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ACK	ACKnowledgement
AP	Access Point (WLAN)
AWGN	Additive White Gaussian Noise
BS	Base Station
CAP	Contention Access Phase
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CDF	Cumulative Density Function
CEPT	European Conference of Postal and Telecommunications Administrations
CGN	Coordinated Group Navigation
CRLB	Cramer Rao Lower Bound
DAA	Detect And Avoid
D(B)PSK	Differential (Binary) Phase Shift Keying
DTN	Delay Tolerant Network
EAP	Exclusive Access Phase
ECC	Electronic Communications Committee
EIRP	Equivalent Isotropic Radiated Power
ETSI	European Telecommunications Standards Institute
GCS	Global Coordinates System
HB	Human Body communications
HID	Hub IDentifier
HME	Hub Management Entity
IR	Impulse radio
ISM	Industrial Scientific & Medical radio bands
LCS	Local Coordinates System
LDC	Low Duty Cycle
MAC	Medium Access Control layer
MAP	Managed Access Phase
LSIMC	Large-Scale Individual Motion Capture
LSGMC	Large-Scale Group Motion Capture
LTE	Long Term Evolution (4G Cellular)
MF	Matched Filtering
ML	Maximum Likelihood

MOCAP	MOtion CAPture
NB	Narrow Band
NID	Node IDentifier
NME	Node Management Entity
NWK	NetWorK layer
OSI	Open Systems Interconnection
PHY	PHYsical layer
QOS	Quality Of Service
RAP	Random Access Phase
RMSE	Root Mean Squares Error
RSSI	Received Signal Strength Indicator
RTLS	Real Time Locating System
(RT-)TOF	(Round Trip -) Time Of Flight
TDOA	Time Difference Of Arrival
TOA	Time Of Arrival
TWR	Two Way Ranging
UMTS	Universal Mobile Telecommunications System
UWB	Ultra Wideband
WBAN	Wireless Body Area Network
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network

ABSTRACT

Wireless Body Area Networks, which currently benefit from the emergence of *Ultra Low Power* radio technologies, like the *Impulse Radio - Ultra Wideband*, may be massively disseminated in the public space in the near future, as distributed elements of a more global heterogeneous communication architecture. Besides, user-centric and context-aware services have been progressing significantly for the last past years, requiring e.g. that the location information is delivered on the mobile user side, with a limited access to the infrastructure. In the context of wearable networks, new cooperative communication schemes, involving peer-to-peer radio links between mobile nodes or terminals, provide natural interactions at the body scale (i.e. on-body cooperation) and/or between mobile users (i.e. body-to-body cooperation). The cooperative links are thus not only expected to improve data rates, communication robustness or coverage, but they shall also enable to retrieve relative range measurements, based on transmitted signals (e.g. based on *Round Trip - Time of Flight* or *Received Signal Strength*).

The CORMORAN project aims at investigating such cooperation mechanisms *in* and *between* body area networks, mostly for large scale individual motion capture and coordinated group navigation applications. Typically, simultaneously operating networks sharing the same neighbourhood can generate interferences and coexistence issues (which must be anyway assessed), but they can also represent relevant sources of information diversity and redundancy to both communications and localization. Determining the adequate cooperation level and modes will help to achieve a precise radiolocation of on-body nodes and/or pedestrians, as well as an optimal management of the communication quality of service at the protocol level, while complying with consumption and regulation constraints. One more stake consists in taking into account the highly specific characteristics of wearable networks, such as finite network topology, ultra-short transmission ranges, space-time radio channel correlations under (biomechanical and social) mobility, etc.

This document, entitled "D1.1 - Application Scenarios, System Requirements and Prior Models (Initial Document)", summarizes the work and thoughts carried out in the frame of Task 1 since the beginning of the project. More particularly, the deliverable regards the definition of canonical application scenarios and needs, based on realistic end-users' feedback, as well as their mapping onto preliminary system requirements and specifications. The latter are briefly discussed, while keeping in mind current standardization and regulatory trends. Finally, in order to provide a common framework for future performance evaluations, a preliminary set of relevant indicators, models and simulation tools, is provided.

1. INTRODUCTION

The recent advent of integrated sensing and short-range communication technologies has been disclosing interesting perspectives for body-centric services. The *Wireless Body Area Networks* (WBANs), which consist of small wearable wireless devices, are indeed on the verge of fulfilling new market needs in a variety of applications such as emergency and rescue, healthcare, personal entertainment and multimedia... WBANs rely on emerging radio technologies that claim *Ultra Low Power* (ULP) consumption, low complexity, and low cost, e.g. Bluetooth - *Low Energy* (Bluetooth-LE) or *Impulse Radio – Ultra Wideband* (IR-UWB), as put forward in the recent IEEE 802.15.6 standard [std_IEEE802.15.6].

Besides WBAN considerations, numerous location-dependent services have also been appearing for the last past years, such as pedestrian navigation in indoor environments or urban canyons, location-dependent commercial offers or contextual information broadcast, assisted mobility in dangerous and/or confined environments, smart inventories in warehouses or containers for logistic applications, self-localized *Wireless Sensor Networks* (WSN) for forest terrain or home monitoring... One common requirement is to bring high-precision location information (say, with an accuracy better than 1m) into unaddressed applicative environments where classical satellite-based solutions can not operate properly. Many of those services are intrinsically user-centric, in the sense the location information would be required on the end-user side, possibly with decentralized resources and with limited access to the infrastructure. Among the proposed technical solutions providing such location and tracking capabilities on top of standard communication means, *Low Data Rate* (LDR) ULP radio technologies similar to that considered in the WBAN context are favoured today, such as IR-UWB (e.g. IEEE 802.15.4a) or, more marginally, Zigbee (e.g. IEEE 802.15.4).

But another disruptive aspect of modern short-range wireless communications concerns *Machine to Machine* (M2M) cooperation, allowing mobile nodes or terminals to exchange data through peer-to-peer links. In the very WBAN context, cooperative schemes could be applied either within one single wearable network (i.e. providing intra-WBAN/on-body cooperation in case of mesh networking), between distinct wearable networks at short transmission ranges (i.e. providing inter-WBAN/body-to-body cooperation), or even with respect to elements of infrastructure (i.e. providing so-called off-body cooperation). In turn, WBANs are expected to be massively present in public areas (e.g. streets, shopping malls, train stations), where direct *Body to Body* (B2B) interactions and heterogeneous network access are likely to offer the highest and most promising potential. From a localization-oriented perspective, cooperation is expected to provide information redundancy, better coverage and higher location precision for navigation purposes. Finally, there is also a growing interest today in acquiring even more precisely the human motion and gesture with low-cost and low-complexity stand-alone technological solutions (typically through radio means), as an alternative to the relatively cumbersome, geographically restricted and too specific video means (used by professionals in the field of motion capture). This may be particularly useful for e.g., coarse gesture/body-based remote control, large-scale individual or collective sports capture for statistical analysis or real-time display, video animation (e.g. video postproduction, video gaming, virtual and augmented reality, etc.).

Overall, fusing cooperative short-range communications and radiolocation capabilities within mobile groups of WBANs thus looks relevant to cover motion capture and navigation needs. In this general context, the CORMORAN project (ANR 11-INFR-010 01) intends to study and develop solutions that could benefit from cooperative on-body, inter-body and off-body radio links, with the double objective to make available localization functions and to enhance globally the quality of service of wireless communications (mostly from a protocol perspective).

As a preliminary step of the study, a questionnaire was prepared and distributed to potential users and integrators of the CORMORAN technology. Based on the gained feedback, one idea in Task T1.1 was to define relevant application scenarios, along with their actual needs. These identified scenarios and settings are currently explored in priority in the project, in particular in Tasks T2 and T3 (respectively in charge of the physical measurement/modelling and algorithmic investigations on localization and cross-layer protocol). One step ahead in Task T1.2 consisted in "translating" these application needs into a set of technical system requirements and, as much as possible, to confront them to current worldwide standardization and/or regulatory trends. Finally, given the targeted scenarios and requirements, in Task T1.3, common performance indicators were defined and a preliminary list of existing models and simulation tools was drawn so as to enable a realistic performance assessment of the solutions developed in Task T3.

The very document, which accounts for the efforts made in Task T1 since the beginning of the project, is structured as follows.

In Section 2, based on an in-depth analysis of the questionnaire's answers, we describe and specify two main application scenarios, namely the *Large-Scale Individual Motion Capture* (LSIMC) and the *Coordinated Group Navigation* (CGN) scenarios. We also provide related figures regarding the required levels of location precision and refreshment rate, the maximum pedestrian speed, the number and the preferred locations of on-body nodes, the maximum distance and the number of users in a group, etc.

In Section 3, we introduce a few radio standards that could be of interest as a working basis in the very context, namely the IEEE 802.15.6, IEEE 802.15.4, IEEE 802.15.4a and the IEEE 802.15.4f standards. We also discuss regulatory aspects, regarding e.g., the occupied bandwidth and the transmitter activity (in terms of duty cycle). On this occasion, we also derive a few practical implications for CORMORAN's investigations.

In Section 4, we provide high-level system requirements, regarding the radio features (e.g. data rates, occupied bandwidth, single-link ranging precision and transmission range), the network topology (including multi-WBAN concerns), the localization application (e.g. decentralized vs. centralized calculations, location information refreshment rate and latency, etc.).

Finally, we report in the Appendices the users' questionnaire (in French), an exhaustive list of possible deployment scenarios (as a function of the underlying application) and finally, a (non-definitive) selection of models and simulation tools, available at the beginning of the project and regarding the different OSI layers. This selection is considered as a very preliminary basis for the integration of a cross-layer co-simulation tool developed in T2.4.

2. APPLICATION SCENARIOS AND NEEDS

2.1. APPLICATION NEEDS

2.1.1 APPLICATION DOMAINS AND ACTORS

One strong claim of CORMORAN is to provide industrial or institutional actors with new technological solutions relying on cooperative wearable networks, so as to enable better worker ergonomics, saved time/energy/goods, or unprecedented services for end-users (e.g. citizens, clients…). The related innovation potential concerns *a priori* a plurality of application fields, such as:

- augmented group navigation (e.g. fire-fighters progressing in a building on fire with physiological monitoring and relative position information, coordinated squads of soldiers on urban battle-fields);
- low-cost & infrastructure-free tracking of collective systems (e.g. real-time capture and/or sports analysis);

- nomadic social networking (e.g. sharing personal location-dependent information in a decentralized way among authorized members of a given community);
- augmented reality for collective entertainment (e.g. mobile interactive group gaming);
- context-dependent information diffusion (e.g. data broadcast to identified clusters of people with common interests, needs or locations);
- wireless network optimization (e.g. handover between different radio access technologies for clusters of people experiencing the same mobility patterns, optimal data routing under users mobility);
- distant health care, monitoring and rescue systems (e.g. collective launching or notification of emergency alarms, routine medical treatments at home)...

Besides those general expectations, one first concern at the very beginning of the project was to define a reduced set of concrete and canonical application scenarios, which could make sense for further research investigations and partial demonstrations. These scenarios, by bringing us the knowledge of realistic applications expectations, allow a better characterization of the target performance and of the issues to solve. The retained approach then consisted in building up and disseminating a questionnaire to various professional entities, identified in the ecosystem of the project partners. This questionnaire, which is detailed in Appendix 1 (See Section 7.1), comprises various fields, accounting for e.g.

- underlying applications and enabled functionalities;
- sensors/body location precision and refreshment rates;
- number of sensors/users and related deployment constraints;
- typical mobility;
- operating environments;
- calibration needs, etc.

Based on the gained feedback, the objective was to better understand the actual needs of potential users and/or integrators of the CORMORAN technology (See Section 2.3). One side goal was to derive the key technical features (See Section 4) of the derived scenarios (See Section 2.2). The 13 targeted technology users (among which only 2 have decided to remain anonymous) cover a broad field of domains related to image and multimedia, human motion animation, personal navigation, military and security applications...

It appears that one subset of sounded users is mostly interested in ***large-scale individual motion capture*** (LSIMC), whereas another group is interested in ***coordinated group navigation*** (CGN), as shown below in Figure 2.1**.** The two preferred applications are also equally represented among these users/integrators. Half-way between the two latter options, the ***large-scale group motion capture*** (LSGMC) application was more marginally cited (only once). Hence, in the following, we will focus in priority on specifying the MSIMC and CGN applications (keeping in mind that the third one would anyway consist in their combination).

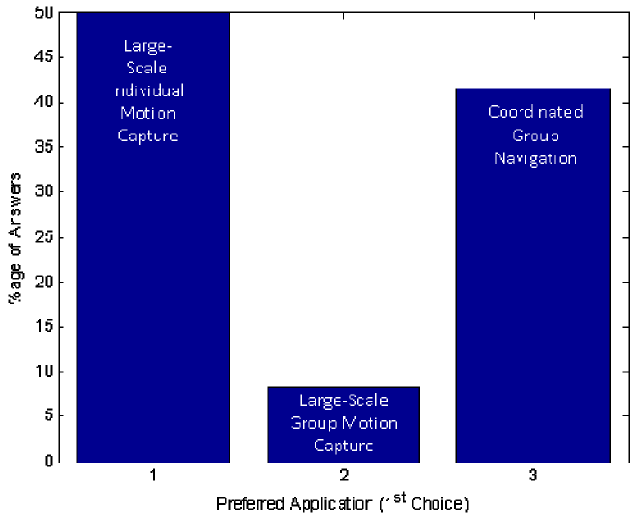


Figure 2.1: Preferred applications according to possible users/integrators of the CORMORAN technology.

The first users subset (See Table 2-1) is somehow already familiar with *motion capture* (MoCap) applications that traditionally require a rather high level of accuracy while locating the sensors, but they also seek for alternative stand-alone solutions to achieve this MoCap function autonomously on a larger scale (i.e. contrarily to video systems, which are geographically restricted to small areas), with a limited access to fixed and costly elements of infrastructure around (i.e. fixed access points, base stations or wireless anchors in our radio case).

The second users subset (See Table 2-2), which is mostly concerned by coordinated group navigation, does not necessarily seek for motion capture functionalities at first sight, but navigation is intended in a rather classical way. However, in the WBAN context, one more question is raised by CORMORAN: How can a wearable wireless network deployed on each mobile agent improve the availability and accuracy of the coordinated group navigation functionality (including benefits through inter-body or off-body interactions)?

Group 1(Large-Scale Individual Motion Capture)		
Name	**Website**	**Activity**
Artefacto	www.artefacto.fr	Virtual and augmented reality
Cityzen Sciences	N/A	New usages related to smart clothes
Dynamixyz	Dynamxyz.com	Human face analysis and synthesis for video games and cinema
Golaem	www.golaem.com	Virtual humans animation
M2S Lab	www.m2slab.com	Biomechanics and humanoid animation
Anonymous #1	N/A	N/A

Table 2-1: First group of users/integrators of the CORMORAN technology interested in large-scale individual motion capture.

Group 2 (Coordinated Group Navigation Application)		
Name	**Website**	**Activity**
Movea	www.movea.com	Motion intelligence solutions & data fusion
Euromedia France	www.euromedia-france.com	Provider in television & multimedia broadcast facilities
Trimaran	eng.trimaran.com	Interactive 3D visual effects and animation
Thales Communications	www.thalesgroup.com	Military applications and public safety
Pole Star	www.polestar.eu	Indoor and outdoor personal navigation and localization
Cassidian	www.cassidian.com	Security applications
Anonymous #2	N/A	N/A

Table 2-2 : Second group of users/integrators of the CORMORAN technology interested in coordinated group navigation.

2.1.2 IN-DEPTH ANALYSIS OF APPLICATION NEEDS

In the following, for each field of the questionnaire detailed in Annexe 1 (See Section 7.1), the shown results (i.e. number/percentage/rank of expressed answers on each proposed option) are conditioned on the application scenario. For the sake of convenience, the results are also presented while respecting approximately the same order as in Section 7.1.

- *On-Body Nodes Location Precision*

As shown on Figure 2.2, most applications would require a precision at least equivalent to 0.1m. Among the motion capture applications, two dominating classes of precision can even be identified, as follows:

- 0.05m-0.20m (Low precision)
- 0.01m (High precision)

As for navigation-oriented applications, the figures related to on-body nodes location precision are likely irrelevant and meaningless (only the macroscopic/average body position shall be of interest).

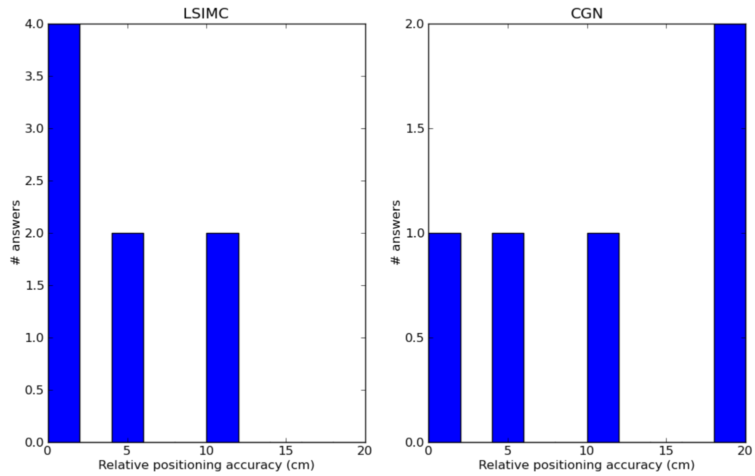


Figure 2.2: Required on-body nodes location precision, depending on the preferred application.

- *Macroscopic Body Location Precision*

On Figure 2.3, it seems that most applications would necessitate sub-meter precision levels for navigation (with an error < 1 m in 90% of time and a median error around 30 cm), including large-scale motion capture with absolute body positioning. This means that one single global specification could be chosen for both families of applications.

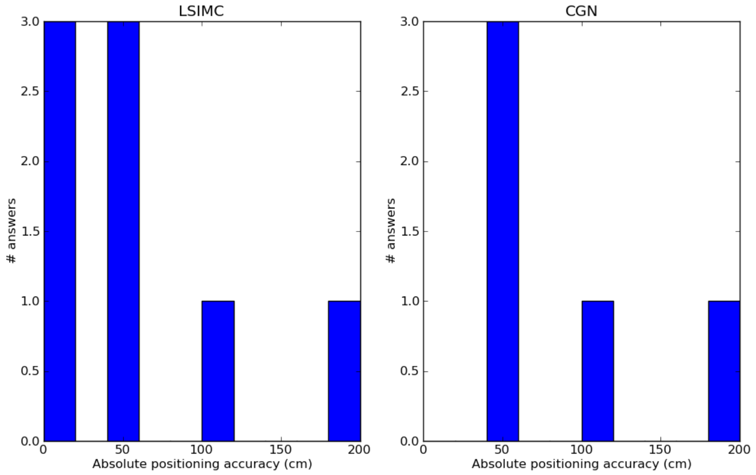


Figure 2.3: Required body location precision, depending on the preferred application.

- *Location Information Refreshment Rate*

On Figure 2.4, one can distinguish two different classes of refreshment period, which are rather well correlated with the targeted application:

- < 100 ms for motion capture (possibly, with two modes: high precision requiring a period < 10 ms and a low precision mode, requiring a period <100 ms);
- ~ 1 s for navigation;

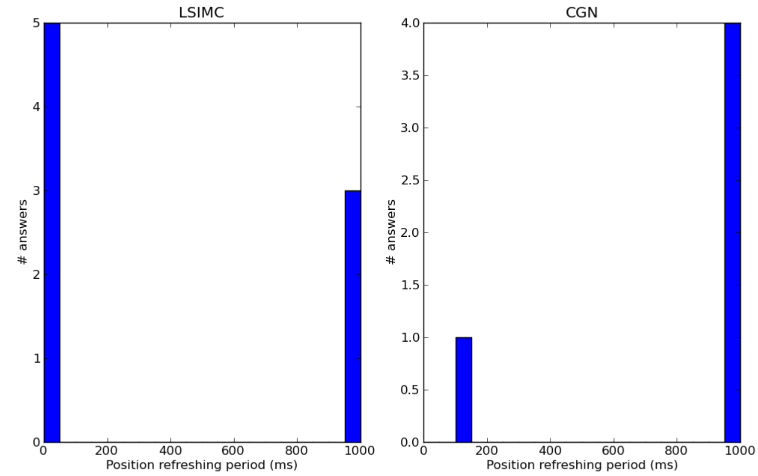


Figure 2.4: Required location information refreshment rate, depending on the preferred application.

This may have an impact on the affordable communication and localization latency for the two intended scenarios and represent a certain challenge as regards to system design. However, if one only needs high refreshment rates but can tolerate delayed information delivery, thus communications can be somehow replaced by memory capabilities. Moreover, note that this high refreshment rate shall be uniquely applicable for the most demanding nodes only (e.g. the fastest on-body nodes on arms of legs), hence alleviating the constraints on less demanding nodes.

- *Place to Deliver Positioning Information*

According to Figure 2.5, the global trend is that the navigation-oriented scenario requires a user-centric representation and storage of the positioning results, as expected, whereas the information required for motion capture is equally relevant at the mobile user or at a centralized external server (and much more marginally shared in groups).

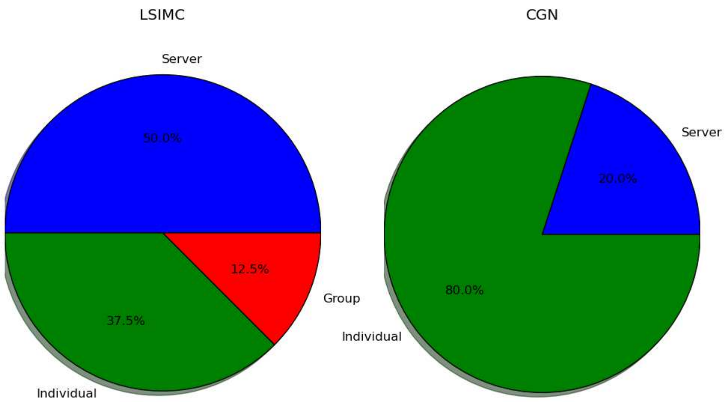


Figure 2.5: Place where the positioning information shall be issued, depending on the preferred application.

- *Operating Environment*

As seen on Figure 2.6, the motion capture function is intended almost equally in indoor or outdoor environments. As expected, the navigation function is expected to be available in dense indoor environments, where GNSS solutions can not operate properly.

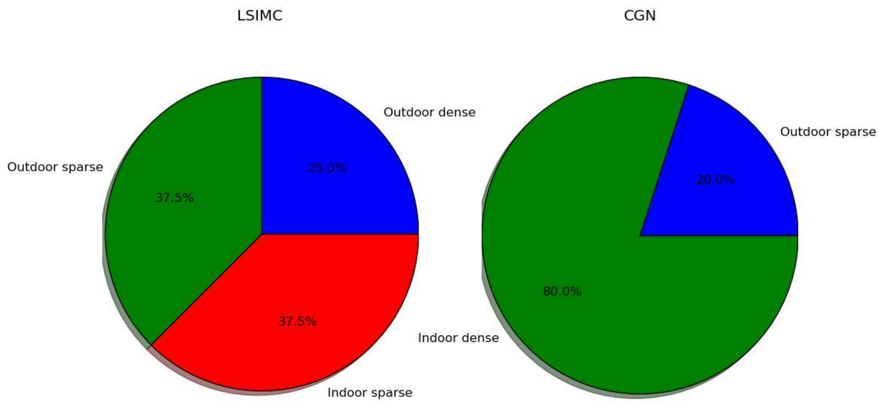


Figure 2.6: Working environment, depending on the preferred application.

- *Human Mobility Patterns*

At first sight, on Figure 2.7, static cases are irrelevant (e.g. for posture detection) but a typical pedestrian mobility is considered, including moderate walking and running. Accordingly, one may consider the two speeds 5 and 15 km.h^{-1} as study parameters.

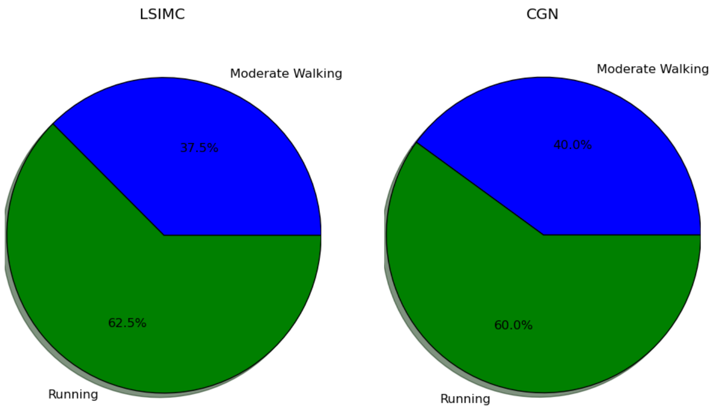


Figure 2.7: Supported human mobility pattern, depending on the preferred application.

- *Number of Persons per Group*

The number of users per group will have no impact on the classical LSIMC application, unless communication-oriented inter-WBAN links are exploited to enhance/reinforce each individual capture result. But the answers got for this very application are rather surprising, or at least ambiguous, since they might indicate that there is also an interest for group motion capture functionalities.

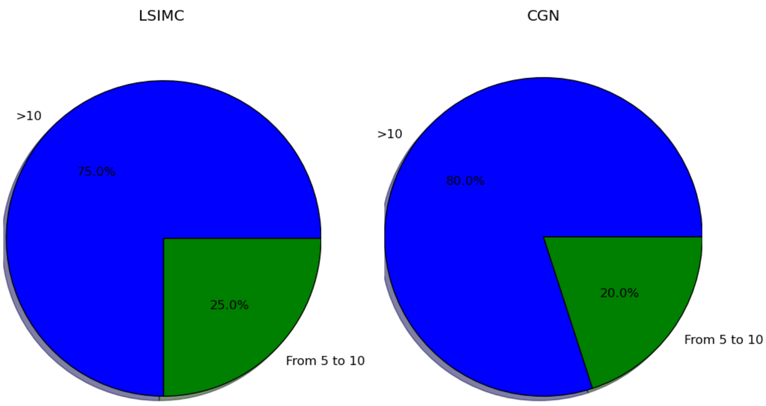


Figure 2.8: Maximum number of persons per group, depending on the preferred application.

As seen on Figure 2.8, a rather large number of individuals may be required in each group for the CGN case (typically >10). This will be very challenging not only in terms of system design (i.e. to ensure coexistence, association and coordination at the protocol level), but also to assess realistic performances through simulations. In a first attempt, it will thus be more reasonable to assume 5 and 10 persons belonging to a given group, keeping in mind that any larger (physically formed) group may be divided into smaller clusters. This clustering is anyway usually recommended in location-enabled *Wireless Sensor Networks* (WSN) to alleviate computational complexity and artificially increase the network connectivity in each cluster.

- *Separation Distance in a Group*

Not so surprisingly, the CGN function would require rather large transmission ranges over inter-WBAN links in a significant proportion of cases. We will thus retain values in the set {1, 5, 10, 50} m to be sufficiently representative. This will have a strong impact on the choice of the radio Physical layer for body-to-body communications as intra-WBAN standards do not generally allow large range communications, but on the contrary, they tend to limit the radiated signal in the immediate vicinity of the body. Accordingly, this opens the floor to heterogeneous network architectures, as it will be seen in Section 4.4.

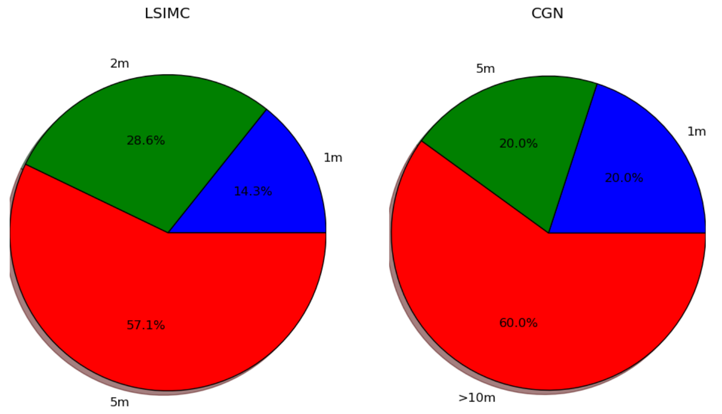


Figure 2.9: Maximum separation distance in a group, depending on the preferred application.

- *Density of Fixed Anchors in the Nearby Environment*

This parameter reflects the spatial density of the fixed elements of infrastructure used as external anchors or landmarks in the absolute localization process (i.e. *Access Points* -APs- or *Base Stations* -BS- or WSN anchors). This density seems to be strongly application-dependent, as follows:

- < 0.05 anchors / m² in motion capture application;
- < 0.01 anchors / m² in group navigation applications;

This result is rather intuitive, in the sense professionals from the motion capture domain are more likely to tolerate equipped environments to reach very high precision (e.g. in a studio dedicated to motion capture) whereas navigation may be intended in unknown environments and/or opportunistic contexts, where the access to fixed elements of the infrastructure is not guaranteed and hence shall be restricted as much as possible.

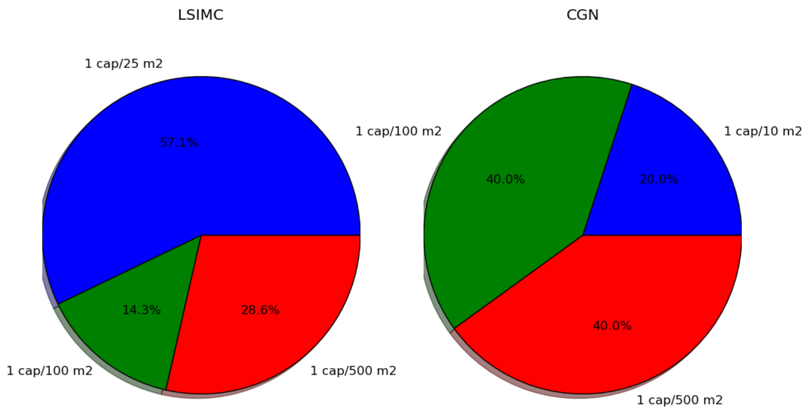


Figure 2.10: Anchors spatial density, depending on the preferred application.

- *Number of On-Body Nodes*

It can be noticed on Figure 2.11 that the group navigation application requires only a few on-body sensors. Here, the presence of >2 nodes on each body in a WBAN context enables to enhance the navigation performance through measurements redundancy and spatial diversity over body-to-body or off-body links, while intra-WBAN communications shall be uniquely used to merge the information, as it will be seen in Section 4.4. It will be one purpose of CORMORAN to demonstrate the interest for the user of wearing a gradually higher number of WBAN sensors for achieving better navigation accuracy (e.g. 1 to 5 per body).

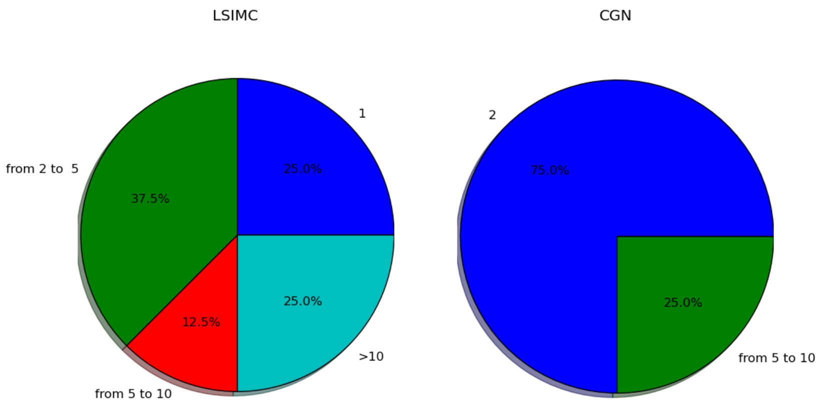


Figure 2.11: Maximum number of on-body nodes, depending on the preferred application.

As expected, on the contrary, the LSIMC application authorizes a much larger number of on-body nodes. While assessing the corresponding performances in CORMORAN studies, one can then span typical values from 5 to 20 nodes.

- *On-Body Nodes Locations*

Figure 2.12 has been produced by ranking each sensor position on the body, depending of their rank in the obtained questionnaire responses. Appearing first ranks 1, second ranks 2 etc., meaning that the lowest the overall score, the higher the sensor position is desired for the end-user. If the answer is not containing the whole set of positions, all non appearing positions rank equally. The obtained rank for the 2 application scenarios are then directly readable along the x axis, sorted by increasing order.

