PROGRAMME
INFRASTRUCTURES MATERIELLES ET
LOGICIELLES POUR LA SOCIETE
NUMERIQUE – ED. 2011

Key Words: *Game Theory, Wireless Sensor Network, Cooperative Communications, Body Area Networks*

Project Acronym	CORMORAN (ANR 11-INFR-010 01)
Document Title	D3.1 Enhanced Communications through Cooperation
Contractual Date of Delivery to ANR	M30 (30/06/2014)
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Participants	INSA, TPT, UR1
Related Task(s)	T3
Related Sub-Task(s)	T3.1
Security	Public
Nature	Technical Report
Version Number	1.1
Total Number of Pages	72

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Table of Modifications

Version Nb	**Nature of Modifications**	**Responsible Person**	**Date of Modification**
V0.1	Edition of the ToC	A.G. and C. G. (INSA)	28/03/13
V0.2	Update of the ToC and edition of section 1	A.G. (INSA)	30/06/13
V0.3	Edition of the sections 1.2 and 2	A.G. (INSA)	29/07/13
V0.4	Update of section 2. Edition of section 3 and 4	A.G. (INSA)	5/08/13
V0.5	Update of section 3 and 4	A.G. (INSA)	12/10/13
V0.6	Update of section 3 and 4. Edition of section 5	C.C (TPT), A.G. (INSA)	25/03/14
V0.7	Update of section 5. Edition of section 6	C.C (TPT), A.G. (INSA)	26/04/13
V0.8	Update of section 6.	A.G. (INSA)	20/06/13
V0.9	Edition of introduction	A.G. (INSA)	25/06/13
V1.0	First complete version	A.G. (INSA)	27/06/13

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ABSTRACT

The emergence of the *Wireless Body Area Networks*, such as small wearable wireless sensors, is on the verge of fulfilling new market needs in a variety of applications such as emergency and rescue, healthcare, personal communications, entertainment, multimedia, fashion and clothing applications... In the past few years, much of the research in the area of BAN has focused on issues related to wireless sensor designs, sensor miniaturization, low-power sensor circuitry, signal processing, and communications protocols. But further research should also consider the study of Ultra Low Power consumption, low complexity and low cost, e.g. *Impulse Radio - Ultra Wideband.*

In this context, the research community recently increased the interest on many coherent aspects, including physical (PHY) layer, medium access control (MAC) layer, network layer, channel modeling, security, etc.

However, some classical issues in the propagation channel, e.g. shadowing and fading, cannot be compensated properly by the *time, frequency or spatial diversity.* Indeed, because the *channel is slowly varying* (slow fading), time diversity may lead to a significant latency. Frequency diversity can be interesting if the frequency bandwidth is small enough compared with the available bandwidth. Furthermore, if strong shadowing effects are observed, neither time nor frequency diversity is efficient. Spatial diversity is more appealing, but putting several antennas on the same node seems unrealistic because of size and power consumption constraints.

For these reasons, the cooperative schemes could be the answer 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*).

(Livrables D.1.4.1 D 3.1 et D 2.1BANET / D1.1 CORMORAN)

1. INTRODUCTION

1.1. SELECTED APPLICATION SCENARIOS AND RELATED NEEDS

At the beginning of the CORMORAN project, it was defined the desire to offer new technological solutions relaying on cooperative wearable networks. At first, it was identified several application fields (e.g. augmented group navigation, wireless network optimization, distant health care, monitoring, rescue systems) that could be interesting for different industrial or institutional actors. However, in order to focus and understand the actual needs of potential users and/or integrators of the CORMORAN technology, it was built up and disseminated a questionnaire to various professional entities, identified in the ecosystem of the project partners (See CORMORAN Deliverable D1.1 Section 2).

The results show one group of users interested in ***large-scale individual motion capture*** (LSIMC), whereas another group is interested in ***coordinated group navigation*** (CGN).

1.1.1 LARGE-SCALE INDIVIDUAL MOTION CAPTURE

The group interested in LSIMC is looking for alternative stand-alone solutions to achieve Motion Capture (MoCap) function autonomously on a larger scale, 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). For this subset we identified also three sub-scenarios:

- ***Relative On-Body Nodes Ranging :*** In this first sub-scenario, one considers a set of mobile wireless devices placed on one single body, with unknown positions. The objective is then uniquely to estimate the relative Euclidean distances separating those nodes.

- ***Relative On-Body Nodes Positioning:*** In this second sub-scenario, we consider two categories of wireless devices placed on a body: **Simple mobile nodes** with unknown positions 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 under body mobility.

- ***Absolute On-Body Nodes Positioning:*** This last sub-scenario is the same as the previous one, but the coordinates system is external to the body. We may thus consider the deployment of some fixed wireless elements at fixed known locations in the environment as **anchor nodes.** The coordinates of the nodes placed on the body is now time-variant in a ***Global Coordinates System (GCS)*** under pedestrian mobility. And they also depend on the body attitude, the motion direction et/or speed.

