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# UWB location tracking devices in the railroad environment

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# Foreword

This Technical Report (TR) has been produced by ETSI Technical Committee Electromagnetic compatibility and Radio spectrum Matters (ERM).

The present document includes necessary information to support the co-operation under the MoU between ETSI and the Electronic Communications Committee (ECC) of the European Conference of Postal and Telecommunications Administrations (CEPT).

# Introduction

The present document describes devices using Ultra Wide Band (UWB) sensor technology for location tracking applications in railway environment.

The intended railway scenarios target both indoor and outdoor environments. For example, a subway station is located under the ground and therefore is essentially indoors, whereas a signal placed at the side of a railway line in open country is most definitely outdoor. Regulation for indoor UWB, and for some mobile and fixed outdoor UWB devices in certain circumstances is already included in the Electronic Communications Committee (ECC) decisions and recommendations issued in the recent years [i.1], [i.2], [i.3], [i.9], [i.10] and [i.11]. Nevertheless, no specific regulation is pointed for UWB applications having fixed outdoor installed devices or infrastructure belonging to rail or tram networks. There is evidence that location tracking application with good range resolution is needed in railways. Therefore, the present document describes a solution for location tracking in railway environment where fixed outdoor installation of UWB equipment is needed and may be operated according the current ECC regulations.

In UWB location tracking in railways, a transmitter (TX) or a receiver (RX), or both are installed in a moving rail vehicle. The vehicle is tracked by using fixed wayside network which can be implemented by using UWB TX, UWB RX or both. A network of fixed wayside equipment around an area to be covered, called as Area-Of-Interest (AOI), communicate with a UWB equipment installed in a rail vehicle. The 3D position of a rail vehicle can be found by analysing, e.g. time-of-arrival and/or angle-of-arrival of the radio signal relative to the known reference stations.

The presented system is tracking a rail vehicle within an area around a certain Point-Of-Interest (POI). Position information are applied to stop a rail vehicle in POI with sub-meter accuracy. When a rail vehicle is stopped, transmission is turned off.

A tracking system of presented application can be realized in three different ways:

- Transmitter installed into a rail vehicle and receiving fixed wayside equipment (option 1, see Figure B.1).

  The UWB signals emitted by a transmitter installed in a moving rail vehicle are detected by a wayside network of receiving fixed equipment placed at known, fixed points around the area to be covered. By centralized computational means the location of a rail vehicle can be determined. This is a typical application.

- Receiver installed into a rail vehicle and transmitting fixed wayside equipment (option 2, see Figure B.2).

  The UWB signals emitted by a wayside network of transmitting fixed equipment placed at known, fixed points around the area to be covered are detected by receiving equipment installed in a moving rail vehicle detecting their own position.

- Transmitter/receiver installed into a rail vehicle and transmitting/receiving fixed wayside equipment (option 3, see Figure B.3).

  A combination of options 1 and 2; both units installed in a rail vehicle and the fixed wayside equipment can receive and transmit UWB-signals.

In railways, high precision in range measurement is required. The ranging signals necessarily have to have a very large bandwidth to attain a good range resolution. Detailed technical description is given in annex B.

There is evidence that this system is needed in railway industry, and the proposed system will lead to greater addressable markets. Detailed market information are discussed in annex A.

# 1 Scope

The present document describes a railway application utilizing ultra wideband technology operating in the preferred frequency ranges from 3,1 GHz to 4,8 GHz and from 6 GHz to 8,5 GHz. Operation is foreseen for indoor and outdoor applications, including either mobile devices installed onboard the train cars and fixed devices installed on ground, as reference stations. These stations, belonging to the fixed infrastructure, will be allowed to operate as UWB emitters only in the lower frequency band, from 3,1 GHz to 4,8 GHz, in compliance with the compatibility studies and with the latest recommendation [i.9] proposed by ECC/CEPT, as this provision would allow the deployment of such fixed UWB devices in the railway environment according to the "registration and coordination" process recently proposed by ECC/CEPT 167 [i.10].

In railway applications, location tracking is performed within specified areas, called as an Area-Of-Interests (AOIs), which are areas around Point-Of-Interests (POIs). The POIs are listed below:

- Point in passenger platform
- Railway signal
- Railway crossing
- Generic POI

The UWB radio technology is required to track with sub-meter accuracy any rail vehicle to the purpose of stopping it in the appropriate POI. The length of AOI is defined by the braking distance of a rail vehicle, and it is typically hundreds of meters.

The generic regulation on UWB technology for use in rail and road vehicles onboard applications, such as - for instance - in subway underground stations, within the frequency ranges of 3,1 GHz to 4,8 GHz and 6 GHz to 8,5 GHz has been recently updated in the last Electronic Communication Committee (ECC) amended ECC/DEC(06)04 [i.1] including the suitable reference to mitigation techniques. According to [i.2], underground station should be considered as an indoor environment because surrounding structures shields any emitted radio signal, providing the necessary attenuation to protect primary radio communication services against harmful interference.

However, in railway stations and trackside signalling installations there may not be structures blocking the propagation of emitted signals, and therefore the outdoor environment regulation should apply. The outdoor usage of UWB devices in location and tracking applications such as person and object tracking in industrial, automotive and transportation environments are described in [i.4] and [i.5]. Nevertheless, these applications do not include the location / tracking specific application in railway environments, which may occur at many points across a public rail or tram network. Actually, the latest generic ECC regulation [i.11] for the deployment of UWB devices in vehicles and the ECC/REC(11)09 [i.9] on provisions relevant to fixed UWB infrastructures do not deal with specific railway application issues, but are actually permitting the deployment of such UWB, respectively, onboard the trains and along the wayside of railway infrastructures. Therefore, the present document describes the railway application of UWB devices and collects specific information, including:

- Market information (annex A).
- Technical information (annex B).

# 2 References

References are either specific (identified by date of publication and/or edition number or version number) or non-specific. For specific references, only the cited version applies. For non-specific references, the latest version of the referenced document (including any amendments) applies.

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## 2.1 Normative references

The following referenced documents are necessary for the application of the present document.

Not applicable.

## 2.2 Informative references

The following referenced documents are not necessary for the application of the present document but they assist the user with regard to a particular subject area.

[i.1] ECC/DEC/(06)04 of 24 March 2006 amended 6 July 2007 at Constanta on the harmonised conditions for devices using Ultra-Wideband (UWB) technology in bands below 10.6 GHz (2007/131/EC) amended 6 July 2007.

[i.2] Commission Decision 2007/131/EC of 21 February 2007on allowing the use of the radio spectrum for equipment using ultra-wideband technology in a harmonised manner in the Community.

[i.3] ECC/DEC/(06)12 of 1 December 2006 amended Cordoba, 31 October 2008 on supplementary regulatory provisions to Decision ECC/DEC/(06)04 for UWB devices using mitigation techniques amended 31 October 2008.

[i.4] ETSI TR 102 495-5: "Electromagnetic compatibility and Radio spectrum Matters (ERM); System Reference Document; Short Range Devices (SRD); Technical characteristics for SRD equipment using Ultra Wide Band Sensor technology (UWB); Part 5: Location tracking applications type 2 operating in the frequency bands from 3,4 GHz to 4,8 GHz and from 6 GHz to 8,5 GHz for person and object tracking and industrial applications".

[i.5] ETSI TR 102 495-7: "Electromagnetic compatibility and Radio spectrum Matters (ERM); System Reference Document; Short Range Devices (SRD); Technical characteristics for SRD equipment using Ultra Wide Band Sensor technology (UWB); Part 7: Location tracking and sensor applications for automotive and transportation environments operating in the frequency bands from 3,1 GHz to 4,8 GHz and 6 GHz to 8,5 GHz".

[i.6] The Association of the European Rail Industry (UNIFE).

NOTE: Website: http://www.unife.org/.

[i.7] CEPT/ECC Report 64: "The protection requirements of radiocommunications systems below 10,6 GHz from generic UWB applications", Helsinki, February 2005.

[i.8] IEEE 802.15.4a: "Standard for Information Technology - Telecommunications and information exchange between systems - Local and metropolitan area networks - specific requirement Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs)".

[i.9] ECC/REC(11)09: "UWB Location Tracking Systems Type 2 (LT2)".

[i.10] ECC Report 167: "The Practical Implementation of registration/coordination mechanism for UWB LT2 systems".

[i.11] ECC/DEC (06)04: " The harmonised conditions for devices using UWB technology in bands below 10.6 GHz ".

[i.12] ECC Report 170: "Specific UWB applications in the bands 3.4 - 4.8 GHz and 6 - 8.5 GHz Location Tracking Applications for Emergency Services (LAES), location tracking applications type 2 (LT2) and location tracking and sensor applications for automotive and transportation environments (LTA)".

# 3 Definitions, symbols and abbreviations

## 3.1 Definitions

For the purposes of the present document, the following terms and definitions apply:

**activity factor:** effective transmission time ratio, actual on-the-air time divided by active session time or actual on-the-air emission time within a given time window

**distance:** Euclidean distance between two objects, i.e. real distance

**duty cycle:** defined as the ratio, expressed as a percentage, of the transmitter "on" relative to a given time period as specified in the technical requirements

**fixed equipment:** UWB location tracking device on a fixed position

**mobile equipment:** UWB location tracking device to be used while in motion or during halts at specified points

**range:** measured distance between two objects, i.e. erroneous distance

**range resolution:** ability to resolve two targets at different range

## 3.2 Symbols

For the purposes of the present document, the following symbols apply:

| | |
|---|---|
| AF | activity factor |
| BW | bandwidth |
| c | velocity of light in a vacuum |
| dBm | decibel relative to 1 mW |
| $\Delta h$ | Transmission interval |
| $\Delta t$ | Transmission on |
| $D_{data}$ | data rate |
| $\delta R$ | range resolution or multipath rejection resolution |
| r | Range of UWB device |
| $R_{data}$ | ranging packet length |
| $T_p$ | pulse width |
| $U_r$ | Update rate |

## 3.3 Abbreviations

For the purposes of the present document, the following abbreviations apply:

| | |
|---|---|
| 3D | Three Dimensional |
| AF | Activity Factor |
| AFR | Activity Factor Restriction |
| AOI | Area-Of-Interest |
| BSS | Board SubSystem |
| CBT | Communication-Based Train Control |
| CBTC | Communication-Based Train Control |
| CEPT | European Conference of Post and Telecommunications Administrations |

| | |
|---|---|
| CIS | Commonwealth of Independent States |
| $CO_2$ | Carbon Dioxide |
| DAA | Detect-And-Avoid |
| DCR | Duty Cycle Reduction |
| e.i.r.p. | Equivalent Isotropic Radiated Power |
| ECC | Electronic Communications Committee |
| ETCS | European Train Control System |
| FS | Fixed Service |
| GSM-R | Global System for Mobile Communications-Railways |
| GSS | Ground SubSystem |
| LDC | Low Duty Cycle |
| LOS | Line-Of-Sight |
| MAC | Medium Access |
| NAFTA | North American Free Trade Agreement |
| NLOS | Non-line-of-sight |
| OBU | OnBoard Unit |
| PHY | Physical |
| POI | Point-Of-Interest |
| PSD | Power Spectral Density |
| QoS | Quality-of-Service |
| RX | Receiver |
| TDD | Time Division Duplex |
| TPC | Transmission Power Control |
| TX | Transmitter |
| UWB | Ultra WideBand |

# 4 Presentation of the system or technology

In a railway network, there are two important functions that rely on knowing the position and speed of the train. The first, and the oldest, is signalling and the control of the track. The second function is train control, which was once performed by the train driver alone.
One important part of the train control function in urban railways is stopping the train in the right place at a platform, and if the platform has gates this requires centimetric accuracy and is always done automatically.