It appears from this representation that the ankle is a strategic position for the gait analysis, and is not surprisingly the top appearing sensor position for LSIMC. Knees and bends which correspond to joint positions, where it is not comfortable wearing anything, logically appear at the worst ranks. Finally, rather surprisingly, wearing a sensor on the head is seen either tolerable or even required within some applications. As for group navigation, the number of answers is not so significant but one can very straightforwardly note that the shoulders, torso and back appear at the top rank positions, what also makes sense for the addressed functionality.

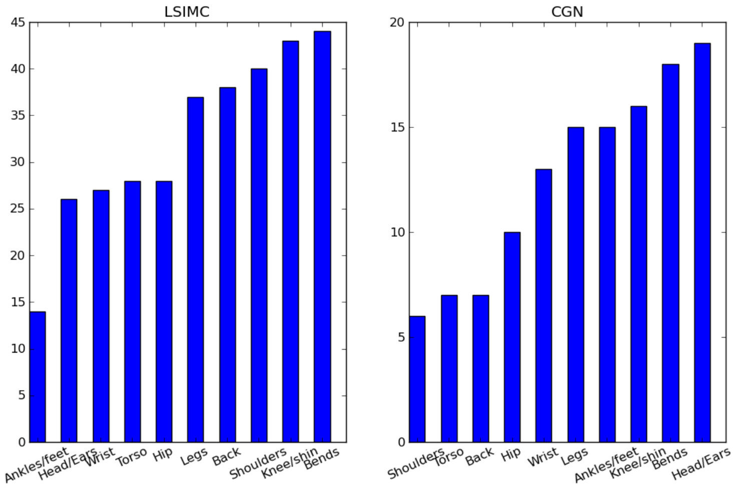


Figure 2.12: Rank of preferred on-body sensors locations, depending on the preferred application.

- *Prior Calibration Efforts*

According to Figure 2.13, there is a strong demand for building an autonomous system requiring the lightest calibration efforts. This is one more challenging constraints from the users to the CORMORAN consortium.

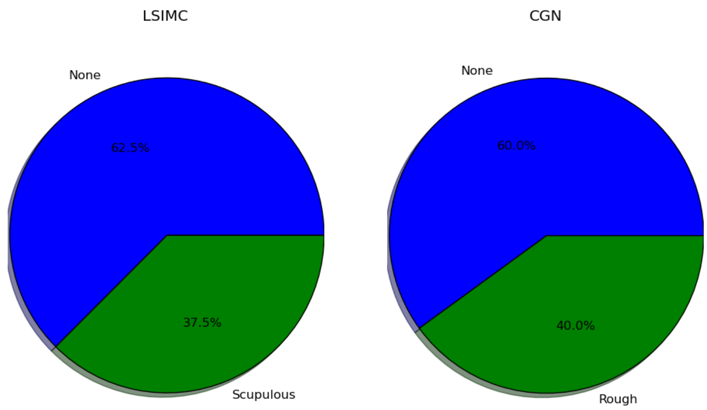


Figure 2.13: Tolerated pre-calibration/configuration of the system from scratch, depending on the preferred application (None: No calibration is tolerated in a totally plug & play system; Rough: Only a coarse deployment convention is required from the user; Scrupulous: A precise deployment pattern shall be respected by the user).

The following features, which do not directly fall into the scope of CORMORAN's studies on localization, will have a limited impact on the system requirements definition. They are provided mostly for information purposes.

- *Kind of Co-located Physical Sensors*

Obviously, in motion capture applications, the inertial modality, already largely in use in the community, represents an intuitive and natural complementary means.

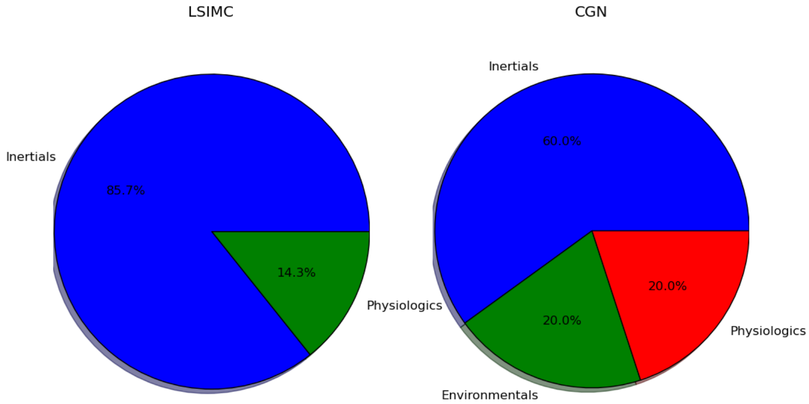


Figure 2.14: Kind of physical sensors, depending on the preferred application.

In turn, the required very high positioning accuracy could be reached by exploiting the combination of radio observations with inertial sensors data using co-located devices. This is however not the purpose of CORMORAN to address data fusion issues. Regarding navigation, the inertial sensors may also play an important role to mitigate non-line of sight radio obstructions or assist location estimation in geographic areas leading to poor geometric dilution of precision.

- *Physical Sensors Refreshment Rate*

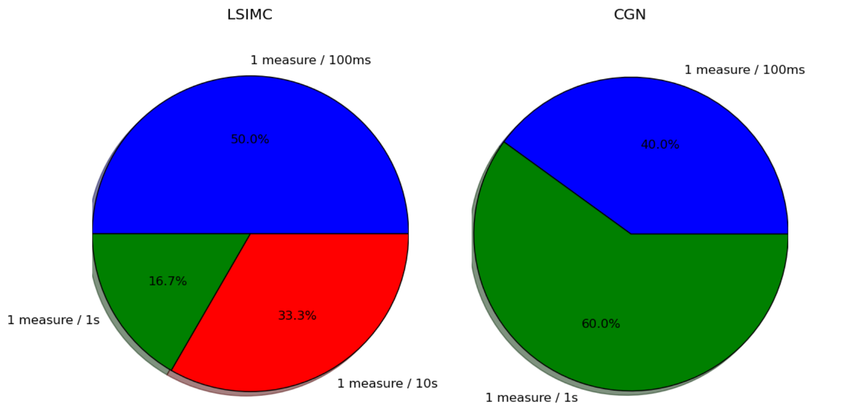


Figure 2.15: Physical sensors refreshment rate, depending on the preferred application.

- *Geo-referencing of Physical Measurements*

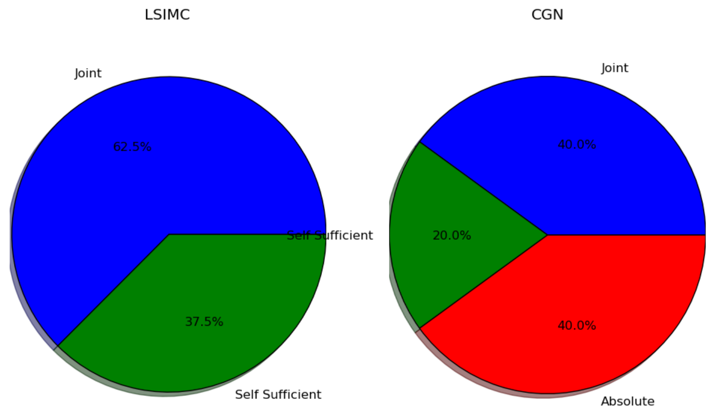


Figure 2.16: Kind of geo-referencing required for the physical measurements carried out at embedded sensors, depending on the preferred application (relative: relative on-body nodes locations; absolute: absolute body location; joint: both relative on-body nodes locations and absolute body location; self-sufficient: no geo-referencing is required).

- *System Autonomy*

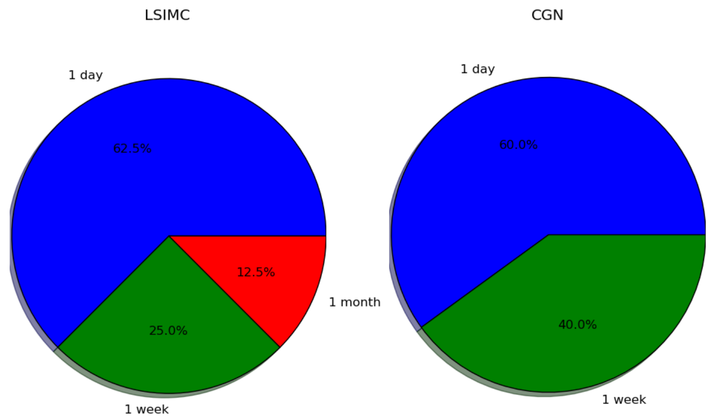


Figure 2.17: Minimum tolerated duration in use before stopping the system (e.g. for system maintenance, power refill, software update, etc.), depending on the preferred application.

2.2. SELECTED APPLICATION SCENARIOS AND RELATED USE CASES

In this sub-section, we define more precisely the functions that are intended within each selected application scenario.

2.2.1 LARGE-SCALE INDIVIDUAL MOTION CAPTURE

- *Relative On-Body Nodes Ranging*

In this first sub-scenario, one considers a set of mobile wireless devices placed on one single body (under arbitrary deployment), with unknown positions. The objective is then uniquely to estimate the relative Euclidean distances separating those nodes. Accordingly, at each time stamp, one can retrieve a relative body topology, independently of the way the underlying nodes coordinates could be expressed or referenced (i.e. whatever their reference coordinate system). Only the relative range information is of interest. This mode shall remain marginal in our context, since most of the targeted use cases would require that the nodes coordinates are explicitly expressed into a local (i.e. body-strapped) system or into a global absolute system (likely external to the body), as seen in the two following paragraphs.

Possible Use Case(s): *WBAN optimization through distance-based packet routing, WBAN self-calibration…*

- *Relative On-Body Nodes Positioning*

In this second sub-scenario, we consider a set of wireless devices placed on a body, which can be classified into two categories. Simple mobile nodes with unknown positions (still under arbitrary deployment) must be located relatively to reference anchor nodes, which are attached onto the body at known and reproducible positions, independently of the body attitude and/or direction (e.g. on the chest or on the back). A set of such anchors can thus define a Cartesian *Local Coordinates System* (LCS) under mobility, which remains time-invariant (i.e. as expressed in the LCS) under body mobility. The estimated coordinates of the mobile nodes are then expressed into this LCS. This functionality is also occasionally depicted as "Nodes positioning at the body scale".

Possible Use Case(s): *Raw gesture or posture detection for animation (e.g. gaming, augmented reality, video post-production, etc.), emergency and rescue alerts (e.g. elderly people or fire-fighters falling down on the floor), coarse attitude/body-based remote sensing (e.g. house automation, remote multimedia browsing & control)…*

- *Absolute On-Body Nodes Positioning*

This last sub-scenario is the same as the previous one, but the coordinates system used to express the estimated on-body mobile nodes locations is no more body-strapped but external to the body. In this framework, one may thus consider as anchor nodes, some fixed elements of infrastructure (e.g. beacons/landmarks, base stations, access points or gateways) disseminated at fixed known locations in the environment. Accordingly, the coordinates of the nodes placed on the body chest or back, which used to be time-invariant in their LCS, shall now vary in a *Global Coordinates System* (GCS) under pedestrian mobility. They directly depend on the body attitude, as well as on the motion direction and/or speed. By default, this sub-scenario, which makes sense since we claim a "large-scale" nomadic service in comparison with video systems that operate in more restricted geographical areas (due to the presence of relatively dense and heavy pieces of infrastructure), will be the preferred motion capture sub-scenario in the following. It may also be viewed as a combination of relative motion capture (i.e. at the body scale) and classical single-user navigation capabilities. Finally, note that defining the on-body nodes locations into a LCS may be still required here, as an intermediary step of the calculations.

Possible Use Case(s): *On-field sports gesture live capture and analysis, physical activity monitoring at home for non-intrusive & long-term physical rehabilitation or diet assistance…*

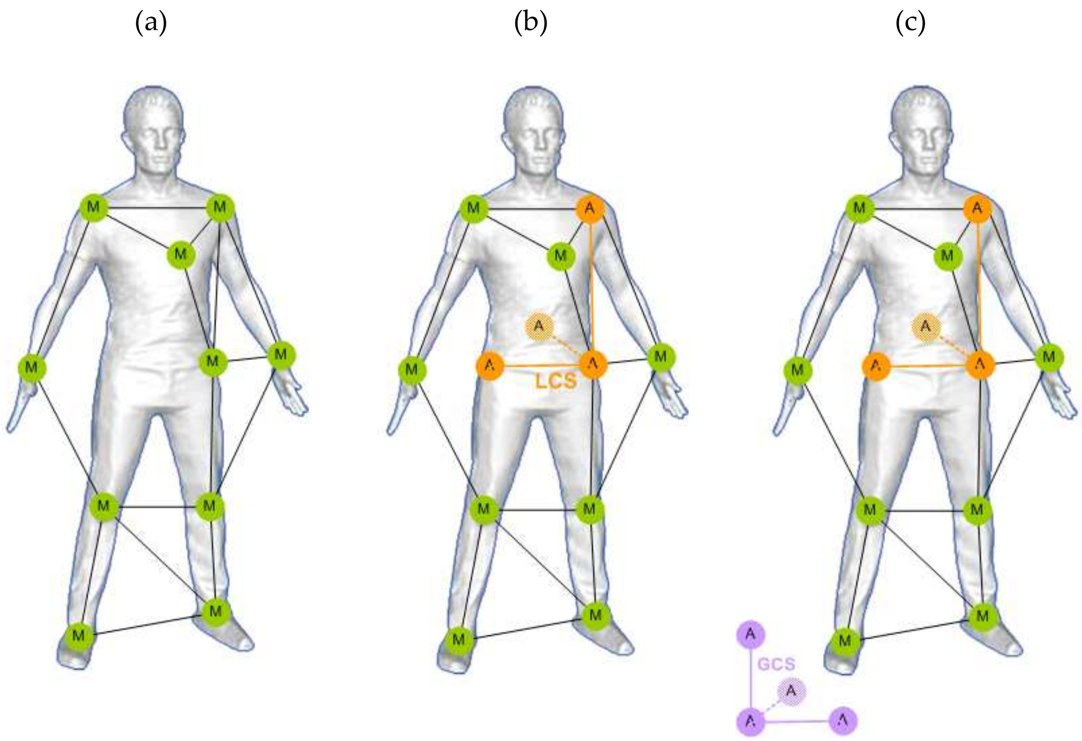


Figure 2.18: Examples of relative on-body nodes ranging (a), relative on-body nodes positioning (b) and absolute on-body nodes positioning (c) configurations for large-scale single-user motion capture applications.

2.2.2 COORDINATED GROUP NAVIGATION

- *Relative Body-to-Body Ranging in a Group*

In this first navigation sub-scenario, people wearing several on-body wireless sensors and forming a group of mobile users must localize them-selves with respect to other mates in the very group. The inter-body range information is required, that is to say, only the relative group topology, independently of the actual locations (and orientations) in the room or in a building. Accordingly, no external anchor nodes would be required in this embodiment.

Possible Use Case(s): *Relative deployment or soldiers or fire-fighters, people finding in nomadic social networks, proximity detection or collision avoidance in confined, blind or dangerous environments (e.g. for security, collective gaming)…*

- *Absolute Body Positioning in a Group*

In a second preferred sub-scenario, which is intended in a more classical pedestrian navigation sense, one must retrieve the absolute coordinates of several users belonging to the same mobile group, with respect to an external GCS. This shall imply the use of fixed and known elements of infrastructure around, like previously within large-scale motion capture applications based on absolute on-body nodes positioning. In comparison with other State of the Art navigation solutions, the presence of multiple wearable on-body nodes (i.e. in the WBAN context) is expected to enhance navigation performance by providing spatial diversity and measurements redundancy (i.e. over off-body links with respect to the infrastructure and/or over inter-WBAN/body-to-body links with respect to other mobile neighbours), and possibly, further cooperative on-body information exchanges (i.e. through intra-WBAN links).

Without loss of generality, note that navigation-oriented scenarios will aim at retrieving mostly the "macroscopic" position of the body, but note the on-body-nodes in details… Hence, a reference point on the body shall be chosen to account for this average position (e.g. the geometric center of the body torso or the barycentre of all the on-body nodes).

Possible Use Case(s): *Absolute deployment or soldiers or fire-fighters, Analysis of social mobility patterns and habits in commercial centres, enhanced and/or augmented personal pedestrian navigation…*

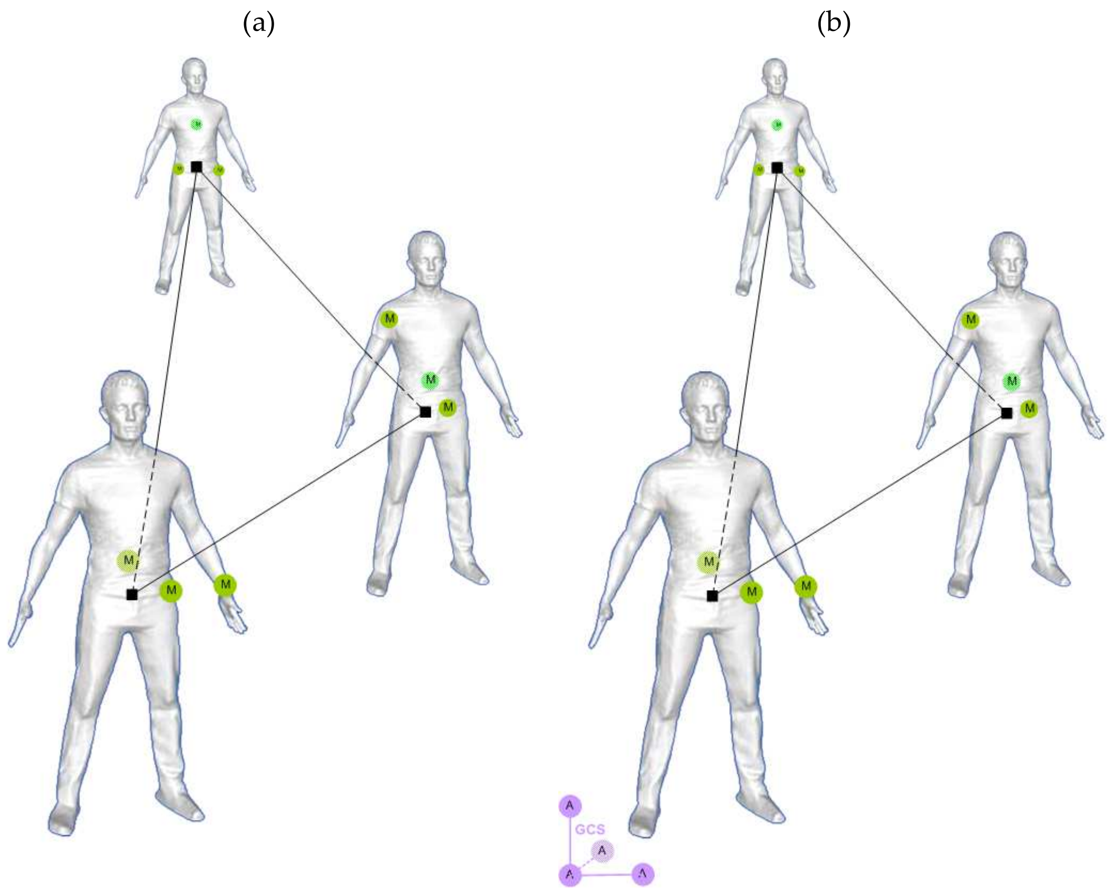


Figure 2.19: Examples of relative body-to-body ranging (a) and absolute body positioning (b) configurations for coordinated group navigation applications.

2.2.3 LARGE-SCALE MOTION CAPTURE WITHIN COORDINATED GROUPS

This last sub-scenario is nothing but the combination of the two latter scenarios.

2.3. SUMMARY OF APPLICATIONS NEEDS

Table 2-3 summarizes the main needs for the two identified classes of application.

	Large-Scale Individual Motion Capture		Coordinated Group Navigation
	Low Precision	High Precision	
On-Body Nodes Location Precision (Relative)	$\varepsilon_{90} < 25$ cm (worst case CDF @ 90%) $\varepsilon_{50} \approx 5$ cm (median CDF @ 50%)	$\varepsilon_{90} < 5$ cm (worst case CDF @ 90%) $\varepsilon_{50} \approx 1$ cm (median CDF @ 50%)	N/A
Average Body Location Precision (Absolute)	$\varepsilon_{90} < 1$ m (worst case CDF @ 90%) $\varepsilon_{50} \approx 0.3$ m (median CDF @ 50%)		
Nodes Location Refreshment Rate	100 ms	10 ms	1s
Maximum Speed	{5, 15} $km.h^{-1}$		
Anchors Density	< 0.05 anchors / m^2		< 0.01 anchors / m^2
Nb Persons per Group	N/A		{5, 10}
Maximum Inter-Body Distances	N/A		{1, 5, 10, 50}
Nb of On-Body Nodes	{5, 10, 20}		{2, 5}
Rank of Preferred On-Body Nodes Location	**An-He-Wr-To-Hi-Lg-Ba-Sh-Kn-Bd**		**Sh-To-Ba-Hi-Wr**
Environment	{Outdoor, Indoor}		Indoor
Place for Final Location Info	{Server, User}		User
Pre-Calibration (Deployment Convention to be Respected)	{None, Precise Deployment Pattern}		{None, Rough Deployment Pattern}

Table 2-3 : Summary of application needs in both large-scale individual motion capture (Within low precision and very high precision modes) and group navigation applications[1].

3. RELATED STANDARDS AND REGULATION

3.1. REVIEW OF RELATED STANDARDS

3.1.1 IEEE 802.15.6

- *Generalities*

The IEEE 802.15.6 standard [std_IEEE802.15.6] intends on completing the IEEE 802.15 personal area networks family by specifying a medium access control and three physical layers dedicated to body area networks. Bluetooth was initially designed for peripherals

[1] An : Ankles ; He : Head ; Wr : Wrist ; To: Torso; Hi: Hips; Lg: Legs; Ba: Back; Sh: Shoulders; Kn: Knees; Bd: Bends

interconnection and Zigbee for building small networks of embarked nodes. IEEE 802.15.6 target BANs, operating close or inside a human body. IEEE 802.15.6 focuses on medicine-oriented WBANs, which require a better *Quality Of Service* (QOS) than classical applications. That's why the *Medium Access Control* (MAC) layer, even though it remains in the tradition of the IEEE standards, proposes numerous methods to access the wireless channel and the physical layer provides short-range communication in a variety of frequency bands (*Industrial Scientific & Medical* -ISM- bands, but also *Ultra Wideband* -UWB- and *Human Body* -HB- communication band). Besides the specification of the communication layers, IEEE 802.15.6 specifies several data security mechanisms (authentication and confidentiality) that are necessary considering the sensitive nature of medical information. These basic security mechanisms are considered as sufficient for CORMORAN. The high level application specifications of the IEEE 802.15.6 standard are summarized in the table below:

Topologies	Star or meshed, bidirectional
Setup time	Insert / desinsert. time < 3s
Number of nodes	Typ. 6, max. 256
Bit rate	Typ. 0.1-1 Mbits/s, max. 10 Mbits/s
Range	> 3m at lowest bit rate with IEEE channel model
PER	Mean PER < 10% for 95% of IEEE channel model realizations
Latency	< 125 ms (medical), < 250 ms (non medical)
Jitter	< 50 ms
Differentiated Latency	< 1s for alarms, < 10ms for applications with feedback
Autonomy	> 1 year (with 1% duty cycle and a 500 mAh battery), > 9h (always « on » with a 50 mAh battery)
Coexistence (intra system)	Resilience to 10 BANs in a 6*6*6m3 volume
Coexistence (inter system)	Undefined. Severe environnement (WiFi, Bluetooth, etc).

Table 3-1 : WBAN requirements specified in IEEE 802.15.6

- *WBAN operation*

The IEEE 802.15.6 standard supports body area networks composed of a main node, called coordinator or hub, which is the center of a star-like network of small devices. Considering the transmission range of the nodes, the WBAN can span across no more than two hops. If this limit can be perceived as a constraint, especially in the multi-WBAN context of CORMORAN, it only concerns the link-layer of the standard *Open Systems Interconnection* (OSI) model. Communication with nodes at a distance greater than two radio ranges requires a routing protocol; whose specification and tuning will be the topic of one CORMORAN work-package. A body area network, seen from the link layer, is therefore able to cover a full human body in most situations, and the two-hops extensions specified in the standard constitute a progress compared to other IEEE standards.

Addressing

Nodes addresses are allocated by the hub that chooses a random 1-byte network identifier (WBAN ID: from 0x00 to 0xFF). This WBAN ID must be different from close WBANs to avoid confusions and reduce the addresses collision probability. The standard remains very elusive on how to detect and react to WBAN IDs collisions. However, as CORMORAN specifically targets multi-WBAN networks, distributed algorithms and policies can be implemented and deployed to avoid and solve these situations.

The hub then chooses its own address, a *hub identifier* (HID on 1 byte) and attributes to each of its WBAN nodes a *node ID* (NID on 1 byte). The node IDs of regular unicast nodes is comprised between 0x02 and OxF5, which limits a single WBAN size to 244 nodes. Considering the expected individual WBAN topology in CORMORAN, this limitation does not need to be addressed specifically.

The frames headers include the WBAN ID and the NID or HID as short source and destination addresses. Note that each node also possesses a classical EUI-48 address on 48 bits that can be utilized to communicate beyond the WBAN boundaries.

WBAN creation

The creation and initialization of a WBAN is the role of the node that will act as the hub. This node begins by selecting a wireless channel that can be modified later and an operational mode (with or without beacon, with or without superframe structure, see below). Once these parameters are selected, the hub begins to send beacons or to explicitly poll non-connected nodes using a specific address to invite them to join the WBAN.
When receiving such a message, a node choosing to join the announced WBAN sends a `Connection Request` message (IEEE 802.15.6 - §6.4.2 [std_IEEE802.15.6]) that is followed by a `Connection Assignment` confirmation in case of success (IEEE 802.15.6 - §6.4.2 [std_IEEE802.15.6]). A hub can acknowledge multiple connections in a single message sent in local broadcast (`Multinode Connection Assignment;` IEEE 802.15.6 - §6.4.2 [std_IEEE802.15.6]).

Each node is connected to one and only one hub. Consequently, the inter-WBAN communications addressed by CORMORAN should pass through the hub.

- *Physical Layer*

IEEE 802.15.6 defines three physical layers: *Narrowband* (NB), *Impulse Radio - Ultra Wide Band* (IR-UWB) and *Human Body* (HB) communications. However, we will focus hereafter only on the UWB option, which is the only one to provide intrinsic localization capabilities at the body scale (i.e. due multipath resolution and precise timing) over very short-range intra-WBAN links.

IR-UWB symbol structure

The IR-UWB symbol structure is illustrated on Figure 3.5. Each symbol consists of an integer number of pulse waveform positions N_w, each of duration T_w. The symbol duration is divided into two intervals of duration T_{sym} in order to enable on-off signaling.

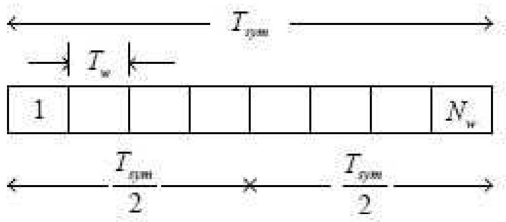


Figure 3.1: UWB symbol structure

The duty cycle factor during a symbol time is given by the ratio between the time a pulse waveform is on over the overall symbol time (when a pulse waveform is on and off), that is:

$$\rho = \frac{T_w}{T_{sym}}$$

Such duty cycle shall be kept down to 3.125% for any data rate and modulation in order to maintain constant pulse power for a given EIRP and low power consumption.

The additional N_w-1 (Differential Phase Shift Keying -DPSK- modulation) or N_w/2-1 (*On-Off Keying* -OOK- modulation) waveform positions are used for time hopping in order to support multi-WBANs for coexistence, which may be of interest in the CORMORAN context of body-to-body cooperation.

Operating frequency bands

The UWB PHY operates in two main frequency bands, namely the “low band” and the “high band”. Each band is divided into sub-channels, characterized by a bandwidth of 499.2MHz, as seen on Table 3-2. The low band consists of 3 channels (1-3) only. The channel 2, which is mandatory, has a central frequency of 3993.6MHz. The high band consists of eight channels (4-11), where channel 7, which has a central frequency around

7987.2 MHz, is also considered as a mandatory channel, whereas all others channel are optional. Note that a typical UWB device should support at least one of the mandatory channels.

Band Group	Channel number	Central frequency	Bandwidth	Channel attribute
Low Band	1	3494.4	499.2	Optional
Low Band	2	3993.6	499.2	Mandatory
Low Band	3	4492.8	499.2	Optional
High Band	4	6489.6	499.2	Optional
High Band	5	6988.8	499.2	Optional
High Band	6	7488.0	499.2	Optional
High Band	7	7987.2	499.2	Mandatory
High Band	8	8486.4	499.2	Optional
High Band	9	8985.6	499.2	Optional
High Band	10	9484.8	499.2	Optional
High Band	11	9984.0	499.2	Optional

Table 3-2: UWB operating frequency bands

Waveform

A pulse waveform $w'(t)$ of duration T_w is formed by either a single pulse (denoted as "single pulse option") or a concatenation of pulses (denoted as "burst pulse option") and given by:

$$w'(t) = \begin{cases} p(t) & \text{single pulse option of duration } T_w = T_p \\ \sum_{i=0}^{N_{cpb}-1} p(t - iT_p) & \text{burst pulse option of duration } T_w = N_{cpb}T_p \end{cases}$$

where $N_{cpb} > 1$ and T_p is the duration of pulse $p(t)$.

In order to reduce spectral spikes due to long strings of pulses with the same polarity in the burst pulse option, spectral shaping through scrambling shall be used (either static or dynamic).

There is not a mandatory pulse shape. However, the pulse waveform duration PRF and peak PRF shall comply with the timing parameters of Table 3-3 and Table 3-4. Moreover, the pulse shapes shall fulfill the transmit spectrum mask and regulatory spectral mask where applicable.

R0,R1,R2	PRF (MHz)	Nw	Nhop	Tw (ns)	Tsym (ns)	Uncoded bit rate (Mbps)	FEC rate	Coded bit rate (Mbps)	Ncpb	P.PRF (MHz)
000	0.487	32	16	64.103	2051.300	0.487	0.81	0.3948	32	499.2
100	0.975	32	16	32.051	1025.600	0.975	0.81	0.7897	16 2	499.2
010	1.950	32	16	16.026	512.820	1.950	0.81	1.579	8	499.2
110	3.900	32	16	8.012	256.410	3.900	0.81	3.159	4	499.2
001	7.800	32	16	4.006	128.210	7.800	0.81	6.318	2	499,2
101	15.600	32	16	2.003	64.103	15.600	0.81	12.636	1	499.2
011	r	r	r	r	r	r	r	r	r	r
111	r	r	r	r	r	r	r	r	r	r

Table 3-3: Data rates for on-off signalling.

R_0,R_1,R_2	PRF (MHz)	N_w	N_{hop}	T_w (ns)	S_f	T_{sym} (ns)	Mod	Uncoded bit rate (Mbps)	FEC rate	Coded bit rate (Mbps)	N_{cpb}	P.PRF (MHz)
0 0 0	0.487	32	32	64.103	1	2051.300	DBPSK	0.487	0.5	0.243	32	499.2
1 0 0	0.975	32	32	32.051	1	1025.600	DBPSK	0.975	0.5	0.457	16	499.2
0 1 0	1.950	32	32	16.026	1	512.820	DBPSK	1.950	0.5	0.975	8	499.2
1 1 0	3.900	32	32	8.012	1	256.410	DBPSK	3.900	0.5	1.950	4	499.2
0 0 1	7.800	32	32	4.006	1	128.210	DBPSK	7.800	0.5	3.900	2	499.2
1 0 1	7.800	32	32	4.006	1	128.210	DQPSK	15.600	0.5	7.800	2	499.2
0 1 1	3.906	32	32	8.012	7	1794.900	DBPSK	0.557	0.5	0.278	4	499.2
1 1 1	3.906	32	32	8.012	7	1794.900	DQPSK	1.114	0.5	0.557	4	499.2

Table 3-4: Data rates for DBPSK/DQPSK modulations

- *Medium Access Control Layer*

IEEE 802.15.6 defines 8 priority levels to access the medium. The first five levels are similar to the classical traffic classes defined by IEEE 802.1D (from background traffic for the lowest priority to Voice and Video for the highest one). However IEEE 802.15.6 does not introduce sub-levels for voice and video classes and does not dedicate a class to network management frames. It then frees three traffic classes identifiers that are assigned the highest medium access priorities and that are dedicated to medical applications.