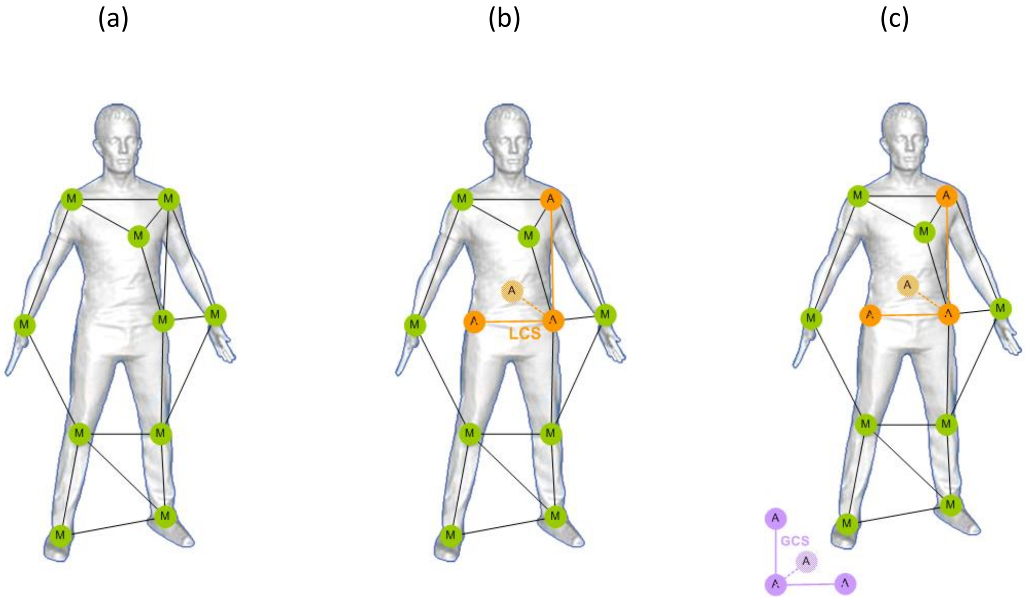

Figure 1-1: Examples of relative on-body nodes ranging (a), relative on-body nodes positioning (b) and absolute on-body nodes positioning (c) configurations for large-scale single-user motion capture applications.

1.1.2 COORDINATED GROUP NAVIGATION APPLICATION

This group interested in CGNA, is seeking for solutions to improve the availability and accuracy of the coordinated group navigation functionality within the wearable BAN deployed on each mobile agent (including benefits through inter-body or off-body interactions). For this group, it was identified two sub-scenarios:

- ***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.

- ***Absolute Body Positioning in a Group***: In this sub-scenario, one must retrieve the absolute coordinates of several users belonging to the same mobile group, with respect to an external GCS. For this, we may consider the use of fixed and known elements of infrastructure around. With this, the presence of multiple wearable on-body nodes is expected to enhance navigation performance by providing spatial diversity and measurements redundancy and possibly, further cooperative on-body information exchanges.

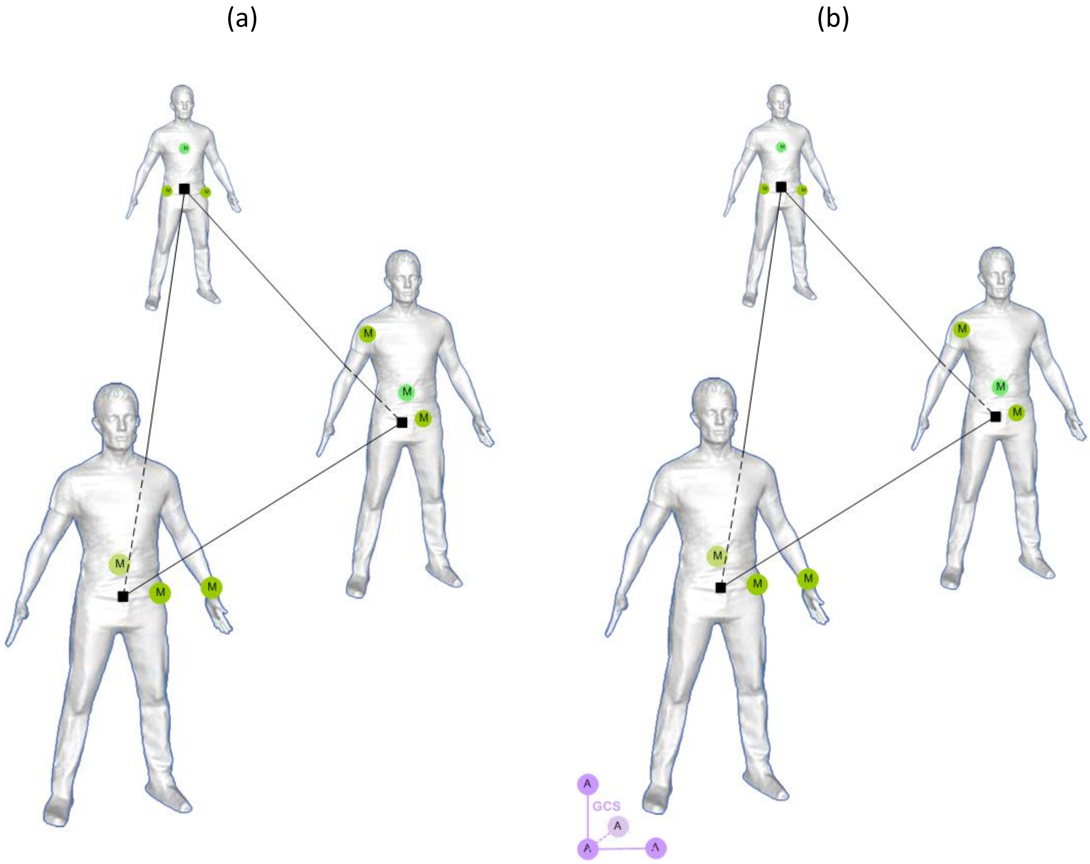

Figure 1-2: Examples of relative body-to-body ranging (a) and absolute body positioning (b) configurations for coordinated group navigation applications.

1.2. TECHNICAL REQUIREMENTS

At the beginning of the CORMORAN project, it was defined the desire to offer new technological solutions relaying on cooperative wearable networks. At first, it was identified several application fields (e.g. augmented group navigation, wireless network optimization, distant health care, monitoring, rescue systems) that could be interesting for different industrial or institutional actors. However, in order to focus and understand the actual needs of potential users and/or integrators of the CORMORAN technology, it was built up and disseminated a questionnaire to various professional entities, identified in the ecosystem of the project partners (See CORMORAN Deliverable D1.1 Section 2).

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

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

2. COOPERATIVE COMMUNICATIONS FOR WBAN

2.1. OVERVIEW

Cooperation is the process of working or acting together. It stands as the opposite of competition where each agent looks for leadership in a contest. Recently, such concepts have been adopted from social sciences and economics to constitute a major research area in wireless communication networks. The idea of employing cooperation in wireless communication networks has emerged in response to the user mobility support and limited energy and radio spectrum resources, which pose challenges in the development of wireless communication networks and services in terms of capacity and performance.