This system can be used by other train-borne systems to sense the train's position along the railway. Using this system the onboard equipment will stop the train precisely. In fact these functions are real innovations because very often there are stringent requirements by customers in subways where good efficiency in difficult radio propagation environments (e.g. tunnels) has to be guaranteed.

Currently the state-of-the-art to perform the train positioning includes inductive cables or railroad circuit to detect which is the block to be taken by the train and it is easy to understand that using these systems only low position accuracy is achievable. The conventional line signalling and illustration of braking train when approaching railway crossing are depicted in Figure 1. In here, the train is receiving information to stop from a wayside device, and the train is stopped by using, e.g. inductive cables as illustrated Figure 2. The OnBoard Unit (OBU) is a device installed in a train which takes care on communication between a train and wayside network.

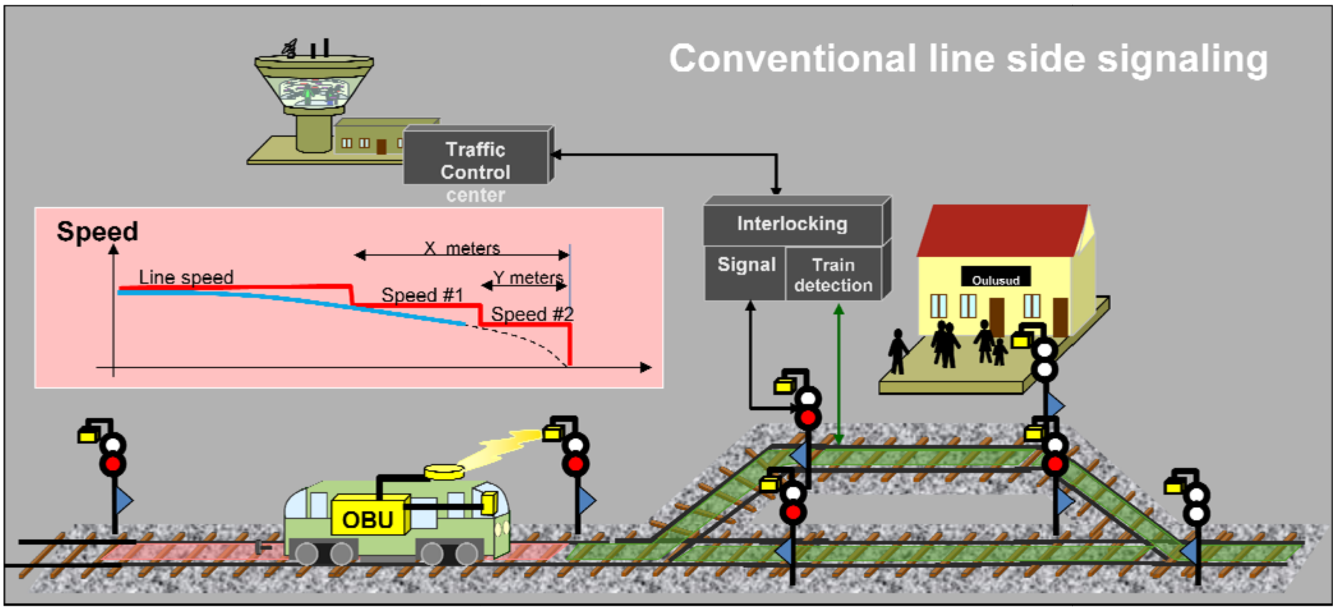

Figure 1: Conventional line side signalling

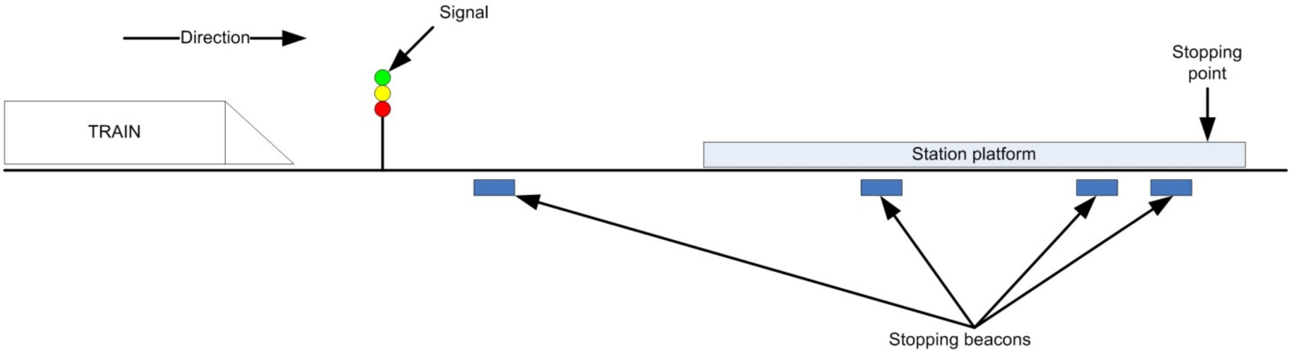

Figure 2: Conventional stopping of a train

The heart of this proposed system is the ultra-wideband radio that will introduce high-level performances and benefits, reaching good results for all the requirements listed above. In fact, basically high accuracy positioning combined with high velocity of the train can be considered as the main challenge. It raises a concern on the ability of the current wireless technologies to respond to these challenges. Based on this consideration, UWB is the technology that currently offers the best guarantees.

Specialities for positioning application in railway environment are:

- Cost-efficient
- High velocity
- The information of the train's physics (acceleration...)
- Track discrimination
- High accuracy
- Interference tolerant
- Energy saving

Railway environment can be divided in the following environments:

1) Subway and underground
2) Depot

3) Ground Station or Railway station

4) Railway signal or Point-of-Interest (POI) along railroad

Apart from some urban or local transit systems, a "railway" is a part of a very much large network, even on a national scale. And large cities may have multiple inter-working railways (notably in London). Even a new self-contained railway system is likely to include parts with different characteristics - for example some underground and some on the surface, station spacings varying greatly, or some on roads (for trams or light rail) and some on segregated tracks. While it is obviously an advantage to use one sensor type throughout, other considerations may determine that one (e.g. UWB) is only used in a part of the network. Also, different parts of the network may be different environments as far as radio regulations are concerned. The clearest case of this is where part of the network is underground or enclosed (hence "indoors", though this word might seem a little odd for a large railway station) and part is in the open.

## 4.1 Subway and underground

The subway represents a classic indoor use scenario for railway applications of UWB. Typically, subway trains are operating under the ground and stations are located also under the ground as presented in Figure 3. Installation of devices in the subway environment is illustrated in Figure 4 where UWB transmitter (BSS, Board SubSystem) is installed in a train and UWB receivers (GSS, Ground SubSystem) are mounted in the ceiling.

In the subway environment, there are structures that block or attenuate an emitted signal, and thus does not interfere other radio systems. The operating time varies from 20 h to 24 h per day in large and congested subway stations, and operating frequency is handling 20 to 60 trains per hour.

**Figure 3: Typical subway station**

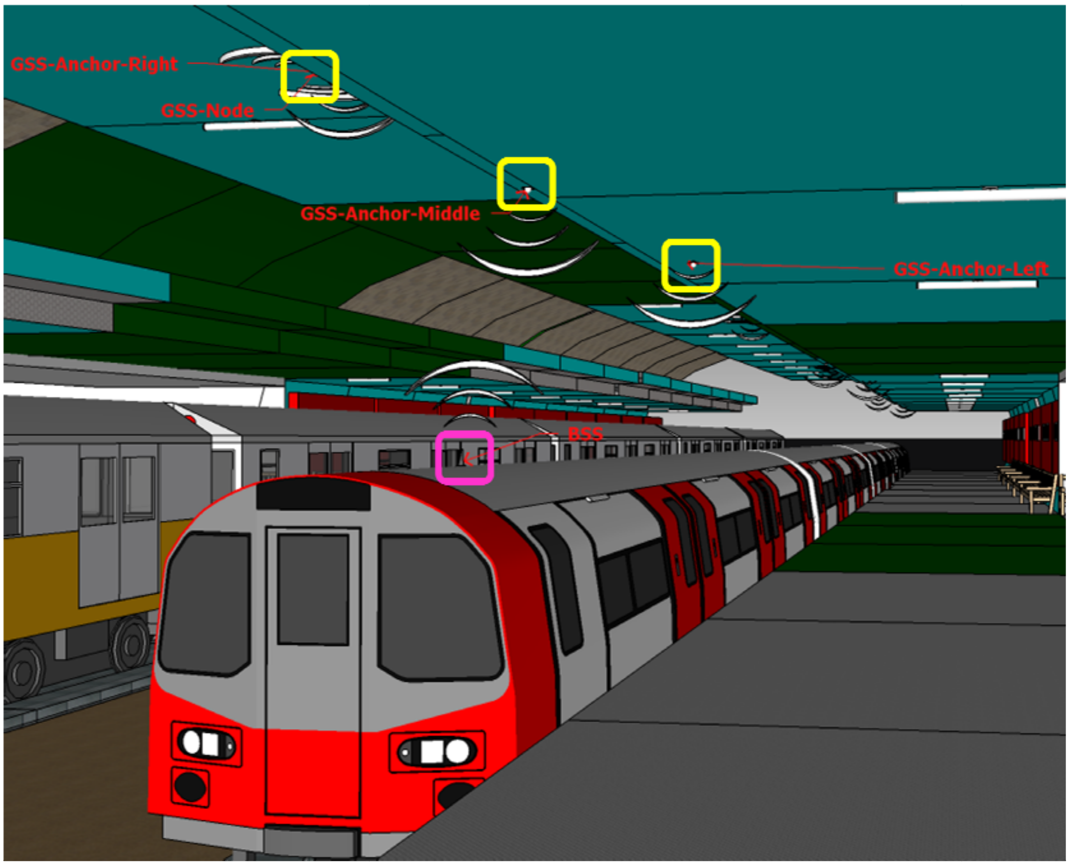

**Figure 4: Installation of UWB devices**

## 4.2 Depot

The railway depot is an area for maintenance and storage of trains in, for example, an indoor environment such as a wide and open shed where the walls of the shed attenuate an emitted signal.

## 4.3 Ground Station or railway station

An uncovered railway station represents a good example of an outdoor railway scenario as illustrated in Figure 5, as does the ground tram station shown in Figure 6. In these scenarios, there are not always shielding structures providing necessary attenuation of an emitted signal to protect other radio systems such as Fixed Service (FS) or satellite communications, and there may be many such installations across a public rail network covering (for example) a city or country. Therefore, mitigation techniques to give enough protection for other radio systems are needed to be carefully studied.

In typical railway station, the operating frequency is 10 to 20 trains per hour 24 hours per day.

The railway waysides are authorized areas and are restricted from unauthorized persons' presence.

Figure 5: Typical railway station

Figure 6: Typical ground tram station

## 4.4 Railway signals or POI along railroad

A railway signal (see Figure 7) is an electrical device installed along a track to pass information relating the state of the line ahead to a train. A generic Point-of-Interest can be a stopping point in a loading platform for instance. It is important to stop a train accurately so that there is no need to relocate a train for loading. Again, these situations represent largely outdoor use of UWB, and there may be significant numbers of signals across a public rail or tram network.

**Figure 7: Typical railway signal**

# 5 Radio spectrum regulations and compliance

## 5.1 Technical justification for spectrum

### 5.1.1 Technical justification for power levels

UWB positioning can only make use of a fraction of the energy emitted by a UWB transmitter: that portion which reaches a receiver via the direct path. Only the signal travelling along this path conveys information about the location of the transmitter relative to the receiver. This is in contrast to communications systems, which may utilize signals travelling along any or all paths between the transmitter and receiver (e.g. systems involving rake receivers).