The MAC procedure is relatively classical. Inside a WBAN, it is possible to use a random access procedure, such as the *Carrier Sense Multiple Access with Collision Avoidance* (CSMA/CA) or Slotted ALOHA, to let the hub decide of the frames scheduling (preallocated transmission opportunities announced in a beacon), or to let the hub explicitly invite nodes to transmit (poll) or to receive (push) a frame.

IEEE 802.15.6 specifies these access modes, their usage conditions and their sequence by defining several transmission phases:

- **EAP (*Exclusive Access Phase*)**: a random access phase (CSMA/CA or Slotted ALOHA) reserved for the transmission of highest priority frames. The hub is authorized to emit after a short constant time (SIFS).
- **RAP (*Random Access Phase*) and CAP (*Contention Access Phase*)**: standard random access phases (CSMA/CA or Slotted ALOHA). The difference between RAP and CAP is the type of announce (through a beacon or other signaling frame)
- **MAP (*Managed Access Phase*):** a phase entirely controlled by the hub. It can involve and mix three transmission modes:
  - **Improvised access:** the *hub* invites nodes to emit a frame (*polling*) or sends them a frame (*posting*) in order to accommodate a traffic surplus. Allocations can be granted and announced through acknowledgment frames (Poll+Ack). Allocations can be specified in time, analogously to the transmission opportunities (Type-I, e.g. invitation to emit during 5 ms), or in number of frames (Type II, e.g. invitation to emit 3 frames)
  - ***Scheduled access*:** the hub defined the whole scheduling and the access in such a period will be without contention. Thus type of allocation more specifically addresses periodical traffic. Medium access allocations can be of type I or of type II, as in the improvised access method.
  - ***Unscheduled access*:** it is a best effort version of the scheduled access mode.

IEEE 802.15.6 therefore supports a vast variety of access modes that should be sufficient in the context of CORMORAN. Depending on the WBAN mode of operation (see below), the various access strategies can be combined to offer a versatile scheduling that can accommodate multiple traffics with multiple constraints. However, the early versions of IEEE 802.11 and IEEE 802.15.4 did not support scheduled access, as it was not required for certification. Therefore, a particular attention should be paid to the first IEEE 802.15.6 hardware that will be produced, especially considering the complexity of the MAC procedure defined. As the WBAN context is specifically targeted to medical applications, there is a reasonable chance that QoS support will be included in the early releases.

BAN operation modes

According to the IEEE 802.15.6 standard, a WBAN can choose among three operational modes listed hereafter:

- **Beacons emission with superframe**: in this mode, the hub periodically broadcasts a beacon to the whole BAN. This beacon specifies the WBAN parameters and defines the superframe boundaries. A superframe is, in this case, a time interval that restarts every time a beacon is sent and that can be composed of the following sequence of access modes: EAP_1 ; RAP_1 ; MAP ; EAP_2 ; RAP_2 ; MAP ; CAP
  Some of these periods can have a zero-length, only the RAP and CAP must last at least as long as specified by the hub in the connection assignment frames. This mode of operation alternates random access periods and scheduled access periods and is therefore designed to combine traffic that requires guarantees with elastic traffic. This mode of operation is very close to the classical IEEE wireless standards (802.11, 802.15.4…) but takes into account multiple priorities levels.
- **Without beacons but with a superframe**: in this mode, the hub controls and schedules most of the transmission within the WBAN. The only phase allowed is the MAP and the lack of beacon forces the hub to explicitly poll or push nodes. Nodes are only clients and have a very limited freedom to change their traffic profile.
- **Without beacon or superframe:** This mode combines in parallel time slots allocations (unscheduled MAP) and random access mode (CSMA/CA). Both access methods contend to access the medium, that's why allocated time slots cannot be guaranteed and a scheduled access is impossible. This mode is the most lightweight for the hub and, if history repeats, could be the only one to be developed in the first implementations.

Random access procedure

Random access in the IEEE 802.15.6 standard shall comply to the CSMA/CA or Slotted Aloha methods. The introduction of Slotted Aloha is original compared to classical *Wireless Local Area Network* (WLAN) or *Wireless Personal Area Network* (WPAN) standards.

In the case of CSMA/CA (IEEE 802.15.6 - §6.5. [std_IEEE802.15.6]), nodes use a contention window that depends on the traffic class, in which an integer random backoff is drawn. This backoff is then decremented one by one when the channel remains free during a time that is a proportion of the unit slot time. The decrementing procedure stops as soon as the channel becomes occupied or when the limit of the RAP or CAP is reached.

In the case of Slotted Aloha access, nodes use a transmission probability that depends on the traffic class to emit in each time slot.

Frames acknowledgments

IEEE 802.15.6 specifies multiple procedures to enhance transmission reliability. Frames can, according to a field in the MAC header, be acknowledged in several ways. The lack of reception of such an acknowledgment triggers a retransmission.

- **No acknowledgment (N-Ack)**: no acknowledgment is expected
- **Immediate acknowledgment (I-Ack)**: the receiver should acknowledge each frame individually (*stop-and-wait* ARQ)
- **Block acknowledgment (B-Ack and L-Ack)**: the receiver acknowledges a group of frames with a single acknowledgment. The acknowledgment header field of each of the frame of the group needs to be positioned to L-Ack and the last one, triggering the acknowledgment emission, should be labeled B-Ack.
- **Group acknowledgment (G-Ack)**: a node can ask the hub to acknowledge the reception of multiple frames, emitted by a group of nodes (multiple emitters).

• *Other aspects relevant for CORMORAN*

Cross-layer

The standard does not exclude the possibility to communicate between the OSI layers and defines management entities (IEEE 802.15.6 - §4.3 [std_IEEE802.15.6]) to allow this communication (*Node Management Entity* -NME- for a regular node and *Hub Management Entity* -HME- for a hub). The upper layers could share variables with layers 1 and 2, but the standard does not specify how such communication should be realized or what it could address.

Two-hop extension

The standard authorizes certain nodes to play the role of a layer-2 relay. It defines the adaptations of the various access modes (how to ask and how to guarantee a regular transmission, etc.). It also gives some recommendations concerning the selection of relay nodes (pre-arrangement or on the basis of the received control frames).

Clocks synchronization

The standard defines a procedure that allows compensating clocks drifts in order to allow medium access control to operate correctly. The nominal accuracy of the embedded clocks will probably not be sufficient for the ranging techniques based on *Time OF Arrival* (TOA) estimation. However, note that there exist cooperative transactions at the protocol level (e.g. 3-way ranging) that enable to calibrate the relative clock drifts out of raw *Round Trip - Time of Flight* (RT-TOF) measurements between *a priori* asynchronous entities [MAMAN08].

WBANs coexistence

The standard evokes beacons collisions and interference at the physical level. It proposes to introduce an offset to solve the beacons collisions problems and specifies a channel change method to reduce interferences. Other issues such as WBAN ID collisions are not mentioned.

3.1.2 IEEE.802.15.4

- *Introduction*

The 802.15.4-2006 standard is dedicated to low rate WPAN (Wireless Personal Area Networks). The nominal range of such applications is considered to be on the order of 10m, corresponding to the POS (Personal Operating Space). This limitation could be a problem at first sight for inter-WBAN links in large-scale groups of users and/or off-body links with respect to distant elements of infrastructure in a few applicative cases covered by CORMORAN , but obviously not for intra-WBAN cooperative links. However, the standard can also support longer transmission ranges at smaller data rates.

Besides, this standard is compliant with some of CORMORAN's goal: ease of installation, reliable data transfer and low energy consumption. However, several publications [Hertefeux12, Dieng12] pointed out that this standard, or at least its implementations in the 2.4GHz band failed to achieve localization accurately enough for CORMORAN applications when using signal propagation. As IEEE 802.15.4 devices are usually not equipped with ranging-dedicated technology and as the core version operates in the ISM bands, this technology does not appear relevant to be the only intra-BAN communication layer or for BAN relative positioning.

- *General description*

Two different devices can participate in a 802.15.4 network: a Full Function Device (FFD), and a Reduced Function Device (RFD). It must be noted that a RFD can only communicate with a FFD. As a consequence, in order to be able to support relaying and cooperatives schemes, the network should be composed of FFD only. However, in this case, we are not able to take advantage of the low resources consumptions of the RFD.

- *Network topologies*

A network is defined by at least 2 devices communicating on the same physical channel within a POS. We can note that there must be at least 1 FFD as RFD can not communicate. By default, the FFD will be the PAN coordinator.

The IEEE 802.15.4 standard defines 2 topologies:
- star topology: the communication is made between devices and a central coordinator. The coordinator initiates the PAN and is responsible for the address allocation. The coordinator also chooses a PAN identifier currently available in the radio sphere of influence. Thus, the coordinator should be mains powered.
- peer to peer topology: the communication can be made between any nodes. This requires that all the nodes are FFD. The main advantage of this topology is the possibility of multi-hops communications, thus this topology is suitable for CORMORAN. This topology also enables the cluster tree, where RFD can connect to FFD as a leaf device.

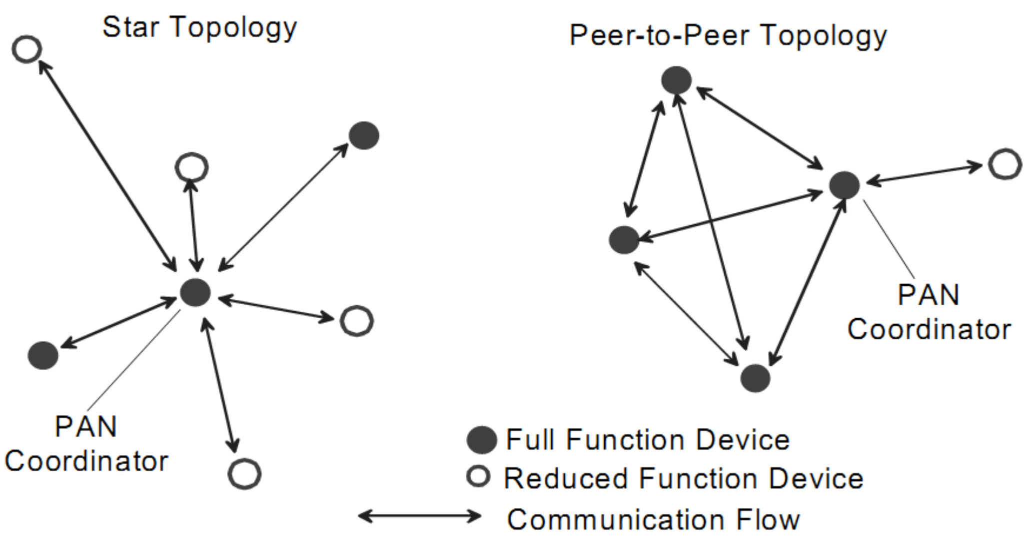


Figure 3.2: Star and peer to peer topology examples

- *Architecture*

The communication can use the following unlicensed bands: 868-868.6MHz, 902-928MHz, 2400-2483.5MHz.
In a beacon-enabled PAN, the superframe format is defined by the coordinator, and is delimited by NETWORK beacons (sent by the coordinator). The beacon frame is sent in the first slot of the superframe, for the attached devices synchronization, the PAN identification and the description of the superframes structure. In between the beacon, there is the active part followed or not by an inactive portion. The active part is at least containing by the CAP: Contention Access Period, divided into 16 slots (with equal length). We can also dedicate up to 7 GTS (Guaranteed Time Slots) to low latency applications. The GTSs form the Contention Free Period (CFP). The device willing to transmit data to the coordinator, will use slotted CSMA-CA at the appropriate time, and

can request an acknowledgment. Furthermore, the coordinator can also indicate in the beacon that it has some data for a device. Then, it will wait for the data request from the concerned device before sending the data.
In a nonbeacon-enabled PAN, the device, will transmit its data frame using unslotted CSMA-CA to the coordinator. Furthermore, when the coordinator wishes to transfer data to a device, it will wait for the appropriate device to request the data.
Consequently, in both nonbeacon-enabled and beacon-enabled PAN, the transmission process is based on CSMA-CA. However, thanks to the beacon, the beacon-enabled PAN uses slotted CSMA-CA, and the emitting device waits for a random number of backoff slot. On the contrary, in the nonbeacon-enabled PAN, the device waits for a random backoff.

- *PHY specification*

The standard specifies 4 PHY layers, based on 4 frequency bands, and modulation and spreading formats, as summarized in the following table.

PHY (MHz)	Frequency band (MHz)	Spreading parameters		Data parameters		
		Chip rate (kchip/s)	Modulation	Bit rate (kb/s)	Symbol rate (ksymbol/s)	Symbols
868/915	868–868.6	300	BPSK	20	20	Binary
	902–928	600	BPSK	40	40	Binary
868/915 (optional)	868–868.6	400	ASK	250	12.5	20-bit PSSS
	902–928	1600	ASK	250	50	5-bit PSSS
868/915 (optional)	868–868.6	400	O-QPSK	100	25	16-ary Orthogonal
	902–928	1000	O-QPSK	250	62.5	16-ary Orthogonal
2450	2400–2483.5	2000	O-QPSK	250	62.5	16-ary Orthogonal

Table 3-5: Frequency bands and data rate

The PHY details (narrow band modulation and spreading formats) will not be more detailed in this report as CORMORAN plans to consider a different PHY layer based on ultra wide band modulation. However, we can note, that the receiver sensitivity should be -85dBm to be compliant with the 802.15.4 standard.
Besides, the PPDU (PHY Protocol Data Unit) is defined to be composed of 3 main components:

- SHR: the synchronization header
- PHR: the PHY header, which contains frame length information
- PSDU: the PHY payload, whose length is at most 127 octets).

This is represented in Figure 3.3.

		Octets		
		1		variable
Preamble	SFD	Frame length (7 bits)	Reserved (1 bit)	PSDU
SHR		PHR		PHY payload

Figure 3.3: Format of the PPDU

Finally, for localization issues, 2 measurements could be used in this standard:

- ED (Energy Detection) : it is an estimate of the received power within the bandwidth of the channel, averaged over 8 symbol period
- LDQI (Link Quality Indicator) : it is a characterization of the strength and/or the quality of the signal. It is obtained with the receiver ED and/or the signal to noise ratio estimation. This value is reported to the MAC sublayer.

- *MAC specification*

The MAC layer is responsible for the following tasks (whose primitive are detailed in the standard):

- Generating network beacons if the device is a coordinator
- Synchronizing to network beacons
- Supporting PAN association and dissociation
- Supporting device security
- Employing the CSMA-CA mechanism for channel access
- Handling and maintaining the GTS mechanism
- Providing a reliable link between 2 peer MAC entities with optional acknowledgment of the data frames.

Similarly to the PHY frame format, the MAC frame (MPDU : MAC Protocol Data Unit) is composed of 3 basic components :

- MHR (MAC Header), which contains, in particular, the frame type indication (beacon, data, acknowledgment and MAC command).
- MAC payload whose length is constrained such as the PPDU does not exceed the 127 octets.
- MFR (MAC footer)

Octets: 2	1	0/2	0/2/8	0/2	0/2/8	0/5/6/10/14	variable	2
Frame Control	Sequence Number	Destination PAN Identifier	Destination Address	Source PAN Identifier	Source Address	Auxiliary Security Header	Frame Payload	FCS
		Addressing fields						
MHR							MAC Payload	MFR

Figure 3.4 : Format of the MPDU

3.1.3 IEEE.802.15.4A

• *Generalities*

The IEEE 802.15 Low Rate Alternative PHY Task Group (TG4a) for *Wireless Personal Area Networks* (WPANs) was initially created to propose an amendment to the Low Data Rate IEEE 802.15.4 standard, aiming at defining an alternative *PHYsical layer* (PHY) [IEEE802.15_TG4]. Over the existing standard, the main goal was to provide:

- Joint communications and high-precision ranging service (typically with sub-meter accuracy);
- High aggregate throughput ;
- Ultra low power consumption ;
- Scalable bit rates ;
- Longer achievable ranges ;
- Low cost ;
- Compliance with worldwide regulation ;
- Possibility for different receiver architectures (hence tolerating trade-offs between performance and complexity);

In this framework, the *Impulse Radio* (IR) transmission technology operating in the unlicensed *Ultra Wideband* (UWB) spectrum has been identified as one of the preferred PHY options. Several features of this new standard and technology may sound particularly relevant and meaningful into the CORMORAN context, especially regarding the scenarios involving body-to-body and off-body links:

- Practical peer-to-peer transmission range: on the order of a few tens of meters (i.e. typically 20m);
- Environments: mostly indoor (i.e. office/industrial/residential) and marginally outdoor;

- Underlying network topology: infrastructureless ;
- Optional peer-to-peer ranging: supported at both the PHY layer (i.e. *Time Of Arrival* -TOA- estimation based on processed synchronization headers) and the MAC layer (i.e. protocol mechanisms enabling 2-Way ranging transactions for *Round-Trip Time Of Flight* -RT-TOF- estimation);

For instance, the specified frequency band plan (e.g. addressing the mandatory channel 3 centred around 4.5GHz in the low band), bandwidth (i.e. about 500MHz at -10dB PSD), and modulation schemes (i.e. BPSK / 2-PPM + Polarity) should be carefully taken into consideration in CORMORAN. Moreover, the available IEEE 802.15.4a channel models [Molisch04], [Molisch06] (again mostly for body-to-body and off-body links) and the described ranging procedures should be of interest. The reference P802.15.4a document was internally issued to TG4a members in 2007 [IEEE802.15.4a07].

- *PHY Layer*

Band Plan

Table 3-6 shows the IEEE 802.15.4a band plan.

Band Group	Channel Number	Center Frequency (MHz)	Chip Rate (MHz)	Mandatory/Optional
0	1	399,36	499,2	Optional in Sub-Gigahertz band
1	1	3494,4	499,2	Optional in low band
	2	3993,6	499,2	Optional in low band
	3	4492,8	499,2	Mandatory in low band
	4	3993,6	1331,2	Optional
2	5	6489,6	499,2	Optional in High Band
	6	6988,8	499,2	Optional in High Band
	7	6489,6	1081,6	Optional in High Band
2	8	7488	499,2	Optional in High Band
	9	7987,2	499,2	Mandatory in high band
	10	8486,4	499,2	Optional in High Band
	11	7987,2	1331,2	Optional in High Band
2	12	8985,6	499,2	Optional in High Band
	13	9484,8	499,2	Optional in High Band
	14	9984	499,2	Optional in High Band
	15	9484,8	1354,97	Optional in High Band

Table 3-6 : UWB PHY channel frequencies (band plan) of the IEEE 802.15.4a standard.

Waveform

The transmitted pulse shape is constrained by its cross-correlation function $\Phi(t)$ with respect to a reference pulse, as follows:

$$\Phi(t) = \frac{1}{\sqrt{E_r E_p}} \Re e\left[\int_{-\infty}^{+\infty} r(t) p^*(t+\tau) dt\right]$$

where $p(t)$ is the transmitted pulse and $r(t)$ is a reference root raised cosine pulse with a roll-off factor β equal to 0.6 and a pulse duration T_p that depends on the addressed band:

$$r(t) = \frac{4\beta}{\pi\sqrt{T_p}} \frac{\cos\left[(1+\beta)\pi t/T_p + \frac{\sin\left[(1-\beta)\pi t/T_p\right]}{4\beta(t/T_p)}\right]}{\left(4\beta t/T_p\right)^2 - 1}$$

The main lobe of the cross-correlation function $\Phi(t)$ must exceed 0.8 over a duration of at least 0.5ns and any side lobe shall be lower than 0.3. The pulse duration figures provided in the table below give an idea about the actual multipath resolution power in a TOA estimation context, inherently to the UWB transmitted signal (i.e. Rx hardware capabilities apart)

Channel Number	Pulse Duration, Tp (ns)
{0:3, 5:6, 8:10, 12:14}	2.00
7	0.92
{4, 11}	0.75
15	0.74

Table 3-7: Pulse duration as a function of the addressed band (channel number)

Power Spectrum Density Mask

The transmitted spectrum shall be less than -10dBr for $f_c - 0.65R_{chip} < f < f_c + 0.65R_{chip}$ and -18dB for $f_c - 0.8R_{chip} < f < f_c + 0.8R_{chip}$ with a 1MHz RBW and a 1kHz VBW. An example of transmit spectrum mask is shown below on Figure 3.5 for the "mandatory channel 3".

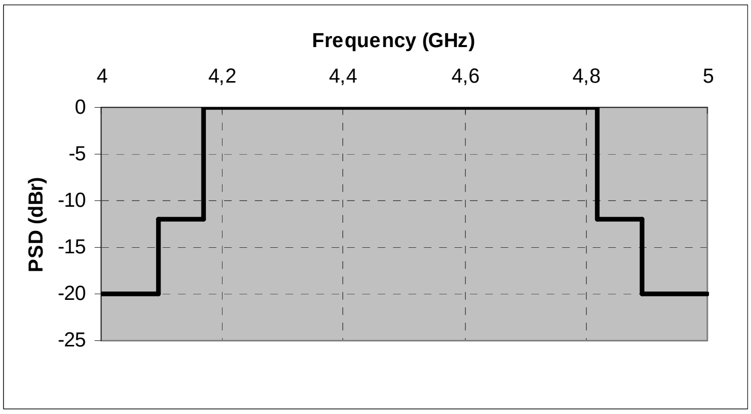


Figure 3.5: Example of transmit spectrum for the mandatory channel 3

Clock accuracy and Other Main RF specifications

As 15.4a systems are expected to be low-cost, the standard-compliant clock accuracy lies within +/- 20 ppm, applying to both centre frequency and chip rate. This clearly impacts the precision of ranging through cooperative protocol exchanges such as *Two Way Ranging* (TWR), if no relative clock drift compensation mechanism is implemented.

The maximum input level is -45 dBm/MHz and the minimum sensitivity is -85 dBm for a PER=10^{-2} with a 20-byte PSDU.

PHY Protocol Data Unit Format

The format of the *PHY Protocol Data Unit* (PPDU) is slightly the same as a classical IEEE 802.15.4 structure (Figure 3.5), including a *Synchronisation Header* (SHR), which is composed of a Preamble and a *Start of Field Delimiter* (SFD), and a *PHY Header* (PHR). In comparison with IEEE 802.15.4, a few features have been added:

- Variable preamble length ;
- Variable data rate ;
- Ranging support ;

Consequently, new fields have been included in the PHR:

- Preamble length ;
- Data rate ;
- Ranging flag ;

		Octets 2		variable
Preamble	SFD	Rate	Frame Length	PSDU
SHR		PHR		PHY payload

Figure 3.6: PPDU structure

As for the SHR (Figure 3.7), the preamble is a concatenation of a given sequence chosen among 8, as defined by the *PicoNet Coordinator* (PNC). It can have variable length for:

- Ranging purposes (for TOA estimation)
- Trade-offs between packet efficiency and processing gain

Finally, the SFD is built as a convolution of a ternary code with the preamble sequence.

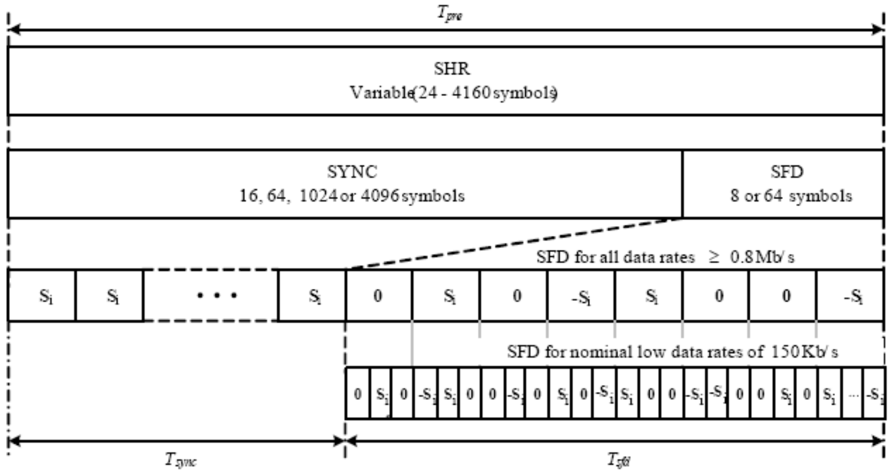


Figure 3.7: SHR structure

Regarding the PHR (Figure 3.8), it conveys information necessary for a successful decoding of the packet:

- next packet preamble mode
- data rate of the data field
- length of the frame payload

RATE (1 octet)								LENGTH (1 octet)							
Bit 7	6	5	4	3	2	1	0	Bit 7	6	5	4	3	2	1	0
RES	RES	RES	R4	P3	P2	R1	R0	RES	L6	L5	L4	L3	L2	L1	L0
Reserved			Ranging Packet	Preamble duration field		Data rate encoding field		Res.	Frame length field						

Transmit order (from left to right)

Figure 3.8: PHR structure

Finally, a variable data rate is supported for better scalability:

- Optional low rate ~110 kbps
- Mandatory nominal rate ~850 kbps
- Optional high rates from 1.7 Mbps to 27.24 Mbps (under certain conditions)

Modulation and Coding

The standard aims at providing:

- Possible implementation of both coherent RAKE receivers or non-coherent (e.g. energy detection based) receivers → Combining of BPSK and 2-PPM modulations
- Forward error correction → Compatible with both modulations and generic receivers
- Ranging support → Preamble and data parts exhibiting different structures
- Optional bit rates → Benefitting from the inherent scalability of IR-UWB modulations

The preamble is composed of a ternary sequence, as shown on Figure 3.9. The sequence duration depends on the *Pulse Repetition Frequency* (PRF).

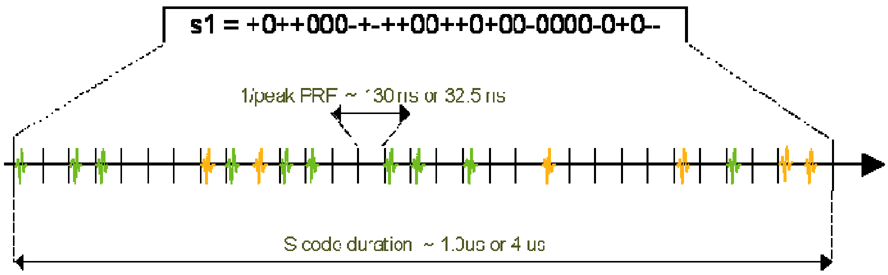


Figure 3.9: Preamble structure

The payload is composed of bursts of pulses, as shown on Figure 3.10. The number of involved pulses also depends on the PRF.

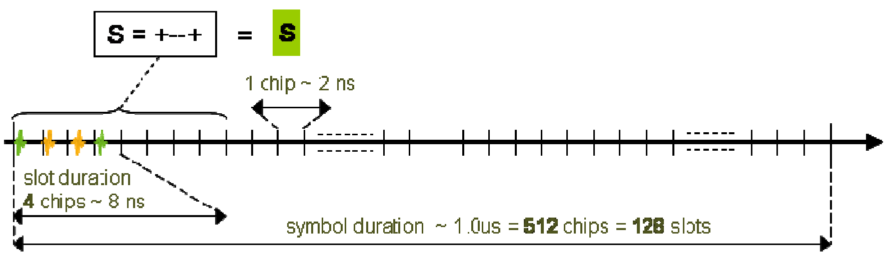


Figure 3.10: Payload structure

There are 2 mandatory mean PRFs:

- A low PRF at ~4.0 MHz enabling :
    - Larger pulse amplitudes for Tx duty cycling;
    - Longer pulse repetition intervals for ISI mitigation;
- A high PRF at ~16.1 MHz enabling :
    - Pulse amplitudes easily compatible with advanced CMOS process;
    - Higher scalability in bit rate;

The peak PRF is:

- 499.2 MHz during data payload ;
- 7.8 MHz and 31.2 MHz resp. during preamble;

The mean PRF is kept constant along the PPDU for a given PRF.

Figure 3.11 shows a simple 2-PSK + 2-PPM modulation applied to the burst of pulses for a low PRF and the nominal bit rate, while Figure 3.12 shows the polarity scrambling added for spectrum smoothing purposes (i.e. an initial sequence S value is changed at each symbol through pulse by pulse polarity scrambling) and *Time Hopping* (TH) added for the mitigation of interference effects from other piconets.

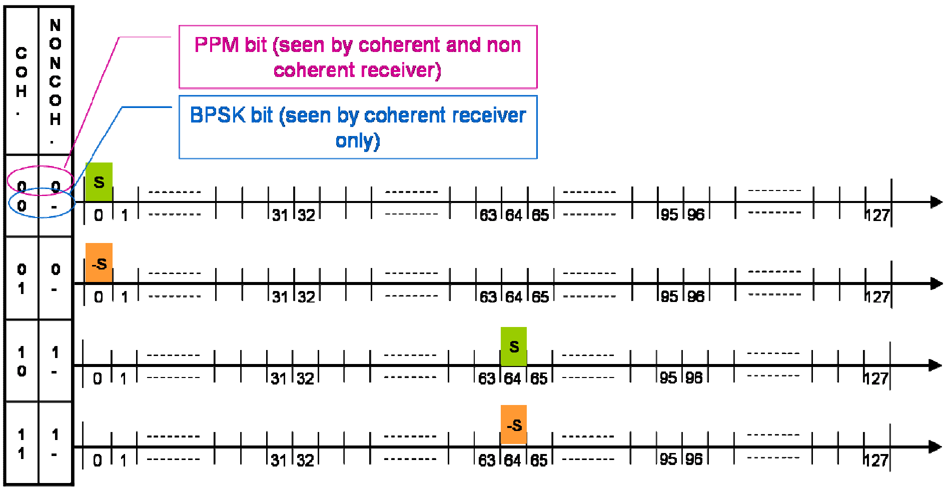


Figure 3.11: Payload modulation for a low PRF and the nominal bit rate.

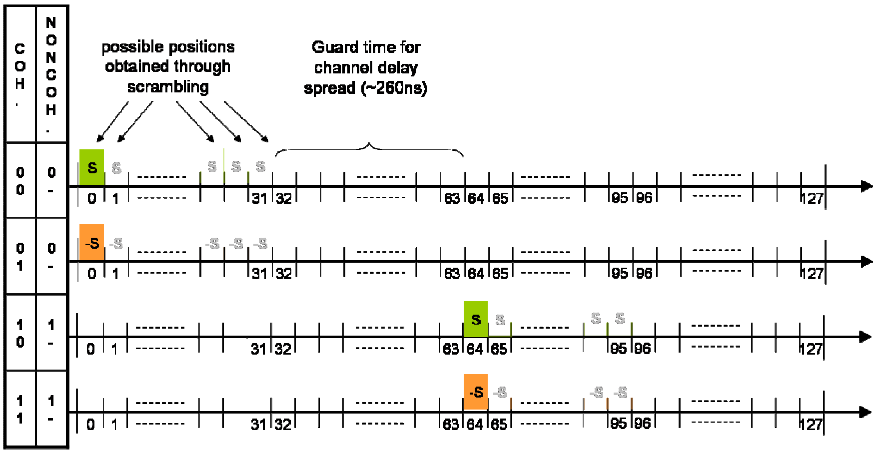


Figure 3.12: Payload modulation and scrambling for a low PRF and the nominal bit rate.

Bit Rates

The bit rate is adjusted with the number of pulses per burst (per symbol), keeping a constant mean PRF (i.e. a constant pulse amplitude), as shown in the following table.

Mean PRF (MHz)	Nb. (*N*) *pulses per symbol*	Symbol duration (ns)	Bit rates		Mean PRF (MHz)	Nb. (*N*) *pulses per symbol*	Symbol duration (ns)	Bit rates	
			Symbol rate (MHz)	Bi rate (Mbps)				Symbol rate (MHz)	Bi rate (Mbps)
15.6	128	8205,13	0,121875	0,11	3.9	32	8205,13	0,121875	0,11
15,6	**16**	**1025,64**	**0,975**	**0,85**	3,9	16	4102,56	0,24375	0,21
15,6	8	512,82	1,95	1,70	3,9	8	2051,28	0,4875	0,43
15,6	4	256,41	3,9	3,40	**3,9**	**4**	**1025,64**	**0,975**	**0,85**
15,6	2	128,21	7,8	6,81	3,9	2	512,82	1,95	1,70
15,6	1	64,10	15,6	13,62	3,9	1	256,41	3,9	3,40
15,6	*1*	*64,10*	*15,6*	*27,24*	*3,9*	*1*	*256,41*	*3,9*	*6,81*

Table 3-8: Variable bit rates

Channel Models

A complete channel model (i.e. with specific path loss, power delay profile, and small-scale fading parameters), was provided for 9 different environments [Molisch04] [Molisch06], namely residential LOS and NLOS (resp. Channel Model 1 -CM1- and CM2), Office LOS and NLOS (resp. CM3 and CM4), Outdoor LOS and NLOS (resp. CM5 and CM6), Industrial LOS and NLOS (resp. CM7 and CM8), Outdoor farm (CM9).

