GHz and the 5 GHz frequency bands, as an alternative to basic 20 MHz ones, roughly allowing to double the transmission rate, reaching 130 Mbit/s. Finally, two other appealing features are worth mentioning, namely the reduction of the guard interval (GI) between two consecutive OFDM symbols from 800 ns to 400 ns (which raises the transmission rate to 150 Mbit/s), and the possibility of replacing classic convolutional codes with the more robust low-density parity-check (LDPC) ones.

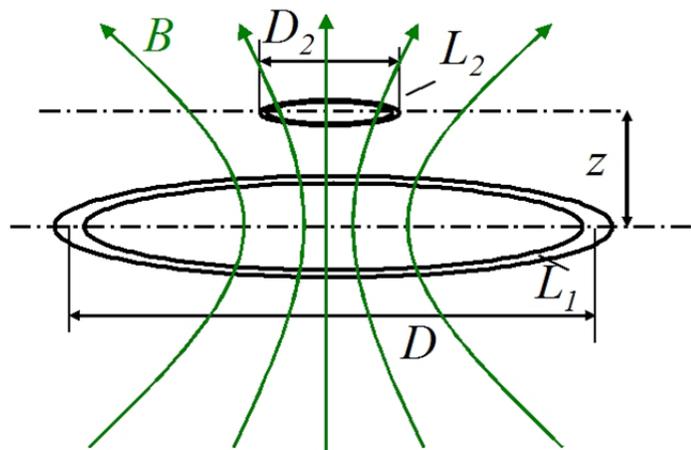
Concerning MIMO capabilities, the baseline scheme for the exploitation of a multi-antenna MIMO system is represented by Spatial Division Multiplexing (SDM), which consists in subdividing the payload in independent data streams, each assigned to a different transmit antenna. In this case, the raw transmission rate of the system at PHY layer increases with the number of independent data streams. The amendment defines at most a 4x4 system, with 4 transmitting and 4 receiving antennas, to reach the raw transmission speed of 600 Mbps. In addition, multiple antennas could alternatively be used to send redundant information with the aim of increasing communication reliability. To this purpose, a useful technique is Space-Time Block Coding (STBC), according to which consecutive OFDM symbols are opportunely encoded in time and sent over different antennas in order to maximize the decoding probability at the receiver, at the expense of the bitrate.

On the other hand, IEEE 802.11 operates mainly in the 2.4 GHz Industrial, Scientific and Medical (ISM) band, also adopted by other wireless technologies such as IEEE 802.15.4 and IEEE 802.15.1, likely resulting in coexistence problems and poor channel conditions. To avoid packet losses and ensure fair access to the medium, the Distributed Coordination Function (DCF) of the MAC sublayer adopts the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme. According to this strategy, devices use a combination of Carrier Sensing (CS) and random backoffs in order to minimize the collision probability.

Although CSMA/CA has proven to be effective in general purpose communication systems, its adoption in the industrial context can be actually detrimental rather than beneficial. Indeed, industrial traffic is often characterized by real-time requirements, such as low jitter on cyclic operations and bounded latency on alarm packets that, clearly, can be seriously compromised by latencies and randomness introduced by both CS and backoff. To cope with these issues, some available industrial communication protocols (e.g. Wireless HART and ISA100.11a based on IEEE 802.15.4) adopt high layers services to resolve contentions and transmission errors, for example exploiting a master-slave relationship in a polling or TDMA-based scheme: hence, distributed and stochastic channel access schemes do result unnecessary, if not dangerous, since they might downgrade the overall performance. Taking all this into account, there are several efforts around IEEE 802.11 in order to adapt its current MAC layer, so the communication system meets the real-time requirements.

### 4.1.7 Magnetic Induction

There are situations in industrial environments where power and/or data need to be transferred to rotating or moving elements (e.g. shaft monitoring, machine tool monitoring, etc). Conventional solutions for this kind of connections are based on sliding contacts, such as slip rings; however, these solutions tend to degrade quickly, reduce the reliability of the machine, and require expensive maintenance. Wireless links based on magnetic induction [5] are a solution for this kind of situations, as they allow contactless transfer of power and data over short distances taking advantage of the coupling between magnetic coils using alternating magnetic fields (Figure 39).



**Figure 39: Inductively-coupled power transfer system [6]**

The efficiency of the power transfer between coil/loop antennas is proportional to: the operating frequency, the number of windings, the area enclosed by the antennas, the angle of the two coils relative to each other, and the distance between them. Typical communication distances are between 15mm and 20 mm, although this depends on the size of the coils, the transmitted power, and the sensitivity of the receiver. This low range is because the magnetic field decreases at a rate of  $1/r^3$ ; however, a link with such a short range reduces potential coexistence issues.

Near-field magnetic links use carrier frequencies in the range of 20-200 kHz. This means that the available bandwidth is small, which allows low data-transfer rates (i.e. a few kbps). If high data rates are required, a second coil with higher resonance frequency needs to be added. On the other hand, loop antennas create high magnetic energy in their near field, and therefore they are suitable for communication through magnetic induction; however, due to the low frequencies of operation, these antennas become electrically small and therefore non-resonant, requiring an additional matching network in order to connect them to 50-ohm transceivers.

Manufacturers of inductive coupling solutions for industrial applications include: Omron [78], BALLUFF [79], PEPPERL+FUCHS [80] and TURCK [81] (Figure 40).



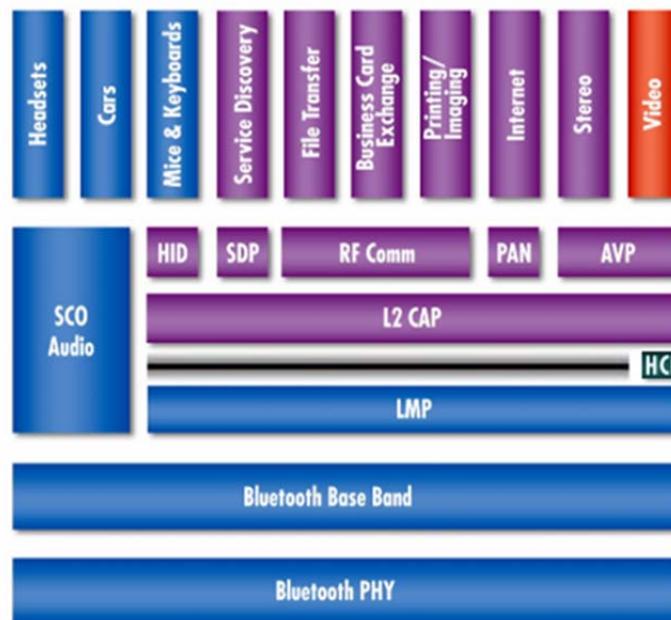
**Figure 40: Commercial inductive coupling solution for industrial applications [81]**

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### 4.1.8 Bluetooth

Bluetooth operates in the ISM band of 2.4 GHz, and uses 79 channels with 1 MHz spacing [82]. Figure 41 shows the protocol stack. Bluetooth has been standardized as IEEE 802.15.1 [83].



**Figure 41: Bluetooth stack**

The range of Bluetooth devices, as well as their transmitted power, depends on the *Class* they belong to (see Table 10).

Class	Maximum Output Power	Range
1	100 mW (20 dBm)	100 m
2	2.5 mW (4 dBm)	10 m
3	1 mW (0 dBm)	1 m

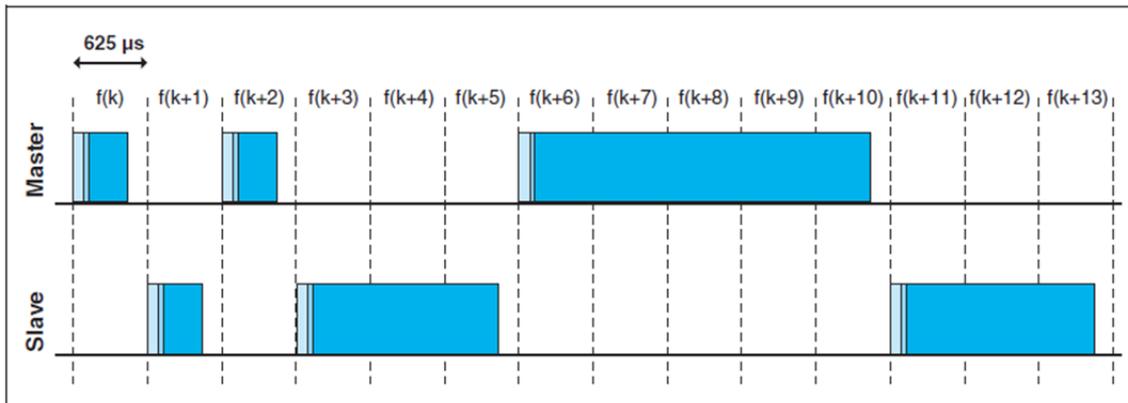
**Table 10: Bluetooth Device Classes**

Two different modulations are used in Bluetooth: Basic Rate (BR) and Enhanced Data Rate (EDR). Table 11 shows their main features. Even though the BR indicates a data rate of 1 Mbps, the actual maximum data rate is 721 kbps for asymmetric links (with a return channel of 56 kbps) and 432.6 kbps for symmetric links.