In the CORMORAN context, the performance of communication protocols for Body Sensor Networks (BSN) or Body Area Networks (BAN) can dramatically be reduced due to the several channel variations in time domain. In fact, the body's absorption of RF energy and the movement create temporal variations of the channel which produces great loss of packets. One way to avoid this problem is by implementing cooperation mechanisms between the nodes of body area networks. In proposals such as [1][2][3][4] [5], it is possible to appreciate the advantages of cooperative networks as a solution for communications networks in harsh transmission environments sensing (e.g. temperature, heartbeat, blood pressure …).

Generally, the BAN nodes should communicate with the whole network and transmit information to a common sink, in a star topology. While this setup is usual in wireless networks, the high instability of the BAN radio channel and the proximity of the body make classical communication protocols inefficient. These networks are further constrained by the low transmission power required for both battery life and health concerns. Opportunistic cooperation techniques are of great interest in such environment to ensure reliable communications.

Moreover, we can find three cooperation scenarios in literature [6]. In the first scenario, cooperation among different entities is employed to improve the wireless communication channel reliability through spatial diversity [7][8]. In the second scenario, the system throughput is improved via aggregating the offered resources from cooperating entities [9] [10]. Finally, cooperation is used to achieve seamless service provision [11] [12] [13][14].

Early research on cooperation focuses on developing strategies at the physical layer to support such a cooperative transmission [1] [5]. However, in order to achieve such cooperation, the design of efficient cooperative protocols at different layers is of great challenge, especially in BAN. In fact, without proper modification of networking protocols at the higher layers, the achieved cooperation gain may not be significant.

2.2. GENERAL REQUIREMENTS

In the last years, BANs are the new object of interest for many researches because they can offer innovative advances on ***lightweight, small-size, ultra-lower-power and monitoring wearable and/or implantable sensors*** [15]**.** In the CORMORAN context, in order to achieve the applications of group navigation and capture large-scale human movement, it is necessary to design and evaluate new and innovative communication protocols adapted to the specific requirements of personal wireless cooperative networks.

2.2.1 WSN AND WBAN DIFFERENCES

Although BANs share many challenges and opportunities with general wireless sensor networks (WSNs), many protocols and algorithms proposed for WSN are not well adapted to the specific requirements of BAN [16] [17]. To understand this point, the differences between WSN and BAN are listed as follows:

- **Deployment and density:** The number of sensors deployed depends on the scenario and application. Typically, WSNs are insensitive to placement error. However, some nodes can be physically unreachable after deployment, which requires that more nodes be placed to compensate for node failures. This creates a dense nodes network and homogeneous. By comparison, BANs are **placed strategically** on the human body and the **node's physical reachability has to be** as easy as possible. Moreover, BANs exhibit **heterogeneity** because of application constraints and sensor requirements.

- **Topology:** WSN can work with **different architectures with or without aggregator** or coordinator. In the other hand, a WBAN may continuously monitor a patient's vital information for diagnosis and prescription or it can be used for multimedia and gaming applications. The information of these applications could be exchanged by different topologies such as star, tree, and mesh topologies. However, the most common is **a star topology** where the nodes process and transfer data to a central coordinator.

- **Communication:** WSNs typically communicate over radiofrequency (RF) channels. Unlike WSNs, WBASNs are challenged by the body shadowing, which, coupled with movement, causes significant and highly variable path loss. Given the high instability and shadowing of the channel (**body motion, shadowing**), an **efficient relaying capacity is also needed** to meet a good reliability. A cooperation and relaying technique could be a good solution to outperform this first evaluation and thus **opportunistic relay** transmission could take advantage of long channel shadowing.

- **Quality of Service:** collision avoidance and network coordination will be essential to maintaining a good performance in both WSNs and BANs. Moreover, low and high rates are possible to reach depending on the application. However, t**he failure of one BAN sensor could threaten life**. BANs must be reliable to control or help assess life-critical physiological events. That's why an opportunistic cooperative transmission could be a solution but it also has to ensure the communication in real time.

- **Energy supply:** WSNs need to maximize battery life-time at the expense of higher latency. By comparison, in BANs **ultra low lower and energy harvesting is needed** to improve reliability and energy consumption. For this purpose, cooperative strategies at the MAC Layer can be interesting to increase transmission rate and throughput by reducing transmission power and improving spatial reuse[6].

2.2.2 ON BODY, BODY-TO-BODY AND OFF BODY GENERAL REQUIREMENTS

As we discussed before, WSN and BAN present differences in terms of requirement and behavior which makes that many existing protocols do not be useful for BAN. Moreover, BAN has a big challenge at architecture level, because BANs may interface with other wireless technologies in or around a human body. In literature, we can find three kind of topologies that may coexist at the same time: **On-Body, Body-to-Body and Off-Body**. These architectures have some general requirements but also particular conditions that demand innovative strategies to ensure reliable communications. In the CORMORAN context, we would like to ensure the cooperative localization with cooperative strategies on the uppers layers. However, many cooperative protocols have been proposed for WSN and there some specific characteristics of BAN that make these protocols obsolete. The general requirements are listed as follow:

At the application level:

- **Flexibility:** Non-invasive sensors must be used to automatically monitor physiological readings, which can be forwarded to nearby devices.

- **Ease of use:** Wearable BAN nodes will need to be small, unobtrusive, ergonomic, easy to put on, few in number, and even stylish

At the hardware level:

- **Cost-effective:** With the increasing demand of body sensors in the consumer electronics market, more sensors will must be mass-produced at a relatively low cost

- **Robustness:** BAN must be small, thin non-invasive, wireless-enabled, and must be able to operate at a very low power level.