Budget Link and Achievable Ranges

A typical link budget analysis is presented in the table below.

Parameter	Value	Unit
PSD	-41,3	dBm/Mhz
fc (arithmetic center frequency)	4492,8	MHz
Bandwidth @ -10dB	648,96	MHz
Peak Payload bit rate (Rb)	0,850	Mbps
Distance (d)	20	m
Maximum Tx Power (PT)	-13,17782071	dBm
Pulse shaping losses	1,5	dB
Power backoff	0,5	dB
Tx Power (PT)	-15,17782071	dBm
Tx antenna gain (GT)	0	dBi
f'c: (geometric center frequency)	4481,1	MHz
Path Loss @ 1m: L1 = 20log10(4.p.f'c / c)	45,46	dB
Path loss exponent after 1 meter (Alpha)	2,00	-
Path Loss @ d m: L2 = 10*Alpha*log10(d)	26,02	dB
Total Path Loss : L= L1+L2	71,49	dB
Rx Antenna Gain (GR)	0	dBi
Rx Power (PR = PT + GT + GR – L)	-86,66	dBm
Average noise power per bit : N = -174 + 10log10(Rb)	-114,71	dBm
Rx noise figure (NF)	6	dB
Average noise power per bit (PN = N + NF)	-108,71	dBm
Minimum required Eb/N0 (S)	17	dB
Implementation Loss (I)	5	dB
Link Margin (M = PR - PN – S – I)	0,04	dB
Proposed Min. Rx Sensitivity Level	-86,71	dBm

Table 3-9: Typical link budget

The required Eb/N0 is obviously highly dependent on the chosen Rx architecture and channel. The experienced path loss indeed varies significantly depending on the environment, and the theoretical achievable range could be significantly degraded accordingly. For instance, at the nominal Rx sensitivity of -84dBm, the standardized path loss exponents in [Molisch04] [Molisch06] spanning from 1.6 (Office Line Of Sight) to 4.6 (Residential Non Line Of Sight), respectively with reference path losses of 35.4dB and 48.7dB at 1m, would lead to practical transmission ranges from 146m down to 3m, that is to say, with a considerable dispersion.

- *Ranging Support on the MAC and Upper Layers*

Strictly speaking, the Mac layer is not standardized but a few insights and recommendations are at least delivered, especially regarding the peer-to-peer ranging add-on.

Basically, at least peer-to-peer *Two-Way Ranging* (TWR) procedures are supported, as shown on the following figure.

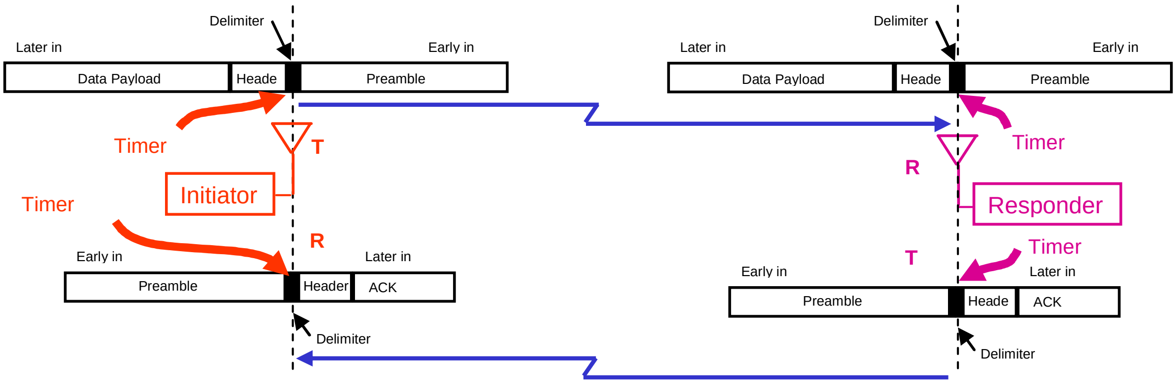


Figure 3.13: Two-Way Ranging (TWR) scheme for Round-Trip Time Of Flight estimation

When the Ranging service is supported, the *DEVice* (DEV) should implement:

- *Figure Of Merit* (FOM) report (i.e. information about the range measurement precision and reliability);
- Optionally crystal characterisation ;
- *Optionally Dynamic Preamble Selection* (DPS), from 16 symbols up to 4096 symbols (1024 by default);
- Optional private/secure ranging mechanisms ;

Practically speaking, the PHY provides the upper layers with a "timestamp report" containing:

- A 4-byte "Start" counter and a 4-byte "Stop" counter: The LSB of ranging counters is 1/128 of a chip time, providing a temporal granularity of ~16ps (i.e. a spatial resolution of 5mm);
- A 4-byte ranging tracking interval: The duration over which the relative clock drift between the Initiator and the Responder is observed;
- A 3-byte ranging tracking offset: Observed temporal clock drift between the Initiator and the Responder;
- A 1-byte Figure of Merit, saying « I am confidence at XXX % that the counter value corresponds to the leading edge of CIR within a time interval of YYY ps »;

Existing primitives are modified accordingly:

- MCPS-DATA.req includes:
    - PRF, Ranging, Preamble length parameters, Data rate;
- MCPS-DATA. confirm and indication include :
    - Ranging timestamp report;

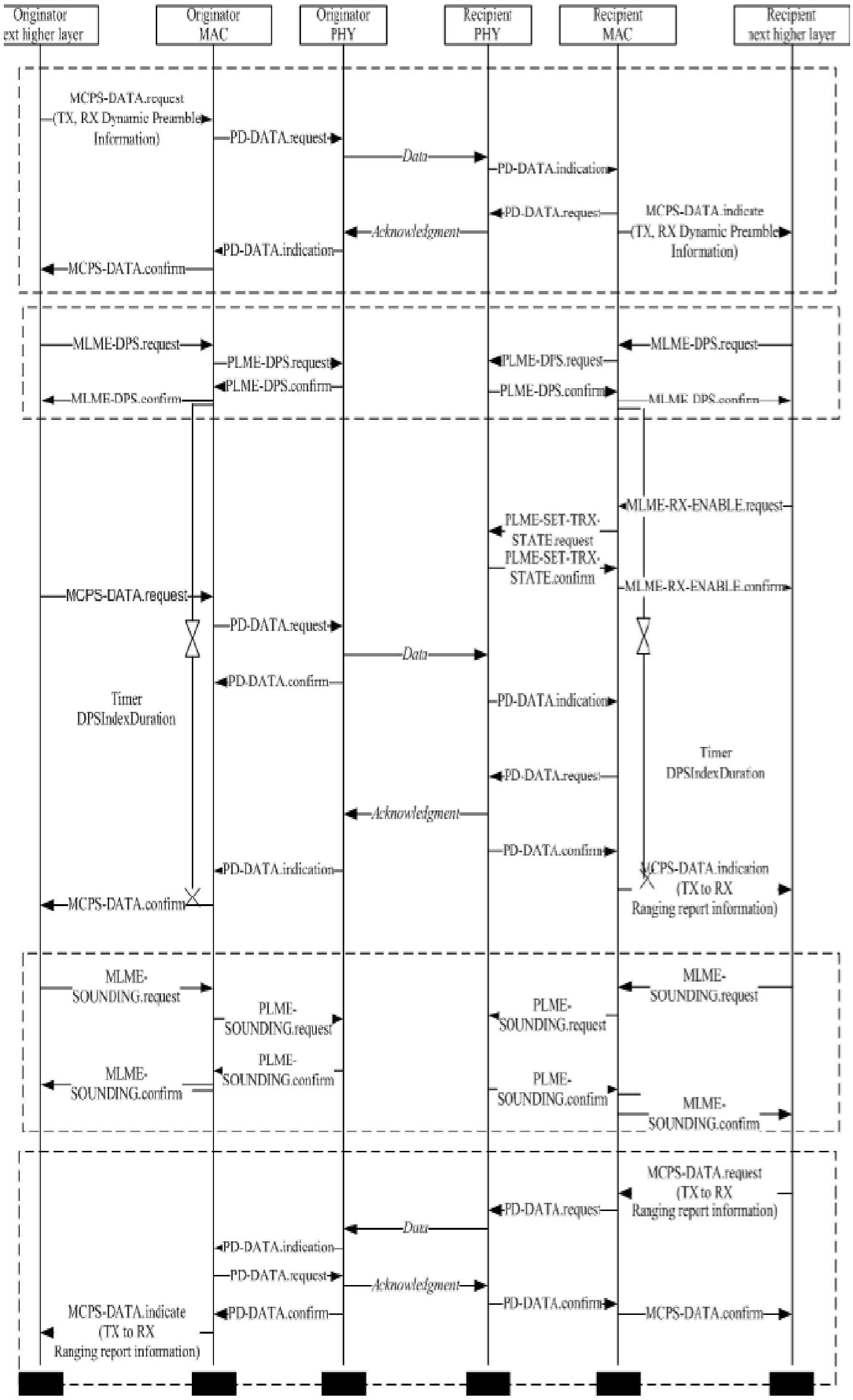


Figure 3.14: Message sequence chart for ranging procedures.

Finally, new primitives are added as shown on the *Message Sequence Chart* (MSC) on Figure 3.14:

- MLME-CALIBRATE: used to get self-calibration of physical layer in terms of internal circuit delays (i.e. between the counter trig and the antenna), and hence to compensate time offsets out of raw ranging measurements afterwards;
- MLME-SOUNDING: possibly used to report a complete channel impulse response estimation in the lack of timestamp report;

3.1.4 IEEE.802.15.4F

- *Generalities*

The IEEE 802.15.4f [IEEE802.15_TG4] Active RFID System Task Group was chartered to define new wireless Physical (PHY) layer(s) and enhancements to the IEEE 802.15.4-2006 standard MAC layer, which are required to support new PHY(s) for Active RFID System bi-directional and location determination applications.

The complete title of this standard [std_IEEE802.15.4f] is: *IEEE Standard for Local and metropolitan area networks – Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs) Amendment 2: Active Radio Frequency Identification (RFID) System Physical Layer (PHY)*.

This amendment defines a PHY layer, and only those MAC modifications required to support it, for Active RFID (readers and tags).

- It allows for efficient communications with active RFID tags and sensor applications in an autonomous manner in a promiscuous network, using **very low energy consumption (low-duty-cycle), and low PHY transmitter power**.
- The PHY parameters are flexible and configurable to provide optimized use in a variety of **active RFID tag operations including simplex and duplex transmission** (reader-to-tags and tag-to-readers), multicast (reader to a select group of tags) uni-cast (reader to a single tag), tag-to-tag communication, and multi-hop capability.
- The PHY specification supports a **large tag population (hundreds of thousands)** which may consist of a number of densely populated (closely situated or packed) tags within a single reader field and **supports basic applications such as read and write with authentication and an accurate location determination capability**. The communication reliability of the system is very high for applications such as active tag inventory counting or auditing.

- The **active RFID device frequency band(s) used are available world-wide, with or without licensing**, and the active RFID PHY is capable of avoiding, or operating in the presence of interference from other devices operating within the Active RFID's frequency band of operation.

The main companies involved in this group are:

- Zebra;
- Time Domain;
- Decawave;
- UbiSense;
- GuardRFID;

Hereafter we focus mostly on PHY aspects.

- *Physical layer*

As shown on the figure below, IEEE 802.15.4f defines three physical layers: *UHF at 433 MHz, 2.4 GHz and Low Rate Pulse repetition frequency (LRP) UWB.*

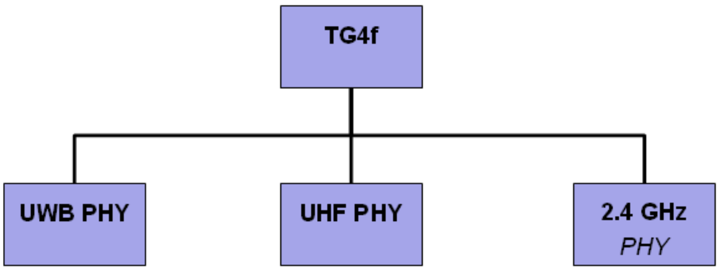


Figure 3.15: IEEE 802.15.4f PHY

UHF – 433 MHz air interface

The UHF interface is in the frequency range 433.05 MHz - 434.79 MHz and 1.74MHz width. A total of 15 frequency channels are considered in this band. Their center frequencies are defined in Table 3-10.

The modulation is based on *Minimum Shift Keying* (MSK). Data Rates are 31.25 kb/s, 100 kb/s and 250 kb/s and symbol rates are 31.25 kbaud, 100kbaud and 250 kbaud. The RSSI is used as location determination mechanism while a *Link Quality Indicator* (LQI) estimates how easily a received signal can be demodulated.

Channel number	Center frequency (MHz)
0	433.164
1	433.272
2	433.380
3	433.488
4	433.596
5	433.704
6	433.812
7	433.920
8	434.028
9	434.136
10	434.244
11	434352
12	434.460
13	434.568
14	434.676

Table 3-10: 433 MHz band channel frequencies.

2.4 GHz air interface

The 2.4 GHz air interface is built on 802.15.4. It could be used standalone for non-precision-RTLS RFID or to provide assistance to UWB PHY.
The default channels considered IEEE 802.15.4f are:

- 2422.5MHz (US + EU)
- 2423.25MHz (US + EU)
- 2442MHz (US + EU)
- 2447.5MHz (US)
- 2462MHz (EU)
- 2477.75MHz (US)

These channels have been chosen in order to do not affect Wi-Fi and Zigbee. The MSK modulation is used with a suggested bit rate of 250kbps. The latter value is considered as a compromise between range, bandwidth and power consumption.

LRP UWB

Three frequency bands are considered for global use, as depicted in Figure **3.16**.

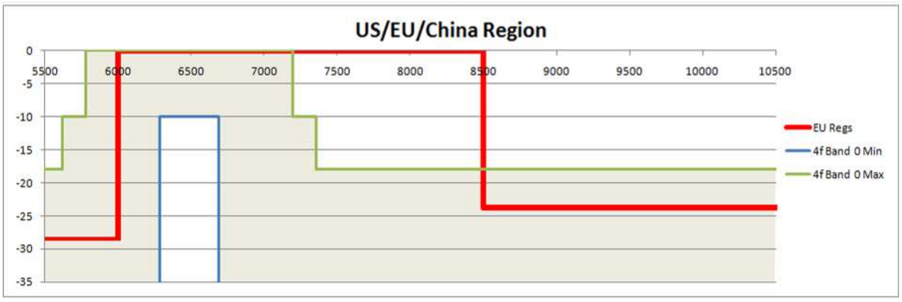
The LRP UWB PHY supports three transmission modes:

- Base Mode: for highest data rate (1 Mb/s)

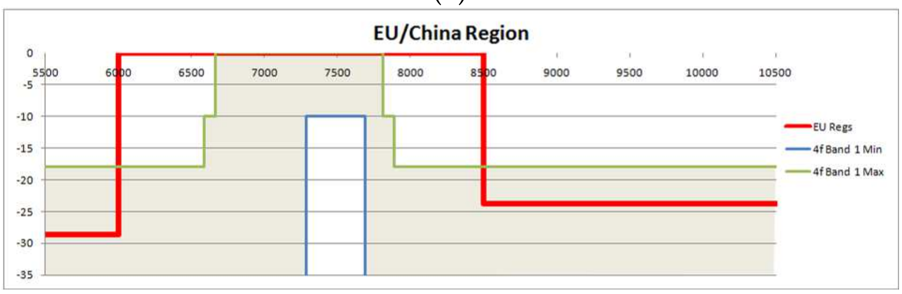
- Extended mode, for moderate date rate (250 kb/s) but improved sensitivity and data detection (using of a convolutional code)
- Long range mode, for the lowest data rate (31.25 kb/s) but the best sensitivity and data detection.

Base mode and extended modes are based on OOK (on-off keying) modulation with 1 MHz Pulse Repetition Frequency and use 1 and 4 chips per symbol respectively. Four chips of binary 1 are inserted after every 128 symbols. This ensures the receiver retains synchronized in the case of a long data sequence of 0 (no signal transmitted).

(a)



(b)



(c)

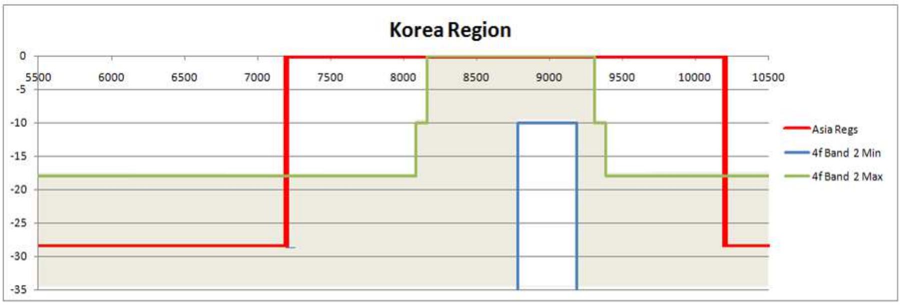


Figure 3.16: UWB band: band 0 (a), band 1 (b), band 2 (c).

Long range mode is based on PPM modulation with 2 MHz Pulse Repetition Frequency. Each symbol encodes one bit using 64 chips with Manchester encoding. A symbol of binary 1 corresponds to the transmission of 32 pulses during the first half of time symbol while no signal is transmitted during the second half. On the contrary, a symbol of binary 0 corresponds to the transmission of pulses during the second half of time symbol. Therefore, this mode provides the best data detection but for the lowest data rate.

The PHY structure is composed by:

- A preamble from 1024 to 8192 pulses, followed by base mode SFD at 1 chip per symbol, followed by 16 to 64 symbols of binary-1 encoded as per data.
- SFD at 64 chips per symbol , encoded as per data
- PHR at 64 chips per symbol, encoded as per data
- Data follows PHR modulated at 64 chips per symbol, Manchester encoded

A *Location Enabling Information* (LEI) Postamble is also defined.

Concerning the synchronization, it is stated that the transmission time of any individual pulse shall not drift more than 11 ns from its nominal transmission time during a 128 symbol period.

3.1.5 CORMORAN'S POSITIONING VS. EXISTING STANDARDS

After browsing through the different radio standards of interest, one can notice a few commonalities, which thus may be viewed as favoured features and core functionalities in WBAN systems. Some of them can be highlighted as regards to the new cooperative communication and localization functionalities foreseen in CORMORAN, such as a beacon-aided & coordinated MAC mode, suitable to finite sets of on-body nodes for intra-WBAN or Slotted TDMA, easing and guaranteeing the scheduling of peer-to-peer ranging transactions and/or positions updates through packet exchanges, etc…

These features are anyway viewed as a starting basis for future investigations carried out in CORMORAN. It is not excluded that the project could come up with innovative proprietary solutions falling out of the scope of those standards.

3.2. REGULATORY ASPECTS

Since regulation differs among countries, it is in principle necessary to monitor and check the regulatory situation worldwide, i.e. in Europe, North America, Japan, China, etc. However, a lot of countries are re-using most or parts of the regulatory decision taken elsewhere, thus knowing the US, European, Japanese and Chinese situations is in most cases enough. We focus here on the European regulation and the worldwide situation.

3.2.1 REGULATION IN EUROPE

The European Commission has issued a standardization mandate for the production by *European Telecommunications Standards Institute* (ETSI) of Harmonized Standards for Ultra Wide Band and a mandate to the *European Conference of Postal and Telecommunications Administrations* (CEPT) for harmonized frequency allocations under the Radio Spectrum Decision.
ETSI produces standards for the whole telecommunications field. Applicable harmonized standards from ETSI can be used to show compliance with European legal requirements in the field of EMC and radio spectrum use.

TC ERM is the Technical Committee responsible for EMC and radio policy matters. Various Task Groups have responsibility for defined areas. The Task Groups produce standards for various devices: some standards are generic, while some are specific to a particular product. The main task group of interest for CORMORAN is TG UWB which deals with specifications for the UWB technology. A typical generic standard is EN 302 065 (see later). A *technical report* (TR) is a working document, e.g. TR 102 495-5. CEPT is an organisation of 47 countries. Telecommunications matters are handled by the ECC – Electronic Communications Committee. There are three Working Groups:

- *Regulatory Affairs* (RA)
- *Frequency Management* (FM)
- *Spectrum Engineering* (SE)

The most important working group for the UWB technology is today the WGFM, and in particular FM PT47 devoted to the UWB technology.

Compatibility studies before new assignments are made and carried out by a WGSE project team.

3.2.2 ECC REGULATION APPLICABLE TO CORMORAN

The ECC (CEPT) regulation useful (reports) and applicable (decisions) for UWB systems in Europe are:

- March 2006: First ECC decision for generic UWB systems : ECC/DEC/(06)04
- December 2006: ECC decision for LDC mitigation technique in the (3.1-4.8 GHz) band : ECC/DEC/(06)12

- March 2006: Amendment to ECC decision for the phased approach in the 4.2-4.8GHz band and for use in vehicles : ECC/DEC/(06)04 amended
- October 2008 : Amendment to ECC decision to include DAA : ECC/DEC/(06)12 amended

In particular, in ECC/DEC/(06)12, it is confirmed that:
The frequency band 6 - 8.5 GHz has been identified in Europe for long-term UWB operation with a maximum mean e.i.r.p. spectral density of –41.3dBm/MHz and a maximum peak e.i.r.p. of 0dBm measured in a 50MHz bandwidth without the requirement for additional mitigation.

However it is stated that:
For devices permitted under this ECC Decision, the technical requirements detailed in Annex 1 of Decision ECC/DEC/(06)04 apply, and, alternatively:

a. *within the band 3.1 – 4.8 GHz, **LDC UWB** devices are permitted to operate with a maximum mean e.i.r.p. spectral density of -41.3dBm/MHz and a maximum peak e.i.r.p. of 0dBm measured in 50MHz; notwithstanding that*

    i. *in case of **LDC UWB** devices installed in road and rail vehicles, no additional mitigation is required as the LDC mitigation technique is recognised to offer a protection level that is at least equivalent to Transmit Power Control (TPC);*

b. *within the bands 3.1 – 4.8 GHz and 8.5 – 9 GHz, **DAA UWB** devices are permitted to operate with a maximum mean e.i.r.p. spectral density of -41.3dBm/MHz and a maximum peak e.i.r.p. of 0dBm measured in 50MHz; notwithstanding that,*

    i. *in case of **DAA UWB** devices installed in road and rail vehicles, operation is subject to the implementation of Transmit Power Control (TPC) with a range of 12dB with respect to the maximum permitted radiated power. If no TPC is implemented, the maximum mean e.i.r.p. spectral density is -53.3dBm/MHz;*

3.2.3 UWB AT ETSI AND CEPT REVISIONS OF THE REGULATION UNDER STUDY

The ETSI standard defines the maximum mean power spectral density (See the table below) and the maximum peal power. The maximum mean power spectral density of the radio device under test, at a particular frequency, is the average power per unit bandwidth (centred on that frequency) radiated in the direction of the maximum level under the specified conditions of measurement.

Frequency (GHz)	Maximum value of mean power spectral density (dBm/MHz)	
	Devices with additional mitigation (e.g. DAA, LDC)	Devices without additional mitigations
f ≤ 1,6	-90	
1,6 < f ≤ 2,7	-85	
2,7 < f ≤ 3,1	-70	
3,1 < f ≤ 3,4	≤ -41,3 (see notes 1, 2 and 3)	-70
3,4 < f ≤ 3,8	≤ -41,3 (see notes 1, 2 and 3)	-80
3,8 < f ≤ 4,8	≤ -41,3 (see notes 1, 2 and 3)	-70
4,8 < f ≤ 6	-70	
6 < f ≤ 8,5	≤ -41,3 (see note 4)	
8,5 < f ≤ 9	≤ -41,3 (see notes 5 and 6)	-65
9 < f ≤ 10,6	-65	
f > 10,6	-85	

NOTE 1: When DAA is implemented, equipment shall implement the whole frequency range from 3,1 GHz to 4,8 GHz. Radio devices shall be capable of selecting an operating channel anywhere within the band 3,1 GHz to 4,8 GHz.
NOTE 2: LDC or DAA is required (see clause 4.1.6 or 4.1.7).
NOTE 3: In case of radio devices installed in road and rail vehicles, operation is subject to the implementation of LDC or combination of TPC and DAA. TPC shall have a range of 12 dB with respect to the maximum value of mean power spectral density. If only DAA is implemented then the following applies:
- 3,1 GHz to 4,8 GHz ≤ -53,3 dBm/MHz.

NOTE 4: In case of radio devices installed in road and rail vehicles, operation is subject to the implementation of LDC or Transmit Power Control (TPC). TPC shall have a range of 12 dB with respect to the maximum value of mean power spectral density. If TPC or LDC is not implemented then the following applies:
- 6 GHz to 8,5 GHz ≤ -53,3 dBm/MHz.

NOTE 5: If DAA is not implemented then the following applies:
- 8,5 GHz to 9 GHz ≤ -65 dBm/MHz.

NOTE 6: In case of radio devices installed in road and rail vehicles, operation is subject to the implementation of either DAA and LDC or DAA and TPC. TPC shall have a range of 12 dB with respect to the maximum value of mean power spectral density. If only DAA is implemented then the following applies: 8,5 GHz to 9 GHz ≤ -53,3 dBm/MHz.

Table 3-11: Maximum value of mean power spectral density specified in the ETSI standard and the current European regulation

According to the ETSI standard, mitigation techniques shall be employed to avoid conflicts with *Broadband Wireless Access* (BWA) systems. Otherwise, UWB radio devices shall implement with *Detect and Avoid* (DAA) algorithms in the presence of Radar signals in the range 3.1GHz to 3.4GHz and 8.5GHz to 9GHz and BWA systems in the range 3.4GHz to 3.8GHz.

An alternative mitigation technique is the employment of *Low Duty Cycle (LDC)*. LDC parameters are listed in the table below, where "Tx on" is the duration of a transmission burst and "Tx off" is the time interval between two consecutive transmission bursts.

LDC parameter	Value
Maximum Tx on	≤ 5 ms
Accumulated minimum Tx off (Σ Tx off)	≥ 950 ms in one (1) second
Maximum accumulated transmission time (Σ Tx on)	18 s in one (1) hour

Table 3-12: LDC parameters in the current European regulation

Other *mitigation techniques* and *mitigation factors* can be taken into account for the calculation of the maximum allowed TX power of an UWB radio device as long as the reached mitigation factors are equivalent or higher than the mitigation factors reached using the presented techniques which have been accepted by the CEPT/ECC and are documented in the CEPT report 120[2] . Examples for additional mitigation factors could be the deployment of the radio device in a restricted indoor area with higher wall attenuation, shielding or the deployment and installation of the UWB system in a controlled manner where the use of BWA terminals is not allowed or coordinated with the deployment of the UWB system. The manufacturer shall provide sufficient information for determining compliance with the transmission emission limits when using equivalent mitigation techniques.

Recently, in May 2011, a new report (Draft ECC report 170) was produced and is now under public consultation, together with the draft ECC decision ECC/DEC/(06)04[3]. This report synthesises nearly 3 years of studies for 3 different applications areas. One of them is LT2 for location and tracking systems:

- a proposal on draft ECC Report 167 on practical implementation of registration/coordination mechanism for LT2 systems was submitted for adoption for publication
- a draft ECC Recommendation on LT2 was submitted for public consultation

3.2.4 WORLDWIDE UWB REGULATION

In the USA, the FCC Part 15 rules permit the operation of classes of radio frequency devices without need for licenses ensuring they do not cause harmful interference to other systems. For indoor communications, a power spectral density of -41.3dBm/MHz is allowed in the frequency band between 3.1 and 10.6GHz. Similarly, outdoor communications are allowed in the same band with a higher constraint on out-of-band emissions.

The UWB regulation, relevant for CORMORAN, is resumed in the table below.

	Band	E.I.R.P	Mitigation factor
Europe	3,1-4,8 GHz	-41.3dBm/MHz	LDC or DAA are applied
	2.7 - 3.4 GHz	-70 dBm/MHz	No mitigation
	3.4 - 3.8 GHz	-80 dBm/MHz	No mitigation
	3.4 - 6 GHz	-70 dBm/MHz	No mitigation
	6-8,5 GHz	-41.3dBm/MHz	No mitigation
	8,5-9 GHz	-41.3dBm/MHz	DAA is applied

[2] All CEPT and ECC reports can be found on http://www.ero.dk/

[3] The chronology of the ECC report, ECC recommendations and draft ECC decisions which are under public consultation at the time of this deliverable writing can be found at http://www.cept.org/ecc/tools-and-services/ecc-public-consultation

Japan	3.4 - 4.8 GHz	-41.3dBm/MHz	DAA is applied
	3.4 - 4.2 GHz	-70 dBm/MHz	No mitigation
	4.2 - 4.8 GHz	-41.3dBm/MHz	No mitigation
	4,8 -7,25 GHz	-70 dBm/MHz	No mitigation
Korea	7.25 - 10.25 GHz	-41.3dBm/MHz	No mitigation
	3.1 - 4.8 GHz	-41.3dBm/MHz	LDC or DAA are applied
	7.2 -10.2 GHz	-41.3dBm/MHz	DAA is applied
U.S.A.	3.1 -10.6 GHz	-41.3dBm/MHz	No mitigation

Table 3-13: Worldwide UWB emission masks

4. SYSTEM REQUIREMENTS

In this section, we translate the needs of the selected application scenarios into a set of preliminary technical requirements regarding data rates, transmissions ranges, network topology, nodes and anchors density, precisions, etc…

4.1. RADIO PERFORMANCES

4.1.1 NOMINAL DATA RATES

In the CORMORAN context, we consider coupling the on-body nodes or body location information with *Wireless Sensor Network* (WSN) applications. Accordingly, sensors may be advantageously co-located with wireless radio devices, such as:

- Inertial or posture sensors (e.g. 3D accelerometers, gyroscopes, magnetometers…)
- Health monitoring sensors (e.g. Electrocardiography, body temperature, embedded blood analysis, blood pressure or respiratory rhythm and depth…)
- Environmental sensors (ex: ambient light or temperature, body exposure to mechanical vibrations, sound waves, electromagnetic or nuclear radiations, dangerous gaz…)

Thus, we do not consider herein applications that require higher data rates, such as multimedia (e.g. on-body transmission of videos from the hip -e.g. a smart phone handset- to a pair of glasses [RUBY12]) but the study is deliberately restricted to the typical *Low Data Rate* (LDR) field, i.e. considering **rates from a few kbps up to a few Mbps**. This is also in line with the capabilities of the intended physical radio layers enabled with localization functionalities (e.g. geo-referenced WSNs, *Real Time Locating System* -RTLS- for logistics...)

4.1.2 EFFECT OF SINGLE-LINK RANGING PRECISION AND TRANSMISSION RANGE

In wireless networks, the localization functionality typically relies on the analysis of radio signals over several single-link transmissions with respect to multiple anchors and/or other mobiles. The measured location-dependent radio metrics, such as the *Received Signal Strength Indicator* (RSSI), the *Round Trip-Time Of Flight* (RT-TOF) or the *Time Difference Of Arrival* (TDOA), then feed a positioning or tracking algorithm to deliver mobile nodes coordinates in a given reference system. The final location precision is then closely related to the level of precision experienced over each single link (i.e. for each marginal measurement).