	BR	EDR	
Modulation	GFSK	$\pi/4$ -DQPSK	8DPSK
Symbol rate	1 Ms/s	1 Ms/s	1 Ms/s
Air data rate	1 Mbps	2 Mbps	3 Mbps

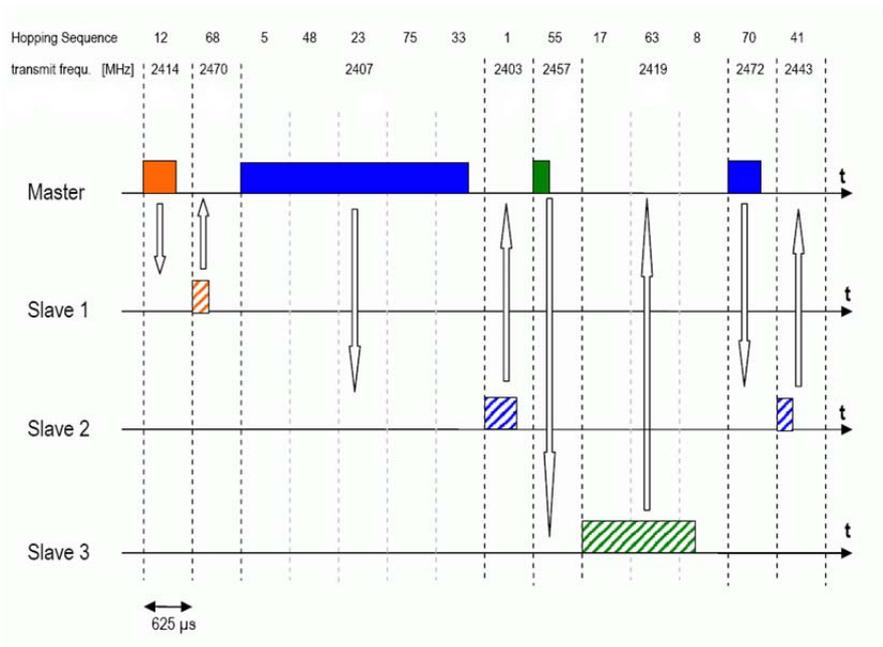
**Table 11: Bluetooth modulations and data rates**

The Bluetooth network topology follows a Master-Slave approach. Communications are divided in time-slots with a duration of 625  $\mu$ s, so that the available bandwidth is shared by the different slaves in the network (see Figure 42). This technique is called *Time Division Multiplexing (TDM)*. The Master is in charge of assigning the time-slots to the Slaves.



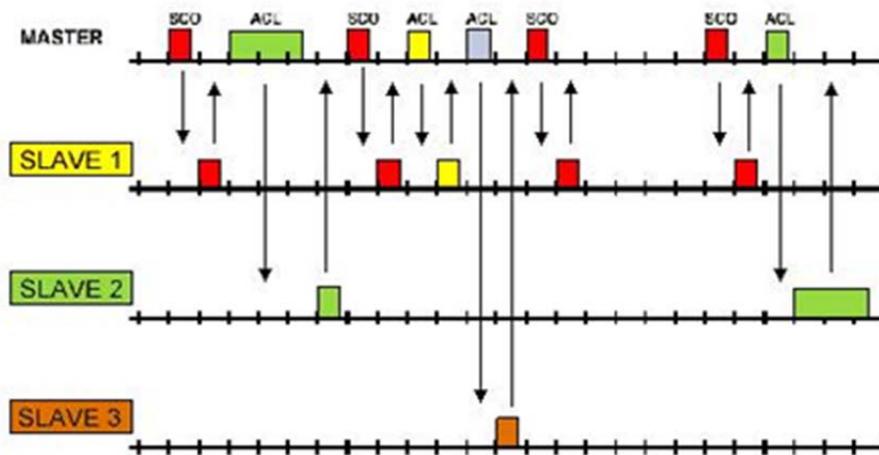
**Figure 42: Time Division Multiplexing in Bluetooth**

In order to avoid interference signals, Bluetooth uses Frequency Hopping Spread Spectrum (FHSS) techniques, allowing full-duplex communications with a maximum of 1600 hops per second (Figure 43). This means that in order to have a Bluetooth communication between two devices, they both need to follow the same frequency-hop pattern (i.e. the Slaves must synchronize to the pattern of the Master): each slave receives the address and clock value of the Master, and calculates the frequency-hopping pattern.



**Figure 43: FHSS in Bluetooth**

On the other hand, in Bluetooth information can be transferred in both synchronous and asynchronous modes (see Figure 44): the *Synchronous Connection Oriented (SCO)* mode is used mainly for voice transmission, while the *Asynchronous Connectionless (ACL)* mode is used for data transmission.



**Figure 44: Information transfer in Bluetooth**

Regarding network topologies, both point-to-point and point-to-multipoint topologies are supported in Bluetooth. Devices communicate through *piconets*; these networks may have up to 8 point-to-point connections. In a *piconet*, one device acts as the Master, while the rest act as Slaves. When devices of different *piconets* connect with each other, a so-called *scatternet* is created.

In order to improve the coexistence with other devices, Bluetooth includes the so-called *Adaptive Power Control (APC)*, which modifies the required output power to the value necessary to reach a specific receiver, and *Adaptive Frequency Hopping (AFH)*, which excludes from the frequency-hopping pattern those channels that the Master considers busy or too noisy. The minimum number of operational channels is 20.

The latest version of Bluetooth (v4.2) offers two wireless technologies: BR/EDR (Basic Rate / Enhanced Data Rate) and Bluetooth Low Energy (BLE) [84a]. BLE was created in order to support low-power devices with short data transfers. Those devices which communicate through *classic* Bluetooth and BLE (i.e. dual-mode devices) are called *Bluetooth Smart Ready*, while those which support only BLE (i.e. single-mode devices) are called *Bluetooth Smart*. An example of a *Bluetooth Smart Ready* device could be a laptop computer or a Smartphone, while a *Bluetooth Smart* device would be an equipment with critical low-power operation, such as those using coin cell batteries.

The main difference between the PHYs of Bluetooth and BLE is that BLE has a bit rate of 100 kbps and operates in 40 channels with spacing of 2 MHz (as opposed to the 1 Mbps, 79 channels and 1 MHz spacing of Bluetooth). These channels are separated into: three fixed channels for broadcasting, which avoid interference with IEEE 802.11 systems, and 37 channels which are switched by the FHSS mechanism (Figure 45).

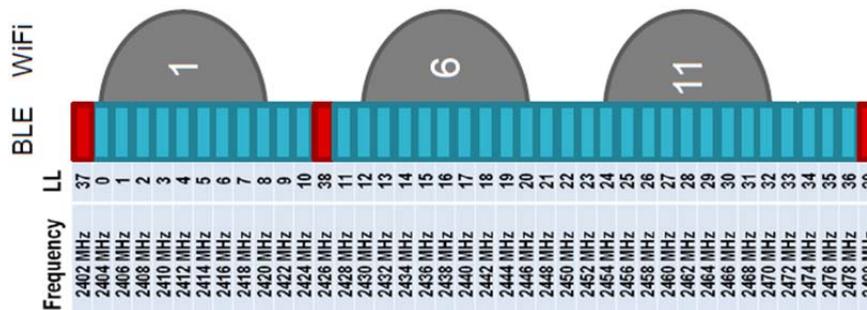


Figure 45: Channel distribution in BLE

Figure 46 shows the protocol stack of BLE, which is divided into two sections called *Controller* and *Host* (this separation is because in the initial Bluetooth devices these two parts were implemented in separate devices).

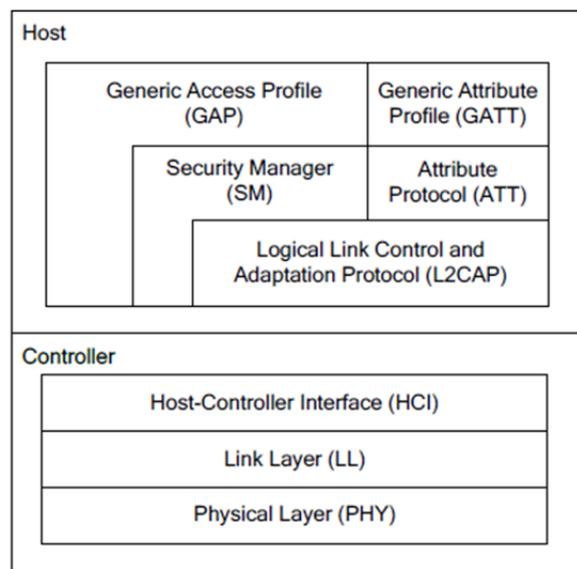


Figure 46: BLE protocol stack

There are several BLE ICs in the market, such as those provided by Nordic Semiconductor, ST Microelectronics or Texas Instruments.

Bluetooth offers interesting features for industrial communications, such as an adaptive FHSS scheme and the possibility of synchronous connections. However, it has some limitations regarding network topologies and configuration of the TDMA.