From the communication perspective which is our main object of study (Task 3: New Cooperative Functions for Enhanced Communication and Location), BANs must assure:

- **Effectiveness and efficiency:** the signals that body sensors provide must be effectively processed to obtain reliable and accurate physiological estimations

- **Safety:** Wearable and implanted sensors will need to be bio-compatible and unobtrusive to prevent harm to the user. Safety-critical applications must have fault-tolerant operation with security measures to prevent the unauthorized access or manipulation of the system

- **Reliability:** it is imperative to design appropriate PHY and MAC protocols to ensure higher network capacity, energy efficiency, and adequate quality of service (QoS)

For this purpose, cooperative techniques may be the key to improve the general communication of the BANs at the three level of architecture. In the CORMORAN context, the architectures on-Body, Body-to-Body and off-Body may cohabit together to ensure cooperative localization for the **large-scale individual motion capture (LSIMC)** and the **coordinated group navigation (CGN)** applications. Therefore, each of these architectures has particular requirements from the cooperative point of view:

- For the LSIMC scenario, we need to accept the existence of three kinds of nodes: **On-Body nodes, On-body anchors and infrastructure anchors**; and two kinds of links: **Intra-BAN links and Off-Body links** (Figure 1-1). Intra-BAN links connects On-Body nodes with unknown positions and On-Body anchors which are attached onto the body at known and reproducible positions. Thus, this relation defines a **relative localization** to a **Local Coordinate System (LCS)** for a motion caption at the body scale. In the other hand, Off-Body links represents the connection between all On-body nodes/anchors and infrastructure nodes to perform an **absolute localization in**

a Global Coordinate System (GCS) for a navigation and motion caption at the building scale**.**

For the first case, relative localization may have the biggest problem of reliability. In fact, as some nodes are positioned on body parts with a constant mobility (e.g. hands, legs and head) we may lose the communication links with the anchors nodes. Moreover, body shadowing and intra-nodes interference are another problem for communication for these nodes. That's why relaying strategies and opportunistic communications may provide the localization add-on.

In the second case, absolute localization will have mostly a problem of interoperability. In fact, the range of On-Body nodes, working with the UWB technology, may not be sufficient to communicate with off-body nodes. Thus, the On-Body central node may work with two technologies, NB and UWB, and this may need a better synchronization, power consumption and cooperative strategies for transmission.

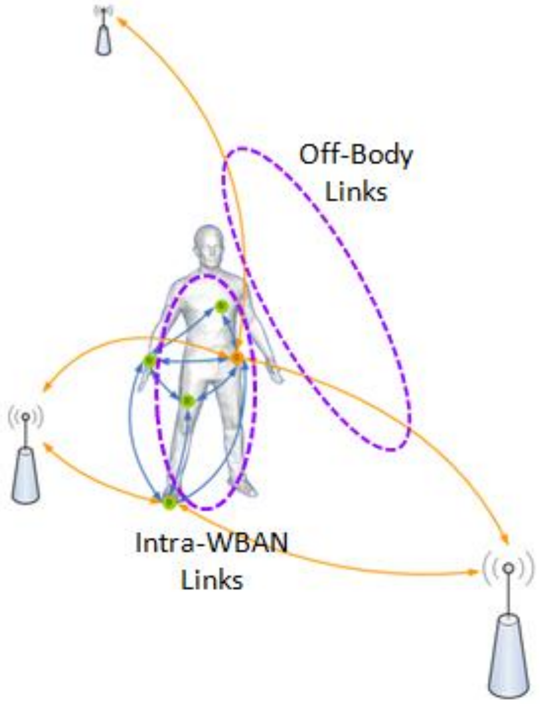


Figure 2-1: Localization types and definitions of the LSIMC scenario

- For the CGN scenario, we define the existence of five kinds of nodes: **On-Body nodes, On-body anchors, Inter-body nodes, Inter-body anchors and infrastructure anchors**; and three kinds of links: **Intra-BAN links, Inter-BAN links and Off-Body links** (**Figure 2-2**)**.** Intra-BAN links are the same as the LSIMC scenario. Inter-BAN links connect inter-body nodes with unknown positions and inter-body anchors to ensure a **relative Body-to-Body ranging** in a Group. Finally, Off-Body links represents the connection between all On/Inter-body nodes/anchors and infrastructure nodes to perform an **absolute Body positioning** in a group.

Compared to the LSIMC scenario, the CGN scenario encounters the same problems such as mobility, body shadowing and interference on intra-body, and interoperability on inter-body and off-body. However, in this scenario we can also find interference between inter-nodes/anchors. To reduce this problem, some cooperative and scheduling strategies may be used.