The UWB system under consideration operates (depending on target scenario) either in the 3,1 GHz to 4,8 GHz or in the 6 GHz to 8,5 GHz frequency region and is mainly operating under the Line-Of-Sight (LOS) conditions, and thus a maximum PSD limit of -41,3 dBm/MHz, as defined in ECC/DEC(06)04 [i.1] recently amended in [i.11], is enough for the applications described in the present document.

It is worth to distinguish between very short range (<10 meters) applications and short range ones (up to 50 m).

Indeed, after the definition of "exterior limit" [i.11], several UWB emitters maybe installed "on board" the train cars, provided that the proposed "PSD exterior limits" (-53,3 dBm/MHz) are satisfied by each of these mobile UWB emitters, operating either in the frequency band from 3,1 GHz to 4,8 GHz and in the higher band from 6 GHz to 8,5 GHz.

This deployment of multiple UWB emitters on-board, transmitting outwards the train cars, is free of limitations (with the duly exception of the said "PSD exterior limits" [i.11] and activity factor LDC <5 %) as, in other words, devices registration is not required and they may be coupled with a suitable number of "ground-based" wayside receiving devices, deployed in the frame of a purely "passive" fixed infrastructure, in such a way that tracking accuracy is enhanced, together with availability and reliability. Graceful increase of railway signalling system availability/reliability maybe proportioned to the actual multiplicity of such "mobile" UWB emitters and of the corresponding "ground-based" receivers installed at fixed reference points belonging to the wayside infrastructure.

Dealing with tracking operation at increased ranges, up to ≈50 meters, the system operation should cope with several critical factors which may impair the tracking availability and accuracy wayside, unless provision of appropriate countermeasure is adopted in terms of power level and of other design provisions. As experienced in real installation, the following list of critical factors is provided as an exemplary, but not limitative, description of main technical challenges, associated with the operation of short-range low-power UWB tracking systems in railway environment. Technical descriptions are provided in annex B, including system architectures and corresponding link budgets, shown in the following clause B.3.

**Table 1: Critical factors limiting the performance of UWB systems in railway environment**

| Frequency (GHz) | Area of Operation | Critical factors impairing system performance | Countermeasures compatible with limits and ECC regulations |
|---|---|---|---|
| $3,11 < f < 4,8$<br>PSD <-53,3 dBm/MHz for unregistered UWB unlicensed mobile devices with 5 % activity LDC<br>PSD <-41,3 dBm/MHz for registered devices | very short range (<10 meters) | Multipath<br>Broadband interferers (e.g. automotive UWB) | Multiple UWB emitters onboard the train cars real-time processing<br>Multiple "ground-based" fixed receivers |
| | short range (<50 meters) | Multipath + path loss<br>Broadband interferers | Multiple UWB emitters at 3,1 GHz to 4,8 GHz deployed as "ground-based" fixed references for real-time processing |
| $6 < f \leq 8,5$<br>PSD <-53,3 dBm/MHz for unregistered UWB mobile devices with 5 % LDC | very short range (<10 meters) | Multipath | Multiple UWB emitters onboard the train cars real-time processing<br>Narrow-beam antenna |
| NOTE: At highest frequencies ($6 < f \leq 8,5$ GHz) very short-range (<10 meters) applications only are affordable, due to the fact that fixed infrastructures made of UWB emitters are not allowed by ECC. | | | |

It is easy to demonstrate that, either onboard and in the fixed infrastructures, the adoption of multiple UWB emitters improves the system performance and maximises its availability for tracking ranges extending up to 50 meters and over. On the other hand, the most recent ECC recommendation [i.9], aiming the protection of existing services, dictates that each UWB emitter belonging to fixed infrastructure is limited to an average PSD of -41,3 dBm/MHz e.i.r.p. in the lower frequency band only, that is from 3,4 GHz to 4,2 GHz, and maybe extended from 4,2 GHz to 4,8 GHz, when complying with tighter limit of -47,3 dBm/MHz in the higher portion of this lower band. Moreover, a registration/coordination process should be undertaken, in charge of national authorities, according to the proposed guidelines given by ECC Report 167 [i.10] and ECC Report 170 [i.12].

Therefore, the perspective of using UWB devices in railway tracking applications, extending up to 50 meters and over, appears less favourable and much less affordable than tracking for just shortest ranges (<10 meters), due to the combined effect of four critical factors: multipath, path loss, PSD/band limitations and registration/coordination mechanism.

It is clear that UWB devices afford advantages over other wireless technologies particularly in the very short-range applications, where they maybe suited for widespread "unregistered" use, provided that each UWB emitter installed onboard the train cars complies with the tightest PSD "exterior limit" of -53,3 dBm/MHz, as ECC recently stated [i.11].

### 5.1.2 Technical justification for bandwidth

The accuracy of radio ranging location devices is determined by the occupied bandwidth of the signal, provided it is processed coherently. For example, in a pulse-based system, if the device has to reliably measure different transmitter-receiver ranges when the transmitter is moved from one point to another, the difference in the travel time of the signal from the transmitter to the receiver at the two different positions should be greater than the pulse width. Similarly, a direct path signal and a reflected multipath signal can be separated if the extra time interval required for the signal to travel the reflected path rather than the direct path is greater than the pulse width.

The bandwidth required to provide the same resolution as a pulse of width $T_P$ is approximately $1/T_P$.

Therefore, for a range resolution or multipath rejection resolution of $\delta R$, the bandwidth requirement for the UWB location tracking devices is given by:

$$BW = \frac{c}{(\delta R)},$$

where $c$ is the velocity of light in a vacuum.

For a range resolution of 10 cm, this gives a bandwidth requirement of around 3 GHz. For a measurement accuracy of 10 cm, the resolution can be somewhat larger, so that a bandwidth of 1 GHz to 1,5 GHz can be enough.

## 5.2 Compliance to current regulations

The radio regulations for indoor environments, i.e. subway, underground, and depot as discussed in clauses 4.1 and 4.2 are included in amended ECC/DEC(06)04 [i.11] excluding fixed outdoor location tracking installations as shown in Table 2.

**Table 2: Current regulations (excluding fixed outdoor installations) for UWB systems**

| Frequency (GHz) | Area of Operation | Maximum value of mean power spectral density [dBm/MHz] |
|---|---|---|
| $3.1 < f < 4.8$<br>$6 < f \leq 8.5$ | generic usage in train vehicles | < -41.3 (exterior limit -53.3)<br>(assuming implementation of LDC mitigation as stated in ECC/DEC/(06)04 [i.11]) |
| $3.1 < f < 4.8$<br>$6 < f \leq 8.5$ | train vehicles in underground and indoor environment | < -41.3 (exterior limit of -53.3 over 0 ° not necessary, see ECC report 170 [i.12]) |
| NOTE: No active UWB outdoor transmitter; Base stations outdoor are passive, all active UWB transmitters are onboard train vehicles. | | |

## 5.3 Additional compliance to ECC recommendation

A railway network will usually have some parts that qualify as "indoor" for UWB regulations, and some that are "outdoor". However, the same UWB terminals may need to operate in both. Not only will terminals on trains move between such environments, but fixed terminals throughout the network will need to operate with low activity factor, just in case these mobile terminals come around. In addition, within the network there will be a few places with many trains and lines, most of the network will have a much lower density.

The ECC recommendation [i.9] has proposed limits for type 2 location tracking UWB fixed emitters applications in the frequency range 3,4 GHz to 4,8 GHz as shown in Table 3.

**Table 3: Current ECC recommendation [i.9] for LT2 applications**

| Frequency GHz | Maximum value of mean power spectral density [dBm/MHz] |
|---|---|
| 3,4 < *f* < 4,8 | ≤ -41,3 dBm/MHz fixed outdoor subject to implementation of DCR and subject to some coordination/registration [i.10] for licensing.<br>the maximum mean e.i.r.p. spectral density in the band 4,2 GHz to 4,4 GHz for emissions that appear 30° or greater above the horizontal plane should be less than -47,3 dBm/MHz. |

It is worth to underline that coordination/registration process [i.10] allows UWB devices deployment at fixed outdoor locations (with PSD limit of -41,3 dBm/MHz or -47,3 dBm/MHz), according to [i.9] as LT2 tracking network "registered" infrastructure, only in the lower band from 3,4 GHz to 4,8 GHz.

The main benefit of such deployment of UWB emitters at fixed outdoor locations would be to make more appealing and more affordable LT2 railway applications also for tracking range up to 50 meters and over.

## 5.4 Summary UWB regulation for specific railway application

**Table 4: Summary / Interpretation of existing UWB regulation for this specific UWB railway applications**

| Frequency (GHz) | Area of Operation | System license type | Maximum value of mean power spectral density [dBm/MHz] |
|---|---|---|---|
| 3,1 ≤ f ≤ 4,8<br>6 ≤ *f* ≤ 8,5<br>(Note 1) | generic usage in train vehicles | Unregistered system, licence exempt usage | ≤ -41,3 (exterior limit -53,3)<br>(assuming implementation of LDC mitigation as stated in ECC/DEC/(06)04 [i.11]) |
| 3,1 ≤ f ≤ 4,8<br>(Note 2) | train vehicles in underground and indoor environment, (Note 3) | Unregistered system, licence exempt usage | ≤ -41,3 (exterior limit of -53,3 over 0º not necessary, see ECC report 170 [i.12]<br>(assuming implementation of LDC mitigation as stated in ECC/DEC/(06)04 [i.11]) |
| 6 ≤ *f* ≤ 8,5<br>(Note 2) | train vehicles in underground and indoor environment, (Note 3) | Unregistered system, licence exempt usage | ≤ -41,3 (exterior limit of -53,3 over 0º not necessary, see ECC report 170 [i.12] |
| 3,4 ≤ f ≤ 4,8 | train vehicles | Registered systems [i.10] | ≤ -41,3<br>(Note 4) |
| 3,4 ≤ f ≤ 4,8 | outdoor fixed UWB transmitters | Registered systems [i.10] | ≤ -41,3 dBm/MHz fixed outdoor subject to implementation of DCR and subject to some coordination/registration [i.10] for licensing<br>(Note 5) |

NOTE 1: No active UWB outdoor transmitter; Base stations outdoor are passive, all active UWB transmitters are onboard train vehicles.
NOTE 2: UWB transmitters in the indoor environment can be seen as an device under the Generic UWB rules [i.11], chapter 1.
NOTE 3: For more details clauses 4.1 and 4.2.
NOTE 4: A maximum duty cycle of 5 % per transmitter per second and a maximum Ton = 25 ms apply. The duty cycle should also be limited to 1,5 % per minute or equipment should implement an alternative mitigation technique that provides at least equivalent protection [i.9].
NOTE 5: The maximum mean e.i.r.p. spectral density in the band 4,2 GHz to 4,4 GHz for emissions that appear 30° or greater above the horizontal plane should be less than -47,3 dBm/MHz [i.9].

# Annex A:
# Detailed market information

The proposed specific application using the UWB technology in railway application will play an important rule into the worldwide railway market. This clause shows how this wireless technology matches the requirements defined for this growing market. The following considerations were given by [i.6].

The worldwide rail market has grown tremendously in the past few years and the expectations for the next ten years is to have several new railway projects around the world for upgrading and expanding existing railway lines.

The railway market environment changes in the short time frame and the rail suppliers should adapt their products and services developing new technologies. In this way, they are able to support passenger's mobility needs and cargo transport. In this scenario, innovations make rail transport more attractive adding high technological value.