Bibliography of the paragraph

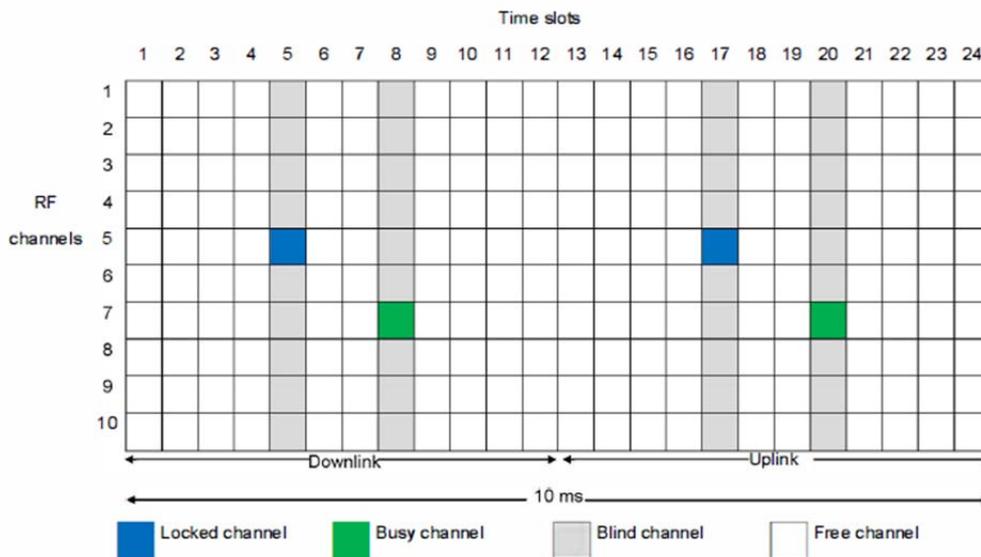
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### 4.1.9 DECT

DECT (Digital Enhanced Cordless Telecommunications) is a standard developed by the European Telecommunications Standards Institute (ETSI) in early 1988 [85a]. Primarily focused to cordless phones with a high energy consumption, a low-power version (DECT– Ultra Low Energy, DECT-ULE) was developed recently, which is suitable for industrial sensor networks [84].

A DECT network consists of a Fixed Part (FP), which provides wireless communication to the Portable Parts (PPs) by broadcasting beacons with system and access right information. The FP may consist of several Radio Fixed Parts (RFPs), which are typically connected between them through wires in order to keep a tight synchronization.

In Europe DECT occupies the licensed and royalty-free block of spectrum from 1880 MHz to 1900 MHz, divided into 10 carriers using the Frequency Division Multiple Access (FDMA). In each carrier, a Time Division Multiple Access – Time Division Duplex (TDMA-TDD) is used which provides 12 time slots for down-link and 12 time slots for up-link (i.e. 240 physical channels in total) with a total frame duration of 10 ms. However, an RFP with a single transceiver can only handle 12 simultaneous calls, as the radio cannot switch between frequencies in a time-slot; an example of this is depicted in Figure 47, where an RFP is busy on 2 channels (marked in blue and green), and therefore cannot communicate in the channels marked in grey (so-called *Blind* channels).



**Figure 47: DECT frequency/time spectrum [15]**

*Locked* channels are the ones where RFPs place their beacons. These channels are selected by the RFP after being powered on, as the channels which have the least interferences (i.e. lowest RSSI, as depicted in Figure 48).

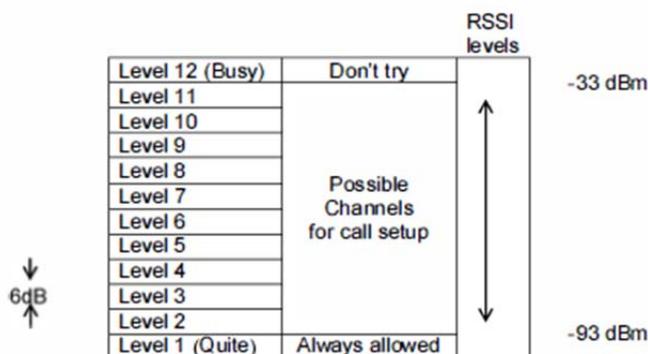


Figure 48: Chanel selection

On the other hand, the duration of a single time-slot will be  $10\text{ms}/24 = 416\mu\text{s}$ , which at a bit rate of 1.152 Mbps results on 468 bits (i.e. 58 bytes of data), which allows 40 bytes of user payload. This implies an effective bit-rate of 32 kbps; in order to allow a higher throughput, more than one time-slot will need to be allocated for a particular link (i.e. 0-32 kbps for one slot, 32-64 kbps for two slots, etc).

Table 12 shows a comparison of DECT with other wireless technologies used in Wireless Sensor Networks.

Radio technology	Operating frequency band	MAC-DLL mechanism	Range	Channel bandwidth	Supported number of devices	Maximum data rate	Modulation	Network architecture
WirelessHART	2400-2483.5 MHz	Channel hopping, blacklisting, TDMA	Indoors: 30m Outdoors: 90m	2 MHz	Hundred	250kbps	O-QPSK, DSSS	Star, Mesh
ISA 100.11a	2400-2483.5 MHz	CSMA/CA, channel hopping, blacklisting, superframe optimization	Indoors: 30m Outdoors: 90m	2 MHz	Hundreds	250kbps	O-QPSK, DSSS	Star, Mesh
ZigBee	868-868.6 <sup>a</sup> , 902-928 <sup>b</sup> , 2400-2483.5 MHz	CSMA/CA, beacon synchronization	Indoors: 30m Outdoors: 90m	0.6 <sup>c</sup> , 1.2 <sup>d</sup> , 2 <sup>e</sup> MHz	Thousands	20 <sup>c</sup> , 40 <sup>d</sup> , 250 <sup>e</sup> kbps	BPSK <sup>c,d</sup> , O-QPSK <sup>e</sup> , DSSS <sup>e</sup>	Tree, Star, Mesh
WiFi	2400-2483.5 <sup>g,h,i</sup> , 5150-5825 <sup>f</sup> MHz	CSMA	Indoors: 33m Outdoors: 95m	20 <sup>f,h,i</sup> , 22 <sup>g,h</sup> , 40 <sup>i</sup> MHz	Hundreds	11 <sup>g</sup> , 54 <sup>f,h</sup> , 150 <sup>i</sup> Mbps	DSSS <sup>g,h</sup> , OFDM <sup>f,h,i</sup>	Mesh
DECT	1880-1900 MHz	DCS, FDMA, TDMA-TDD	Indoors: 75m Outdoors: 300m	1.728 MHz	Thousands	1.152 Mbps	GFSK	Star, Tree

<sup>a</sup>Only allowed in Europe; <sup>b</sup>only allowed in North America; <sup>c</sup>in case of 868 MHz channel; <sup>d</sup>in case of 915 MHz channel; <sup>e</sup>in case of 2450 MHz channel; <sup>f</sup>in case of IEEE 802.11a; <sup>g</sup>in case of IEEE 802.11b; <sup>h</sup>in case of IEEE 802.11g; <sup>i</sup>in case of IEEE 802.11n.

Table 12: Performance comparison of DECT with other wireless technologies [15]

This table indicates the following features of DECT:

1. A single DECT RFP can support hundreds of PPS; therefore, using tens of RFPs thousands of PPs can be supported in a network.
2. The data rate of DECT is higher than WirelessHART, ISA 100.11a or ZigBee.
3. DECT provides long radio range (up to 75m indoors, up to 300m outdoors), due to a high transmission power (250 mW). This avoids using a mesh network topology, even in large and dense networks.

As mentioned earlier, DECT-ULE is a new version of DECT which achieves low energy consumption due to its capacity of going into long sleep mode without losing synchronization. In standby mode, a DECT-ULE chip draws about 5 mA at 3.3V power supply, and 3-5  $\mu\text{A}$  in sleep mode, what allows a radio attached to a sensor to operate for years with a single battery.

As a summary, DECT presents an interesting alternative for WSNs in industrial environments, mainly due to the operation in a non-crowded band and the use of TDMA access to the medium.

#### Bibliography of the paragraph

- [84] K. Das and P. Havinga, "Evaluation of DECT-ULE for robust communication in dense wireless sensor networks," in *Internet of Things (IOT), 2012 3rd International Conference on the*, 2012, pp. 183-190.
- [85a] ETSI, "Digital Enhanced Cordless Telecommunications (DECT), Common Interface (CI); Part 1-5, ETSI EN 300 175-1 to 5, v2.3.1," ed, 2010.

### 4.1.10 Industrial WLAN (Siemens)

*Industrial WLAN* is a custom solution developed by Siemens for achieving high-speed connectivity (up to 450 Mbps) in industrial environments where a high degree of reliability is required. The PHY layer is based on the IEEE 802.11n standard, operating in both ISM 2.4 GHz and ISM 5 GHz bands, and the higher levels of the protocol have been modified in order to support real-time industrial applications. The PHY includes the possibility of connecting three antennas in order to transmit three data streams simultaneously and take advantage of MIMO operation in multipath environments.

Industrial WLAN is covered by the SCALANCE W product range of Siemens. This product range includes clients and access points, both for indoor and outdoor operation (see example in Figure 49). An extensive range of antennas and radiating coaxial cables are also provided for operation with these nodes.



**Figure 49: Siemens SCALANCE W780 [85]**

#### Bibliography of the paragraph

- [85] Siemens. *SCALANCE W780 Access Points*. Available: [http://w3.siemens.com/mcms/industrial-communication/en/industrial-wireless-communication/network\\_components/scalance-w780-access-points/Pages/default.aspx](http://w3.siemens.com/mcms/industrial-communication/en/industrial-wireless-communication/network_components/scalance-w780-access-points/Pages/default.aspx)

#### 4.1.11 Lobometrics

Lobometrics provides wireless network servers (*Lobo* series), Wireless Access Points (*BMAP*) and Customer Premises Equipment (CPEs, *Miura* series) operating in a wide range of bands, including 900MHz (907-922 MHz), 2.xGHz (2.312-2.732 GHz), 3.xGHz (2.7-3.7 GHz) and 5GHz (5.2-5.825 GHz), in licensed and unlicensed ISMs, and with wireless ranges up to 200km per hop. Lobometrics devices are equipped with 1 to 4 radios, with data rates from 17 Mbps to 1 Gbps, and are suitable for both in-building wireless local area networks and outdoor building-to-building bridging applications. These radios can be programmed to both standard and high security non-standard frequencies and variable channel widths (5 to 40 MHz). Other features of Lobometrics radios include a transmitter power from 9 to 36 dBm, and a receiver sensitivity from -76 to -105 dBm. The following IEEE 802.11 standards are covered by Lobometrics radios: IEEE 802.11a, 802.11b/g, 802.11n, 802.11e, and 802.11i.