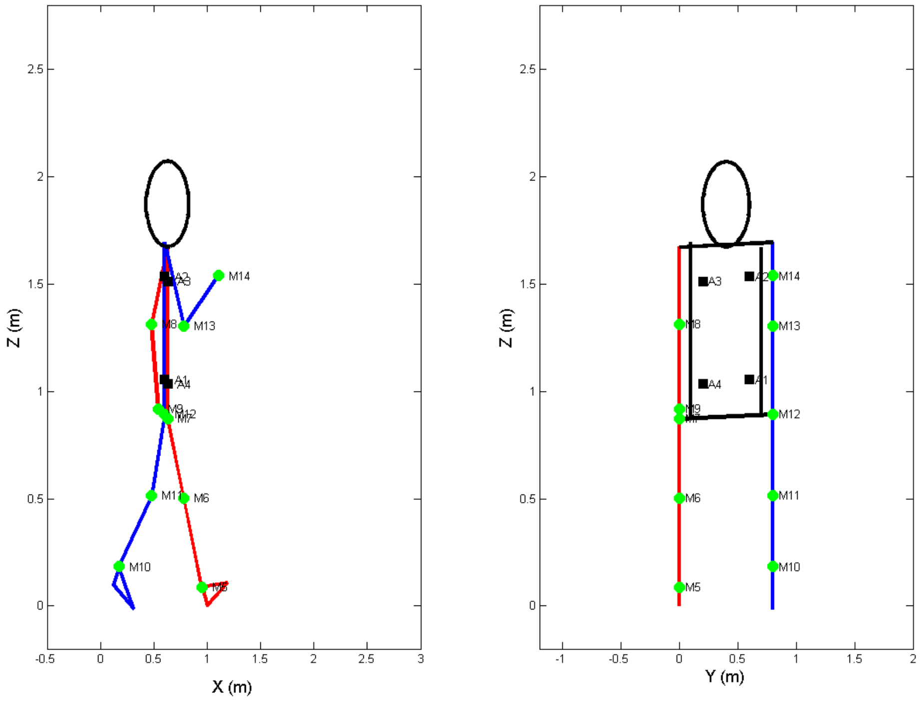


Figure 4.1: Typical deployment scenario for on-body nodes positioning (motion capture), including 4 anchors defining the LCS and 10 mobile nodes to be positioned.

In this subsection, we try to establish a link between the required single-link ranging precision (in terms of standard deviation), the maximum transmission range and the final targeted nodes precision, as specified in the application needs (See Section 2.3). Please note that we are mostly interested here in the new motion capture scenario, that is to say, in ultra-short range links.

For this sake, we apply to the on-body deployment scenario shown on Figure 4.1 the theoretical *Cramer Rao Lower Bound* (CRLB) analysis from [Patwari01], characterizing the best achievable TOA-based positioning *Root Mean Square Error* (RMSE) of unbiased estimators in cooperative mesh contexts, as a function of the pair-wise ranging standard deviation, while making a pseudo-2D approximation onto the torso plane for convenience. Figure 4.2 then illustrate the performance that could be achieved with a maximum transmission range of 2m (i.e. under full intra-WBAN connectivity) and a ranging standard deviation of 15cm. Figure 4.3 shows similar results, but with a transmission range of 1m (and thus, sparser network connectivity) under the same ranging deviation, showing much larger worst-case location errors. These errors mostly concern the nodes that are less connected (i.e. those at the network edges), e.g. on the ankle, despite the fact the chosen transmission range ensures that they have more than three connected neighbours, so that their estimated locations are not ambiguous. Finally, Figure 4.4 shows similar results for the same deployment and transmission range as previously, but with different ranging standard deviations. It appears that under plausible connectivity conditions enabling at least non-ambiguous location estimates (which is the minimum required network configuration here), the **on-body ranging standard deviation per link shall be at least on the order of 15cm to make sure that 90% of the nodes (worst-case error) are positioned with an error better than 25cm** (corresponding to the low precision mode of the LSIMC scenario), otherwise it is recommended to increase network mesh connectivity.

Besides on-body positioning, given the final level of precision expected for the navigation (say around 1m), **off-body and inter-body links** are likely to experience more relaxed **metric precision levels** (e.g through RSSI estimation within NB radios), while benefitting from **larger transmission ranges (e.g. from several 10s up to 100s of meters)**.

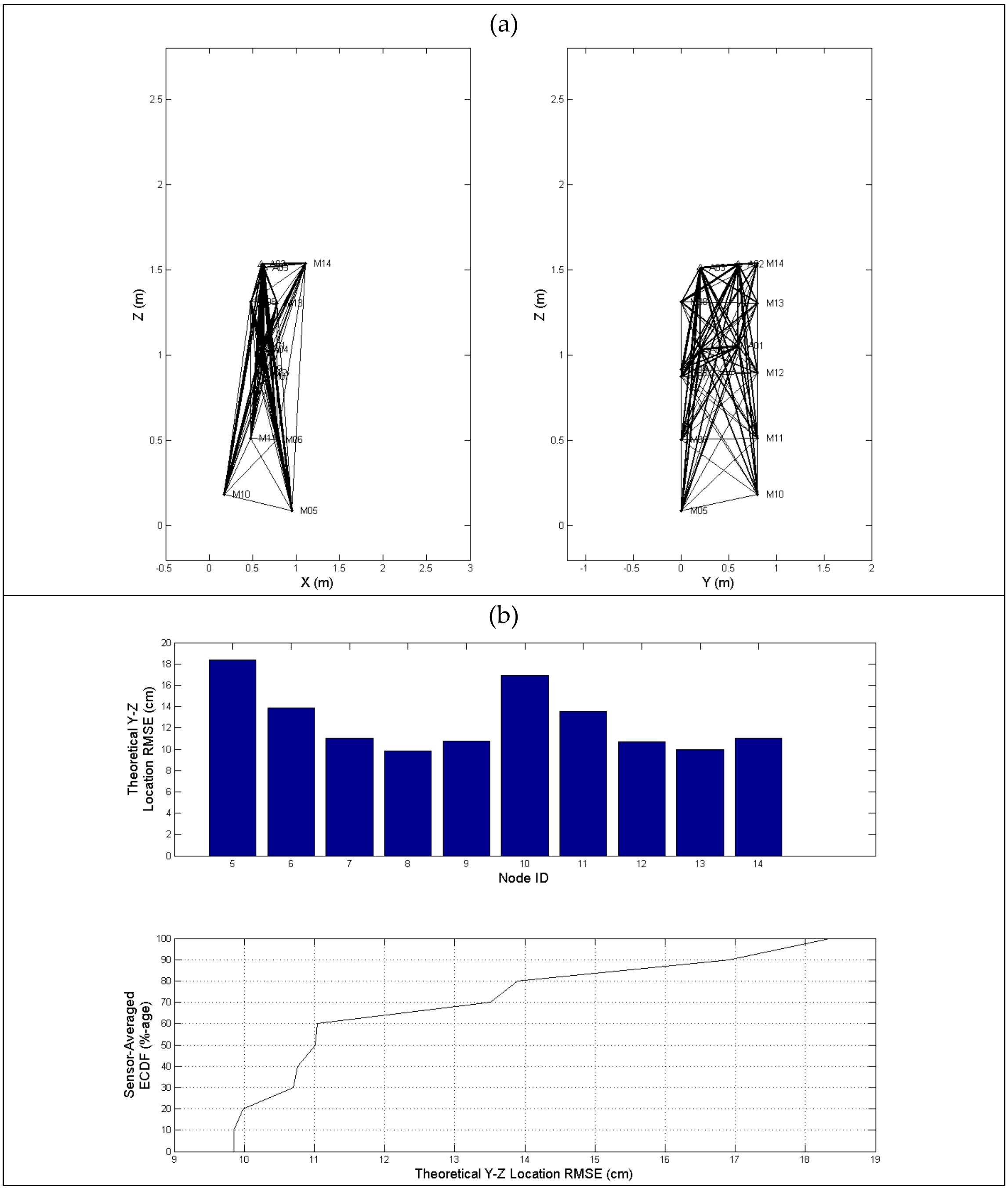


Figure 4.2: Ex. of theoretical on-body nodes positioning performance with a ranging deviation of 15cm, a maximum transmission range of 2 m (i.e. full mesh connectivity with network completeness = 100%), 4 anchors and 10 mobile nodes: Network connectivity (a), Location errors per node in the torso plane and related ECDF (averaged over sensors) (b)

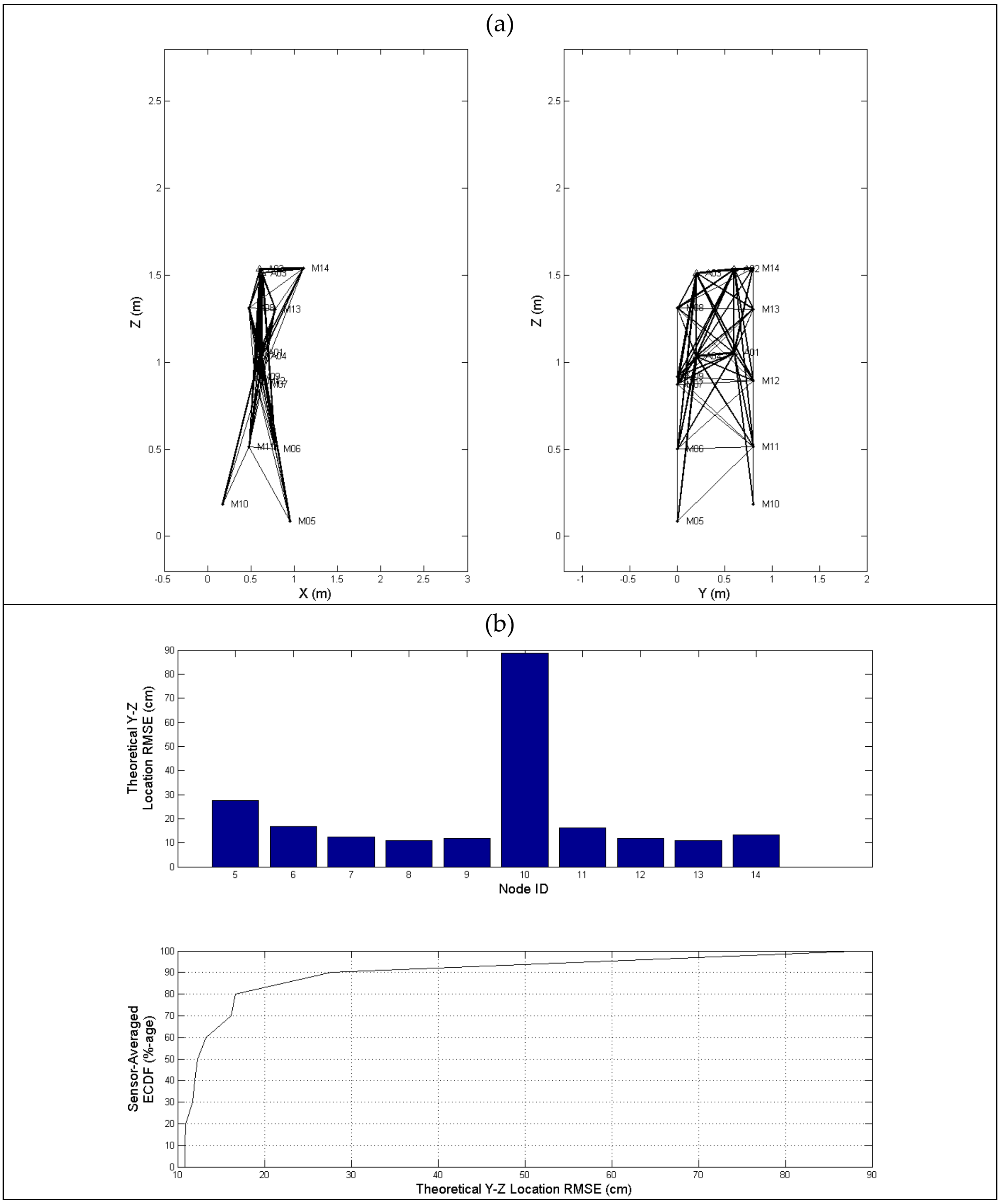


Figure 4.3: Ex. of theoretical on-body nodes positioning performance with a ranging deviation of 15cm, a maximum transmission range of 1m (i.e. partial mesh connectivity with network completeness = 70%), 4 anchors and 10 mobile nodes: Network connectivity (a), Location errors per node in the torso plane and related ECDF (averaged over sensors) (b)

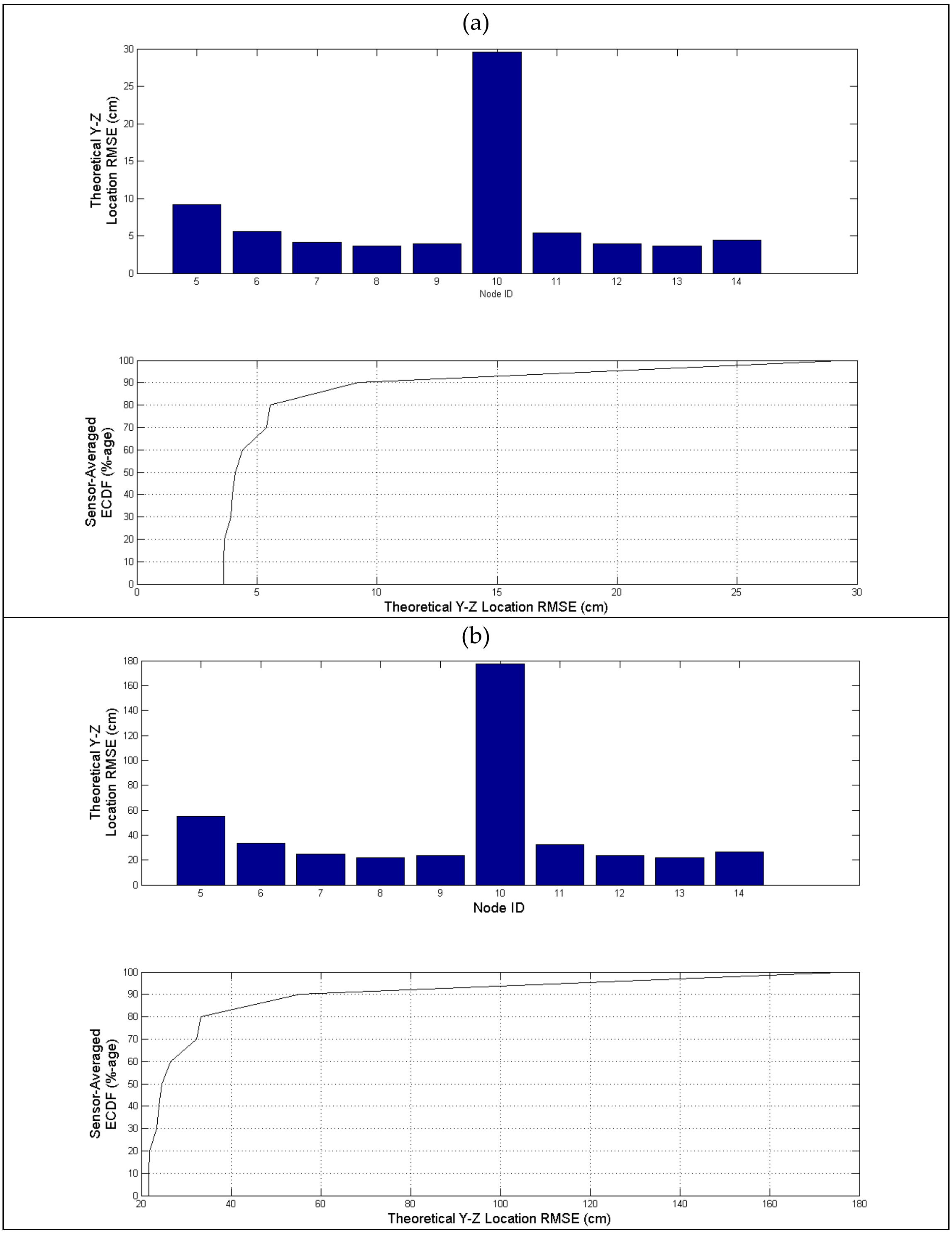


Figure 4.4: Idem as on Figure 4.3 (b), but with ranging deviations of 5cm (a) and 30cm (b).

4.1.3 POWER CONSUMPTION

In CORMORAN, no tangible/quantitative figures can be provided *a priori* in terms of power consumption goal (at least at this stage of the investigations), due to the huge complexity and challenge of assessing the exact consumption through the multiple layers of the communication system, while relying mostly on simulations, models and abstractions. One goal then is to assess and track relative energy gains instead. A rough evaluation may be carried out for some particular blocks of the system (See e.g. packet-oriented event-driven network simulators including battery models and abstractions), by expressing the results in terms of e.g., the average energetic costs to send or receive packets, to sense the channel or to stay in an idle mode.

4.1.4 OCCUPIED BANDWIDTH

- *Bandwidth vs. Single-Link Ranging Precision*

It is well-known that the occupied bandwidth is directly related to the resolution capability in the time domain and thus, to the capability to assess precisely the arrival time of incoming multipath components. Accordingly, it is usual to assume in simplified AWGN channels (i.e. assuming a noisy mono-pulse scenario at the receiver in the UWB case) that the variance of common TOA-based range estimators (e.g. *Maximum Likelihood* -ML- estimators through *Matched Filtering* -MF- and peak detection) is, in first approximation, inversely proportional to the occupied bandwidth [Gezici05], as follows:

$$\sqrt{\mathrm{Var}(\hat{d})} \geq \frac{c}{2\sqrt{2}\pi\sqrt{\mathrm{SNR}}\,\beta}$$

where SNR is the *Signal to Noise Ratio* and β the effective signal bandwidth, as follows

$$\beta \triangleq \left[\int_{-\infty}^{\infty} f^2 |S(f)|^2 df \Big/ \int_{-\infty}^{\infty} |S(f)|^2 df\right]^{1/2}$$

For instance, with an effective signal bandwidth of 1.5 GHz, one could theoretically achieve an accuracy level of less than 3cm at SNR = 0 dB, as shown on Figure 4.5.

Hence, in the lack of further precision regarding the available processing gains (e.g. through the coherent integration of repeated pulses sequences), and **considering the standard SNR levels expected for typical on-body links (i.e. at SNR<0dB), a bandwidth on the order of 1GHz (resp. 500MHz) would be for instance required for ranging precisions on the order of 5cm (resp. 10cm) at -5dB**, in compliance with the requirements in Section 4.1.2. Of course, in more practical cases, one can expect that the accuracy is even more degraded due to the conjunction of multipath effects, body obstructions and receiver hardware capabilities. Note that other temporal radiolocation metrics inheriting from preliminary TOA estimation (i.e. RT-TOF or TDOA) will be influenced similarly by the occupied bandwidth.

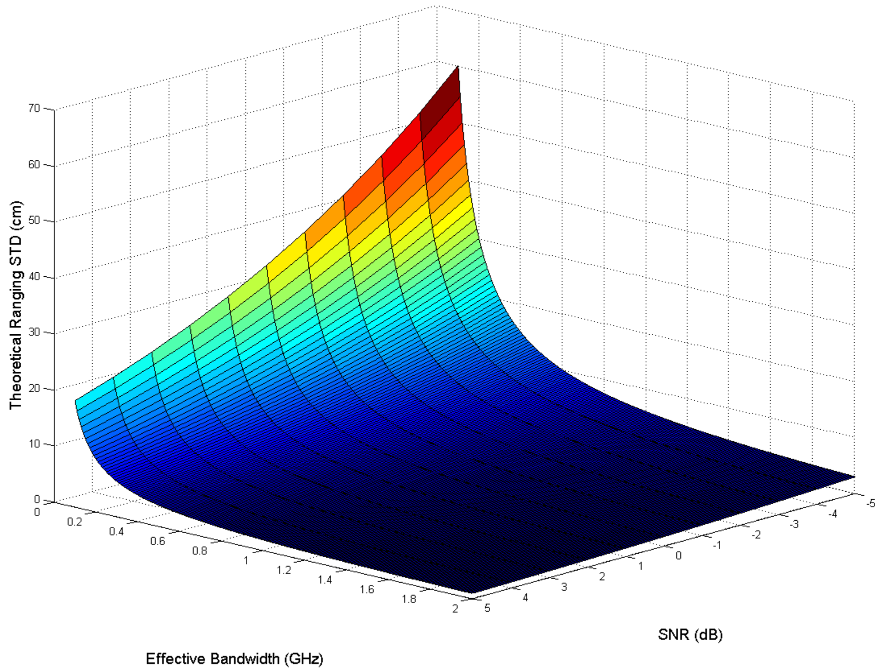


Figure 4.5: Best achievable single-link TOA-based ranging standard deviation, as a function of the effective signal bandwidth and signal to noise ratio, assuming a mono-pulse AWGN scenario.

As for the RSSI metrics in NB systems, the theoretical precision is usually as follows [Gezici05]:

$$\sqrt{\mathrm{Var}(\hat{d})} \geq \frac{\ln 10}{10}\frac{\sigma_{sh}}{n_p}d,$$

where d is the distance separating the nodes, n_p is the path loss exponent, and σ_{sh} is the standard deviation of the zero mean Gaussian random variable accounting for log-normal shadowing.

First of all, the occupied bandwidth will obviously play a role with respect to small-scale fading. However, it is common to assume within RSSI-based localization that those effects are somehow averaged (e.g. based on consecutive RSSI measurements within the channel coherence time over one link).

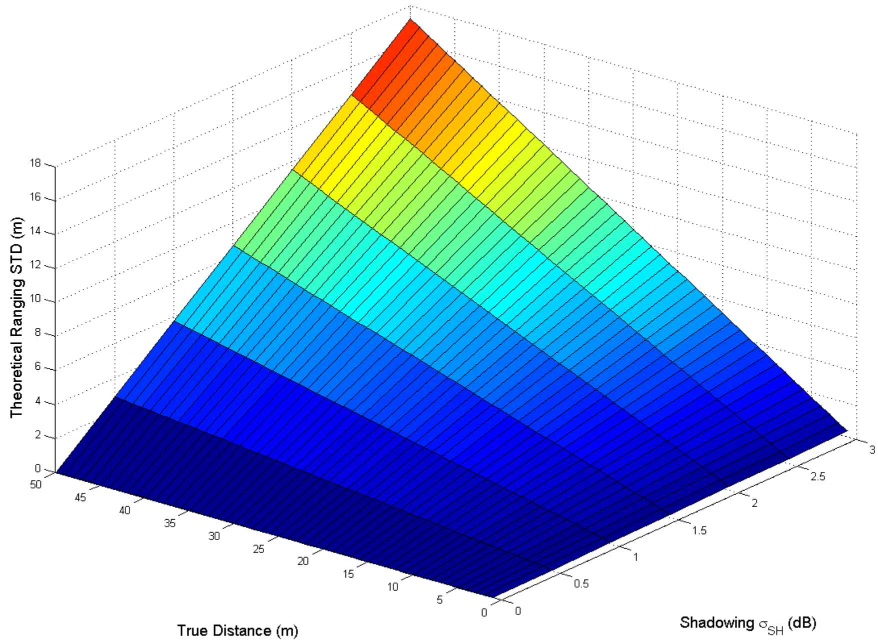


Figure 4.6: Best achievable single-link RSSI-based ranging standard deviation, as a function of the actual distance and shadowing parameter (assuming a path loss exponent equal to 2).

Furthermore, in the classical modelling presented above, the best achievable ranging performance would theoretically depend on both the channel power parameters (i.e. path loss exponent and shadowing deviation) and the distance between the two nodes. But it is adversely well known in the on-body WBAN context that: (i) the received power is less dependent on the actual distance than in any other wireless context, (ii) body shadowing is rather strong (in comparison with the nominal average received power levels), far dominating (in comparison with other effects due to e.g. small-scale fading or distance) and hardly predictable with no *a priori* information (e.g. highly variable as a function of the actual nodes places on the body). Overall, the achievable level of ranging precision is not only hard to predict or specify *a priori* over on-body links, but it is likely insufficient in comparison with the actual nominal Euclidean distances to be measured (say, on the order of one meter). This makes the use of RSSI metrics particularly problematic for on-body localization purposes uniquely based on peer-to-peer ranging (i.e. for motion capture purposes). However, note that RSSI shall still be useful in this on-body context, as an indirect source of information, e.g. to remove geometrical ambiguities (e.g. connectivity, coarse range measurement or bounds), but mostly meaningful for larger-range links in both off-body and body-to-body indoor localization.

In the latter contexts, the achievable precision may indeed be more compliant with navigation requirements (at least under reasonable shadowing) , as seen on the figure below, e.g. with a ranging standard deviation better than 5m at the transmission range of 20m, with both the path loss exponent equal and the shadowing dispersion equal to 2.

Finally, following a more practical approach, in [Neirynck12] the authors account for joint UWB and NB experimentations, which were conducted in a realistic indoor environment (i.e. including typically radio obstructions and dense multipath). The target application concerns senior health monitoring based on medical body sensor networks. On this occasion, the ranging performances of both the IEEE 802.15.4 and the IEEE 802.15.4a standards are benchmarked, based respectively on RT-TOF measurements (with an integrated UWB prototype) and RSSI measurements (with a commercially available standard-compliant component at 2.4GHz). From a CORMORAN perspective, these experimentations help to characterize off-body and body-body ranging in a practical operating indoor environment. The main obtained results, as reported below on Figure 4.7, practically illustrate the order of magnitude between the two levels of precision, an in particular the relatively poor RSSI-based ranging performances.

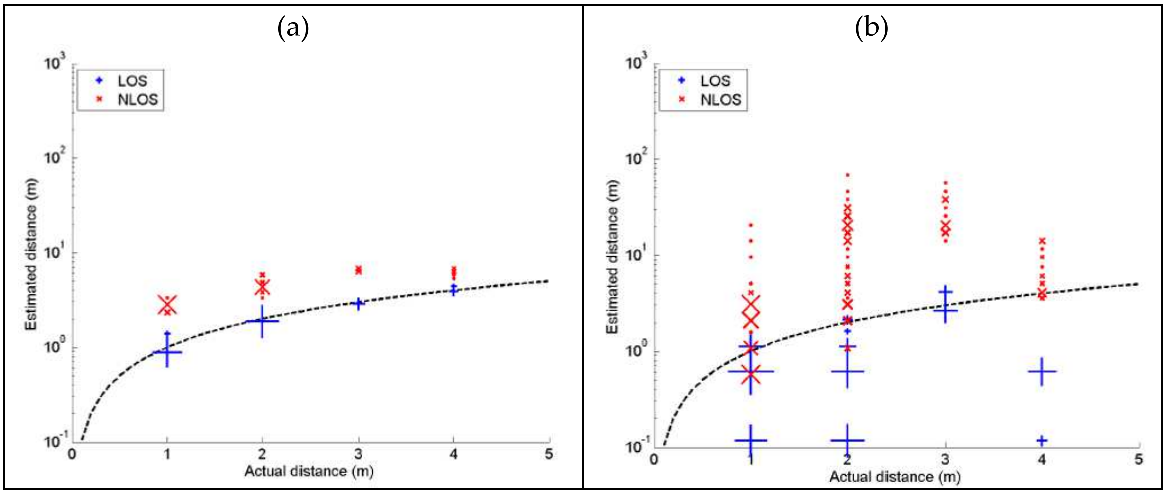


Figure 4.7: Experimental comparison between IEEE 802.15.4a IR-UWB TOF-based ranging (a) and IEEE 802.15.4 Zigbee RSSI-based ranging (b) in a realistic indoor environment for senior health monitoring based on medical body sensor networks [Neirynck12].

- *Bandwidth vs. Regulatory Aspects*

As seen previously, the worldwide UWB regulations present disparities in terms of occupied band, emission level and mitigation techniques. The most favourable one, from the CORMORAN point of view, is the one present at U.S. Indeed the FCC regulates the UWB emission on a very large band with no mitigation techniques. In Europe two bands are generally considered: the so-called "UWB lower band" from 3.1 to 4.8 GHz and the "upper" one from 6 to 8.5 GHz. On the one hand the lower band is advantageous from the propagation point of view and RF circuit design cost, with the respect to the upper band. On the other hand the mitigation techniques required, demand for a higher complexity of the TX module to implement DAA. If LDC is employed as a mitigation technique the limitation is mainly on the length code, bit rate and refresh rate, with in fine an impact on the available localization refreshment rate (See Section 4.3.3).

4.2. NETWORK TOPOLOGY

4.2.1 SINGLE WBAN TOPOLOGY

Considering the applications in the CORMORAN context, the number of nodes placed on a single body can reasonably range from 1 to 3 or 5 and shall not exceed 10. The probable locations of these communicating nodes are on the torso, wrists and ankles. Articulations such as the knee or elbow are generally bad locations.

A local WBAN shall be organized as a star to comply with most standards expectations. Depending on the localization of the main node (hub in the IEEE 802.15.6 terminology), the network may span across 1 or 2 communication hops, as illustrated by the two scenarios on Figure 4.8. Note that the main node has a greater chance to be located at a wrist (watch), on the torso, or on the hip (mobile phone in the pocket e.g.).

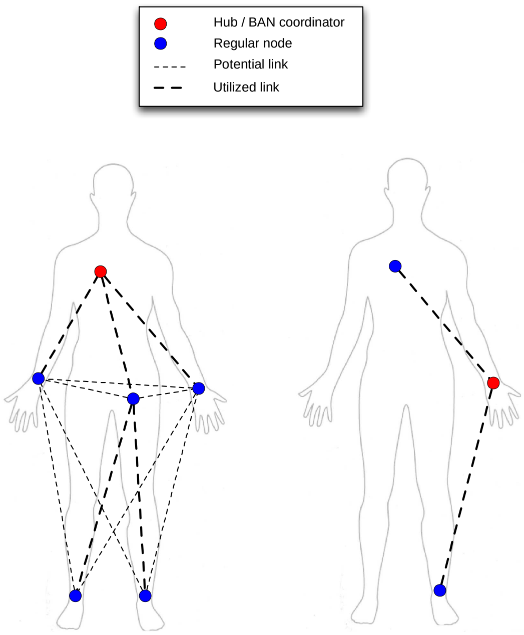


Figure 4.8: Two plausible single-WBAN network topologies

Independently of the topology created by the layer-2 technology or by the routing protocol, additional existing links may be utilized to enhance certain services such as localization. Additional information provided by the links unused for communication may provide valuable information to estimate physical parameters that, in turn, could enhance the accuracy of the ranging technique. For instance, information on multiple links can be combined to estimate the signal attenuation factor that is used to relate RSSI and distance.

4.2.2 MULTI-WBAN TOPOLOGY

The topology of the network composed of the multiple WBANs in a geographic area can be considered as an ad-hoc network composed of star networks, as represented on Figure 4.9. Considering the characteristics such as the range or the throughput of WBAN technologies, the link between the WBANs are expected to use another technology such as IEEE 802.11 ad-hoc mode, IEEE 802.15.4 or Bluetooth (represented by green dotted lines on Figure 4.9). This means that the hubs have to play the role of gateways too to the mobile WLAN and that they are most probably the only nodes that can perform the task of gateway.

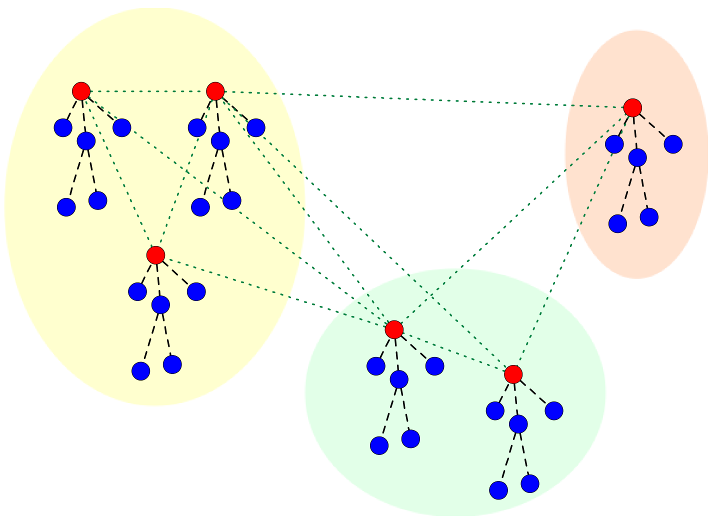


Figure 4.9: Multi-WBAN topology formed of groups of users; users are interconnected by a different technology.

Regarding this WLAN topology, the network behavior is typically pedestrian, unless in very specific scenarios. Realistic mobility models (See e.g. Section **Erreur ! Source du renvoi introuvable.**) may rely on moderate size groups of people (distinguished by colored zones on Figure 4.9) moving together, while the barycenters of these groups move between attraction points located on a map with certain probabilities. The global network topology therefore evolves constantly while maintaining stable links between individuals belonging to the same group. Depending on the network density, some groups may be disconnected or the network may become partitioned from time to time. In these situations, routing strategies adapted to *Delay Tolerant Networks* (DTN) and transport protocols may help to preserve the global service. The suited strategy depends on the profile of disconnections (connection and disconnection time distributions).