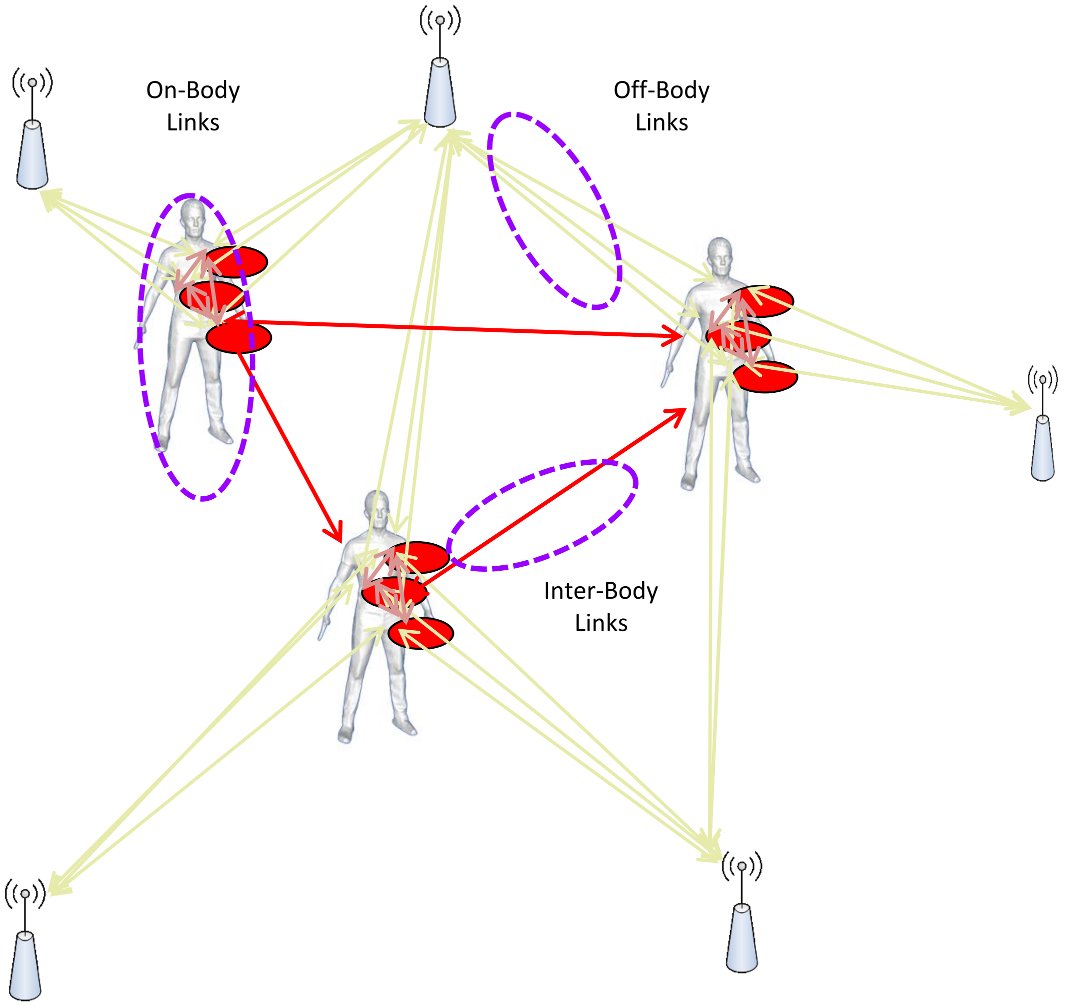


Figure 2-2: Localization types and definitions of the CGN scenario.

2.3. CANONICAL ARCHITECTURES

In Wireless Communication systems, the traditional way to communicate is possible by the point to point channel, in other words, is the association between a user and the base station. **Cooperative communication** [4] can be viewed as an architecture where a user's **communication link is enhanced by the assistance from relays or other users** to forward the information to a specific destination. This communication can be possible with different **relaying techniques and parameters** [1]**.** The choice of these techniques must be well studied, because it has a direct impact on the architecture and protocol behavior:

- **Traditional or distributed Space-Time relaying:** In the first case, traditional relaying takes an **arbitrary number of serial or parallel relays** to deliver the message from the source towards the destination. By comparison, a distributed deployment is composed by an **arbitrary number of synchronized nodes** using the space-time techniques to deliver a message.

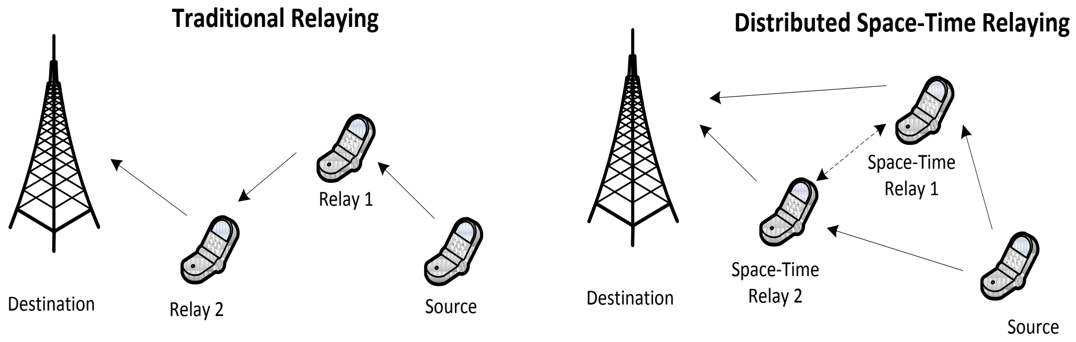


Figure 2-3: Exemplification of traditional and distributed space-time relaying

- **Degree of cooperation:** Supportive relaying can be achieved by placing a node relay between the source and destination to assist in the communication diversity. Therefore, cooperative relaying is an extension for supportive relaying, for this architecture we need at least two nodes cooperating between them as relay to boost their communication at the same time.

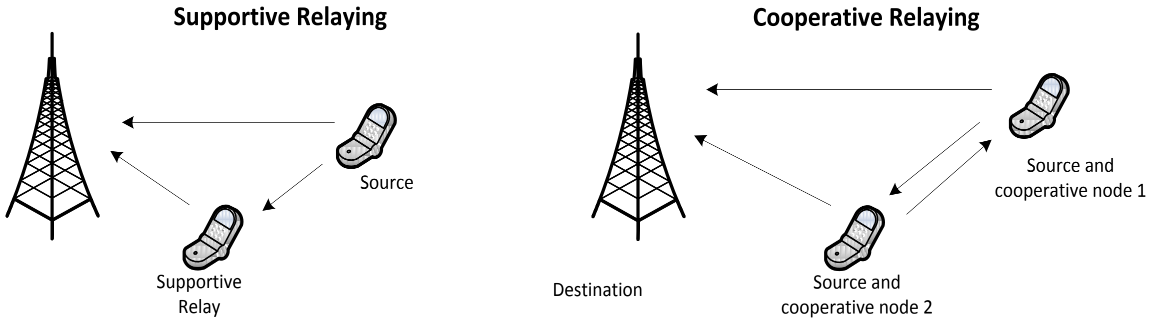


Figure 2-4: Canonical relay architectures with different degree of cooperation

- **Transparent or regenerative relaying:** In the transparent relaying, **the relay amplifies the received signal before transmitting**. These operations correspond to the analog domain such as phase shifting or power amplification. In the regenerative relaying**, the relay has to change the information on the message** by making operations in the digital domain such as channel coding or data compression. For this, the message is decoded, re-encoded and then retransmitted to the destination. These two relaying techniques will be more discussed in chapter 3.