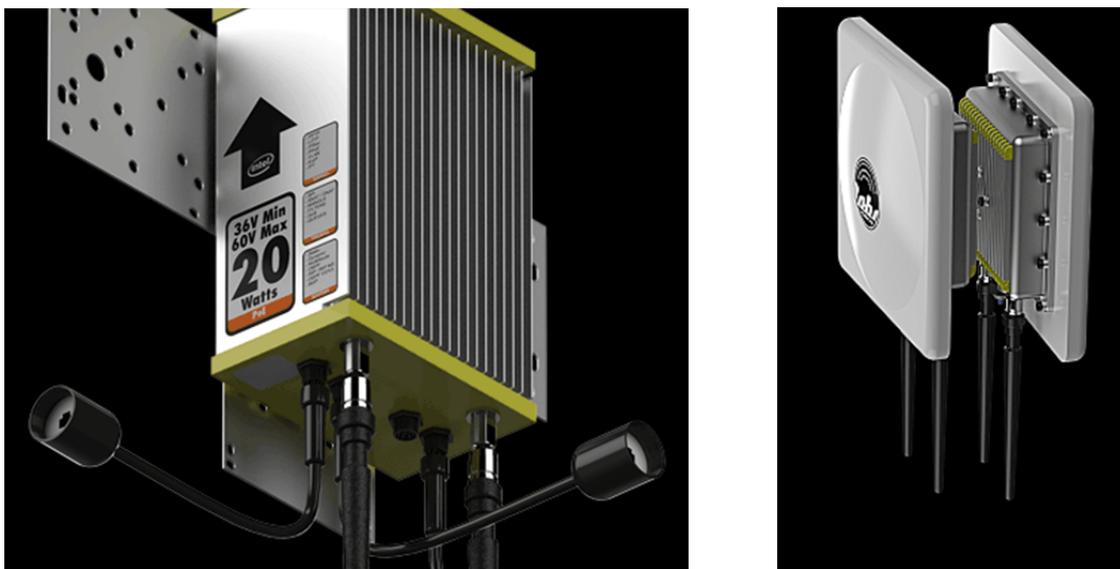


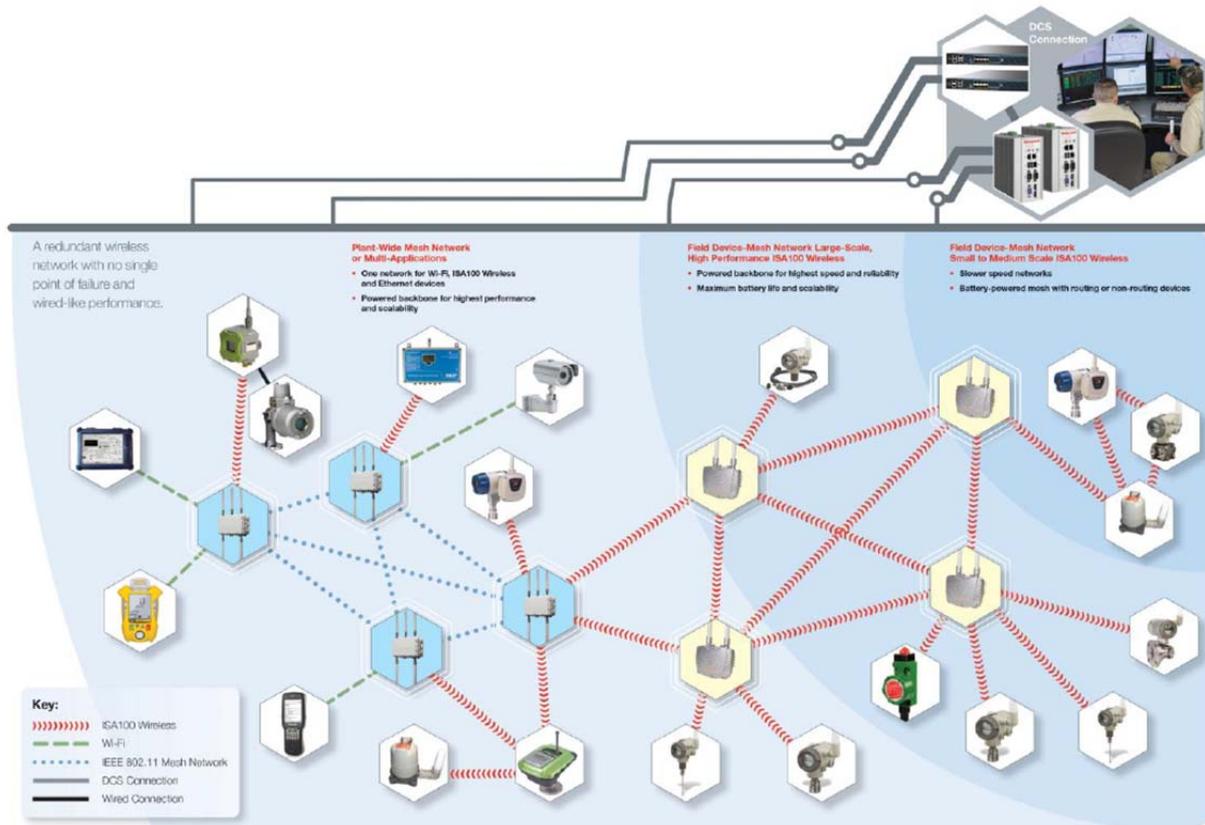
Figure 50: Lobometrics devices [86]

#### Bibliography of the paragraph

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#### 4.1.12 OneWireless (Honeywell)

*OneWireless* is a network composed of a Device Manager, Access Points, and routing and non-routing field devices (Figure 51). The network is compatible with IEEE 802.11 a/b/g/n (operating at 2.4 GHz and 5.8 GHz) and ISA 100.11a (2.4 GHz). It also supports legacy field protocols, such as Modbus or HART.



**Figure 51: OneWireless network topology [87]**

*OneWireless* is suitable for non-critical monitoring purposes (e.g. update rate of one second). It takes advantage of several techniques for improving the robustness of the networks, such as the use of redundant paths, channel blacklisting and antenna diversity.

#### Bibliography of the paragraph

- [87] Honeywell. (2014). *OneWireless Network Overview*. Available: <https://www.honeywellprocess.com/library/marketing/notes/OneWireless-Network-PIN.pdf>

#### 4.1.13 Phoenix Contact

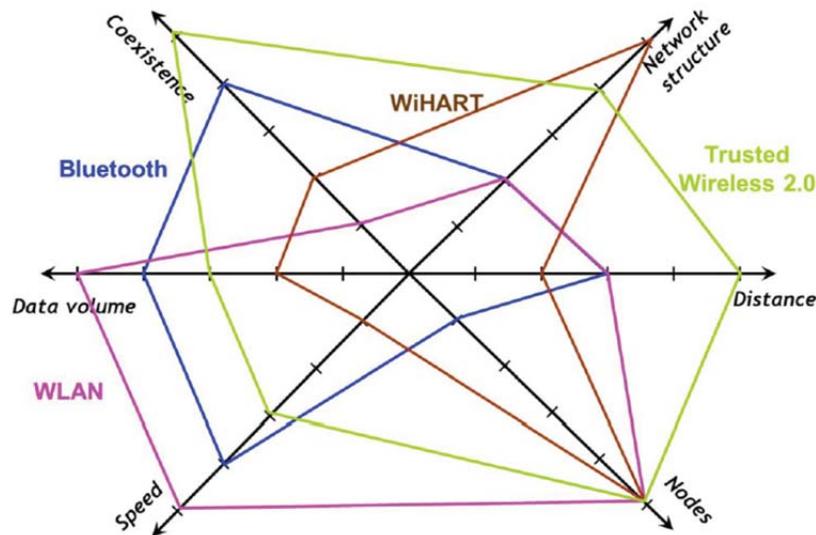
Phoenix Contact offers several wireless solutions, including Bluetooth, WirelessHART, IEEE 802.11 (2.4 GHz and 5 GHz), 3G, and proprietary *Trusted Wireless*.



**Figure 52: Wireless solutions by Phoenix Contact [88]**

*Trusted Wireless* has been specifically developed for industrial use, with the aim of bridging the gap between sensor networks (e.g. WirelessHART) and high-speed networks (e.g. WiFi) - see Figure 53. *Trusted Wireless* offers the following features:

1. Operation at ISM 868 MHz, 900 MHz and 2.4 GHz.
2. *Frequency Hopping Spread Spectrum*: several individual channels are used following a pseudo-random pattern. The choice of the hopping patterns includes the consideration of the blacklisted channels and the minimum channel spacing required in order to compensate multipath fading effects.
3. High transmission power (100 mW for 2.4 GHz, 1W for 900 MHz) and variable data rate for increasing the receiver sensitivity.
4. Mesh networks (up to 250 nodes) with store-and-forward repeater functionality and self-healing capabilities.