Additionally, such models rely on several parameters such as the average density of the network, the group size distribution, the movement speed, the number of attraction points, etc. If these parameters admit some reasonable values (e.g. walking speed can safely be considered to be distributed between 3 $km.h^{-1}$ and 7 $km.h^{-1}$ with a Gaussian distribution), they depend on the scenario and the results of the survey shall help to adapt them to realistic scenario-dependent values.

4.2.3 WBAN INTERCONNEXION

The WBAN can be connected to a global infrastructure (the Internet or a WLAN) either by the means of WLAN access points (e.g. Wi-Fi), or by a cellular network through a mobile phone using UMTS or LTE. In both cases, such an interconnection requires a multi-technologies gateway node that belongs to the WBAN. Considering the classical IEEE 802.15.6 topology and limitations (data rate, maximum frame size, etc.), connecting to a wider network through a fixed node using the WBAN technology is unrealistic.

If Wi-Fi access points and cellular contracts are relatively frequent, not every individual WBAN will have its own gateway. Providing global connectivity therefore requires first that routing happens inside the multi-WBAN network in a multi-hop or DTN-like fashion, and second, that the owner of the global network access gives permission to use its link for the traffic coming from other WBANs, which depends on the contract he owns with his operator.

Figure 4.10 represents such a scenario in which a Wi-Fi access point is able to provide access to the orange and green WBANs, provided that routing happens inside the green WBAN. In the yellow group, a user possesses a cellular phone and decided to open his connection to the members of this group, but not to other groups. Routing should take into account these policies and user preferences.

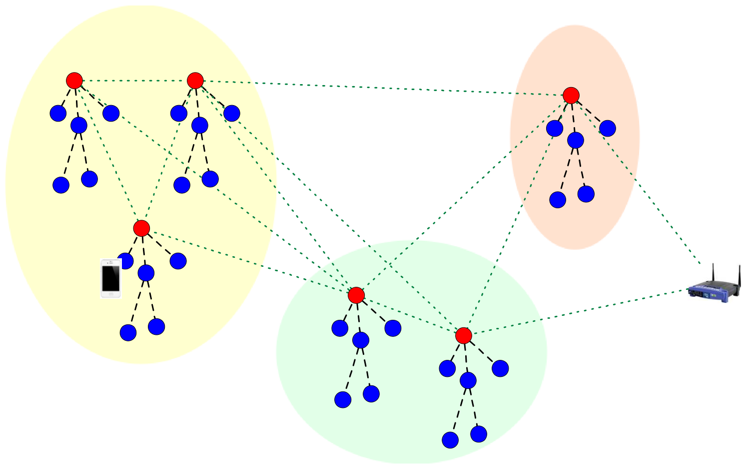


Figure 4.10: Multi-BAN topology with WAN interconnection.

4.2.4 NETWORK COORDINATION

The network should behave as autonomously as possible, which is possible, given the results from the ad hoc, vehicular and delay tolerant networks. There is however the need for an entity, possibly implemented in a distributed manner, that selects the best set of protocols for a given communication.

If the presence of a single management entity is not required for the network to function, control and command centers could be present in some scenarios in which all nodes belong to the same owner who may wish to have a global vision of the WBANs mobility, or to disseminate policies.

4.3. LOCALIZATION APPLICATION

4.3.1 CENTRALIZED VS. DECENTRALIZED COMPUTATIONS

According to classical definitions and classifications, in centralized algorithms, all the available measurements (e.g. peer-to-peer range measurements in our case) are collected into a central point, in charge of computing all the blind locations synchronously. On the contrary, in a decentralized approach, blind nodes locally compute their own locations, based on pieces of information collected in their immediate neighborhood. Intermediate embodiments may also exist (i.e. partially decentralized or locally centralized), if several (blind) nodes locally compute the locations of their neighboring nodes.

In our WBAN context, on-body leave nodes are not expected to have enough computation or storage power to be directly utilized for complex computations. They may at most be involved in some collaborative algorithms, for instance in the estimation of channel parameters or location dependent radio metrics for the purpose of localization, and packet exchanges to locally update their own locations (in decentralized approaches). They may have to log and store a few historical values (RSSI, etc.) and to run very simple algorithms (averaging, standard deviation computation, basic "atomic" operations, etc.). Note that decentralized computations usually come with asynchronous updates.

On the contrary, the hub/gateway node is expected to have more storage and computation capacities and can therefore run more complex algorithms. For instance, it may perform data compression, aggregation, store security certificates and cipher the data with more robust algorithms, and participate in the global network operation (routing, clustering, localization, etc.). This device can also be equipped with human interface devices, receiving input and displaying information to the user.

Centralized computation resources located at fixed positions in the network -or in the Internet- may have a near-to-unlimited computation and storage capacity. Thus they look rather appealing to run algorithms that require a global vision of the multi-WBAN network (mobility pattern estimation, logging, etc.). However, accessing such servers requires to route packets to them and the volume of data they shall receive may be drastically limited by the network capacity and/or by the application tolerance to the inherent latency.

In CORMORAN, **both centralized and decentralized positioning approaches will be evaluated and benchmarked**, in terms of localization accuracy, latency, complexity and required communication volume. It is up to these investigations to determine which scheme is preferable to comply with the application needs specified in Section 2.3.

4.3.2 USER- VS. SYSTEM-CENTRIC RESULTS COLLECTION & DISPLAY

One should make a distinction between the place where the calculations take place and the place where the final location information should be issued. For instance, a decentralized positioning algorithm, which rely on local and asynchronous on-body positions' updates to benefit from low latency (i.e. between the moment when a range measurement is collected and the moment when the related node position can be calculated), may also be coupled with a centralized analysis or display of the time-stamped location results. In this example the real-time decentralized nodes location updates does not contradict the slight delay in making all the estimated nodes locations available in a central point (e.g. Gateway, external server).

Indeed, most realistic applications would necessitate making this kind information available in a centralized way at least at the user, or possibly at an external server. These two options impose distinct relaying requirements and hence, in turn, distinct constraints in terms of latency and traffic. **Both centralized display solutions (i.e. user and server) will also be assessed in the project**, regardless of the underlying application scenario, as seen in Section 2.1.2.

4.3.3 REFRESHMENT RATE AND LATENCY

- *Impact of the Triggering Policy*

One more point concerns the refreshment rate to make the location information available. This will have an impact on the way information shall be routed and relayed through the networks. One shall then distinguish on-demand, periodic/regular, or event-driven update schemes. The first option is user-centric, whereas the two others are likely triggered or organized by the system it-self. It is also up to CORMORAN to **assess these different refreshment modes** (e.g. defining solutions to detect the most demanding nodes and make their update in priority).

The network capability to tolerate mobility under given refreshment rates is obviously dependent on the targeted scenario. By default, as seen previously, the reference figures for nodes/body location refreshment rates, namely 10ms and 100ms for the high and low precision individual motion capture application and 1s for the group navigation application. However, provided that the figures for motion capture are very aggressive and hence may be too challenging for a typical communication system (e.g. within a beacon-aided TDMA MAC with guaranteed time slots for peer-to-peer ranging), they may be intended for all the nodes, but only the nodes requiring to be updated to fall down (the nodes already respecting the precision shall not be necessarily updated).

- *Cross-Layer Protocol Latency*

At this point, It is also clear that the chosen cross-layer protocol (especially the MAC and network layers) critical features with respect to wider-sense location performances (e.g. including latency), impacting:

- The time elapsed to perform and issue radiolocation measurements (e.g. RT-TOF or RSSI);
- The time elapsed to exchange packets including positional information within decentralized positioning schemes (i.e. positioning convergence time);
- The time elapsed to relay all the pair-wise measurements to a sink within the centralized positioning scheme;

- The time elapsed to relay estimated locations to a sink within the decentralized positioning scheme.

- *Imposed Duty Cycle and Transmitting Activity*

As seen before, according to the ECC regulation, UWB radios are subject to stringent *Low Duty Cycle* (LDC) requirements that are likely to impact the refreshment rate available for the localization application. Those constraints are specified as follows:

- Ton max = 5 ms
- Toff mean ≥ 38 ms (averaged over 1 sec)
- Σ Toff > 950 ms per second
- Σ Ton < 5% per second and 0.5% per hour

Ton is defined as the duration of a burst irrespective of the number of pulses contained. Toff is defined as the time interval between two consecutive bursts when the UWB emission is kept idle.

From these definitions, two different interpretations subsist: a burst can be a packet or frame or a burst can be simply a pulse, which is more constraining. Let's take for instance a Pulse Repetition Period of 128 ns, pulse duration of 1 ns, 16 symbols per packet and a very long code of 8x1024. Considering the first definition of Ton we obtain that:

- T_{on} max = 5 ms drives to 4 symbols per packet
- Σ Ton < 5% per second drives to a peak refresh rate of 3Hz
- Σ Ton < 0.5% per hour drives to a mean refresh rate of 0,3Hz

Obviously these results strongly depend on the code choice. It will be important during the project to remind the LDC constraints, and define, when possible, a code and frame structure which could be compliant with LDC implementation while respecting the refresh rate required by the application.

4.4. DEPLOYMENT CONFIGURATIONS

In this section, we intend to translate the application scenarios identified in Section 2.2 into more technical scenarios, including considerations about the deployment configuration and the kind of involved radio links.
The most generic and most complete deployment scenario considered in the frame of CORMORAN involves ultra-short-range *on-body* links (i.e. intra-WBAN cooperation), medium-range *body-to-body* (i.e. inter-WBAN cooperation) and *off-body* large-range links (i.e. with respect to fixed elements of the infrastructure), represented respectively in blue, lavender and orange on Figure 4.11. Note that it is one goal in CORMORAN to

assess the optimal number of involved nodes and links, as well as the resulting trade-off between performances and complexity.

Trivially, over each physical link, the measurement of location-dependent radio metrics for localization purposes (e.g. TOF, RSSI, TDOA, etc.), as represented by plain arrows on Figure 4.11, necessitates underlying communication capabilities (i.e. wireless transmissions of data packets). Nevertheless, note that some of the involved links may be exploited just for communication purposes, without performing any measurement but possibly, so as to transit information related to the localization functionality, such as estimated positions (or estimated accuracies) in a decentralized embodiment. Such communication-oriented links will be represented in the following by dashed arrows (See e.g. Figure 4.12).

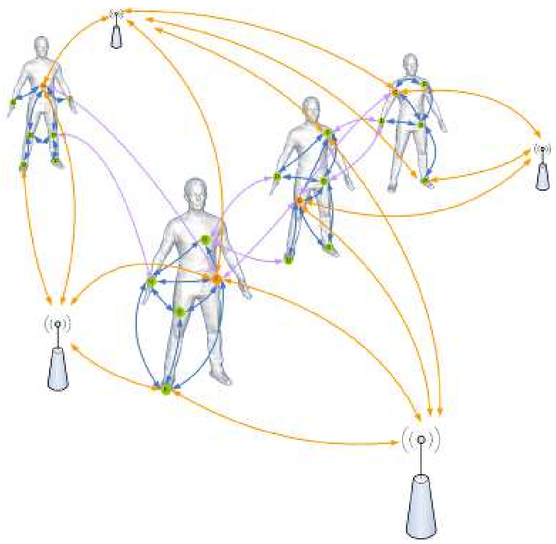


Figure 4.11: Generic deployment scenario for CORMORAN, with ultra short-range intra-WBAN links (blue), medium-range inter-WBAN links (lavender, and large-range off-body links (orange).

For instance, assuming a heterogeneous network embodiment, the intra-WBAN communication and localization functions could be ensured either through IR-UWB (e.g. extended IEEE 802.15.6) or NB communications at 2.4GHz (e.g. BT-LE) (respectively with RT-TOF estimation or on RSSI measurements for the latter function). As for inter-WBAN (body-to-body) and off-body links, one could rely on IR-UWB (e.g. extended IEEE 802.15.4a) or NB communications at 2.4GHz (e.g. Zigbee).

The two sub-scenarios of interest in Section 2.2, which address *Coordinated Group Navigation* (CGN) and *Large-Scale Individual Motion Capture* (LSIMC) applications, directly inherit from the previous generic deployment configuration.

In particular, CGN shall still imply some intra-WBAN cooperation but on-body communication links are exploited mostly to exchange informative data between the sensors disseminated on a body, regarding e.g. the obstruction status of off-body links with respect to fixed elements of infrastructure or body-to-body links with respect to mobile neighbours, or even ultimately, regarding the estimated positions of the other pedestrians that belong to the group. This configuration may be benchmarked with State of the Art configurations enabling single-node cooperative navigation and single-node non-cooperative navigation, as depicted on Figure 4.14.

LSIMC implies that no group is considered as a first step, hence limiting the use of cooperation to intra-WBAN, but still with the possibility, like in CGN, to take benefit from measurements redundancy and diversity over off-body links.

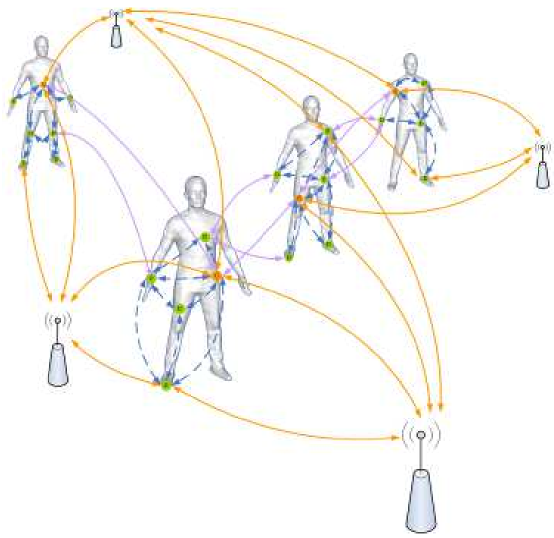


Figure 4.12: Simplified deployment scenario for Coordinated Group Navigation (CGN), with no location-dependent radio measurements (but possibly only data transmissions) over cooperative intra-WBAN links (dashed arrows).

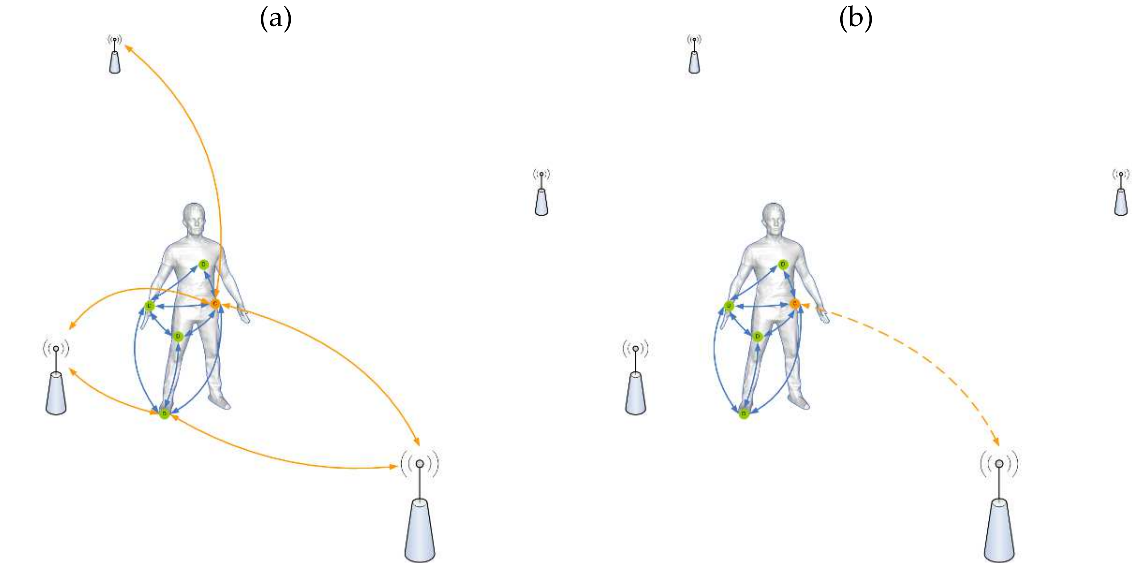


Figure 4.13: Simplified deployment scenario for Large Scale Individual Motion Capture (LSIMC) with absolute nodes positioning (a) and relative nodes positioning or ranging (b), with possible information relay to a centralized external resource (e.g. server).

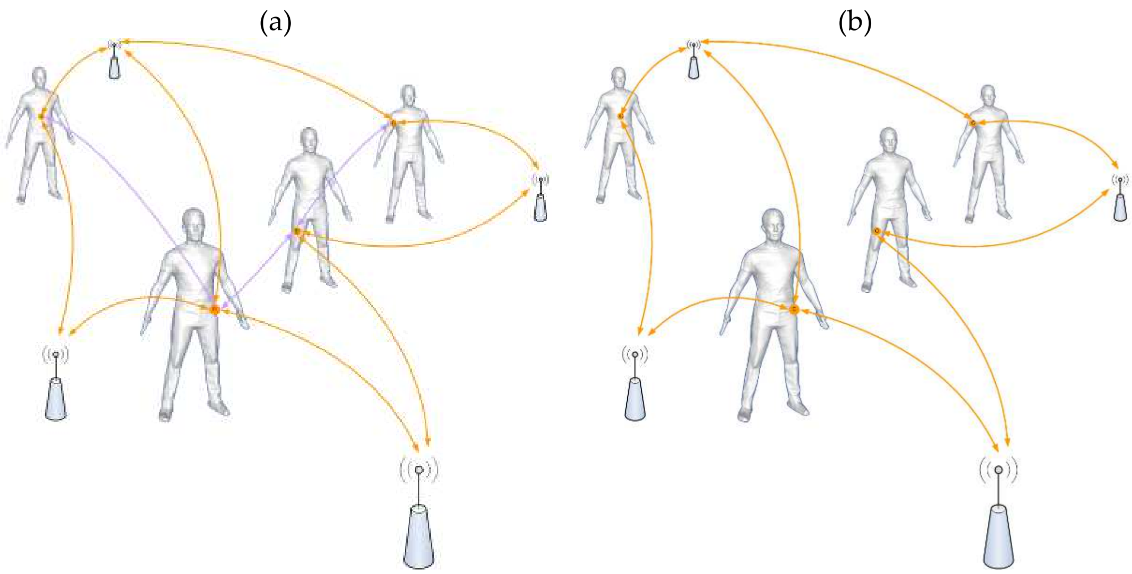


Figure 4.14: State of the Art deployment scenarios enabling single-node cooperative navigation (a) and single-node non-cooperative navigation (b) (to be benchmarked with CGN).

5. PERFORMANCE INDICATORS

Besides classical communication-oriented indicators, traditionally used to assess the QOS of wireless communication systems (e.g. overhead, outage probability, end-to-end-packet delivery ratio and delay), in CORMORAN, we are interested in specific location-oriented indicators, which are more closely related to the targeted navigation and motion capture applications. Hereafter, we propose a set of adequate indicators that define a common evaluation and benchmark framework for the partners. This generic framework shall be used while accounting for new results based on simulations (or possibly experimentations).

5.1. DEFINITIONS AND NOTATIONS

As seen previously, for navigation-oriented sub-scenarios requiring absolute body positioning, a *Global Coordinates System* (GCS) should be assumed for the scene, as defined in Section 2.2. The number of mobile users to be located in group navigation applications is *Nu*. A given user is referred by its index *k*, with $1 \leq k \leq Nu$.

As regards to motion capture oriented sub-scenarios requiring relative positioning of on-body nodes at the body scale, each user shall be equipped with a *Local Coordinates System* (LCS), as defined in Section 2.2. The origin of this coordinate system could be centered on a reference point of the body (center of the chest or pelvis). For sake of simplicity all the LCS can for instance share the same vertical direction, while extending the motion capture functionality to group applications.

Each user can wear up to *Ns* communicating sensors placed at various positions on the body. We assume that each of those positions is indexed by the integer *l*, with $1 \leq l \leq Ns$.

For a human agent, all the on-body nodes are assumed dynamic *a priori*. The number of discrete time samples for localization updates (either asynchronously or periodically) is *Nt*, with $1 \leq t \leq Nt$.

For the purpose of assessing the "average" performance in CORMORAN, one shall consider different network configurations. The number of network realizations is then *Nw*, with $1 \leq i \leq Nw$ where one single network realization *i* refers to one particular geographic network deployment and setting (i.e. specific dynamic positions occupied by equipped bodies and fixed reference anchor nodes, leading e.g. to particular network connectivity and SINR conditions). Given one network realization however, another source of randomness is the noise affecting measured signals.

The true position of sensor *l* (as defined in the chosen reference coordinates system) on a given user *k* for one given network realization *i* at time *t* is noted as

$$\mathbf{p}_{i,k,l}^{t} = \left[x_{i,k,l}^{t}, y_{i,k,l}^{t}, z_{i,k,l}^{t}\right]^{T}$$

Static nodes in the environments (e.g. WLAN AP, Femtocells base station) shall serve as anchors, forming the *a priori* infrastructure. The positions of those helping nodes, which are distinguished from body or on-body nodes positions, are noted as:

$$\mathbf{q}_{i,k'} = \left[x_{i,k'}, y_{i,k'}, z_{i,k'}\right]^T$$

The total number of anchors available across the scenario infrastructure is Na, with $1 \leq k' \leq Na$.

As mentioned previously, performance statistics shall be drawn over different network realizations (i.e. leading to average performance indicators). These realizations can be either random (e.g. through simulations) or deterministic (e.g. trough physical experimentations), as far as they are sufficiently representative. Finally, their number Nw clearly depends on the performance evaluation context. More concretely, while assessing the mean performance through simulations, Nw shall be high (e.g. say on the order of 100s/1000s of random trials) whereas only a few network deployments will be reasonably tested within practical deployments. As already mentioned, given one particular network configuration i at time t (i.e. under particular connectivity and SINR conditions), the performance can also be evaluated over distinct noise occurrences that may affect the available radiolocation measurements (e.g. either location-dependent radio metrics or received radio signals directly). The number of such noise realizations (still conditioned on the current network realization) is Nn, so that $1 \leq n \leq Nn$. This number, just like the number of tested network realizations, depends on the evaluation context. It shall be high for simulation-based evaluations and most probably low for demonstrator-based evaluations, keeping the same formalism in both cases.

5.2. LOCALIZATION LATENCY

The so-called localization latency parameter, as introduced in Section 4.3, refers to the overall duration between the instant when the application is asking for one node position (or even several nodes positions) and the moment when the estimated position is obtained in the proper destination place (e.g. on the WBAN Gateway of a mobile user). Latency may vary significantly depending on nodes density and activity. As already seen, it shall ideally account for the *time* it takes *to collect all the required radiolocation measurements* (LDPs) under realistic connectivity and packet delivery success rates and the *time* it take *to compute all the required positions*, based on the collected measurements.

In first approximation and without loss of generality, we will assume in our performance evaluation that localization latency is independent of the final precision, even if both parameters clearly impact the underlying application (e.g. considering applications that authorize relaxed real-time constraints, precise location estimates may be sufficient, even if slightly delayed in time). Depending on the application the location estimate can be delivered either asynchronously (on demand) or periodically, e.g. with a period *Tp*.

In CORMORAN, we define the estimated position occupied at time *t* delivered to the application layer at time $t+TL_{k,i,l,n}$ as:

$$\hat{\mathbf{p}}^t_{i,k,l,n}(t + TL_{i,k,l,n})$$

$TL_{k,i,l,n}$ then refers to the localization latency for the network realization *i*, node *k*, sensor *l* and noise realization *n*.

5.3. LOCALIZATION QUALITY INDICATORS

Depending on the set of available localization realizations (e.g. through simulations or physical experimentations), one can always define the corresponding RMSE, by adequately choosing the set over which the mean shall be taken. In the following, $E_S[.]$ refers to the theoretical expected value over *s*, whereas $\mu_S[.]$ refers to the corresponding empirical mean over an associated finite sub-set of *s*).

5.3.1 LOCALIZATION ACCURACY

Assume the instantaneous location error at time *t*, network realization *i*, user *k*, sensor *l*, noise realization *n*, viewed as a random variable:

$$\epsilon^t_{i,k,l,n} = ||\mathbf{p}^t_{i,k,l} - \hat{\mathbf{p}}^t_{i,k,l,n}||_2 = \sqrt{(\mathbf{p}^t_{i,k,l} - \hat{\mathbf{p}}^t_{i,k,l,n})^T.(\mathbf{p}^t_{i,k,l} - \hat{\mathbf{p}}^t_{i,k,l,n})}$$

The following localization quality indicators are then defined:

- Time-averaged location RMSE (i.e. conditioned on network *i*, noise *n*, sensor *l* and user *k*)

$$\bar{\epsilon}_{i,k,l,n} = \sqrt{\mathbb{E}_t\left[(\epsilon^t_{i,k,l,n})^2\right]} \approx \sqrt{\mu_t\left[(\epsilon^t_{i,k,l,n})^2\right]}$$

- Time-/network-averaged location RMSE

$$\bar{\epsilon}_{k,l,n} = \sqrt{\mathbb{E}_{t,i}\left[(\epsilon^t_{i,k,l,n})^2\right]} \approx \sqrt{\mu_{t,i}\left[(\epsilon^t_{i,k,l,n})^2\right]}$$

- Time-/network-/noise-averaged, location RMSE

$$\bar{\epsilon}_{k,l} = \sqrt{\mathbb{E}_{t,i,n}\left[(\epsilon^t_{i,k,l,n})^2\right]} \approx \sqrt{\mu_{t,i,n}\left[(\epsilon^t_{i,k,l,n})^2\right]}$$

- Time-/network-/noise-/sensor-averaged location RMSE

$$\bar{\epsilon}_k = \sqrt{\mathbb{E}_{t,i,l,n}\left[(\epsilon^t_{i,k,l,n})^2\right]} \approx \sqrt{\mu_{t,i,l,n}\left[(\epsilon^t_{i,k,l,n})^2\right]}$$

- Time-/network-/noise-/sensor-/user-averaged location RMSE

$$\bar{\epsilon} = \sqrt{\mathbb{E}_{t,i,k,l,n}\left[(\epsilon^t_{i,k,l,n})^2\right]} \approx \sqrt{\mu_{t,i,k,l,n}\left[(\epsilon^t_{i,k,l,n})^2\right]}$$

These position quality indicators can be used indifferently for LSIMC or CGN, depending on the defined reference coordinates system. Notice that the errors on the different sensors are assumed of equal importance in this formulation.

5.3.2 LOCALIZATION ROBUSTNESS

Alternatively, so as to assess more precisely the localization robustness and its compliance with the addressed sub-scenarios, in particular in terms of worst cases behavior (e.g. outage probabilities, rates of erasures, etc.), it is possible to compute the *cumulative density function* (CDF) of the location errors, that is to say, the probability for any location estimate to fall at least into an error circle of radius *x* meters centered around the true location, as follows:

$$CDF_\epsilon(x) = Prob[\epsilon^t_{i,k,l,n} \leq x]$$

An empirical version of the actual CDF can be computed from simulations or experiments. In the most general situation, the frequency of occurrence is computed over all possible noisy measurements *Nn*, all the *Nu* users nodes, all the *Nw* random network occurrences, and all the *Nt* time values. Depending on the context and the scenario this *Empirical* CDF (ECDF) could also be determined on more restrictive sets, as follows:

$$\mathrm{ECDF}_\epsilon(x) = \frac{\mathrm{card}\{\mathbf{1}\left[\epsilon^t_{i,k,l,n} \leq x\right]\}}{\mathrm{card}\{\epsilon^t_{i,k,l,n}\}}$$

where $\mathbf{1}[y]$ refers to the indication function on a discrete set which returns all the elements of the discrete set which satisfies the given logical condition y in the argument.

To assess robustness with respect to scalability, we introduce the two distinct error regimes:

- the median error at 50% of the ECDF:

$$\epsilon_{50} : \mathrm{ECDF}_{\epsilon}(\epsilon_{50}) = 0.5$$

- the so-called "worst-case" error at 90% of the ECDF:

$$\epsilon_{90} : \mathrm{ECDF}_{\epsilon}(\epsilon_{90}) = 0.9$$

For each random network topology, i = 1…Nw, and each independent set of noisy measurements, n=1…Nn, the observed experimental latency TL to locate either one or all the mobile users/nodes can also be assessed (e.g. based on packet-oriented network simulations). So, just like for location errors, the empirical CDF of the elapsed time TL over all the random realizations can be characterized as follows:

$$CDFTL(t) = Prob[TL_{i,k,l,n} < t]$$

The critical values of the previous CDF (e.g. median error at 50% or worst-location at 90% of the ECDF) will be picked up as a function of system parameters, for instance, when assessing robustness with respect to scalability or mobility.

6. CONCLUSION

This D1.2 deliverable accounts for the work realized in the frame of CORMORAN's Task T1. Note that it is seen as a living document, which will be updated at M18 into D1.2, based on the latest project's developments and results.

Based on realistic feedback information from end-users and integrators of the foreseen cooperative WBAN technology, we have identified two application scenarios. In the first *large scale individual motion capture* (LSIMC) scenario, the idea is to provide seamless and geographically unrestricted motion capture capabilities based on stand-alone location-enabled WBANs, at the price of reasonably degraded on-body location precision (e.g. in comparison with costly and physically limited video systems). At first sight, the required accuracy (i.e. on the order of a few centimeters) and refreshment rate (i.e. down to a few 10s of ms) seem rather challenging, considering the available single-link ranging precision level, typical on-body network connectivity, and classical temporal resources management in WBANs. Accordingly, it will be necessary in Task T3 to explore innovative ways in terms of e.g., variable refreshment rates, fixed links detection, nodes scheduling, aggregation and broadcast, asynchronous positioning for low latency, etc. As for the second *coordinated group navigation* (CGN) scenario, the idea consists in benefitting from the presence of multiple on-body sensors disseminated on each pedestrian to guarantee a spatially constant quality of the navigation service, while benefiting from reciprocal mobility in groups and from opportunistic connectivity with the surrounding infrastructure (i.e. in comparison with more classical non-cooperative or cooperative mono-sensor schemes). At this point, one major challenge consists in defining optimal cooperation and data fusion schemes, while dealing with multi-WBAN coexistence and dynamic association in clusters of mobile users.

After browsing through the most relevant radio standards and regulatory constraints (e.g. in terms of occupied bandwidth, low duty cycle…), preliminary system requirements have been put forward, as regards to radio features and performances, networking architectures and mechanisms, and localization application embodiments.

Finally, besides classical indicators related to communication QoS, new performance indicators have been defined, regarding the localization precision and latency (e.g. identifying average and worst-case regimes), along with indications for their practical implementation in future simulation-based performance evaluations. As a support to the latter performance assessment, the cross-layer simulation tool developed in the frame of T2.4 will get inspired by the models and simulation tools listed in the Appendix (concerning each layer of the OSI model, from the physical mobility modeling up to the localization application), where we briefly discuss interfacing and programming issues.

7. APPENDICES

7.1. APPENDIX 1: USERS' QUESTIONNAIRE

On rapporte ci-dessous des captures d'écran correspondant à l'outil de consultation en ligne (questionnaire « Utilisateurs »), exploité dans le cadre des sous-tâches T1.1 et T1.2. http://s7.sphinxonline.net/tp-chaudet/Cormoran/index.htm.

Questionnaire Utilisateurs

Projet ANR
Cormoran
ANR 11 INFR 010 01

Applications de Capture de Mouvement et de Navigation de groupe s'appuyant sur des Réseaux Corporels Sans-fil

Par ordre de préférence (numéroté de 1 à 3), pour quelles applications souhaiteriez-vous voir apparaître une nouvelle technologie sans-fil à bas coût (<10 euros/individus) dans les 5 prochaines années ?

- Navigation de groupe d'individus coordonnés (sans capture du mouvement) - ex: déploiement coordonné de pompiers ou de militaires, réseaux sociaux nomades
- Capture du mouvement individuel à large échelle (typiquement à l'échelle d'un bâtiment) - ex: jeu, réalité virtuelle/augmentée, capture du geste sportif individuel, rééducation posturale à domicile…
- Capture de mouvement de groupe à large-échelle (typiquement à l'échelle d'un bâtiment) - ex: capture du geste sportif collectif, jeux sociaux, réalité virtuelle/augmentée de groupe…
- Autre (préciser le cas échéant)

Pour votre application préférée...

Pour les questions qui suivent, merci de vous prononcer par rapport à votre application préférée (i.e. celle classée 1 à la question 1) et pour le pire cas de fonctionnement, afin de nous permettre de ne pas sur-dimensionner inutilement le système CORMORAN et d'optimiser d'autres paramètres, tels que la consommation électrique (Par exemple, si votre application peut tolérer objectivement une précision de 10cm, merci de ne pas répondre 1cm).