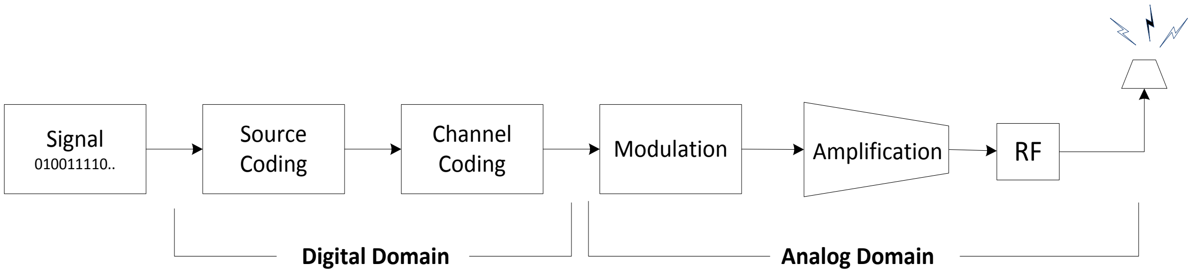


Figure 2-5: Exemplification of the analog and digital domain on a typical PHY Layer channel transmission where transparent and regenerative relaying is applied.

- Moreover, the choice of the number of relaying stages in **dual-hop or multi-hop** is crucial. As such, relays can be connected in series or operated in parallel. **Increasing the number of serial** relaying nodes increases the **path-loss gain**. While **increasing the number of parallel** relaying nodes increases the maximum **diversity gain**.

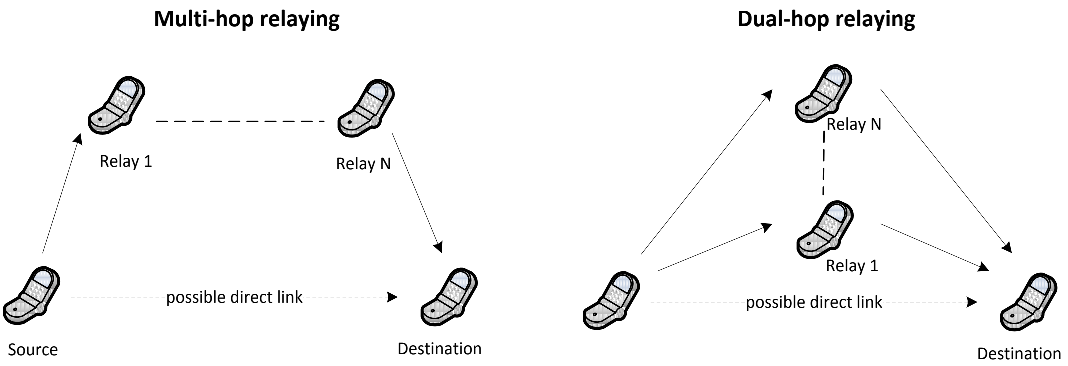


Figure 2-6: Exemplification of multi-hop and dual-hop relaying.

- Finally, **the availability of direct link** between source and destination or various relaying stages can facilitate data transmission. **Without the direct link**, only **path-loss gains** can be achieved; **with the direct link**, the maximum **diversity gain** can also be increased.

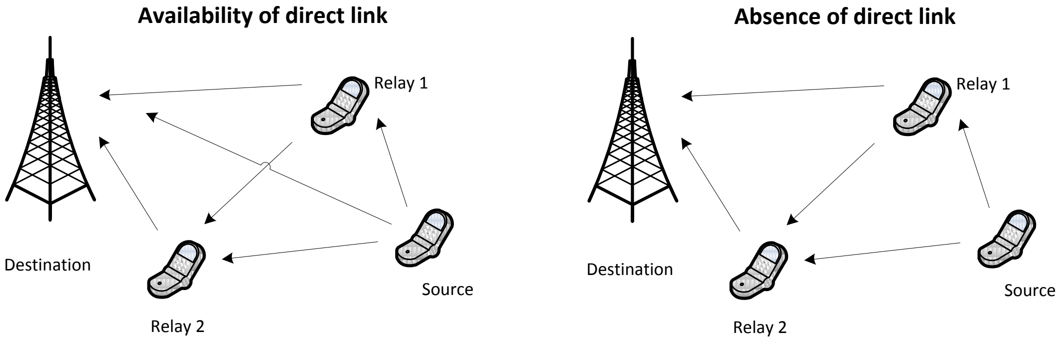


Figure 2-7: Exemplification of multi-hop and dual-hop relaying.

The combinations of these canonical cooperative architectures have a different effect on the performance and behavior of the network. The choice depends on the scenario or application that we want to accomplish.

In the CORMORAN context, we could expect that a dual-hop relaying is more suitable for the on-Body case, but in the case of Body-to-Body applications, it may be more appropriate to use multi-hop relaying nodes. Furthermore, we can suppose that the traditional relaying is more realistic for BANs because of its broadcast transmission nature. By comparison, distributed space-time relaying is difficult to achieve on BAN for the reason that we can find decoding errors at relays, variations in different parts of codeword or different rate/power allocations at the source and relay. In addition, distributed space-time relaying needs complex schedulers and tight synchronization which increase overhead [1].

Moreover, the availability of direct link is an important issue for BANs, since we can find several disconnections due to the body shadowing or the body movement, we need cooperative strategies between the nodes to increase the path-loss and diversity gain. Finally, the choice between transparent or regenerative relaying on the physical layer depends on the suitable complexity for the solution and this has to be supported with cooperative design for the upper layers (MAC, NWK and application).

2.4. PROS AND CONS OF COOPERATIVE COMMUNICATIONS

Although partially discussed before, the advantages and disadvantages of the canonical cooperative architectures for BAN are summarized below.

2.4.1 ADVANTAGES OF COOPERATION

Like any other technique, cooperative communication has advantages but also disadvantages. Among these advantages we quote:

- **Performance Gains:** The performance gain is assured due to a reduction in transmission caused by disturbances of the radio channel. This results in an increase of the channel capacity and improved quality of communication.

- **Infrastructure-Less deployment:** Sharing neighboring antennas as relays increases the utilization of equipment, especially for networks with minimal infrastructure.

- **Reduced Costs:** Reuse of antennas avoids the deployment of new nodes on the network and thus reduces network costs.