**Figure 53: Comparison of *Trusted Wireless* with other wireless technologies [89]**

Bibliography of the paragraph

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#### 4.1.14 LTE Technology Overview

Long-Term Evolution (LTE) is the project name of a new, high performance air interface for mobile communication systems. Developed by the Third Generation Partnership Project (3GPP), LTE is the evolution of the Universal Mobile Telecommunication System (UMTS) towards an all-IP broadband network. LTE's evolved radio access technology—the E-UTRA— provides a framework for increasing data rates and overall system capacity, reducing latency, and improving spectral efficiency and cell-edge performance. It is documented in the 3GPP Release 8 and Release 9 specifications. This LTE overview gives some of the highlights.

OFDMA-based: Unlike UMTS, which is based on wideband code division multiple access (W-CDMA) technology, LTE is based on orthogonal frequency-division multiple access (OFDMA). In the downlink, an OFDMA-based transmission scheme—together with multiple-access techniques—provides high data-rate capacity and high spectral efficiency. In this regard, LTE is similar in concept to Mobile WiMAX™, another emerging technology for wireless broadband access, although the systems operate with different frame structures, sub-carrier spacing and channel bandwidths.

A new, OFDMA-based scheme called single carrier frequency division multiple access (SC-FDMA) was developed for the LTE uplink. SC-FDMA enables a lower peak-to-average ratio (PAR) to conserve battery life in mobile devices.

Flexible modulation schemes: The downlink supports QPSK, 16QAM, and 64QAM data modulation formats, and the uplink supports BPSK, QPSK, 8PSK, and 16QAM.

Spectral efficiency: LTE also features a scalable bandwidth from 1.4 to 20 MHz in both the downlink and the uplink, with subcarrier spacing of 15 kHz and 7.5 kHz possible in the case of multimedia broadcast multicast service (MBMS). Targets for spectral efficiency over 3GPP Release 7 high-speed packet access (HSPA) are three to four times in the downlink and two to three times in the uplink. Sub 5-ms latency will be provided for small IP packets.

MIMO: At present, LTE offers a 100-Mbps download rate and 50-Mbps upload rate for every 20 MHz of spectrum. Support is intended for even higher rates (up to a maximum of 326.4 Mbps in the downlink) using multiple antenna configurations (Figure 61). LTE supports single-user multiple input/multiple output (SU-MIMO) and multiple-user multiple input/multiple output (MU-MIMO) antenna configurations of up to 4 x 4 MIMO. These should enable up to 10 times as many users per cell as 3GPP's original W-CDMA technology.

FDD and TDD modes: To support as many frequency band allocations as possible, both paired and unpaired spectrum operation is supported using frequency division duplex (FDD) and time division duplex (TDD) techniques, respectively. Paired spectrum operation is known as FD-LTE and unpaired spectrum as TD-LTE.

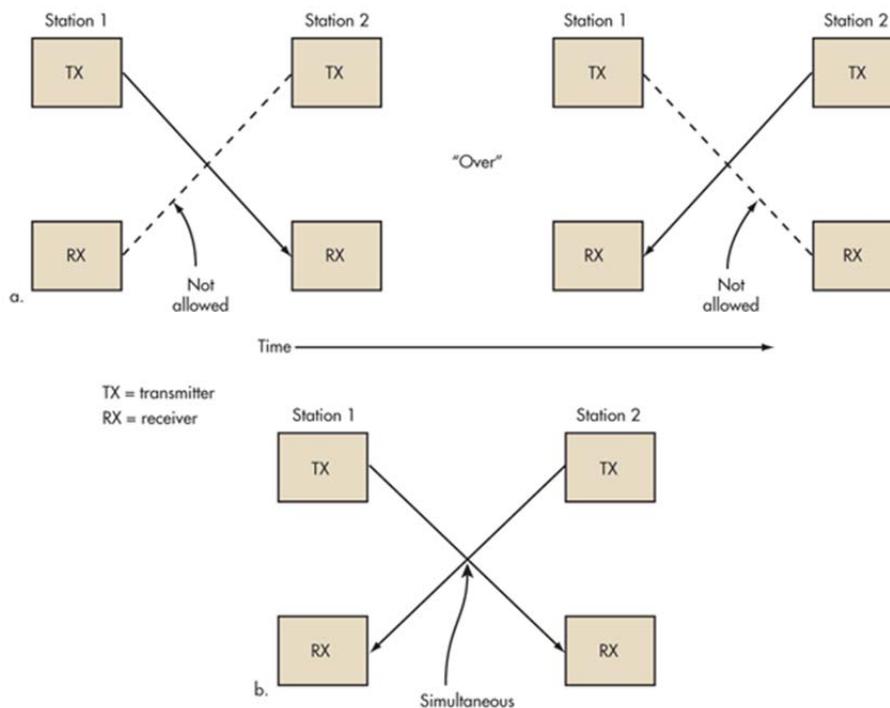


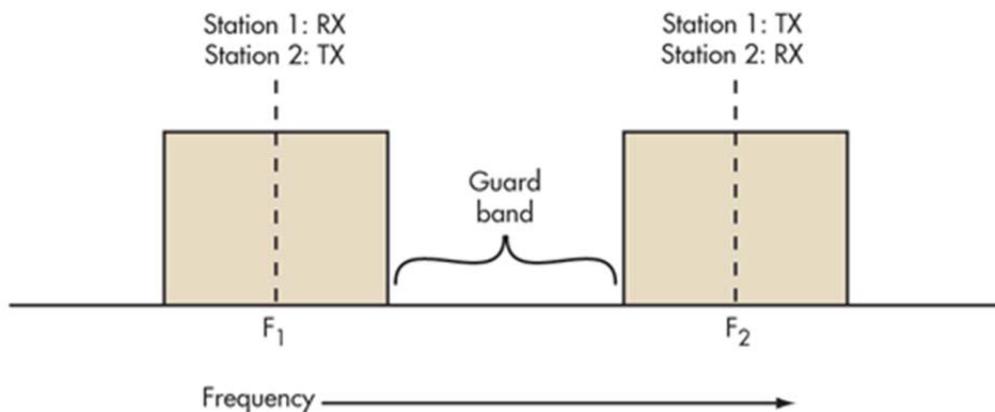
Figure 54. MIMO communication

Co-existence with legacy systems: LTE is designed to support voice as well as data in the packet domain. However, as LTE evolves toward an all-IP network, it will co-exist with legacy systems including 3GPP HSPA, W-CDMA UMTS, and GSM/GPRS/EDGE. In conjunction with the 3GPP Evolved Packet Core (EPC) network, LTE will support inter-domain handovers between packet-switched and circuit-switched systems. Specifications for the EPC network are being developed in a concurrent project known as System Architecture Evolution (SAE).

### Overview of the LTE Frequency Division Duplex

FDD requires two separate communications channels. In networking, there are two cables. Full-duplex Ethernet uses two twisted pairs inside the CAT5 cable for simultaneous send and receive operations.

Wireless systems need two separate frequency bands or channels (Figure 62). A sufficient amount of guard band separates the two bands so the transmitter and receiver don't interfere with one another. Good filtering or duplexers and possibly shielding are a must to ensure the transmitter does not desensitize the adjacent receiver.



**Figure 55: Channel separation**

FDD requires two symmetrical segments of spectrum for the uplink and downlink channels.

In a cell phone with a transmitter and receiver operating simultaneously within such close proximity, the receiver must filter out as much of the transmitter signal as possible. The greater the spectrum separation is, the more effective the filters are.

FDD uses lots of frequency spectrum, though, generally at least twice the spectrum needed by TDD. In addition, there must be adequate spectrum separation between transmit and receive channels. These so-called guard bands aren't useable, so they're wasteful. Given the scarcity and expense of spectrum, these are real disadvantages.

However, FDD is very widely used in cellular telephone systems, such as the widely used GSM system. In some systems the 25-MHz band from 869 to 894 MHz is used as the downlink (DL) spectrum from the cell site tower to the handset, and the 25-MHz band from 824 to 849 MHz is used as the uplink (UL) spectrum from the handset to cell site.

Another disadvantage with FDD is the difficulty of using special antenna techniques like multiple-input multiple-output (MIMO) and beamforming. These technologies are a core part of the new Long-Term Evolution (LTE) 4G cell phone strategies for increasing data rates. It is difficult to make antenna bandwidths broad enough to cover both sets of spectrum. More complex dynamic tuning circuitry is required.

FDD also works on a cable where transmit and receive channels are given different parts of the cable spectrum, as in cable TV systems. Again, filters are used to keep the channels separate.