NB: Bien que déterminantes à terme, les contraintes relatives à l'instrumentation des individus (ex: temps de déploiement du réseau corporel, intégration au « vêtement intelligent » ou système à base de capteurs discrets à sangler sur le corps…) n'entrent pas en considération dans le cadre de cette étude. En conséquence, merci de ne pas vous restreindre dans vos réponses, ni de fonder votre appréciation, sur la base de ces seuls éléments.

Quel serait alors le niveau de précision attendu pour le positionnement relatif des capteurs à l'échelle d'un seul corps (dans au moins 90% des cas) ?

- 1cm
- 5cm
- 10cm
- 20cm

Quel serait alors le niveau de précision attendu pour le positionnement absolu des individus à l'échelle d'un bâtiment (dans au moins 90% des cas)?

- 10cm
- 50cm
- 1m
- 2 m

Avec quel taux de rafraichissement l'information de positionnement des capteurs et/ou individus devrait-elle être délivrée ?

- 1 mesure / 10ms
- 1 mesure / 100ms
- 1 mesure / 1s
- 1 mesure / 10s

Où l'information de positionnement des capteurs et/ou des individus serait-elle la plus utile ?

- Au niveau de chaque individu, de manière indépendante
- Partagée simultanément pour tous les membres d'un même groupe d'intérêt
- Au niveau d'un serveur ou de l'infrastructure environnante (installée à demeure ou déployée de manière opportuniste)

Quel type d'environnement serait-il concerné par l'application ?

- Indoor peu dense (bureau, résidentiel…)
- Indoor dense (résidentiel dense, centres commerciaux, gares…)
- Indoor « maîtrisé » (industriel, professionnel dédié, e.g. studio de capture de mouvement…)
- Outdoor peu dense (open field, e.g terrain de sport…)
- Outdoor dense (urbain dense, e.g. rue encombrée…)

Quel type de mobilité humaine devrait être supporté en priorité pour ces mêmes applications ?

- Corps statique (ex: allongé, assis…)
- Marche modérée (de 1 à 5 km/h)
- Course à pied (< 15 km/h)

Combien d'individus appartenant à un même groupe devraient-ils être pris en charge par l'application ?

- 1
- 2
- de 2 à 5
- de 5 à 10
- > 10

Quelle serait la distance maximale tolérée séparant deux individus permettant de dire qu'ils appartiennent à un même groupe ?

- 1m
- 2m
- 5m
- >10m

Quelle est la densité maximale de capteurs fixes ou balises disséminés dans l'environnement proche (i.e. en dehors des capteurs disséminés sur les individus) ?

- 1 capteur/10m2
- 1 capteur/25m2
- 1 capteur/100m2
- 1 capteur/500m2

Quel nombre maximal de capteurs, disséminés sur chaque individu, vous semblerait acceptable pour un même utilisateur final?

- 1 capteur
- 2 capteurs
- 2 à 5 capteurs
- 5 à 10 capteurs
- plus de 10 capteurs

Classez par ordre de préférence (de 1 à 10), les positions des capteurs qui vous sembleraient les plus acceptables pour l'utilisateur final (et/ou les moins intrusives), indépendamment du nombre de capteurs déployés.

- Hanche
- Cuisses
- Genoux/Tibias
- Chevilles/Pieds
- Coudes
- Poignets
- Torse
- Dos
- Epaules
- Tête/Oreilles
- Autre (à préciser)

Quel(s) type(s) de capteurs, disséminés sur les individus, ou quel(s) type(s) de mesures physiques pourraient-elles s'avérer utiles, en complément de l'information de localisation ?

- Capteurs inertiels et/ou de posture (ex: accéléromètres, gyroscopes, magnétomètres…)
- Capteurs physiologiques et/ou de santé (ex: ECG, température corporelle, chimie du sang « embarquée », rythme cardiaque ou respiratoire…)
- Capteurs environnementaux (ex: température ou luminosité ambiante, exposition du corps aux vibrations mécaniques, ondes sonores, rayonnements électromagnétiques, radiations nucléaires, gaz dangereux…)

Avec quel taux de rafraichissement ces nouvelles mesures physiques devraient-elles être réalisées ?

- 1 mesure / 100ms
- 1 mesure / 1s
- 1 mesure / 10s
- Aucune mesure physique nécessaire, autre que la localisation

A l'aide de quelle(s) information(s) de localisation les mesures physiques issues de ces capteurs devrai(en)t-elles être géo-référencées ?

- Positions relatives des capteurs (à l'échelle du corps)
- Position absolue de l'individu porteur (à l'échelle de la pièce ou du bâtiment)
- Information conjointe des positions relatives des capteurs et de la position absolue de(s) l'individu(s) porteur(s)
- Les mesures physiques se suffisent à elles-mêmes, indépendamment de leur géo-référencement

Quel(s) effort(s) de pré-calibration/configuration vous sembleraient tolérables pour l'utilisateur au démarrage de l'application ?

- Aucun ! (Système totalement Plug & Play à chaque nouvelle utilisation) ex: système s'organisant et s'auto-calibrant seul
- L'utilisateur respecte grossièrement une convention de déploiement des capteurs sur le corps (ex: respect d'un code couleur simple (capteur jaune à disposer dans la partie supérieure gauche du corps, capteur bleu à disposer dans la partie inférieure droite du corps)
- L'utilisateur respecte scrupuleusement une convention de déploiement précis des capteurs sur le corps (ex: respect d'un code couleur simple (capteurs jaune sur le poignet droit, capteur bleu sur la hanche gauche)
- L'utilisateur doit effectuer ces mouvements spécifiques de calibration avant chaque nouvelle utilisation.

Quelle durée d'utilisation maximale serait-elle acceptable (en continu) avant maintenance du système (ex : pour rechargement des batteries et/ou re calibration et/ou mise à jour du logiciel embarqué dans les nœuds/capteurs)?

- 1 journée
- 1 semaine
- 1 mois
- 1 an

Expression libre: N'hésitez pas à nous faire part de suggestions ou de points plus spécifiques que vous souhaiteriez voir traités dans le cadre d'un projet tel que CORMORAN?

Vos coordonnées

Nom, prénom :

Entreprise / Institution / Unité :

Secteur d'activité (en quelques mots-clès) et profil (ex : PME, grand groupe, acteur institutionnel…) :

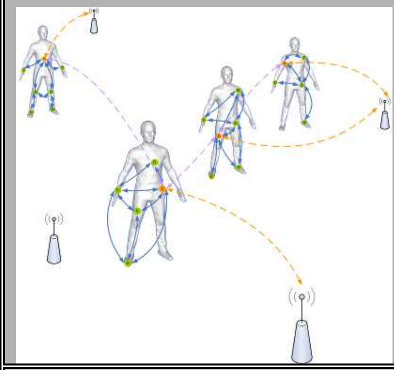
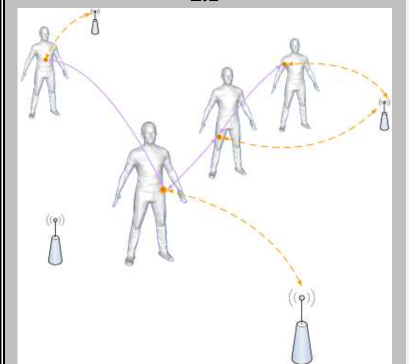
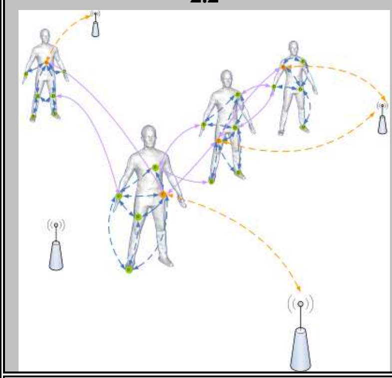
Si vous souhaitez recevoir par e-mail la lettre biannuelle d'information et de dissémination de CORMORAN, reprenant les principaux résultats de recherche issus du projet, merci d'indiquer votre adresse e-mail :

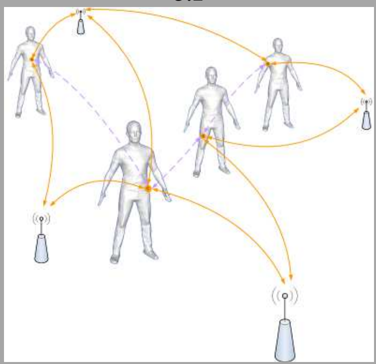
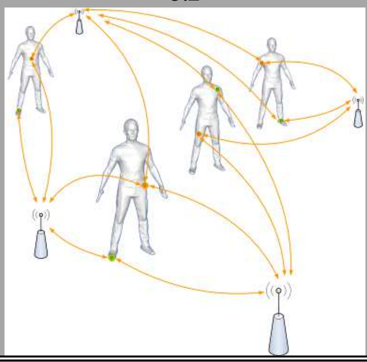
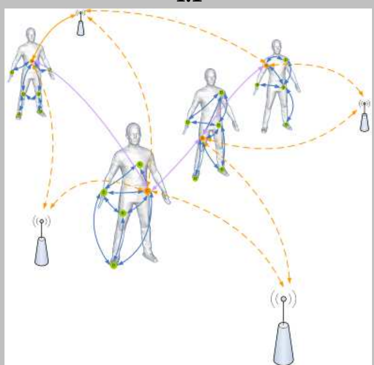
Acceptez-vous que l'identité de votre entreprise/unité, en qualité de « Participant à la Consultation CORMORAN », soit communiquée à l'Agence Nationale pour la Recherche (et uniquement à cette dernière, de façon strictement confidentielle). Dans le cas contraire, nous ne mentionnerons que votre secteur d'activité.

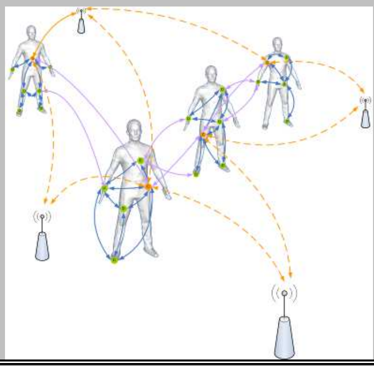
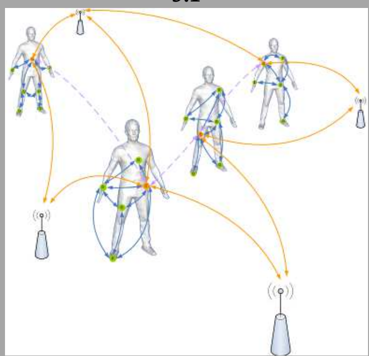
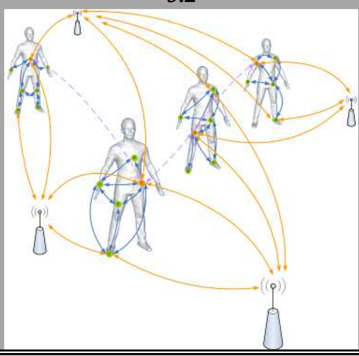
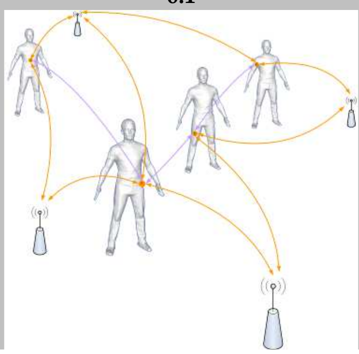
- Oui
- Non

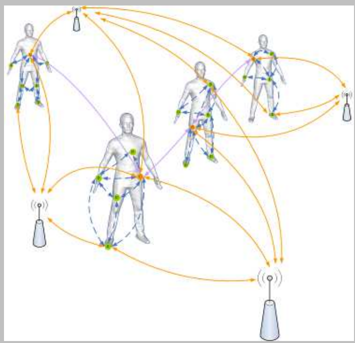
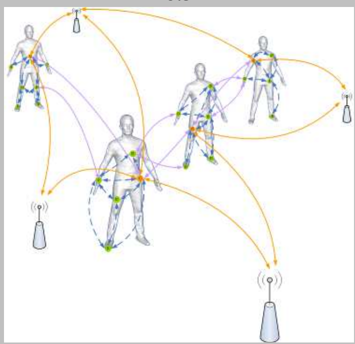
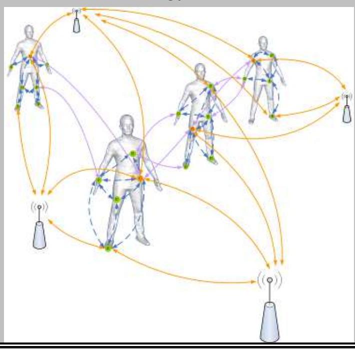
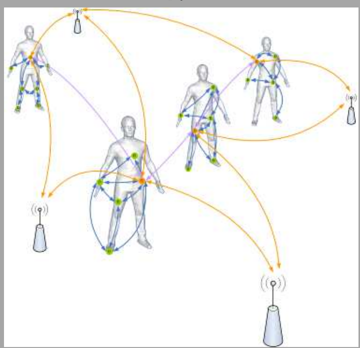
Envoyer

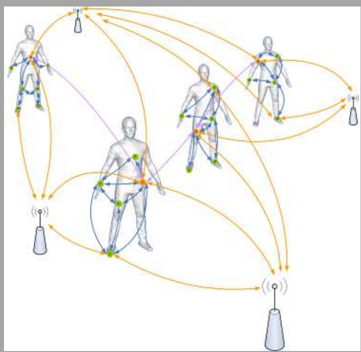
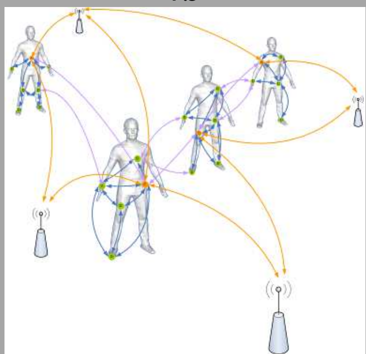
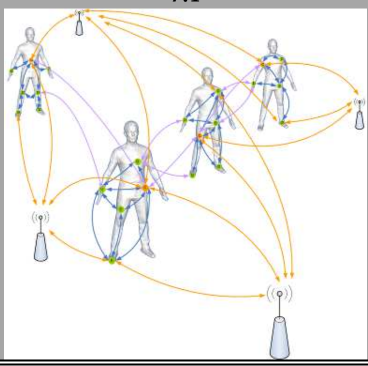
7.2. APPENDIX 2: EXHAUSTIVE LIST OF POSSIBLE DEPLOYMENT SCENARIOS

Involved Links (along columns) vs. Scenario ID (along rows)	Intra-WBAN	Single-Link Inter-WBAN	Multi-Link Inter-WBAN	1 on-body node wrt. multiple infrastructure elements (Off-body)	>1 on-body nodes wrt. multiple infrastructure elements (Off-body)	Applications
1 	Loc	(+ Com)		(+Com)		Body-Scale Motion Capture (Relative positioning)
2.1 		Loc		(+Com)		Group Navigation (Relative Positioning)
2.2 	(+Com)		Loc	(+Com)		

3.1 		(+ Com)		Loc		Individual Navigation (Absolute Positioning)
3.2 	(+Com)	(+ Com)			Loc	
4.1 	Loc	Loc		(+Com)		Motion Capture + Group Navigation (Relative Positioning)

4.2 	**Loc**		**Loc**	**(+Com)**		
5.1 	**Loc**	**(+ Com)**		**Loc**		**Individual Motion Capture + Navigation (Absolute Posiitoning)**
5.2 	**Loc**	**(+ Com)**			**Loc**	
6.1 		**Loc**		**Loc**		**Group Navigation (Absolute Positioning)**

6.2 	(+Com)	Loc			Loc	
6.3 	(+Com)		Loc	Loc		
6.4 	(+Com)		Loc		Loc	
7.1 	Loc	Loc		Loc		Group Motion Capture + Navigation (Absolute Positioning)

7.2 	Loc	Loc			Loc	
7.3 	Loc		Loc	Loc		
7.4 	Loc		Loc		Loc	

Notes:

- « Loc » implies for the considered links that location-dependent radio metrics useful to the localization problem (e.g. TOF, RSSI, TDOA, etc.) are performed and thus, by definition, that packets are transmitted (hence, assuming as well pre-existing wireless communication capabilities « Com » over the same links). In other words, « Loc » actually means « Loc + Com » here.
- « Com » implies that uniquely the communication functionality is activated over the considered links (i.e. without any radiolocation measurement).

7.3. APPENDIX 3: MODELS AND SIMULATION TOOLS

In this section we draw a list of existing models and simulation tools at the very beginning of the project timeline, which could be of interest (either as they stand or necessitating a few adjustments) for the foreseen development of a common cross-layer simulation framework in the frame of CORMORAN (in Task T2.4). The idea is to present those tools or models as possible building blocks (on each OSI layer) of the future overall simulation architecture, while highlighting key integration and interfacing issues. The list hereafter is obviously not exhaustive and will be kept as a living working basis during the project timeline.

7.3.1 MOBILITY

Mobility models are fundamental means for evaluating various mobile applications based on mobile or *ad hoc* networks, especially within highly specific WBAN scenarios. A large number of mobility models already exist to simulate realistic user movement under physical constraints (e.g. obstacles, acceleration, inertia etc.). One need in the proposed context is to merge properly three different hierarchical levels affecting human mobility:

- Social (i.e. group mobility);
- Environmental (i.e. deterministic layout-constrained mobility);
- Biomechanical (i.e. body motion) levels.

- *Pedestrian Mobility*

For the past years a need for *social mobility models* (SMMs) has risen [YYZS_10], [FHR_10]. A recent overview in [FOR_10] describes modern graph theory tools addressing community detection in graphs. In [ZS10] the authors explore socially organized human activities resulting in a certain tendency to form groups. They provide an understanding of the underlying impacting social forces extracted from real human movement traces, along with the proper mathematical framework to reproduce such behaviours within a mobility model.

This problem of social mobility modelling has also been recently connected to the emblematic WBAN scenario of football match players [DNDDB10]. Another important aspect with respect to location-dependent problems is to connect the mobility model to an environment layout in order to avoid making too simplistic random walk assumptions, which would not be representative of actual mobility patterns.

A large collection of mobility models suitable for WBAN has been proposed in [RM_06], investigating complex scenarios using a *Mobility Vector Model* (MVM) for the body motion and a *Reference Point Group Model* (RPGM) for the individual nodes mobility. Similar approaches will be used in the CORMORAN context. The environment influence on mobility is the common (articulation) point with deterministic channel modelling, which also requires a precise layout description as demonstrated in [COT_09], [C0T_10] for military WBAN scenarios.

IETR is currently developing such a tool based on SimPy. SimPy is an object oriented, process-based, discrete event simulation language for Python. It is based on a description of the layout which enables to extract the graph whose nodes are the different rooms of a given building. Independent mobile agents are launched in this environment. Their mobility is driven by different steering behaviours, which enable to emulate various realistic behaviours during their motion (Wall avoidance, queuing...).

- *Group Mobility*

Regarding the group mobility, Stepanov et al. [Stepanov03] propose a generic mobility model that decomposes the users' movement definition in three components. First, the environment, composed of obstacles, points of interest, etc., defines the scene in which mobiles evolve and imposes constraints on the movements. Environment can be extracted from a geographic database. Second, the users' behavior is defined by their activities. Users move when they are on a trip, going from one place to another. Third, the movement dynamics (speed, acceleration...) define how the users move.

The *Condition Probability Event* (CPE) model [Maeda09] proposes to represent pedestrians' mobility as a set of rules that mix probabilities and interactions with the environment.

Hong et al. [Hong99] wrote one of the first contributions to stress out the importance of group mobility. The movement patterns of individual users and devices often depend on other nodes behaviors. Musolesi et al. [Musolesi04] define a group mobility model based on social interactions, using the strength of the connections between users to form an evolving topological space.

GEMM ([Feeley04]) proposes to modify the random waypoint mobility model by defining particular locations, which may act as attraction points. Users are then grouped into classes who are attracted. Hollick et al. [Hollick04] follow the same logic of activities and attraction to model metropolitan area networks. Aravind et al. [Aravind10] use the attraction and repulsion points concept to define the behavior of a vehicular user that travels on a city map when reaching an intersection.

- *Biomechanical Mobility*

Biomechanical modelling clearly plays a central role in mobility modelling when dealing with WBANs. Modelling the human body motion during pedestrian motion, on its own, is a pretty old topic already investigated in computer graphics and robotics [BTT_90], [KST_00]. This material can be exploited further for realistic gait and walking simulations along agent displacement paths. At this point the specific representation and format presented in [C3D] could be of interest.

These generic synthetic mobility models apart, the following simulator block examples make particular sense in the location-enabled WBAN context.

- ***IMUSim***

IMUSim is a simulator for inertial and magnetic sensing systems and algorithms, developed by the University of Edimburgh (www.imusim.org). A detailed description of this simulator is available in [Young2011].

Function

The simulator can generate realistic sensor readings based on sensor and environment models and continuous-time trajectory functions, which can be given analytically or synthesised by spline fitting from existing discrete time motion capture data. Building on this and additional functionality, complete systems of multiple wireless IMUs with distributed on-board processing and radio communications can be simulated with realistic motions. One of the very interesting features is the trajectory generation based on spline fitting of position and rotation sequences. This software package is complementary to the CORMORAN project in the sense that it addresses one of the CORMORAN purpose through Inertial Measurements Units.

Underlying Methods

- Trajectory generation based on spline fitting of position and rotation sequences or jointed rigid body kinematics.
- Deterministic human motion
- 2D and 3D Vizualization of body motion
- Rigid body system
- Import of motion capture data (format .bvh, VIcon,ASF/AMC Files))

OSI Layer(s)

IMUSim is a generic platform, which involves different layers:

- Mechanical ;
- PHY & MAC ;
- Application

Interfacing

No explicit information has been provided yet.

Programming language

IMUSIM is written in Python and C making use of NumpY, Scipy, SimPy, Cython and MayaVi.

OS

IMUSim was developed on Linux and Mac OS X, and has also been tested under Windows

Intellectual Property

IMUSim is free software: one can redistribute it and/or modify it under the terms of the GNU General Public License, as published by the Free Software Foundation, either version 3 of the License, or (at your option) any later version. Copyright University of Edinburgh

- *Cylinder-Based Biomechanical Model*

Function

It generates body mobility patterns as a function of time stamps, providing the true dynamic positions of on-body nodes and the obstruction conditions per link.

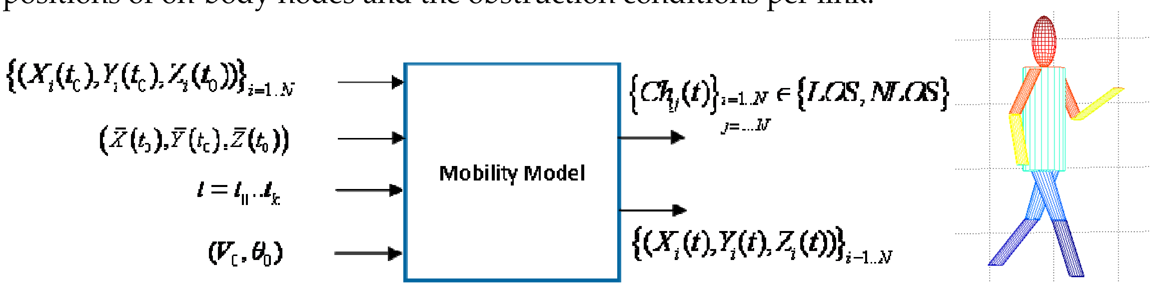


Figure 7.1: Inputs/Outputs of the cylinder-based biomechanical model.

Underlying Methods

The approach relies on a mix between random and deterministic models:

- Macro mobility applied to the body Barycentre = Random Gauss Markov Model realization (Random) [BenHamida10]
- Body elements/slices mobility = Proprietary biomechanical model based on cylinders (Deterministic).

OSI Layers

Only the PHY layer is concerned.

Interfacing

Inputs:

- Initial 3D absolute position of the body barycenter $\left(\bar{X}(t_0),\bar{Y}(t_0),\bar{Z}(t_0)\right)$;
- Initial speed and angle characterizing the barycenter movement [BenHamida10] (V_0,θ_0);
- Time-stamp basis (observation time, refreshment rate) $t = t_0..t_k$;
- Initial 3D absolute positions of deployed on-body nodes $\left\{(X_i(t_0),Y_i(t_0),Z_i(t_0))\right\}_{i=1..N}$;

Outputs:

- Time-stamped 3D positions of all the on-body nodes $\left\{(X_i(t),Y_i(t),Z_i(t))\right\}_{i=1..N}$;
- Time-stamped obstruction conditions per link $\left\{Ch_{ij}(t)\right\}_{\substack{i=1..N\\ j=1..N}} \in \left\{LOS, NLOS\right\}$;

Programming language

Matlab.

OS

Windows or Linux, indifferently

Intellectual Property

None (Public)

7.3.2 RADIO

- *Deterministic Simulator of the Indoor Radio Propagation*

  - ***PyRay (Python Propagation Localization UWB Simulator platform)***

PyRay (Python Propagation Localization UWB Simulator) is a suite of tools for radio wave propagation simulation in indoor environment. It provides different Classes to handle Layout, Rays, UWB Signal, ray Signatures, localization algorithms taking advantages of UWB signals for indoor localization applications. This tool implements also a node mobility engine based on SimPy a process-based discrete-event simulation language for Python.

PyRAy is an interactive platform, used for deterministic channel simulation, using python and C as programming languages. This tool allows the evaluation of the propagation channel conditions, in indoor environment, between radio nodes for different antenna directions and waveforms. It consists in several interacting python modules as well as a set of various high level commands coded in C which exchange information through files. The main class which is used for defining a Simulation is called Simul which defines the different parameters files relative to a given multilink simulation. The simulation workflow goes through several steps; each one is managed by an independent bloc which corresponds to a standalone command. Those commands are originally written in C.

- launching ;
- tracing ;
- tratotud;
- evalfield;

It is foreseen to gradually convert all those different blocks in Python. During this transition period where co-exists both python and C tools, we have to deals with various data formats which feed either the old version of the code or the most recent one written and python and which uses parsing of *ini* files.

The technical choice which has been made is to use *ini* files which are simple ascii file which can easily be parsed into Python dictionary and which human readable. One of the interest of the *ini* file is their flexibility because the order the data appear in each section is not relevant.

The following figure presents a summary of the different PyRay elementary blocs, along with an overview of the simulation Workflow:

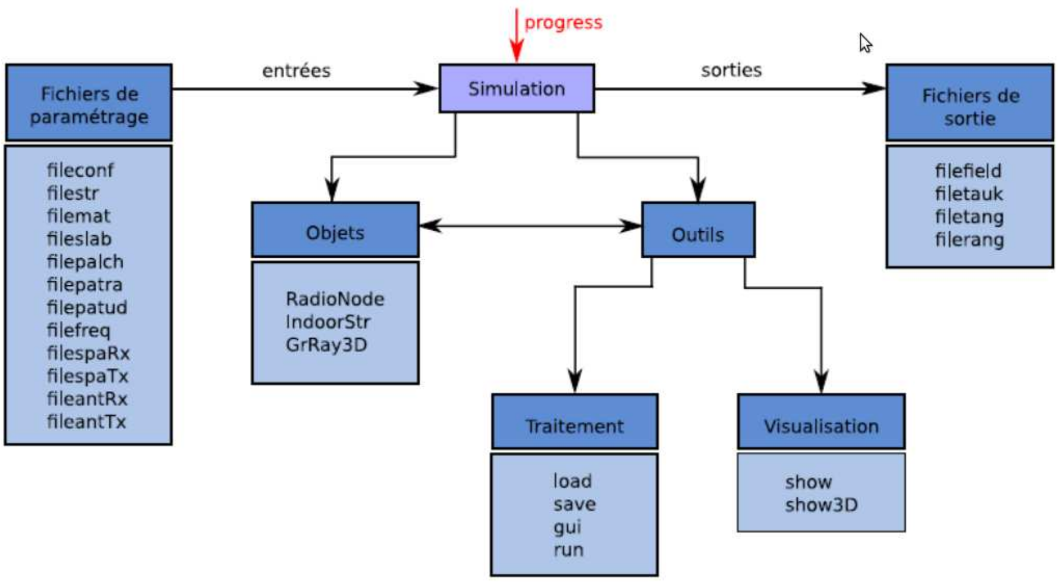


Figure 7.2: PyRay simulator elementary blocs.

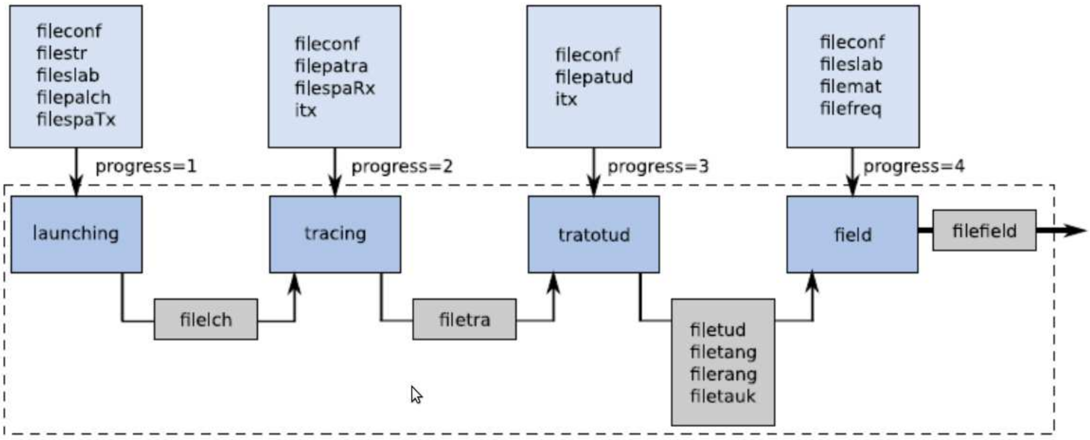


Figure 7.3: Overview of the PyRay workflow.

The environment is described in the **Layout** class. The following modules are used to handle the building Layout and its constitutive properties:

- Layout file handle in Layout.py module (.str2 or .str)
- Mat file handle in Slab.py module (.mat)
- Slab file handle in Slab.py module (.slab)
- **filestr**: geometric details of the propagation environment such as the number of points and their coordinates (expressed in meter), the number of segment represents the walls, their starts, ends, lengths... and the number of co-segments (windows, floors...)
- **fileslab**: represents the different dielectric layers, their number and thickness
- **filemat**: represents the characteristics of the materials defined in fileslab (relative permittivity, permeability, conductivity).

The configuration file **fileconf** contains the list of parameter files that are necessary for a simulation run.

- *Ray Launching Sub-block*

Function

In this part of the simulator, knowing the Tx position, the aim is to build a tree which facilitates the further calculation of rays. The launching phase generates different rays the Tx using a pre-calculated visibility matrix. Note that this approach is currently being completely reinterpreted by using dedicated graph data structure.

Underlying Methods

Geometrical optics.

OSI Layers

Physical layer

Interfacing

The parameters of this module are given by the input files:

- filepalch
- filestr
- filetx.spa

Once the launching is achieved, the output file is filelch. This file contains a tree emanating from the transmitter and goes through the entire layout until i-th layout. Breadth and depth exploration of the graph is balanced by using various propagation heuristics.

Both Input and Output files are ASCII files

Programming language

The block is written in C.

OS

It works on Linux and not tested on windows

Intellectual Property

University Rennes 1

- ***Ray Tracing Sub-block***

Function

At this step of simulation, the coordinates of the receivers are used to calculate the rays between the receivers and transmitter

Underlying Methods

Geometrical optics.

OSI Layers

Physical layer

Interfacing

The parameters of the tracing module are given by the input file: filepatra, the filelch is used as input to determine the rays to the receivers. As the launching module an output file filetra is generated. Both Input and Output files are ASCII files.

Programming language

The block is written in Python & C.

OS

It works on Linux and not tested on windows

Intellectual Property

University Rennes 1

- ***TUD-based 3D Rays Computing Sub-block***

Function

After ray launching and tracing, all we have is geometric models for rays between the Tx and Rx, on which we need to apply electromagnetic models. In order to have the 3D-TUD rays.

Underlying Methods

Uniform theory of diffraction.

OSI Layers

Physical layer

Interfacing

The input files are: filepatud for TUD parameter and the tracing file filetra. At the end 4 files are generated: filetud: containing 3d-TUD rays, filetauk: relative to propagation delay for each ray and fileang and filerang: for departure and arrival angles for each ray. Both Input and Output files are ASCII files.