The market rail could be divided into:

- Rail Control
- Infrastructure
- Rolling Stock
- Services

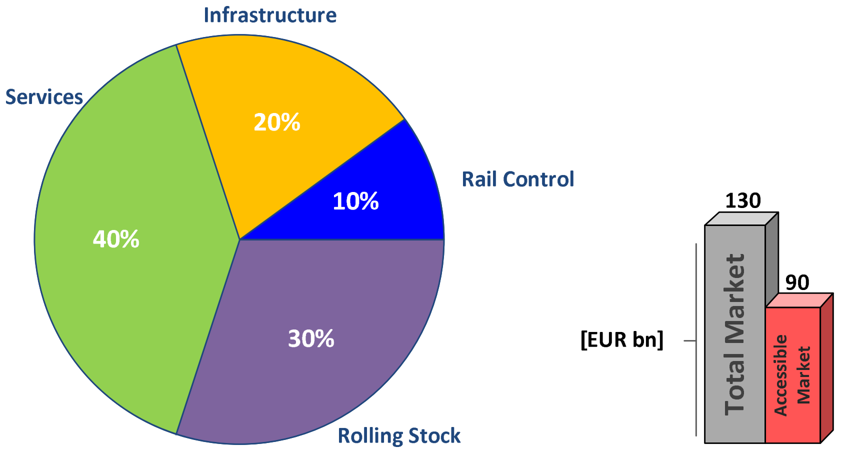

**Figure A.1: Average annual market volumes in the last few years**

Figure A.1 shows the annual average market volumes and how it is distributed, moreover it describes which is the "accessible market" opened to external suppliers.

In the last years this market has grown and this trend will be maintained with an expected annual growth till 2,5 % in the seven years reaching a volume of EUR 160 billion of which EUR 115 billion will be accessible (71,8 %).

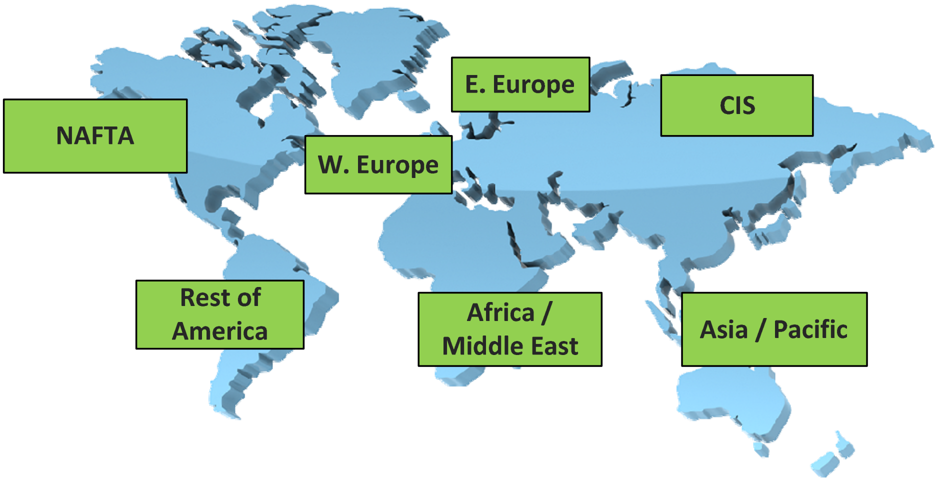

**Figure A.2: World segmentation**

Reading Table A.1, the most important markets are: Europe, NAFTA and ASIA/Pacific region but with the expected dynamic growth, Asia/Pacific will surpass NAFTA in the next six years. On the other hand, the marketing forecast shows also that the growth in NAFTA will continue but below the world average. The estimated rail market for the last years listed in Table A.1 has focused on 50 countries that include 95 % of the whole global rail market.

**Table A.1: Distribution of Accessible market in the world in the last years**

| | Rail Market % (EUR bn) |
|---|---|
| **W. Europe** | 33 |
| **E. Europe** | 5 |
| **CIS** | 12 |
| **NAFTA** | 20 |
| **Rest of America** | 3 |
| **Asia / Pacific** | 25 |
| **Africa / Mid. East** | 2 |

Rail suppliers are companies that manufacture rail infrastructure, rolling stocks and rail signals. Besides these are multinational companies that spread over thousands of suppliers and sub-suppliers. The telecommunications systems are key part of these complex systems and the introduction of new technologies in this field pulls the railway products making these more attractive.

In the medium and long term period, the rail industry follows new trends reported below:

- Ecological awareness
- Resources scarcity
- Urbanization
- Competition with other modes of transport
- Standardization

The companies answer to these treats developing new products where (for example):

1) emissions are reduced ($CO_2$ emissions limits, noise control, electromagnetic pollution reduction);
2) transport capacity is increased;
3) efficient rolling stocks are developed;
4) standardization activates are included.

Besides, the competition with other modes of transport will push rail companies to fulfill new requirements to cut the travel times providing more traveller benefits.

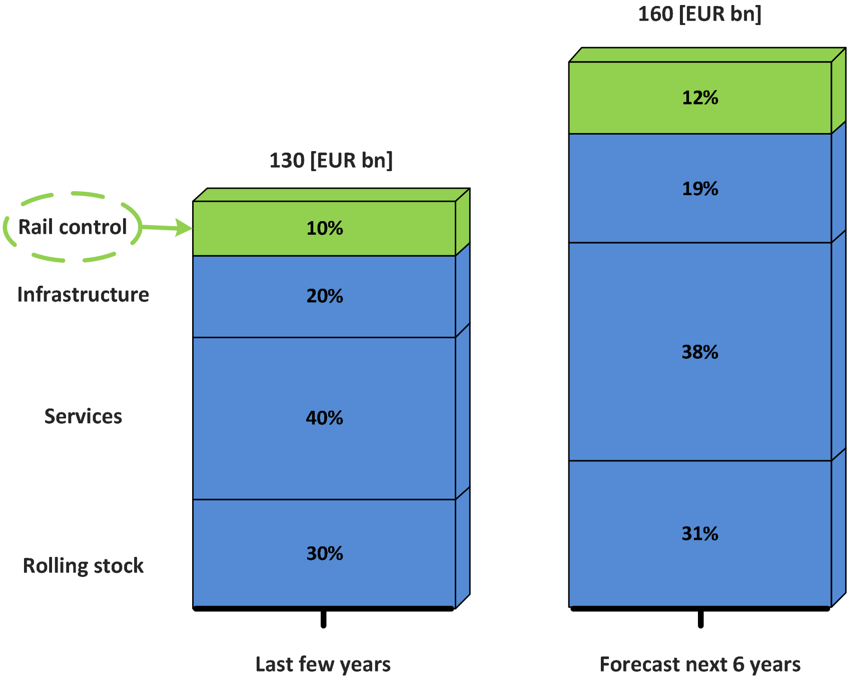

Figure A.3: Development of the world total rail market.

In Figure A.3, the development of the total rail market during the next 6 years is presented, and the Rail Control segment is underlined because in Europe it will be one of the most important, followed by Asia/Pacific area. Rail Control is the market where the telecommunications play as top-tier player because railway signalling solutions (interlocking, trackside products, etc.), train protection (CBTC - Communication-Based Train Control, ETCS - European Train Control System, etc.), rail telecommunication and station operation systems are included.

Starting from all the previous considerations, ultra-wideband technology gives a fundamental contribution in the development of new rail systems because it matches many key requirements listed in the present document.

Using UWB in railway could increase the train positioning accuracy, giving on the other hand the chance to increase the transport capacity in subways and light rail transit systems. This benefit could be amplified by the huge number of new metro and light rail systems expected to build in Europe and Asia (urbanization).

The innovation introduced by wideband wireless communication will make rail systems more efficient and create an infrastructure for sustainable transportation, which is essential for economic growth, prosperity and increased safety.

# Annex B:
# Detailed technical, density and activity information

## B.1 Detailed technical description

The following description covers a range of possible system architectures, so as to be technology neutral. However, the detailed parameters and calculations in the present document relate to only one specific case.

A tracking system of presented application can be realized in three different ways:

- Using transmitter which is installed into a rail vehicle and fixed receiving wayside equipment (option 1, see Figure B.1).

  The UWB signals emitted by a transmitter installed in a moving rail vehicle are detected by a wayside network of receivers which are fixed equipment placed at known, fixed points around the area to be covered. By centralized computational means, the location of a rail vehicle can be determined. This is a typical application.

- Using receiver which is installed into a rail vehicle and fixed transmitting wayside equipment (option 2, see Figure B.2).

  The UWB signals emitted by a wayside network of transmitting fixed equipment placed at known, fixed points around the area to be covered are detected by receiving equipments installed in a moving rail vehicle detecting their own position.

- Using transmitter/receiver which are installed into a rail vehicle and fixed transmitting/receiving wayside equipment (option 3, see Figure B.3).

  A combination of options 1 and 2; both units are installed in a rail vehicle and the fixed wayside equipment can receive and transmit UWB-signals.

**Table B.1: Options for implementation of location tracking system**

| Option | Vehicle | Wayside |
|---|---|---|
| 1 | TX | RX |
| 2 | RX | TX |
| 3 | TX/RX | TX/RX |

For option 1, the location tracking system of a train can be realized as illustrated in Figure B.1, where UWB transmitter (TX) is installed in a moving train. An emitted UWB signal is detected by a network of fixed UWB receivers (RX) placed at known, fixed points around the area to be covered. Each UWB RX transmits its information to rest of the network for further processing, where the position of a train is computed in centralized fashion. The 3D position of an UWB TX can be calculated by detecting an emitted signal at a number of receivers and analysing the time-of-arrival or/and angle-of-arrival of the emitted signal at each receiver. Since trains only run on tracks, full 3D positioning is not always needed. If it is not, then fewer terminals are needed at each position along the track - in some architectures only one.

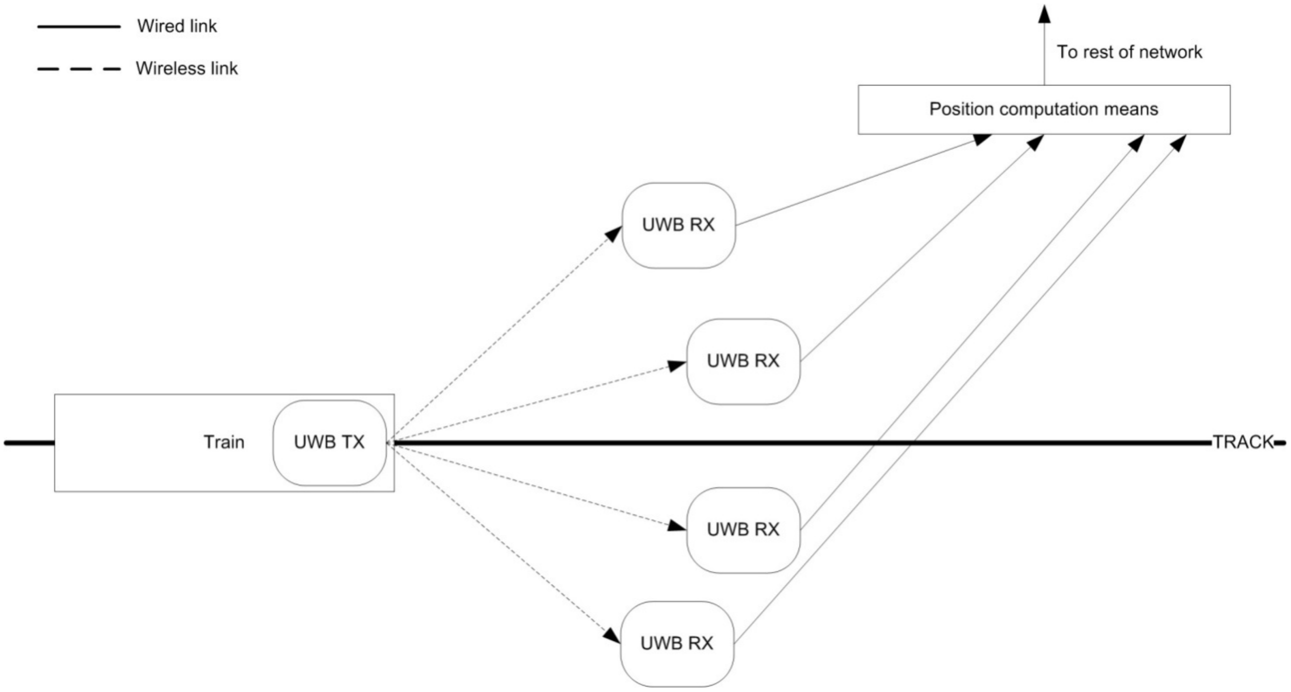

Figure B.1: Components of a UWB location tracking system (option 1)

In option 2, the location tracking system applies transmitting fixed wayside network, and position is calculated in the receiver installed in a moving rail vehicle as shown in Figure B.2. Position information can be transmitted to a backbone network by using, e.g. Global System for Mobile Communications-Railways (GSM-R).