E-UTRA Band	Uplink Frequency Range (MHz) eNB Receive/ UE Transmit	Downlink Frequency Range (MHz) eNB Transmit/ UE Receive	Supported Channel Bandwidth (MHz)
1	1920 - 1980 MHz	2110 - 2170 MHz	5, 10, 15, 20
2	1850 - 1910 MHz	1930 - 1990 MHz	1.4, 3, 5, 10, 15, 20
3	1710 - 1785 MHz	1805 - 1880 MHz	1.4, 3, 5, 10, 15, 20
4	1710 - 1755 MHz	2110 - 2155 MHz	1.4, 3, 5, 10, 15, 20
5	824 - 849 MHz	869 - 894 MHz	1.4, 3, 5, 10
6	830 - 840 MHz	875 - 885 MHz	5, 10
7	2500 - 2570 MHz	2620 - 2690 MHz	5, 10, 15, 20
8	880 - 915 MHz	925 - 960 MHz	1.4, 3, 5, 10
9	1749.9 - 1784.9 MHz	1844.9 - 1879.9 MHz	5, 10, 15, 20
10	1710 - 1770 MHz	2110 - 2170 MHz	5, 10, 15, 20
11	1427.9 - 1452.9 MHz	1475.9 - 1500.9 MHz	5, 10, 15, 20
12	699 - 716 MHz	729 - 746 MHz	1.4, 3, 5, 10
13	777 - 787 MHz	746 - 756 MHz	1.4, 3, 5, 10
14	788 - 798 MHz	758 - 768 MHz	1.4, 3, 5, 10
17	704 - 716 MHz	734 - 746 MHz	Not Defined

**Table 13: FDD Frequency Bands**

## Overview of the LTE TDD technology

LTE is the next step in the evolution of the UMTS technology. As the successor to UMTS, LTE should make transmissions possible at data rates of over 100 Megabit/s in the downlink and over 50 Megabit/s in the uplink as well as reduce latency for packet transmissions. LTE supports bandwidths of up to 20 MHz. Scalable bandwidths help ensure that LTE is compatible with existing mobile radio systems. Orthogonal frequency division multiple access (OFDMA) is the multiple access method used in the LTE downlink. The LTE uplink is based on the single-carrier frequency division multiple access (SD-FDMA) mode. This mode is similar to OFDMA, but has the advantage that SCFDMA signals exhibit a lower peak-to-average power ratio (PAPR).

Orthogonal frequency division multiple access (OFDMA) is the multiple access method used in the LTE downlink. The LTE uplink is based on the single-carrier frequency division multiple access (SD-FDMA) mode. This mode is similar to OFDMA, but has the advantage that SCFDMA signals exhibit a lower peak-to-average power ratio (PAPR). LTE has two different duplex modes for separating the transmission directions from the user to the base station and back: frequency division duplex (FDD) and time division duplex (TDD). In the case of FDD, the downlink and uplink are transmitted using different frequencies. In TDD mode, the downlink and the uplink are on the same frequency and the separation occurs in the time domain, so that each direction in a call is assigned to specific timeslots. This article describes the details of the LTE TDD (TD-LTE) technology and highlights any differences from the LTE FDD technology. Special characteristics and specific challenges to be faced during network planning are also described. See R&S Application Note 1MA111 for a complete description of the LTE FDD technology.

### Frequency bands

The TDD duplex mode is used for transmissions in unpaired frequency bands. This means that the TDD bands already defined for UMTS can also be used for LTE TDD. The TDD bands defined by 3GPP are presented (table 14), although it is possible that more bands will be added.

E-UTRA Band	Uplink Frequency & Downlink Frequency range (MHz)	Supported Channel bandwidth (MHz) Bandwidth
33	1900 to 1920 MHz	5, 10, 15, 20
34	2010 MHz to 2025 MHz	5, 10, 15
35	1850 MHz to 1910 MHz	1.4, 3,5, 10, 15, 20
36	1930 MHz to 1990 MHz	1.4, 3,5, 10, 15, 20
37	1910 MHz to 1930 MHz	5, 10, 15, 20
38	2570 MHz to 2620 MHz	5, 10, 15, 20
39	1880 MHz to 1920 MHz	5, 10, 15, 20
40	2300 MHz to 2400 MHz	5, 10, 15, 20

**Table 14: : Frequency range and bandwidth for E-UTRA bands**



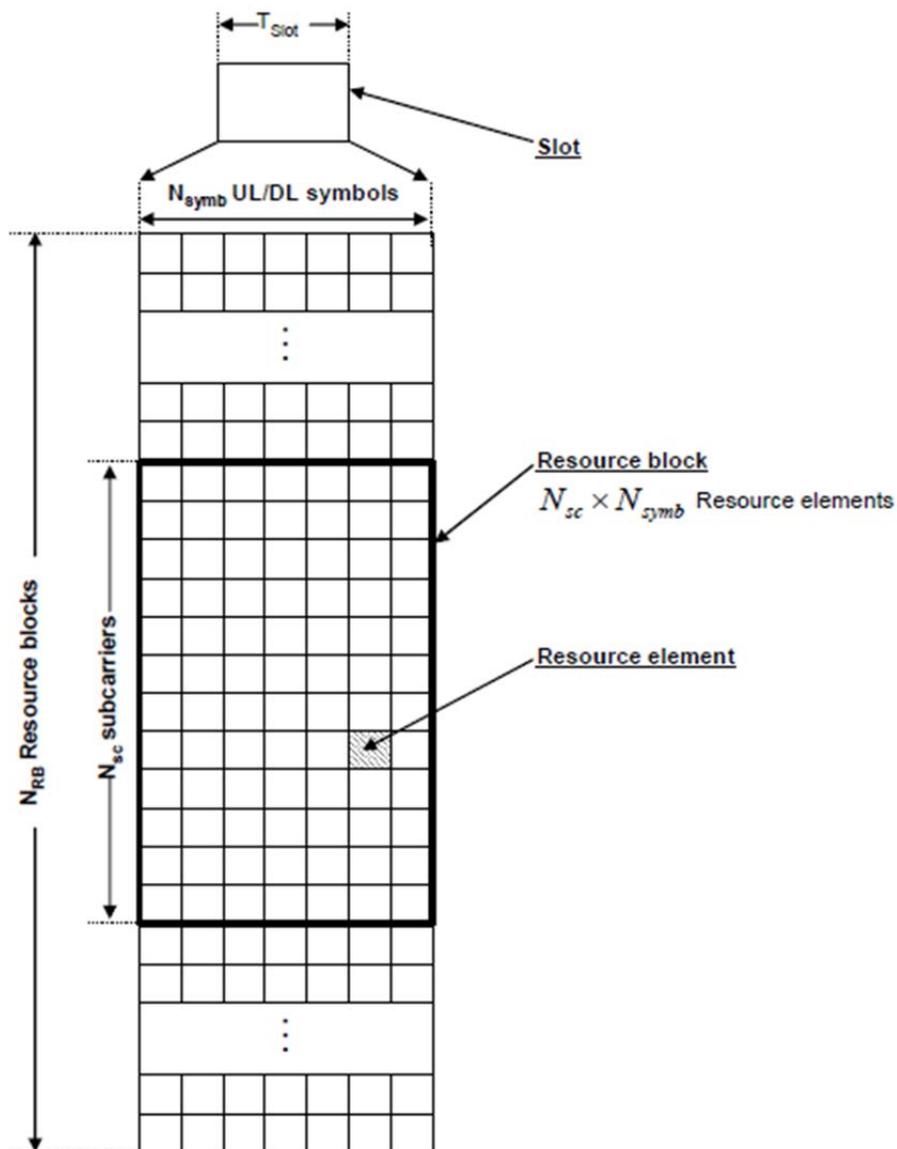


Figure 57. Ressource structure

	Configuration	Subcarrier spacing $\Delta f$	$N_{sc}$	$N_{symb}$
Downlink	Normal cyclic prefix	$\Delta f = 15 \text{ kHz}$	12	7
	Extended cyclic prefix	$\Delta f = 15 \text{ kHz}$	12	6
		$\Delta f = 7 \text{ kHz}$	24	3
Uplink	Normal cyclic prefix	$\Delta f = 15 \text{ kHz}$	12	7
	Extended cyclic prefix	$\Delta f = 15 \text{ kHz}$	12	6

Figure 58. Uplink and Downlink parameters



In contrast to UMTS WCDMA/HSPA, various different bandwidths are supported for LTE, making it compatible with existing mobile radio networks. The channel bandwidth is defined by the number of available resource blocks NRB and is scalable. This scalability allows radio resources to be used efficiently. Table 15 lists the bandwidths supported by LTE and the associated number of resource blocks NRB. These parameters are defined the same for LTE TDD and LTE FDD.

Channel bandwidth (MHz)	1.4	3	5	10	15	20
Resource block number	6	15	25	50	75	100

**Table 15. Bandwith supported**

Uplink/downlink configurations

LTE TDD uses the same frequency bands for the uplink and the downlink. The transmission directions are separated by carrying the UL and DL data in different subframes. The distribution of subframes between the transmission directions can be adapted to the data traffic and is done either symmetrically (equal number of DL and UL subframes) or asymmetrically. Figure 66 shows the UL/DL configurations that are defined for LTE TDD. In this table, "D" means that DL data is transmitted in this subframe. Similarly, "U" indicates uplink data transmission and "S" specifies that the special fields DwPTS, GP and UpPTS are transmitted in this subframe.

Uplink/downlink configuration	Downlink-to-Uplink Switch-point periodicity	Subframe number									
		0	1	2	3	4	5	6	7	8	9
0	5 ms	D	S	U	U	U	D	S	U	U	U
1	5 ms	D	S	U	U	D	D	S	U	U	D
2	5 ms	D	S	U	D	D	D	S	U	D	D
3	10 ms	D	S	U	U	U	D	D	D	D	D
4	10 ms	D	S	U	U	D	D	D	D	D	D
5	10ms	D	S	U	D	D	D	D	D	D	D
6	5 ms	D	S	U	U	U	D	S	U	U	D

**Figure 59. Uplink/Down link configurations**

**Application Examples**

Most cell-phone systems use FDD. The newer LTE and 4G systems use FDD. Cable TV systems are fully FDD.

Most wireless data transmissions are TDD. WiMAX and Wi-Fi use TDD. So does Bluetooth when piconets are deployed. ZigBee is TDD. Most digital cordless telephones use TDD. Because of the spectrum shortage and expense, TDD is also being adopted in some cellular systems, such as China’s TD-SCDMA and TD-LTE systems. Other TD-LTE cellular systems are expected to be deployed where spectrum shortages occur.