Programming language

The block is written in Python & C.

OS

It works on Linux and not tested on windows

Intellectual Property

University Rennes 1

- ***Electromagnetic Field Evaluation Sub-block***

Function

This bloc allows the evaluation the electromagnetic filed by executing the field module of simulation.

Underlying Methods

Combination of ray tracing, optical geometrics and TUD methods.

OSI Layers

Physical layer

Interfacing

Input file: filefreq for the frequency range and the output file is filefield containing the relation the matrix connecting the transmitted and received field. Both Input and Output files are ASCII files.

Programming language

The block is written in Python & C.

OS

It works on Linux and not tested on windows

Intellectual Property

University Rennes 1

- ***Multi-wall Propagation Sub-block***

One alternative electromagnetic solver included in the PyRay platform that could be used for this project is based on a solver which evaluates the Path Loss through the different walls along a radio links. This is an adapted Motley-Keenan model which exploits the PyRay multilayer description of dielectric slabs. This approach takes only into account the attenuation along a direct path between Tx and Rx. It does not take into account the effect of multipaths.

- *Half-Deterministic On-Body Models*

  - ***Power Loss Prediction based on Cylindrical Diffraction Representation***

Function

This model is based on a cylindrical description of the body. The loss suffered between different antennas placed on the body is approximated by using close-form expressions from the diffraction theory. This work is still ongoing, focusing on the determination of a convenient way to handle properly the radiation of antennas mounted on or close to the body in exploiting a preliminary measurement campaign carried out in April 2012.

Underlying Methods

Geometrical theory of diffraction by cylinders

OSI Layers

Physical layer

Interfacing

No information has been provided yet.

Programming language

The block is written in Python & C.

OS

It works on Linux and not tested on windows

Intellectual Property

University Rennes 1

- *SNR Generation through Simplified Cylinder-based Obstructions*

Function

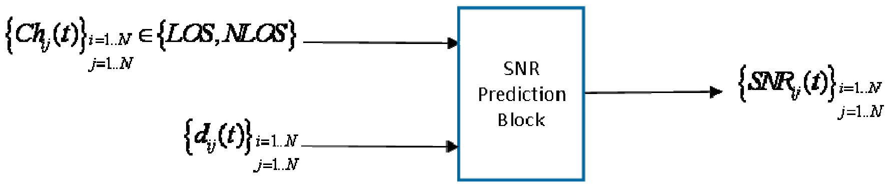
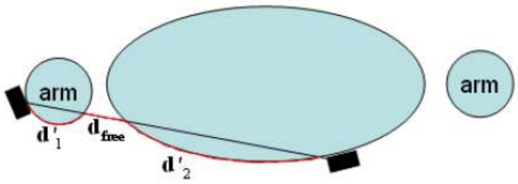


Figure 7.4: Inputs/Outputs of the intra-WBAN cylinder-based SNR generator.

This model, whose parameters are fitted to measurements, generates realistic SNR levels based on simple radio obstruction assumptions.

Underlying Methods

The parametric deterministic model adapted from [Maman09] accounts for both the path loss and dynamic body shadowing, considering parts of the distance travelled by transmitted signals "on the body" (dbody) or "over the air" (dfree) based on predicted intersections between the geometric path and body cylinders. Conditional propagation models are then applied to each sub-part accordingly.



$$PL_{i,j}(f,d_{free},d_{body})[dB] = PL_{body,i,j}(f,d_{body})[dB] + PL_{free,i,j}(f,d_{free})[dB]$$

$$PL_{free,i,j}[dB] = A \times log(d_{free}) \times (1 - e^{-\frac{d_{free}}{d_0}}) + PL_{free,0}$$

Figure 7.5: Cylinder-based obstruction model with travelled radio distances and related path loss prediction formula [Maman09].

OSI Layers

Physical layer

Interfacing

Inputs:

- Time-stamped channel obstruction conditions per link $Ch_{ij}(t) \in \{LOS, NLOS\}$;
- Time-stamped real distance per link $d_{ij}(t)$;

Outputs:

- Time-stamped Signal to Noise Ratio per link $SNR_{ij}(t)$;

Programming language

Matlab.

OS

Windows or Linux, indifferently

Intellectual Property

CEA-Leti

- *Conditional TOA-based On-body Ranging Error Model*

Function

This model enables to generate realistic errors affecting the TOA-based range measurements per link, as a function of dynamic obstructions and SNR conditions.

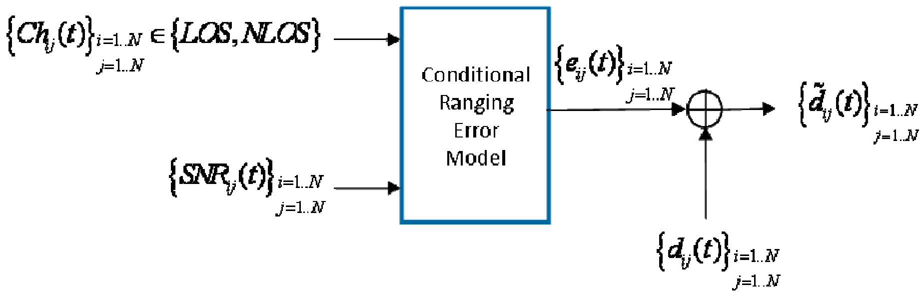


Figure 7.6: Inputs/Outputs of the TOA-based on-body ranging error model.

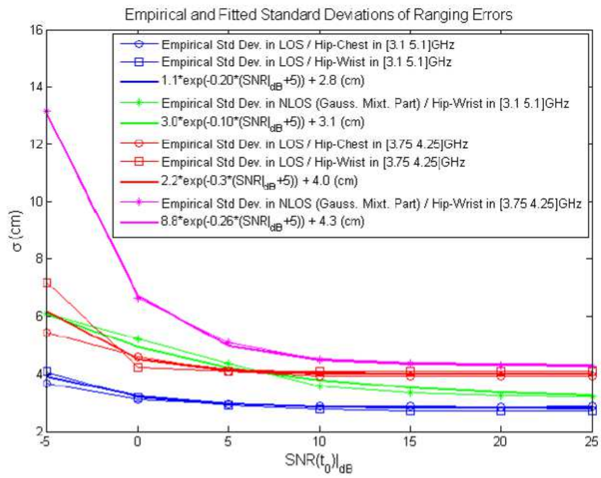


Figure 7.7: Example of TOA-based ranging error standard deviation as a function of a reference SNR value [Hamie12].

<u>Underlying Methods</u>

Conditional biased Gaussian random model, with statistical parameters (standard deviation and bias) as a function of the reference Signal to Noise Ratio and channel conditions

<u>OSI Layers</u>

Physical layer

<u>Interfacing</u>

Inputs:

- Time-stamped channel obstruction conditions per link $Ch_{ij}(t)$;
- Time-stamped Signal to Noise Ratio per link $SNR_{ij}(t)$;

Outputs:

- Time-stamped ranging errors per link $e_{ij}(t)$;
- Range measurements per link $\tilde{d}_{ij}(t)$;

Programming language

Matlab.

OS

Windows or Linux, indifferently

Intellectual Property

CEA-Leti

7.3.3 MAC & NWK

- ***WSNet***

Function

WSNet is a simulator for wireless networks on a large scale developed at the CITI laboratory [BenHamida09]. It is written in C, uses free and accessible libraries and it is configured using XML files. In comparison with the existing network simulators at the time of its conception, WSNet was designed to stand out on two particular points:

- Management of a massive number of nodes, up to several thousand, to meet the specific needs of the wireless sensor networks.
- A "realistic" physical layer for researchers and engineers working on the development of algorithms for the upper layers of the cell networks.

At first, only the second point should be interesting to work within the CORMORAN project, which is the utility of the PHY and MAC layers. These layers can be defined and customized by the user. However, in the study of BAN networks behavior in a crowd simulation, the scaling can be interesting.

A number of secondary constraints were placed on the development of WSNet and are now as features of the simulator:

- Complete and modular model for the software architecture of nodes, i.e. the different layers of the OSI model.
- Taking into account the actual hardware architecture of sensors when the simulation is coupled to WSIM.
- Modeling of collisions and interference.
- Modeling of mobility and physical environment - such as the presence of obstacles or fire.

Underlying Methods

- *Simulation with discreet events*

WSNet uses a mode of simulation said in discrete events. The principle is to consider that the system fits its behavior only to the appearance of events in time. By opposition to a simulation at continuous time, a simulator with discreet events can so save up a great deal of intermediate calculations, to focus only on the critical moments of the simulation. It supposes nevertheless that the evolution and the behavior of the system is in agreement with the hypothesis of departure.

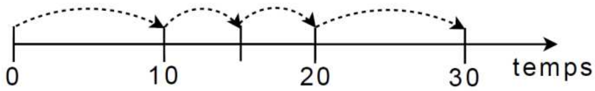


Figure 7.8 : Appearance of events at specific times of the temporal evolution line (Ben Hamida, 2009)

In the Figure 7.8, we can see the discreet moments when the simulator is going "to wake up" and to update the state of the system. The temporal notion is considered, but no update of the simulated system is sensible to be made outside these moments of awakening. Within the framework of simulation of network, these events will be mainly the sending and the reception of packages, and the evolution of the position of nodes and the physical environment within the framework of simulation with mobility.

- *Architecture*

WSNet possesses a modular structure, which is partially represented on the Figure 7.93. A node is a set of **superimposed layers**, which communicate directly with the lower or upper layers by the intermediaries of functions TX and RX. In every layer corresponds a particular model, which must be written and compiled in C. These models include at the same time either the instances of the TCP/IP protocol for high layers, or else simple mathematical calculations of BER (Bit Error Rate) for a modulation layer.

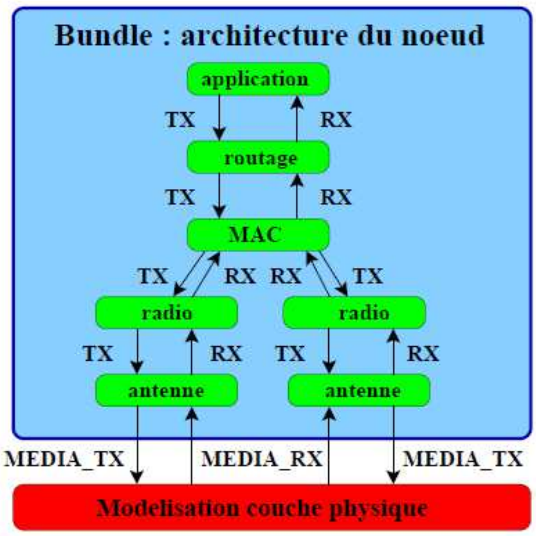


Figure 7.9 : Node architecture in WSNet and modules organization (Ben Hamida, 2009)

The modeling of the radio takes care of the decision of reception or non-reception of packages, leaving the MAC layer to arbitrate in the access to the channel. The models existing for the MAC layer concern mainly the protocol 802.15.4, in 868MHz, 902MHz and 2.4GHz. These models implement particularly the back-off described in the protocol.
The modeling of the physical layer is common to all the nodes and is composed of following modules:

- **Propagation:** this module is the lowest of the layer, and represents the path loss and all the effects bound to the power of the signal, such as the shadowing or the fading. The interferences are calculated by another module.
- **Interference:** this module gets back the value of the SNR of the propagation module and calculates the SINR, the ratio Signal on Interferences + Noise. This calculation can be made with an arbitrary granularity, which is once for the entire package, or once on every bit, or for any intermediate division.
- **Modulation:** this module sends back the BER following the value of the SNR or SINR of the propagation or interference layers.
- **Antenna:** this module allows integrating the properties of antennas, especially the different gains following the angle of transmission between the nodes.

- *Channel model and current limits of the simulations*

At present WSNet integrates the following propagation layers into its basic version:

- **File Static:** this model simulate a binary radio link with a certain probability of error, defined first in a file for all the links.
- **Disk model:** this model is a link on-off where the path loss is neglected until a certain distance, then maximal beyond.
- **Free Space:** this model simulate a path loss in free-space depending on the distance between nodes ([Rappaport98), p. 71)
- **Two-ray ground:** this model simulate a propagation of type double ray, by considering a perfectly flat ground ([Rappaport98], p. 89)
- **Lognormal shadowing:** this model combines the *free-space* propagation, which is multiplied by a log-normal random variable for every drawing of the channel.
- **Rayleigh fading, Nakagami fading:** these two models combine the propagation free-space with a component of shadowing, which can follow a Rayleigh's law or a Nakagami's law.

Although WSNet allows a finer simulation of the propagation layer than the other simulators, it remains however limited. The propagation layer generates in fact only a scalar value of SNR, which is passed in the interference layer, or modulation layer. Then, the modulation layer calculates a BER following this value of SNR (or of SINR if the interferences are considered), and the value of BER is then dismissed to the simulator which will update a probability of error for the package. The considered statistics are only of order

1, the spatial or temporal correlation of the channels must be integrated into the current models.
In order to deal with this problem, a usable temporary solution was to create a propagation model reusing measures or simulations made in an external way to WSNet. At the first, all the links are generated outside WSNet, and transmitted during the initialization of the simulation under the valuable shape of SNR. In every event, WSNet gets back the SNR corresponding in the table of the pre-generated values, and adds to it a log-normal shadowing component and a fading component (Rayleigh, Rice or Nakagami).

This model has the advantage to be extremely flexible, because we can use as base of simulation of the measures already made in real conditions, either the successful tools of generation of signals contained in Matlab for example. Furthermore, it is simple to integrate the spatial and temporal correlation of the state of the links. Nevertheless, it is necessary to pre-calculate all the values of SNR for the links, what reduces considerably the interest of the in time discreet simulator. When this calculation is made, we can nevertheless reuse channels generated for several simulations.

In the case of the BAN, following the models studied in particular in [EO10], the evolution of the random variable of masking follows a normal law, which is correlated in the time. This temporal evolution is modeled under the shape of an auto-regressive series. Consequently, to simulate such a series, it is necessary to apply an auto-regressive filter with a white noise. The generation cannot thus suffer from the absence of certain samples and it is not possible to jump from a time t_1 to another time t_2 without generating all the intermediate values.

Interfacing

Inputs:
The nodes are instantiated and described in the central XML file of configuration. The simulation chain is the following one:

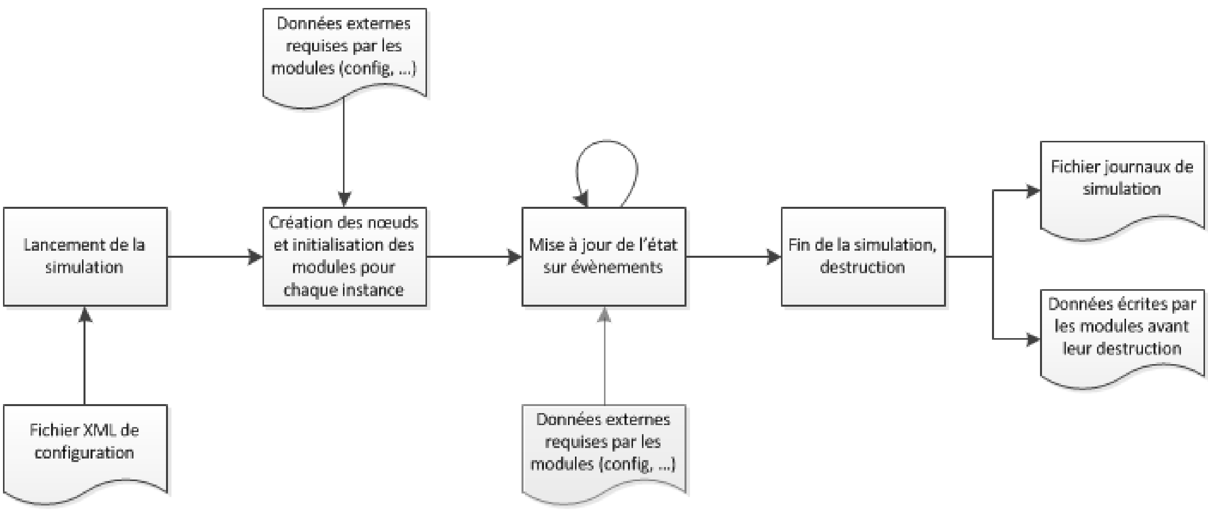


Figure 7.10 : Progress of a simulation in WSNet

The file XML allows to store certain valuable number of initialization for modules, these values which can be then completed by external files as indicated on the Figure 7.10.

Outputs:
In release, log files are generated, in particular for the mobility of nodes and these log files can be replayed in a graphic interface.

Programming Language:

C

OS:

Linux

Intellectual Property:

The WSNet simulator is under the CeCILL Free Software License Agreement. This software is open for all the members of the project CORMORAN: it is a simulator free of access and the manipulation remains simple and intuitive to the C programmers.

- ***NS-3***

Function

NS-3 ([Carneiro10], [Kopena2008]) is also a discrete event network simulator. This means that the simulation consists of a series of independent events that change the state of the simulation. Events are actions such as a packet being sent, a new node being added to the network, or a timer expiring. Each scheduled event runs until completion without advancing the simulation time, and then the simulation time is increased to the start time for the next scheduled event.

This simulator has a C++ core consisting of a scheduler and several useful classes defining nodes on a network, packets, and other similarly near-universal concepts. Various models use portions of this core package to implement specific network types, such as WiMAX, (or possibly WBAN in turn), or simple wired Ethernet networks. Scripts then define network topologies of nodes connected using the networks defined in these models, and generate traffic between them.

NS-3 is the successor of NS-2 [Fall2010], it is written from scratch and this makes an incompatible package and a different architecture between the two simulators. Significant differences include the programming languages used for development, the addition of a smart-object and memory management system, a more efficient and realistic data storage and packet system, a more realistic Node model, notable improvements to both memory usage and computational requirements to run a simulation, support for industry standard trace files and support for standard application interfaces such as POSIX sockets.

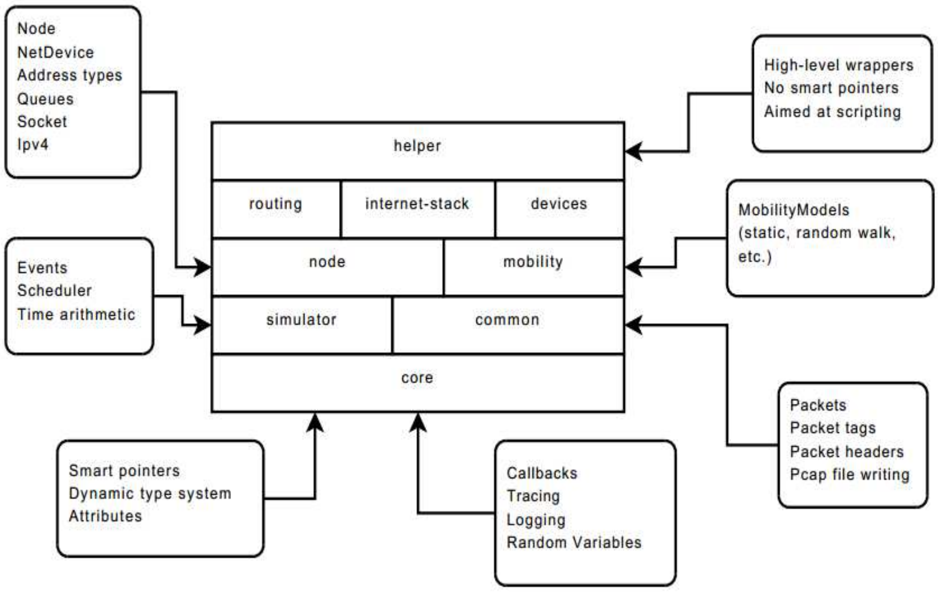


Figure 7.11 : Source Code

- *Available modules:*

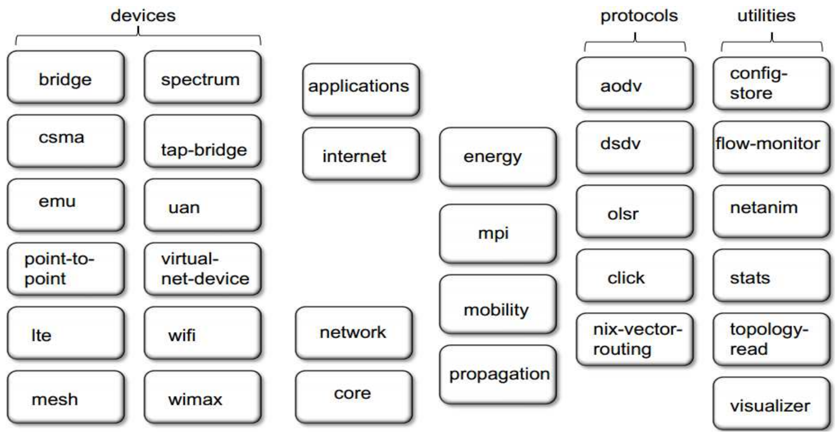


Figure 7.12 : modules supported by NS-3

<u>Underlying Methods</u>

- *Memory management:*

The NS-3 core module includes several classes that can be used to automate some memory processes like new, delete, malloc, free…

The ns3::Object class serves as the parent (or in many cases grandparent or higher) of most classes in NS-3 models. It contains functions to allow for reference counting with automatic de-allocation of the object when the reference count reaches zero. This is especially useful when dealing with Packet objects, which are frequently created, destroyed, and copied when processing traffic.

- *Object aggregation:*

NS-3's Object class also provides an aggregation system, by which Objects can be attached to other Objects at runtime. This is useful for removing bloat from classes like Node. The NS-3 node has, by default, very little included. Other objects such as NetDevices (interfaces), internet stacks, and routing protocols are added only as needed. This means that, for example, a node on a wired network that has no use for location information does not waste storage space with parameters to track that. Similarly, if a user requires a customized internet stack, that user simply aggregates the custom class to the Node instead of the default IPv4-based stack, and there is no ambiguity or confusion over which is present.

- *Packets:*

The NS-3 approach to packet storage is extremely different from NS-2's. A packet consists of a single buffer of bytes, and optionally a collection of small tags containing meta-data. This means that when a packet is received, or even when it is passed around internally in a given node, there is no easy to way to determine what headers or data is or is not present, or where any present data is located in that buffer. The idea is that the buffer corresponds exactly to the stream of bits that would be sent over a real network.

All information that is to be added to the packet is done by use of subclasses of either Header, which adds information to the beginning of the buffer, or Trailer, which adds to the end. These classes consist of whatever data storage is convenient when working with them, and several specific functions to write the data to or read it from the byte buffer

- *Nodes:*

An ns-3 Node is a husk of a computer to which applications, stacks, and NICs are added. This means that it can support key interfaces such as sockets API and IP/device driver interface (in Linux) and support the reuse of kernel and application code.

- *Performance:*

NS-3 offers substantially and consistently superior performance both in required computation and memory footprint compared to NS-2. The source of the memory footprint gains are fairly straightforward, as discussed above the aggregation system prevents unneeded and sometimes very large parameters from being stored when they are unnecessary, and packets do not contain large amounts of meta-data and unused, reserved header space.

<u>Interfacing</u>

Inputs/Outputs:

- Create a bunch of C++ objects
- Configure and interconnect them
- Each object creates events with Simulator: :Schedule
- Call Simulator::Run to execute all events

So at the end, NS-3 allows to report events across non-contiguous layers and there is also the possibility to have a visualization status (NS-3-PYVIZ).

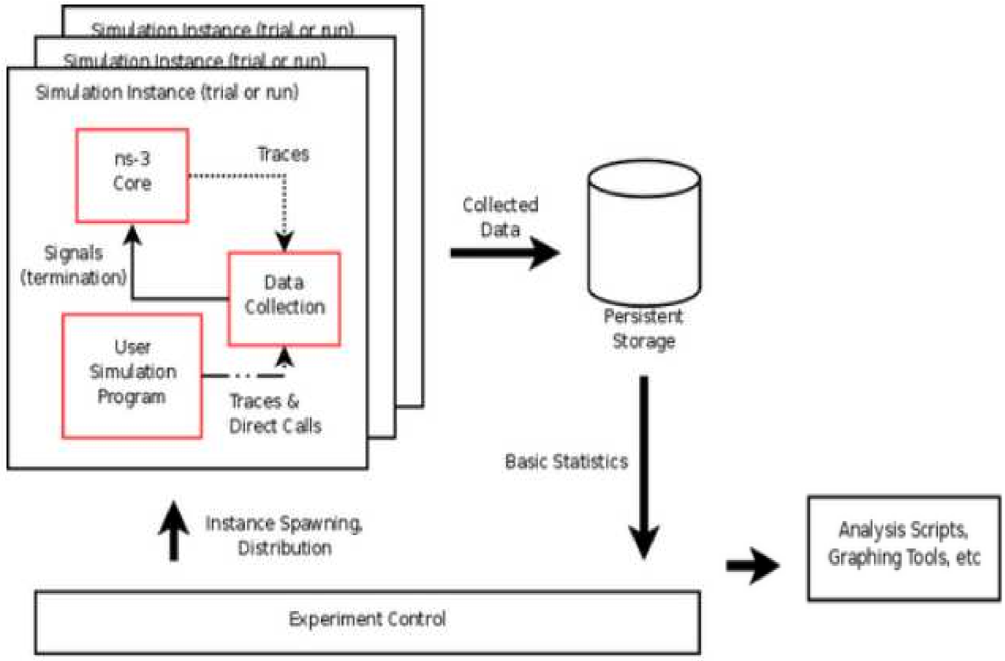


Figure 7.13 : Simulation Framework

Language:

NS-3 can be developed entirely in C++. This also makes NS-3 somewhat more accessible to new users, as concerns about interfacing between multiple languages are eliminated, and only knowledge of C++ is required. A simulation script in NS-3 is written as a C++ program with a main() function, which is not possible in NS-2. NS-3 does include limited support for Python in scripting and some related high-level tasks such as visualization.

OS:

Linux and Windows (cygwin, Python, mercurial)

Intellectual Property:

NS-3 is targeted primarily for research and educational use. It is free software, licensed under the GNU GPLv2 license, and is publicly available for research, development, and use.

- ***Omnet++/Castalia***

Function

Omnet ++ is a base of simulators with discreet events, conceived for the simulation of communication networks. Omnet ++ supplies the engine of simulation (scheduler, architecture, API, human-machine interface, etc.) on whom can be added libraries of models.

Underlying Methods

Castalia is a set of models built on the engine of Omnet++ and dedicated to the simulation of sensors networks. Castalia took recently an orientation towards BAN. If Omnet ++ allows to simulate all the layers of the model OSI, Castalia especially emphasizes the lower layers, in particular the MAC and the physical layers. It supplies advanced channel models which can receive in entrance a mapping of the mitigations. It considers as well certain aspects of the electronics (drift of clock, consumption).

As regards the MAC layer for BAN, the simulator has at the moment only a the IEEE 802.15.4 model, but it can take in entrance a model of path loss channel resulting from measures. In the absence of a standard IEEE 802.15.6, however, it is not surprising that this protocol is not integrated into the simulator.

Certain protocols of routing are included but their support remains limited (for sensors networks, for example only the CTP is proposed, but no model of RPL is integrated). It is capable of realizing simulations at typical time of the order of a few seconds with a few minutes according to the number of nodes and the simulated time.

Interfacing

During a simulation, Castalia creates a track of the events on frames (sending, error channel, collision, queue loss, reception, etc). This track is a simple file text which it is possible to interpret easily. Castalia also supplies aggregate reports (loss rate, etc.) and it is possible to modify its format.

Omnet ++ and Castalia are written in a modular way in C++ and impose their architecture. Some modules of interface exist with the other tools of simulation (vehicular, electric domains), thus it is possible to create such an interface if the need arises.

Programming Language

Omnet++ and its libraries of models are written in C++.

OS

Omnet++ works on any Unix systems or approaching (Linux, Mac OS X, cygwin).

Intellectual Property:

Castalia is developed by the NICTA (National ICT Australia) and it is distributed free of charge for all the academic users (and more widely for quite user non-profit). Omnet++ is too distributed under public academic license.

- *WSim*

Function

WSim is a full system emulator for micro-controller based platforms. WSim uses an emulation loop that is byte precise and cycle precise on instruction boundaries. This behavior allows debugging and analyzing application using the same firmware as the target platform (WSim currently support many Ti MSP430 micro-controller models as well Chipcon radio chips and several other devices).

This simulator should be interesting to the CORMORAN project for too many reasons. First of all, WSim is supported for full system and environment simulation. It is also a support for energy consumption simulation and for nodes advanced debugging modes.

Moreover, the simulator can be used in standalone mode for debugging purposes when no radio device is used in the design (or when the radio simulation is not needed). And finally, its interface can works with the WSNet simulator to perform the simulation of a complete sensor network.

Underlying Methods

The simulator is able to perform a full simulation of hardware events that occur in the platform and to give back to the developer a precise timing analysis of the simulated software.

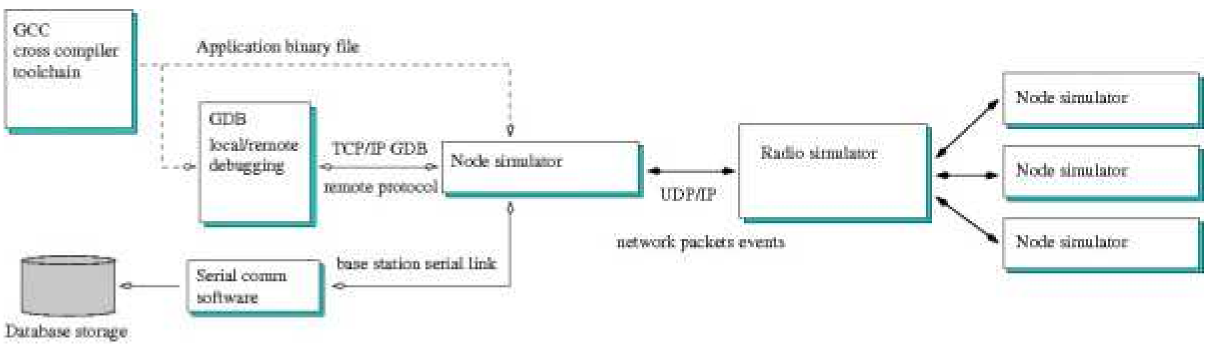


Figure 7.14 : Progress of a simulation in WSim (http://wsim.gforge.inria.fr)

The native software of the node can be used in the simulator without the need to reconfigure or recompile the software. It uses a classical GCC cross-compiler tool-chain and the simulation is not attached to any particular language nor operating system. It is thus able to debug and evaluate performances of the full system at the assembly level. A precise estimation of timings, memory consumption and power can be obtained during simulation.

WSim can easily use 10 to 15 nodes in a simulation on a reasonable machine. The CPU load will mainly depend on the wireless network activity you are simulating.

Larger simulations can also be easily built using simulation distribution across several machines on a local network. The distributed parallel simulation technique used between WSim nodes and WSNet relies on multicast IP in order to be able to distribute the simulation on a set of machines. If it is necessary to simulate a large number of nodes then it should dedicate a processor to the WSNet program as it will be the central synchronization point for all nodes and thus be on the critical path concerning performance issues.

Interfacing

No explicit information available yet.

Programming Language:

C

OS:

WSim should compile and run on any Unix-like platform and Windows using cygwin or mingw32.

Intellectual property:

The WSim (http://wsim.gforge.inria.fr/) simulator is partly under the CeCILL Free Software License Agreement and the GNU GPLv2 License agreement. Both licenses are open source and complient to the FSF open source licensing terms.

7.3.4 SENSORS-ORIENTED SIMULATORS

Besides radio considerations, simulators are widely used in the field of wireless sensor networks. Besides classical packet-level network simulators, there exist a few simulators that are specific to the sensors world. These simulators often render quite well embedded operating systems or hardware aspects but have an approximate representation of the wireless channel. They therefore behave more like emulators than simulators.

- ***TOSSIM***

TOSSIM (http://www.cs.berkeley.edu/~pal/research/tossim.html) runs TinyOS applicative code on large-scale networks. It simulates the network stack down to the physical layer but does not provide any accurate representation of the modulation, coding or wireless channel.

- *Cooja*

Cooja (http://www.contiki-os.org/) is the equivalent of TOSSIM for the Contiki Operating system. It is based on Java and uses JNI to run native Contiki code. It therefore includes a full Contiki operating system implementation, including the μIP minimalistic IPv6 stack. It can be interfaced with MSPSim to run MSP430 microcontrollers bytecode.

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