- **Balanced Quality of Service:** relaying allows balancing fairness on resources to improve capacity and coverage in shadowed areas. This could be achieved with game theory algorithms that propose cooperative strategies for nodes and users.

2.4.2 DISADVANTAGES OF COOPERATION

In exchange, cooperation raises several challenges. The involvement of other nodes in communication requires the resolution of several issues:

- **Timing:** Several cooperative communication protocols use several relays at the same time. This requires a high level of synchronization which complicates the protocol performance. Any gains due to cooperation at the physical layer dissipate rapidly if not handled properly at medium access and network layers.

- **Selection of relay:** Each cooperative protocol must provide a mechanism to select the best relay among neighbors in the network. This could take a long time of decision which increases latency and overhead.

- **Traffic control:** the use of cooperation increases traffic control. Cooperative protocols require additional traffic management and synchronization for the relay selection process.

- **Complex schedulers:** for a system with many nodes and relays, relaying requires more sophisticated schedulers since not only traffic of different nodes and applications needs to be scheduled but also the relayed data flows.

The questionably largest problem in research on cooperative relaying systems is the evident lack of a well-accepted taxonomy. Some first steps have been done through past journal papers published in the area where all conclude that is needed a careful system design to realize the full gains of cooperative relaying systems and to ensure that cooperation does not cause deterioration of the system performance.

2.4.3 COOPERATION SYSTEM TRADEOFFS

We further discussed some advantages and disadvantages of using cooperation. Generally, these factors essentially lead to tradeoffs that generate several discussions on the choice between the different techniques to achieve a good performance. Such tradeoffs are similar at different levels of the network but:

At the architecture level, as we discussed before, the designer must take a decision depending on the suitable complexity for the cooperation strategy:

- **Transparent versus Regenerative Relaying**
- **Traditional versus Distributed Space-Time Relaying**
- **Dual Hop versus Multi Hop**

At the system level, we have the choice of the suitable performance for the solution:

- **Coverage versus capacity:** cooperative system allows more coverage by the cost of capacity deterioration. Equivalently, this is traduced by increasing diversity or multiplexing gain.
- **Algorithmic versus hardware complexity**
- **(Interference – Cost – Easy Deployment) versus Performance**

At the physical layer, it is suitable to increase gains and for that we must consider:

- **Outage versus Data Rate**: these performance gains will be more explained on the next chapter.
- **Diversity versus Multiplexing Gains:** increasing the multiplexing gain led the increase of the transmission rate at the cost of the performance of the system. By opposite, increasing the diversity gain reduce the probability of outage.

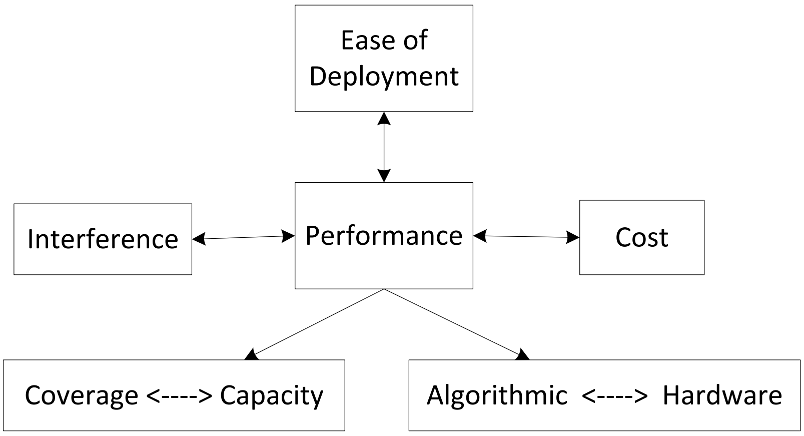


Figure 2-8: For a specific performance, a choice must be taken to improve coverage or capacity, algorithmic or hardware complexity. Moreover, Performance can be traded with interference, ease of deployment and cost.

3. COOPERATIVE COMMUNICATIONS FOR THE PHY LAYER

3.1. OVERVIEW

In Section 2, we introduce the definition of cooperative communication and its general pros and cons. We also explained that cooperative strategies can be achieved by the PHY, MAC and NWK layers leading to different improvements for better reliable communication. In the context of Wireless Body Area Network systems, cooperation means resource sharing and coordination among different body nodes in order to enhance transmission quality. Cooperative communications at physical layer yields several gains in diversity, capacity and rate outage. For this purpose, these gains are quantified by considering the properties of the wireless channel [18] under cooperative scenarios [1].

Among the different techniques proposed in literature, we can find the theory of Multiple Input Multiple Output (MIMO) channels [19] to increase the number of antennas on transmission. However, in the case WSN and specially WBANs, the nodes are not large enough to support multiple antennas, which make infeasible the MIMO approaches. The reliability of communications then passes mainly through cooperative approaches between these nodes [20] e.g. relaying techniques. In [7], we can see a general evaluation of different cooperative protocols, such strategies include transparent and regenerative relaying e.g. Amplify and Forward (AF) [21], Decode and Forward (DF) [1] and Compress and Forward (CF) [3]. In these methods, the relay nodes have to choose best level to perform cooperation i.e. transmitting either amplified signal (AF), decoded and re-encoded message (DF) or retransmit the source message with channel coding (CF). For these strategies, the source node and relaying node need to know the channel coefficients to perform an optimal decoding at the destination node. For that, the channel estimation and exchange of coefficients is important for cooperative techniques at PHY layer e.g. in the case of WBAN where the channel coefficients are time variant as explained in Deliverables 2.2, 2.3 and 2.4. However such techniques increase the complexity at destination nodes, since it need a more sophisticated receiver to store the different relayed packets and combine them for decoding (Maximal Ratio Combining techniques) [3].

In this section we will discuss about the benefits and disadvantages of cooperation at the PHY layer. First, in chapter 3.2 we introduce the performance bounds to quantify the cooperative gains. In chapter 3.3, we present the different relaying protocols proposed in literature. Finally, chapter 3.4 shows the challenges to consider in the adoption of cooperative strategies at PHY Layer for the CORMORAN scenarios.