**Conclusion**

TDD appears to be the better overall choice, but FDD is far more widely implemented because of prior frequency spectrum assignments and earlier technologies. FDD will continue to dominate the cellular business for now. Yet as spectrum becomes more costly and scarce, TDD will become more widely adopted as spectrum is reallocated and repurposed.

## **4.2 SUITABILITY FOR THE RAILWAY DOMAIN**

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Amongst all technologies described during Chapter 4, the most suitable ones are the wireless technologies which have a deterministic behaviour both in the transmission and reception of the data frames. Taking this into account, most of the presented technologies can be considered for inter-consist and intra-consist communication links. Notice that the bandwidth and latency specifications are related to the requirements obtained from the Task 2.1; therefore, in this first approximation we cannot discard any solution that fulfils deterministic condition. In this sense, a list of suitable technologies would be: Bluetooth, WirelessHart, ISA 100.11a, WIA-PA, WISA, DECT, Industrial WLAN, OneWireless and Phoenix contact.

On the other hand, magnetic induction is a technology suitable for low-bandwidth and short-distance communications, as it takes advantage of a point-to-point link for deterministic behaviour; therefore, in railway environment magnetic induction can be applied mainly for exchanging small volumes of data in proximity applications (e.g. vehicle configuration information when one vehicle is being coupled to another one). It can be used as a complementary link to the main backbone of the train, but for high-bandwidth proximity applications a directive RF link seems a better option.

## 5. STATE OF THE ART IN AUTOMOTIVE

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### 5.1 RADIO TECHNOLOGIES FOR CAR-TO-CAR COMMUNICATION

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#### 5.1.1 ITS-G5 and IEEE 802.11p

In this section, we will give a brief outline of the European approach for wireless communications supporting Intelligent Transport Systems (ITS). The prime objective for the development of V2V and V2I communication is the reduction of traffic accidents which accounted to the second most common cause of death for 5 – 29 years olds according to the World Health Organization [91].

In the context of V2V and V2I communications, the investigated use cases include communications from a moving vehicle to

- Other moving vehicles
- Near infrastructure, e.g. to roadside units, tolling stations, traffic lights, etc.
- Portable units, e.g. for vehicle-to-pedestrian

For these cases, low latency is crucial and it is therefore vital to allow direct communication between the nodes without the need for a base station or central access point. In the following, we will focus on the IEEE 802.11p standard which forms the basis of the European ITS-G5. The term Dedicated Short-Range Communication (DSRC) refers in Europe to a short-range communication system which is standardized by CEN and is mainly applied for electronic toll collection. In the United States and Australia, DSRC refers to systems based on IEEE 802.11p while in Japan it stands for still another system.

For vehicular communications, some adaptations from the baseline 802.11 WLAN standards are required, in order to account for

- support longer communication range of up  $\approx 1$  km
- high speed of vehicles, with up to 500 km/h relative velocities
- multipath environment with long delay spread of up to 5  $\mu s$
- nature of automotive application: broadcast from all vehicles

The 802.11p standard is a variation of the 802.11a standard and includes the MAC enhancement of 802.11e for message prioritization. On the PHY layer, the main adaptation consists in halving the bandwidth, which leads to a halving of the data rates and a doubling of the guard interval, which is advantageous for the expected high delay spreads. The main physical parameters of both 802.11 variants are summarised in Table 16.

	IEEE 802.11a	IEEE 802.11p	Advantage of 802.11p
Data rates in Mbit/s	6, 9, 12, 18, 24, 36, 48, 54	3, 4.5, 6, 9, 12, 18, 24, 27	
OFDM symbol duration	4 $\mu$ s	8 $\mu$ s	
Guard interval duration	0.8 $\mu$ s	1.6 $\mu$ s	Better suited for long delay spread
Subcarrier spacing in kHz	312.5	156.25	
Channel bandwidth	20 MHz	10 MHz	
Frequency band	5 GHz ISM band	5.85 – 5.925 GHz	Dedicated frequency band

**Table 16: Comparison of PHY layers of IEEE 802.11a and 802.11p**

The modulation and coding schemes (MCS) include in both cases the modulations BPSK, QPSK, 16-QAM, 64-QAM and a convolutional code of constraint length 7 with rates 1/2, 2/3, and 3/4.

On the MAC level, the Distributed Control Function (DCF) is applied, which provides MAC-level acknowledgements for unicast transmission, but not for broadcast communication. Prioritization of packets is managed by queues of different priority levels according to IEEE 802.11e EDCA (Enhanced Distributed Channel Access) and is standardized in IEEE 1609.4.

The frequency allocations for wireless ITS systems and in particular for the ITS G5 are given in Table 17 and Table 18.

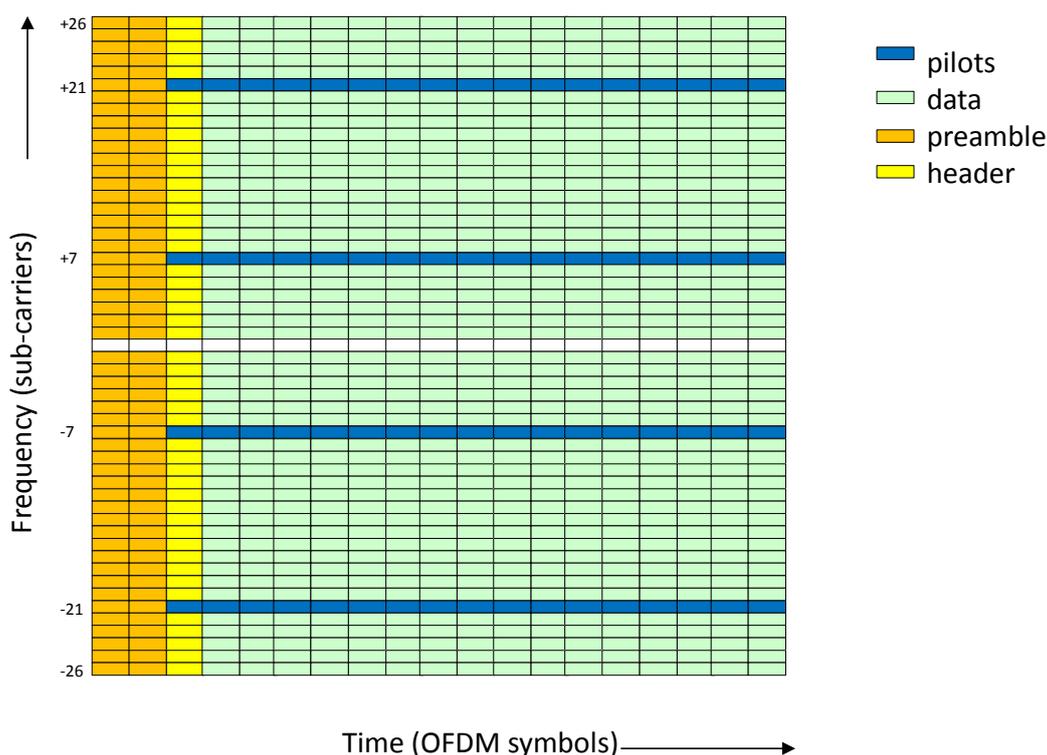
Frequency range in MHz	Usage	Regulation	Harmonized standard
5905 – 5925	Future ITS applications	ECC Decision	EN 302 571
5875 – 5905	ITS road safety	ECC Decision, Commission Decision	EN 302 571
5855 – 5875	ITS non-safety applications	ECC Recommendation	EN 302 571
5470 – 5725	RLAN (BRAN, WLAN)	ERC Decision, Commission Decisions	EN 301 893

**Table 17: Frequency allocation in the EU [90]**

Band	Channel		Centre frequency [MHz]	Transmit power limit [dBm EIRP]	Transmit power density limit [dBm/MHz]
	ETSI	IEEE			
G5A	G5CC	180	5900	33	23
	G5SC2	178	5890	23	13
	G5SC1	176	5880	33	23
G5B	G5SC3	174	5870	23	13
	G5SC4	172	5860	0	-10

**Table 18: European channel allocation [90]**

The allocation of the preamble and the pilot symbols within an OFDM frame is shown in Figure 60. This pilot pattern has been taken unchanged from the IEEE 802.11a standard which was designed mainly for indoor and portable usage. It has been recognized that this pilot distribution is not ideal for a doubly dispersive channel as it occurs in vehicular communications and several research groups have addressed this problem (see e.g. [92] and the references therein).



**Figure 60: Preamble and pilots in an 802.11p frame**

In summary, the IEEE 802.11p standard and its European profile ITS-G5A present a very promising technology for train-to-train communication for the following reasons:

- Dedicated frequency bands have been reserved for ITS road safety
- The standard has been widely investigated for its usage in vehicular communications
- Advanced commercial implementations are available.

While most of the research effort has been directed to car-to-car communications, parallels to train-to-train communication are clearly visible, whereas further research is required to address the particularities of the railway environment.

### 5.1.2 IEEE 802.15.4

Most of the commercial solutions are operating in the InV area, focusing mainly on sensing applications (therefore, the replacement of control wired buses, such as CAN, is not the main scope of these systems).

Sentec Elektronik [92] provides various elements for building an automotive wireless sensor network. It provides sensing elements (e.g. temperature of brake disks, temperature and humidity inside the vehicle, temperature of heating pipes, etc.) as well as wireless transmitters and receivers. Sentec’s wireless network is based on the IEEE 802.15.4 standard, which operates in the 2.4 GHz ISM band. The receiver provides a USB interface for data exchange, with an optional CAN interface and SD memory for data storage.