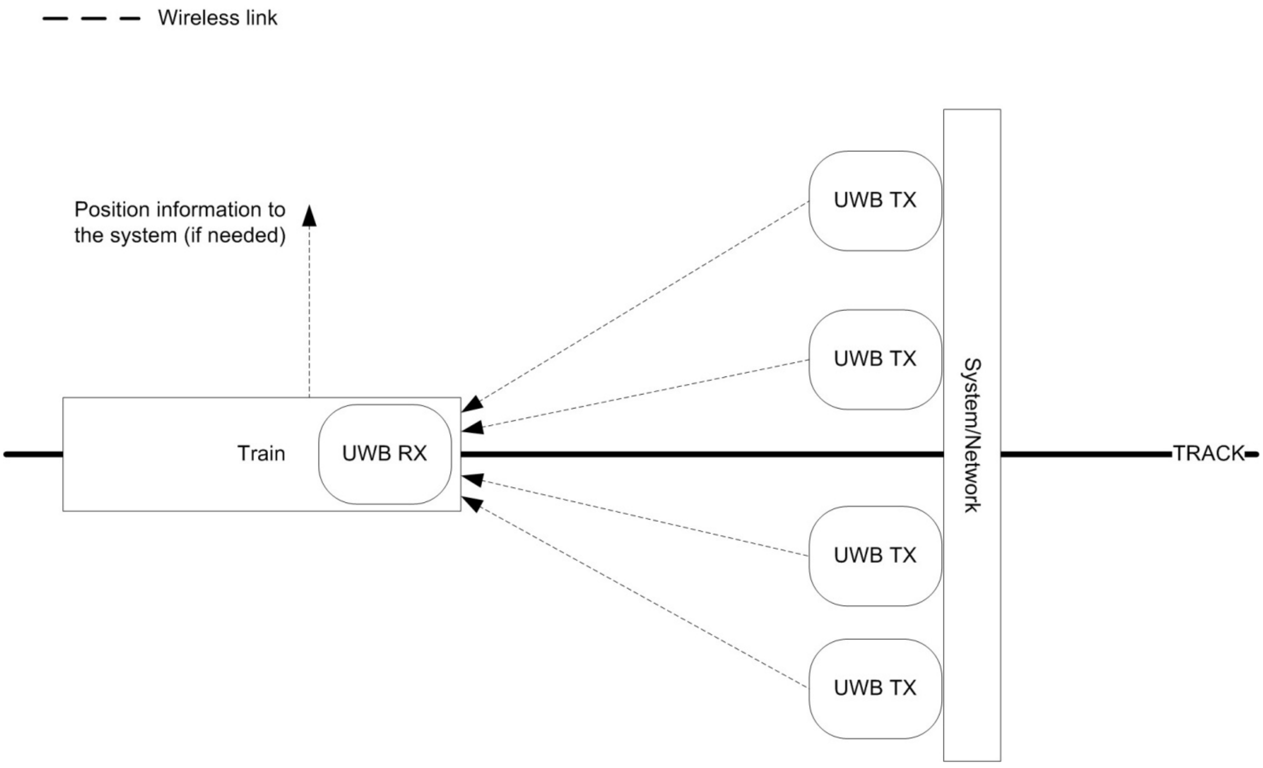

Figure B.2: Components of a UWB location tracking system (option 2)

Option 3 describes the systems where a UWB TX/RX is installed in a moving rail vehicle and fixed wayside network includes in UWB TX/RX nodes as shown in Figure B.3. In this option the position information can be calculated:

a) in a rail vehicle and sent back to a backbone network by using UWB;

b) in a rail vehicle and sent back to a backbone network by using, e.g. GSM-R;

c) in a system and sent back to a rail vehicle by using UWB if needed;

d) in a system and a rail vehicle and then the information can be compared.

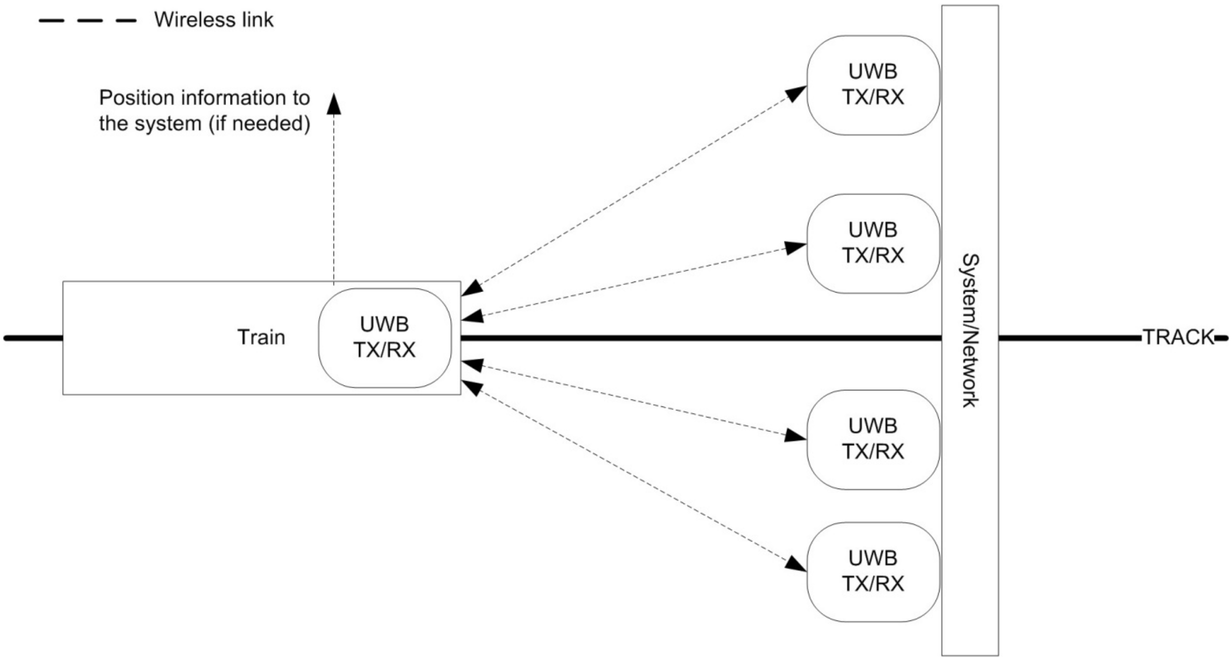

Figure B.3: Components of a UWB location tracking system (option 3)

A train transmits packets only within an area-of-interest (AOI) around a point-of-interest (POI), which can be, e.g. a signal device. The concept of AOI and POI is illustrated in Figure B.4. AOI is the area along a track having a length enough to stop a train to POI. Typically, AOI might be hundreds of meters long along a track. A system tracks a train within AOI to stop a train in POI with sub-meter accuracy. When a train is stopped to POI, transmission is interrupted until a train goes on, and transmission is switched on again. Tracking of a train is needed after POI to ensure that a train is in correct track. The control of signalling of a railway system is done by a railway operator. Therefore, this application is designed for private use, and system usage is very controlled. Because UWB transmission occurs only within AOI, this application is highly site-specific. Moreover, the rail tracks are restricted areas where unauthorised being is forbidden. Due to the path loss, the low power transmitted UWB signal attenuates before being in a location of other spectrum users. The movement of a train is also averaging out the impact of UWB signal on a certain fixed point around a train track. Generally speaking, AOI can be expanded to cover a complete urban/suburban railway network where a train is tracked continuously but this should not be considered as a main application described in the present document.

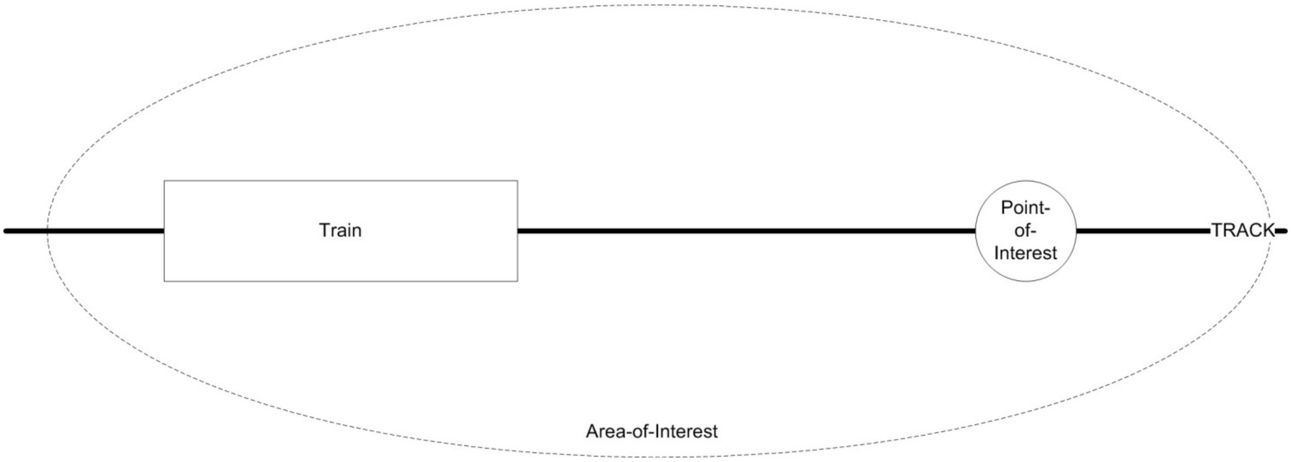

Figure B.4: Area-of-Interest of a UWB location tracking system

In Figure B.5, a scenario where two trains are present is depicted. This illustrates the situation, e.g. in a small railway station. There are three POIs in the system; the point where train #2 can change a track (POI #2) and stopping points POI #1 and POI #3. All of these have their own AOIs. But as it can be seen, these AOIs overlap with each other, and therefore some of the receivers can be applied in several AOIs.