**Figure 61: IEEE 802.15.4 Sentec Elektronik receiver [92]**

Infineon provides several wireless devices aimed at control applications in automotive environments (e.g. keyless entry or tyre pressure monitoring). These devices operate in Sub-GHz frequency bands, use ASK and FSK modulations, and offer a high level of integration (e.g. internal PLL and power amplifier), what reduces the BoM needed to build a complete communication node. Table 19 summarizes the different IC families available from Infineon.

Type		Description
Transmitter	TDK 510x /F	ASK/FSK Transmitter family for low power (2 – 5dBm)
	TDK 511x /F	ASK/FSK Transmitter family for high power (10dBm)
Receiver	TDA 520x	ASK Receiver family
	TDA 521x	ASK/FSK Receiver family
	TDA 522x	ASK/FSK Receiver family with switchable peak detector
SmartLEWIS™ RX	TDA 523x	ASK/FSK Receiver family with digital baseband processing, multi-channel
SmartLEWIS™ MCU	PMA 51xx	ASK/FSK Transmitter family with embedded 8051 Microcontroller
Transceiver	TDA 525x	ASK/FSK Transceiver family

**Table 19: Automotive ICs by Infineon [93]**

Finally, manufacturers such as Digi or OBD Solutions offer nodes which operate as bridges between the internal diagnosis bus of the car (through OBD or J1939 port) and WiFi adapters. This makes internal vehicle data (e.g. status/error messages, liquid levels, pressure values, etc.) accessible from applications on portable/mobile devices, allowing therefore their monitoring and control.

Bibliography of the paragraph

- [90] ETSI ES 202 663. Intelligent Transport Systems (ITS); European Profile Standard for the Physical and Medium Access Control Layer of Intelligent Transport Systems Operating in the 5 GHz Frequency Band.
- [91] Ström, H. Hartenstein, P. Santi, W. Wiesbeck, "Vehicular communications", editorial in Proceedings of the IEEE, vol. 99, no. 7, pp. 1158-1161, July 2011.
- [92] Sentec. *Wireless Sensor Networks for Automotive*. Available: <http://www.sentec-elektronik.de/en/products/wireless-sensor-networks/wireless-sensor-networks-for-automotive.html>
- [93] Infineon. *Receiver, Transmitter and Transceiver ICs for the Sub 1 GHz Frequency Bands*. Available: <http://www.infineon.com/cms/en/product/rf-and-wireless-control/wireless-control/channel.html?channel=ff80808112ab681d0112ab69091f00dc>

## 5.2 RADIO TECHNOLOGIES BETWEEN VEHICLES

The European Project *AutoNet2030* [94] aims at developing an automated driving system, based on a decentralised decision-making strategy enabled by mutual information exchange among nearby vehicles. The project looks for the complementary operation between the different sensors in the vehicle and co-operative wireless communications based on the IEEE 802.11p standard in the 5.9 GHz band.

On the other hand, the IEEE 1609 family of standards for Wireless Access in Vehicular Environments (WAVE) [95] define protocol, services and interfaces which enable a wireless communication link between vehicles. The physical layer of this standard is based on IEEE 802.11p.

### Bibliography of the paragraph

- [94] AutoNet2030. *Co-operative Systems in Support of Networked Automated Driving by 2030*. Available: <http://www.autonet2030.eu/>
- [95] IEEE. *1609 WG - Dedicated Short Range Communication Working Group*. Available: [https://standards.ieee.org/develop/wg/1609\\_WG.html](https://standards.ieee.org/develop/wg/1609_WG.html)

## 5.3 RADIO TECHNOLOGIES FOR VEHICLE TO INFRASTRUCTURE COMMUNICATION

CAR2CAR [96] is a consortium made of companies from the automotive industry and research organizations, whose aim is to increase the security in roads by providing the vehicles with the capacity of communicating among them and also with infrastructures.

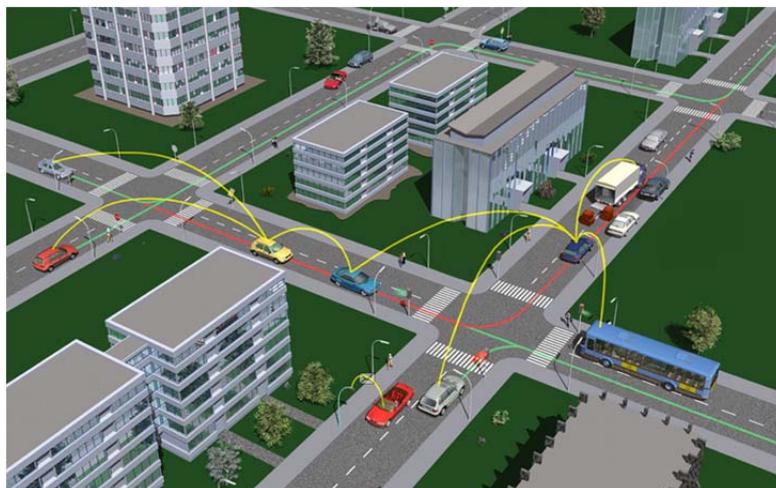


Figure 62: CAR2CAR scenario [30]

### Bibliography of the paragraph

- [96] CAR2CAR. *Communication Consortium*. Available: <https://www.car-2-car.org>

## 5.4 SUITABILITY FOR THE RAILWAY DOMAIN

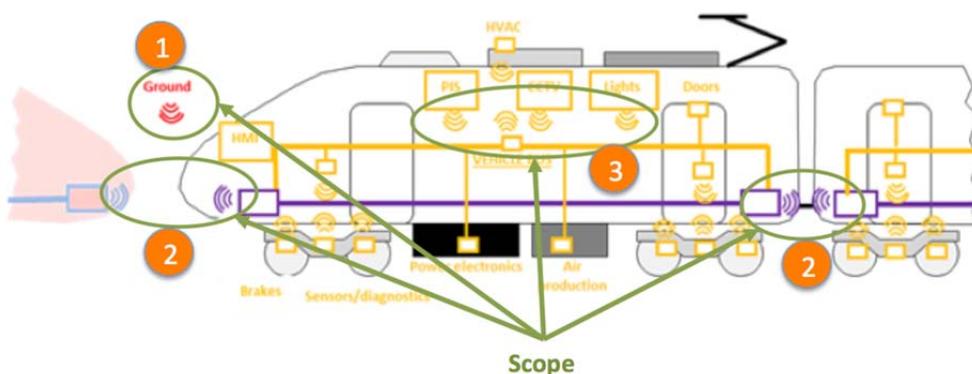
In difference to chapter 4, for automotive sector, suitability for railway domain has been indicated in each sub-chapter, because given name already indicated the scope of use of each technology.

## 6. CONCLUSIONS

A lot of communication technologies exist and has been described into this state of the art. According to the scope of the R2R WP2 work package, the technologies are classified into 3 categories (Figure 70) that are:

- 1) For train to ground communications.
- 2) For inter consist<sup>1</sup> (consist to consist) and intra consist (vehicle to vehicle) communications.
- 3) For inside vehicle communications.

Moreover, the technologies can be put into two categories: communication technologies using an infrastructure and communication technologies without a fixed infrastructure. Some technologies studied into this state of the art are relevant for several categories of services.



**Figure 70: Scope of the R2R WP2 project.**

Considering those aspects, Table 20 presents a summary of the technologies studied in this state of the art against their possible suitability for different type of communication scopes.

For communications intra consist (between cars of a consist) and inter consists, a solution without an infrastructure should be interesting. For train to ground communication, a technology using an infrastructure is the good choice. It is not necessary that the infrastructure is dedicated. Attention must be paid on all the works ongoing dealing with heterogeneous networks interoperability and cognitive radio concepts. This trend are today analysed by ERA (European Railway Agency) and mentioned in TD2.1 and TD2.10 of Shift2rail IP2.

Concerning the architecture of the new radio communication system, the technology choice has to take into account that SIL4 level should be achieve. New trends on dependability analysis should be taken into account and redundancy is not the only solution. Cognitive radio concepts based on SDR is possible good candidate to achieve this. Among these concepts, solution based on duplication of IP traffic is also potential candidates.

As a final conclusion and in line what I was explained in the introduction of the deliverable, within other tasks scope most suitable technologies will be selected using information and recommendation collected in current deliverable.

<sup>1</sup> Inter consist communications means communication between consists physically coupled together. Virtual coupling is out of the scope of the R2R project.

Technology	1 : Train to ground	2: Consist to Consist and Vehicle to Vehicle	3: Intra car
Zigbee		X	X
GPRS	X		
EDGE	X		
WCDMA/UMTS	X		
LTE	X	X	X
TETRA	X		
Wi-Fi	X	X	X
WiMAX	X	X	X
GSM-R	X		
BLE		X	X
Millimetric		X	X
UWB	X	X	X
Marathon project		X	
WirelessHart			X
ISA 100.11a			X
WIA-PA			X
WSAN/WISA			X
Bluetooth			X
DECT			X
Magnetic induction		X	
Industrial WLAN	X	X	X
Lobometrics	X		X
OneWireless			X
Phoenix contact			X
LDACS1	X		
AeroMacs	X		
VDL Mode 2	X		
VDM Mode 4	X	X	
LDACS2	X		
ADS-B 1090ES	X	X	
ADS-B UAT	X	X	
ITS-G5	X	X	

Table 20: Summary of the suitable technologies