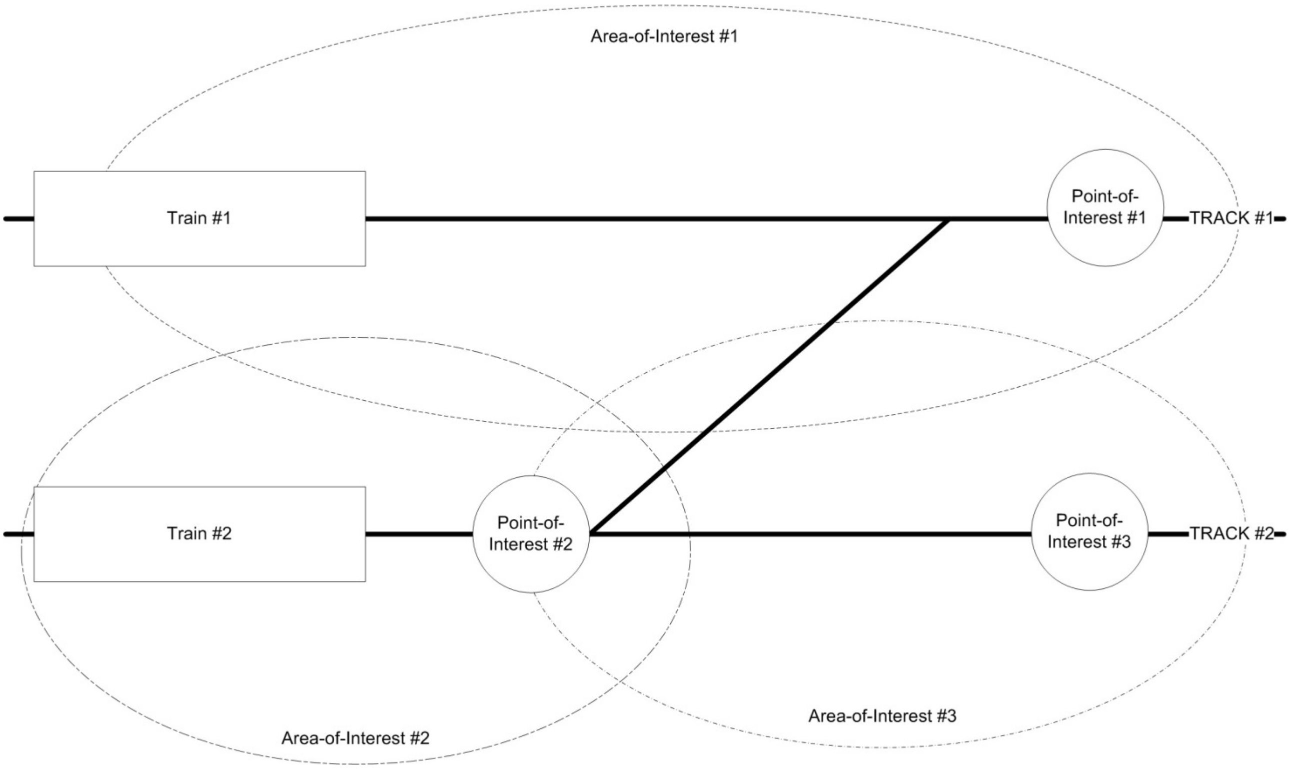

Figure B.5: Case of multiple users

# B.2 Density and activity

## B.2.1 Density of UWB transmitters

UWB device densities and activity factors for the application are considered in point of view of different options described in Table B.1, and a point of view of different scenarios described in the following:

Scenarios are divided for three cases by the width of the service area (Area where positioning application is needed) from the point of view investigated area of 1 km$^2$.

**Case A) Width > 1 km**
This case covers situations where the region where positioning is needed covers an extended outdoor area, i.e. locations where many tracks run parallel to each other. Examples might be areas in and around railway stations or entering train depots.

**Case B) Width <1 km**
This case covers situations where the area where positioning is needed is limited to a more restricted area, for example wayside areas with Point-Of-Interest (POI). These might occur on the railroad network between railroad stations and/or train depots, with POI or POIs where the accurate position is needed. Typically length of this area is ±300 m and width is ±10 m from the POI.

**Case C) Wayside area without POI**
Railroad network between railroad stations and/or train depots, without POI, in other words, area of railroad network where the accurate position is not needed. The service of the positioning application is not needed, and so on all the UWB transmitters are not active. Here, the activity factor will be 0 % and there's no purpose to go on with analysis within Case C) assumptions.

These three cases are illustrated in Figure B.6. It should be noted that Figure B.6 is not any mean in scale or not giving correct example about the application (i.e. number of tracks is only for illustrative purposes only).

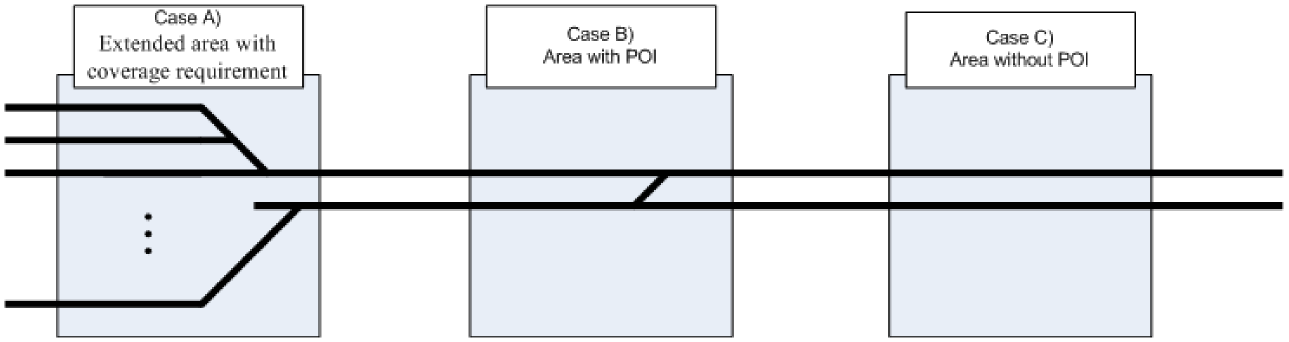

**Figure B.6: Railroad network from the point of view the Positioning Application**

Cases A, B, and C are presented in more details in Figure B.8, Figure B.9 and Figure B.10 and corresponding legend are shown in Figure B.7.

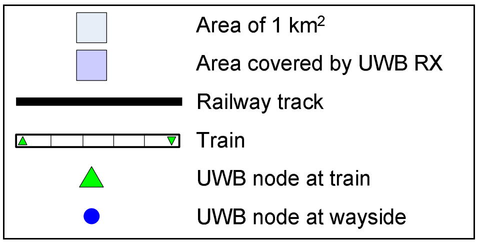

**Figure B.7: Symbols and legend for the Case A, B and C**

**Case A)**

Case A) is illustrated in Figure B.8. Length of the service area is more than 1 km, and width of the service area depends on number of parallel tracks.

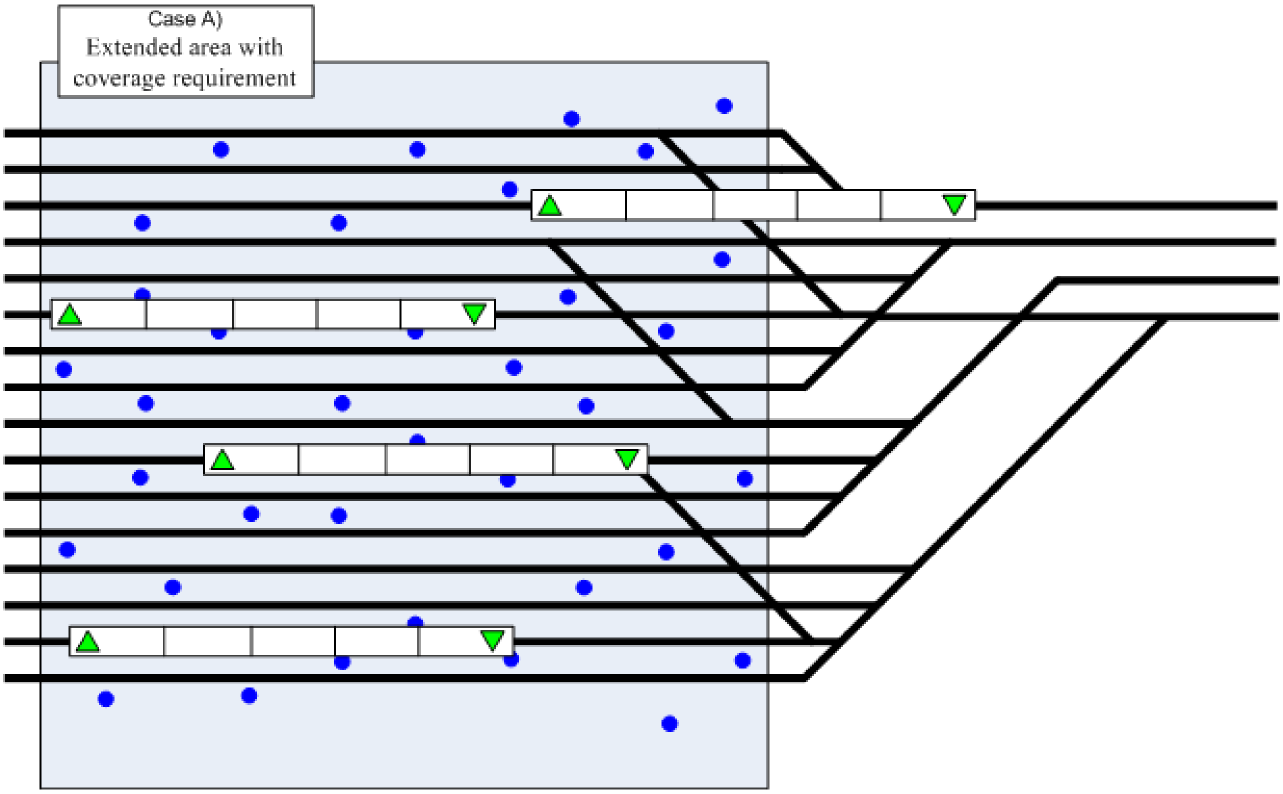

Figure B.8: Illustration of Case A)

In railroad station or train depot entrance area, the worst case scenario can be described with 40 parallel track (e.g. Gare du Nord, Paris with 44 platforms, although 2 tracks are not in use and 14 are for suburban) and train using positioning application at each track. Same worst case assumption holds for the typical train depot area. The following calculations are carried out also with 20 parallel tracks to give an example about scalability.

Distance between each pair of the 40 tracks are assumed to be 4,0 m, making width of the area 160,0 m, and 80,0 m respectively for 20 tracks. Range for the UWB devices is assumed to be 25 m (commercially available, NLOS case). For the positioning application it is required to cover each point of the area several times, i.e. in case of 3D-positioning minimum of 4 reference points (anchors) are required. We derive required number of devices as a function of UWB range ($r$) as

$$\#devices = 4 \cdot \frac{1\ km * (width)m}{\pi r^2}$$

Additionally, the train has at most two active devices at the time. The following estimates are done by assuming two devices active for each train being the worst case scenario. To cover breakdowns it is possible that two or more devices are installed at the train end parallel, but only 1 is active at the time. Table B.2 presents maximum amount of UWB transmitters per km$^2$ with assumption of 40 parallel tracks and respectively Table B.3 with 20 parallel tracks. To have redundancy it is assumed to have 25 % more devices than minimum requirement for the positioning application is.

### Table B.2: Transmitter densities for Case A) with 40 parallel tracks per km$^2$

| Option | Number of transmitters at Trains | Number of transmitters at Wayside | Total |
|---|---|---|---|
| 1 | 80 | 0 | 80 |
| 2 | 0 | 326 + 25 % | 408 |
| 3 | 80 | 326 + 25 % | 488 |
| 3* | 160 | 326 | 486 |

Option 3* shows an alternative solution having 4 transmitters active at one train to achieve redundancy for the quality-of-service (QoS) required by the positioning application. It shows that number of UWB transmitters in worst case scenario is still same on average.

### Table B.3: Transmitter densities for Case A) with 20 parallel tracks per km$^2$

| Option | Number of transmitters at Trains | Number of transmitters at Wayside | Total |
|---|---|---|---|
| 1 | 40 | 0 | 40 |
| 2 | 0 | 163 + 25 % | 203 |
| 3 | 40 | 163 + 25 % | 243 |
| 3* | 80 | 163 | 243 |

**Case B)**

Case B) is illustrated in Figure B.9. Length of the service area is less than 1 km so only a portion of area covered by UWB transmitters covers the 1 km$^2$.

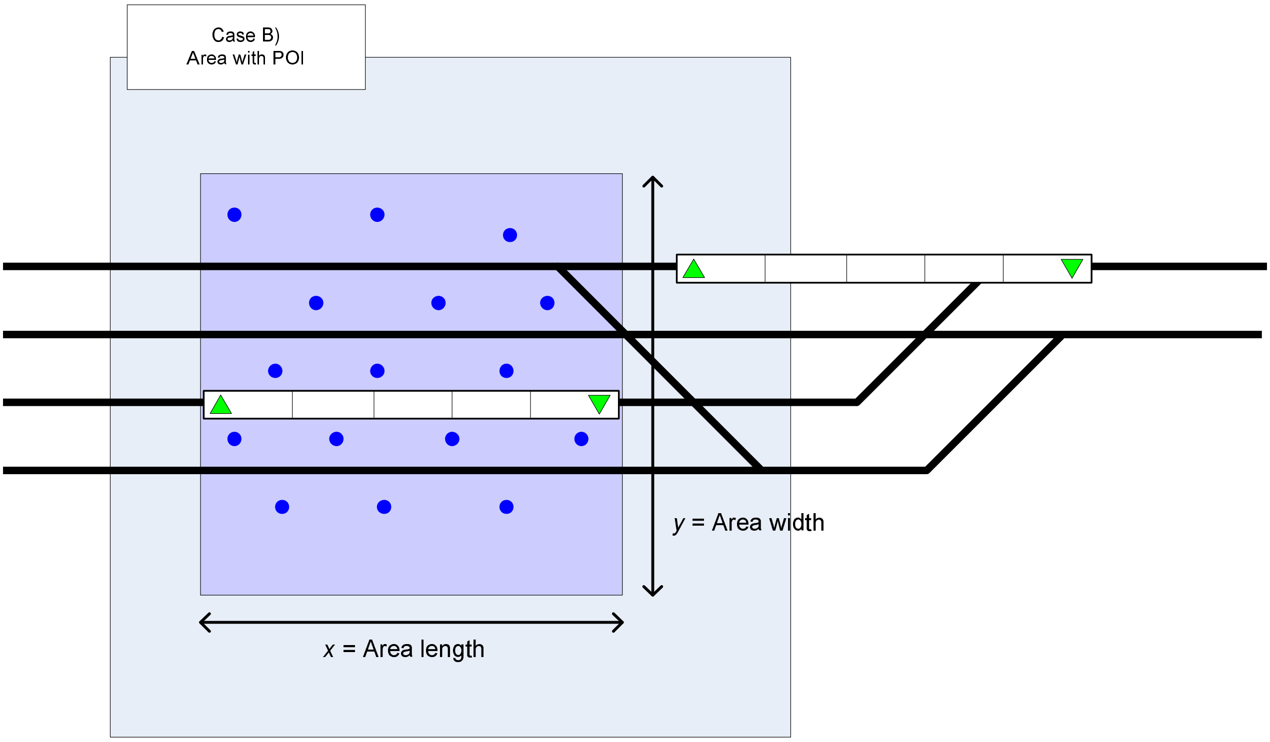

Figure B.9: Illustration of Case B)

Service area outside a station or a train depot usually has not more than 4 railroad tracks, making the width of the area narrow, but not narrower than UWB RX range. Estimate for the UWB TX density can be derived as a following:

$$\#devices = 4 \cdot \frac{600\ m * 25\ m}{\pi r^2}$$

Estimates with UWB TX range $r = 25$ m is illustrated in Table B.4. For redundancy 25 % more devices are taken into account as in previous case.

**Table B.4: Transmitter densities for Case B) per km$^2$**

| Option | Number of transmitters at Trains | Number of transmitters at Wayside | Total |
|---|---|---|---|
| 1 | 8 | 0 | 8 |
| 2 | 0 | 31 + 25 % | 39 |
| 3 | 8 | 31 + 25 % | 47 |

**Case C)**

Case C) is illustrated in Figure B.10. Case C) is the area where no position application is needed. This is presented for illustrative purposes only since several kilometres of railroad network is area of no need for high accuracy positioning service - some non-UWB service can be applied.

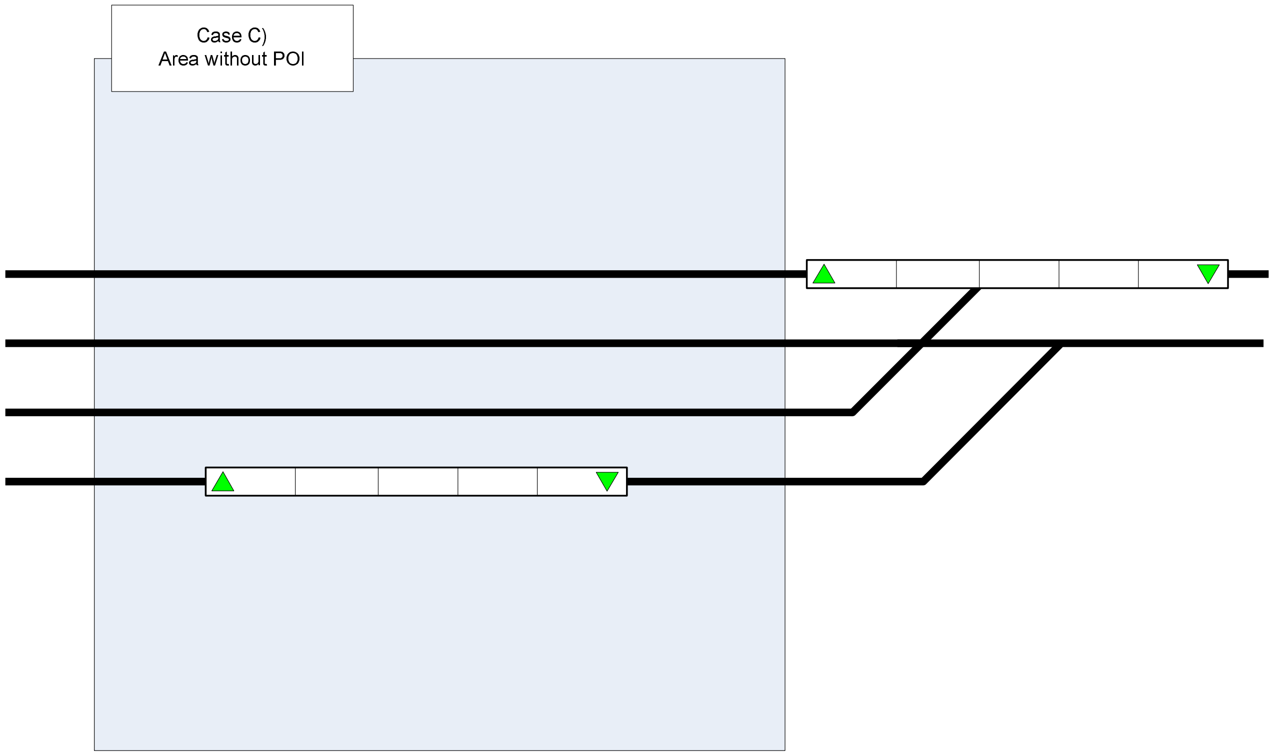

**Figure B.10: Illustration of Case C)**

Although in this discussion concentrating for the worst case scenarios, we rule out Case C), and consider that there exists on the average 1 POI / km.

## B.2.2 Activity Factor

Duty cycle has been ruled out from the following consideration of activity factor as stated in [i.7]: "The activity factor reflects the effective transmission time ratio. It does not take into account reduction factors such as time division duplex (TDD) and pulse duty cycle." Activity factor is defined in the presented document as effective transmission time ratio, actual on-the-air time divided by active session time or actual on-the-air emission time within a given time window.

The derivation for the Activity Factor of single UWB transmitter is illustrated in Figure B.11 and is formalized as following:

$$AF = \frac{R_{data}}{D_{rate}} \cdot Update\ rate \cdot \frac{Service\ time}{Time\ window},$$

where $R_{data}$ is ranging packet length and $D_{rate}$ is data rate (i.e. 0,85 Mbps from IEEE 802.15.4a [i.8]), and service time per time window is ratio which service is on, i.e. time that transmitter is on.

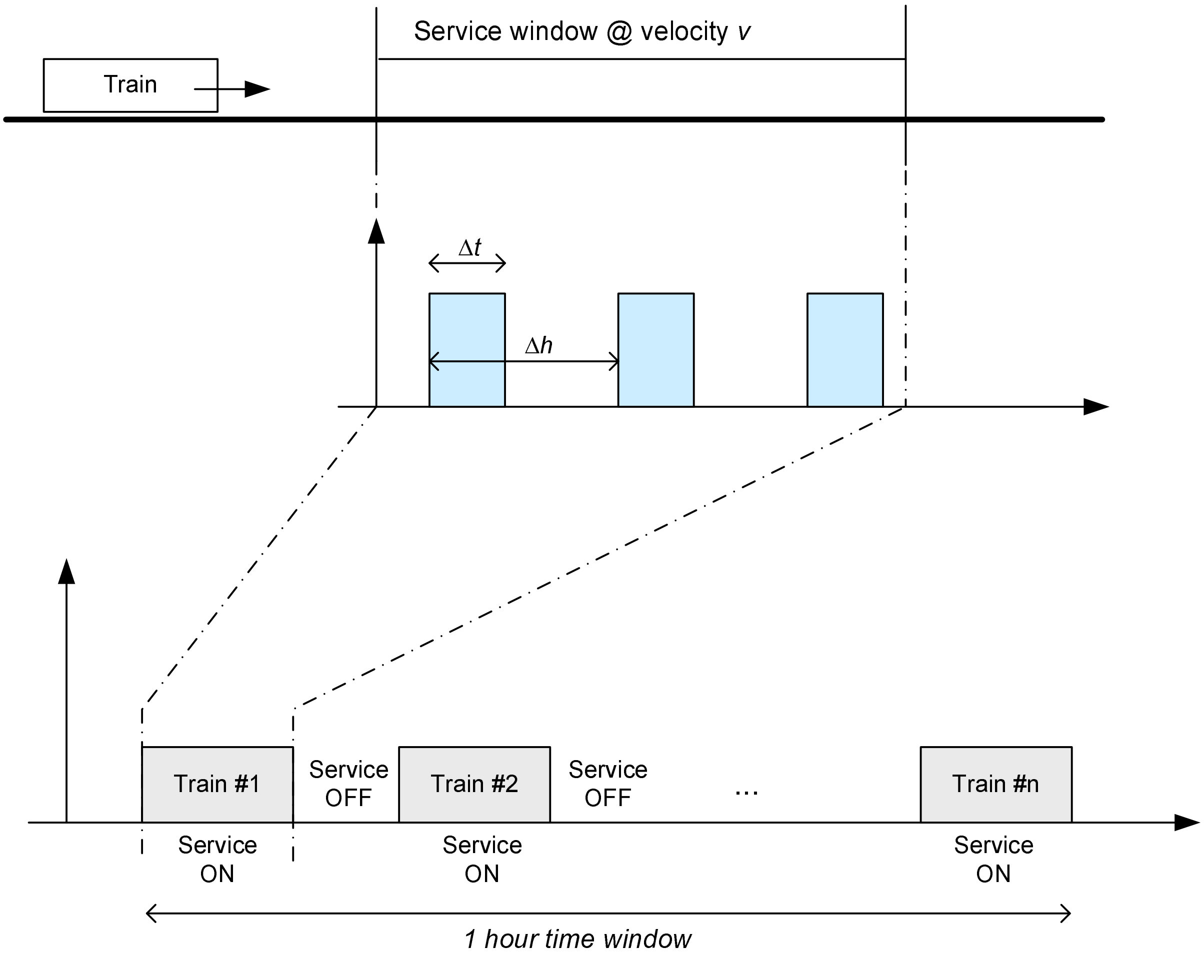

**Figure B.11: Activity Factor**

Figure B.11 presents the following parameters:

$$\text{Transmission on} = \Delta t = \frac{Packet\ length}{Data\ rate} = \frac{R_{data}}{D_{rate}}, \text{and}$$

$$\text{Transmission interval} = \Delta h = \frac{1}{Update\ rate} = \frac{1}{U_r}.$$

From transmission time and transmission interval duty cycle can be derived as a following:

$$\text{Duty cycle} = \frac{\Delta t}{\Delta h} = \frac{R_{data}}{D_{rate}} * Update\ Rate.$$

This result is averaged over an (peak) hour, where ratio of service time per peak hour is defined as:

$$\frac{Service\ time}{Time\ window} = \%\ \text{over 1 hour.}$$

Estimating $R_{data}$ length as maximum of 2 kbit (to cover synchronization header, physical layer header, and data), and assuming that required quality of service for the positioning application can be achieved with 4 ranging messages having guard interval length of one message gives as factor of 7. With update rate of 10 Hz, derivations for the activity factor are presented in Table B.5.

**Table B.5: Activity Factors within 1 hour peak time window**

| Case | Trains per hour | Speed | Service Time (% per hour) | AF (η) |
|---|---|---|---|---|
| Light Transit | 20 | 140 km/h | 14 % | 0,024 % |
| Light Transit | 20 | 60 km/h | 33 % | 0,056 % |
| Light Transit | 20 | 140 km/h → 0 km/h → 140 km/h (see note) | 91 % | 0,15 % |
| Subway | 60 | 110 km/h | 55 % | 0,093 % |
| Subway | 60 | 60 km/h | 100 % | 0,17 % |
| Subway | 60 | 60 km/h ≥ 0 km/h ≥ 60 km/h | 100 % | 0,17 % |
| | 1 | 0 km/h | 100 % | 0,17 % |
| NOTE: Train stands 1 min at the station. | | | | |

It should be noted that Table B.5 presents activity factors for one transmitter. Number of transmitters and density of transmitters are matter of scenario. Table B.6 and Table B.7 present the densities of active UWB transmitters for Case A and Case B, respectively.

**Table B.6: Density of active UWB transmitters per $km^2$ for Case A**

| Case A | Option 1 | Option 2 | Option 3 | Option 3* |
|---|---|---|---|---|
| UWB density (/$km^2$) | 80 | 408 | 488 | 486 |
| Activity factor (η) | 0,2 % | 0,2 % | 0,2 % | 0,2 % |
| Density of active UWB transmitters (/$km^2$) | 16 | 82 | 98 | 98 |

**Table B.7: Density of active UWB transmitters per $km^2$ for Case B**

| Case B | Option 1 | Option 2 | Option 3 |
|---|---|---|---|
| UWB density (/$km^2$) | 8 | 39 | 47 |
| Activity factor (η) | 0,2 % | 0,2 % | 0,2 % |
| Density of active UWB transmitters (/$km^2$) | 2 | 8 | 10 |

# B.3 Technical parameters and implications on spectrum

## B.3.1 Transmitter parameters

### B.3.1.1 Transmitter Output Power / Radiated Power

The transmission masks are compliant with the last amendment [i.11] of ECC/DEC(06)04 and, solely for deployment of UWB emitters at fixed outdoor locations, with ECC/REC(11)09 [i.9].

### B.3.1.1a Antenna Characteristics

For location tracking application, such as this system, omni-directional antennas are needed to cover wide area of interest. Low antenna gains may be used, if applicable to radiated power as defined by clause B.3.2.1. However, directional antennas may be used to reduce interference to/ from some direction. If directional antennas are applied the limits radiated power should be met as defined by clause B.3.2.1. The use of directional antennas are recommended to use in outdoor environment to reduce interference to fixed service systems.

### B.3.1.2 Operating Frequency

There are two possible operating frequencies for the application to be operated using onboard UWB emitters, depending on the target scenario and environment: 3,1 GHz to 4,8 GHz and 6 GHz to 8,5 GHz. From these, the upper frequency range is more favourable by providing more bandwidth, and thus, better time resolution. But on the other hand, the lower band is more attractive due to the availability of chipsets having lower costs and higher antenna efficiency but also because of the lower propagation losses. Moreover, in the lower band there is the possibility of achieving extended tracking ranges up to 50 meters and over by means of the deployment of multiple UWB emitters at fixed outdoor locations wayside, according to the provisions of ECC/REC(11)09 [i.9] and with the registration/coordination process described in [i.10].

Tuneable frequency transmitters allow flexibility in Frequency allocation, according to the registration/coordination mechanism required for LT2 emissions at highest power for tracking distances extended up to 50 meters and over:

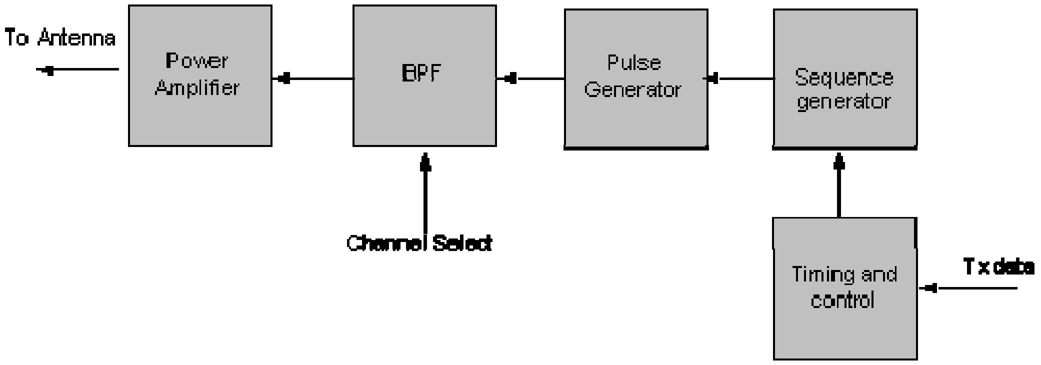

Figure B.12

### B.3.1.3 Bandwidth

The necessary bandwidth of 2 GHz is needed to gain 15 cm resolution, whereas the maximum possible occupied bandwidth is 2,5 GHz in the 6 GHz to 8,5 GHz band.

In the lower band from 3,1 GHz to 4,8 GHz, all the bandwidth is needed to gain as a good range resolution as possible yielding to 18 cm resolution.

## B.3.2 Receiver parameters

Receiver should have such characteristics that ranging can be done with high reliability.

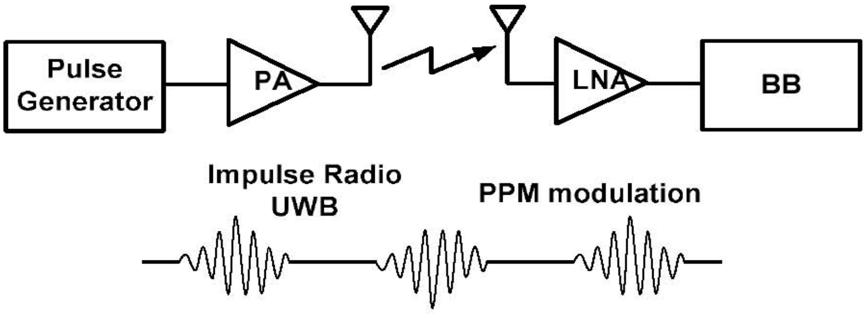

Figure B.13

Receiver architecture include at least an antenna, a low-noise amplifier, followed by a downconverter-to-baseband, and a digital correlator/demodulator which feeds the received raw data to the real-time algorithms needed either for accurate ranging and for communication packet decoding.

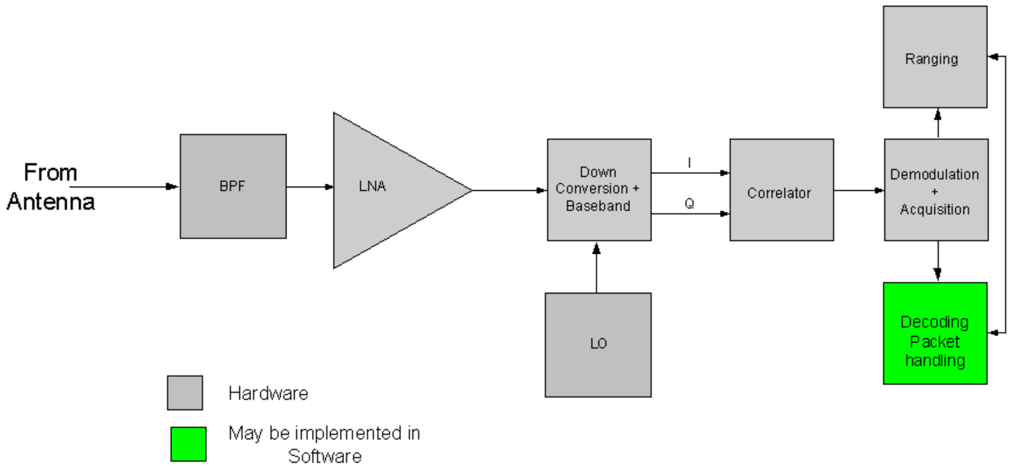

**Figure B.14**

Typical Link Budget, here below estimated for the most favourable Line-of-Sight (LOS) propagation, clearly shows that accurate and reliable ranging/tracking at distance of 50 meters definitely requires Option 3 system configuration, where a UWB TX/RX is installed in a moving rail vehicle and fixed wayside network includes UWB TX/RX nodes as previously depicted in Figure B.3.

The assumed link budget formula is: $$\mathbf{P_r = P_t + G_t + G_r - L_f - L_d}$$

where:

- power received at the receiver input port **$P_r$ = - 79.5 dBm**
- power transmittable according to PSD = -41.3 dBm/MHz **$P_t$ = -10 dBm**
- transmitting antenna gain **$G_t$ = 0 dBi**
- receiving antenna gain **$G_r$ = 10 dBi**
- free space path loss [ 20 Log(4π f / $3.10^{8)}$] f = 4.5 GHz **$L_f$ = 45.5 dB**
- loss due to the distance of 50 meters [ 20 Log (50) ] **$L_d$ = 34 dB**

**Average noise power per bit:** $$\mathbf{No = 10\ Log\ (D_r) + KT_b + F + I = -106\ dBm}$$

where:

- assumed communication peak Data Rate of 1 Mbps **10 Log( $D_r$) = 60 dB**
- Boltzman constant by temperature of 300 °K **$KT_b$ = -174 dB**
- assumed Noise Figure of the receiver **F = 7 dB**
- assumed implementation loss **I = 1 dB**

**Assuming a receiver sensitivity of -80 dBm we finally get:** **Eb/No = 26 dB**

### B.3.3 Channel access parameters

Density of devices is discussed in clause B.2.1. Duty cycle for the presented applications is defined in clause B.2.2.

For typical application (option 1), the ALOHA medium access control (MAC) scheme as defined in [i.8] is proposed to be applied. In the ALOHA protocol, a UWB TX installed in a rail vehicle transmits whenever it is needed without sensing the medium or waiting for a specific timeslot. A UWB TX cannot wait a specific time slot or content the medium to transmit a ranging packet because of the high velocity of a vehicle. The ALOHA is appropriate for the typical application (option 1) because of lightly loaded network, i.e. up to 40 UWB-TXs as discussed in clause B.2.

# History

| Document history | | |
|---|---|---|
| V1.1.1 | October 2012 | Publication |
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