3.2. COOPERATIVE PERFORMANCE BOUNDS

In literature, we can find several metrics of communication performance to quantify the gains, other than the packet error rate. As we explained on Deliverables 2.1, 2.2, 2.3 and 2.4, the links on WBAN are affected by Pathloss, the Shadowing and the Fading and when considering cooperative schemes we can obtain several gains [18] based in the Signal Noise Ratio (SNR):

- **Pathloss Gain**: This is possible by splitting the propagation path. Because the aggregate pathloss of the split path is less than the pathloss of the full-path, we found a non-linear path-loss that yields transmit power gains.

  $$SNR \propto \frac{1}{x^n}$$

  x is the distance between Tx and Rx, n is the path-loss exponent. This is a significant gain and one of the main incentives for using cooperative techniques

- **Multiplexing Gain**: This gain corresponds to the maximum number of independent channels under favorable propagation conditions to send the information. The achievable rate is directly proportional to this gain.

  $$R = r\ \log_2 SNR + \ const,$$

  r is the multiplexing order min (m,n) and is equal to the degrees of freedom of the channel e.g. the number of independent channels over which information can be sent.

- **Diversity Gain:**. This can be achieved by providing additional independent copies of the same information via independent shadowing and fading channels. With this gain we can improve the performance of the system, such as the probability of error (Pe) or outage (Pout).

  $$P_{out}(R) = \frac{const(R)}{SNR^d}$$

  d is the diversity order m*n. Diversity gains improve the performance of the system, such as the probability of error P_e or outage P_{out}.

Moreover there is a tradeoff between Diversity and multiplexing gain, where each system will hence have a maximum diversity gain d_{max} at minimum multiplexing gain r_{min}, and conversely a maximum multiplexing gain rmax at minimum diversity gain dmin:

$$d = -\lim_{SNR \to \infty} \frac{log(P_{out}(r\ \log_2 SNR))}{\log SNR}$$

Moreover, this expression represents the tradeoff between reliability (diversity gain) against capacity (multiplexing gain) for a specific channel and system configuration. These leads into new performance metrics [3] based on capacity or reliability gains.

- **Capacity Gains** (Average Error Rate [Pe]): this gain is referred to the maximum rate achieved within a certain average error rate. This gain is present in the case of an ergodic channel where all fading states are traversed over the duration of a Shannon Codeword (fast fading).

$$C = E_g\left\{\log_2\left(1 + g\frac{S}{N} \right)\right\}$$

g is the instantaneous channel gain/power

- **Rate Outage Gains** (Probability of Outage [Pout])
  This gain is referred to the power saved (on average) within a certain outage probability in the system. This is gain is used in the non-ergodic channels where not all the fading states are traversed over the duration of a codeword (slow fading). The channel is in outage if the rate falls below a threshold information rate R; the corresponding outage event is $C(\gamma) < R$ or $\gamma < (2^R - 1)$

$C(\gamma) = \log_2(1+\gamma)$, $\gamma = g\,S/N$, $p_\gamma(\gamma)$ PDF of the SNR

$$P_{out} = \Pr\left(\gamma < (2^R - 1)\right) = \int_0^{2^R-1} p_\gamma(\gamma)\, d\gamma$$

In the case of WBAN, the shadowing is more influent on packet loss than the fading because of the high mobility of the body, which varies the mean state of the channel in the medium term and thus also affects the packet error rate. Therefore, calculating the packet error rate according to the average link quality is not representative and does not consider the probability that the system ends up in a bad state of shadowing for a considerable time. To overcome this problem, the outage probability of the packet error rate represents the probability that a system enters in a shadowing state which the packet error rate exceeds a defined threshold.

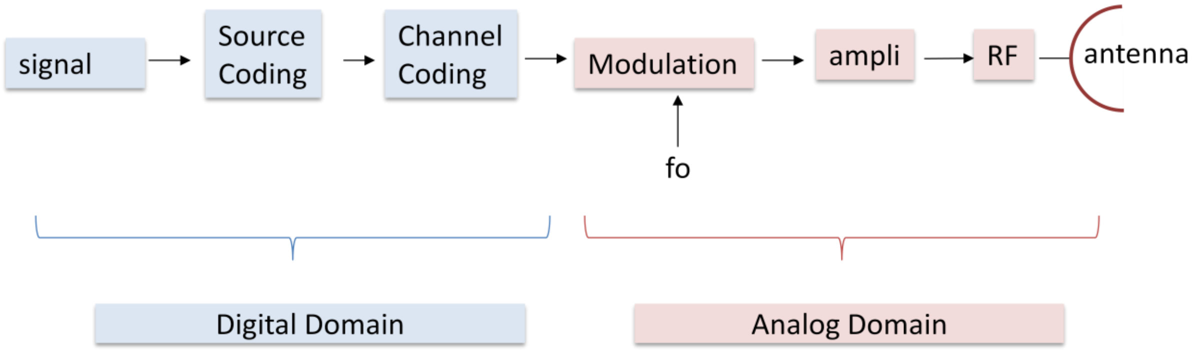
In [22], the author interested in the process of the packet error rate when the nodes in a WBAN had only partial knowledge of the channel. Hence, they define that the fading can be seen as a block fading since the coherence time is large enough to let the fading being assumed constant during a frame. Then, they limited the packet error rate block by the packet error rate under the assumption of fast fading and we extended the fading approximations to the fading block but leading to expressions requiring numerical integrations. The analytical approximation obtained was good for two usual expressions of modulation bit error rate. Therefore, [22] define an outage probability metric of packet error rate in the case where the nodes know only the long term average value of the transmission channels. Moreover, they extend the study for relaying channels in order to know how to allocate the capacity between the source and the relay and to identify where the gain of power control is important, depending on the scenario and the channel model considered.

3.3. RELAYING TECHNIQUES

As is well documented throughout available literature on this subject, a whole scope of different relaying methods exists today. They can be classified into two families of relaying protocols:

- **Transparent relaying:** In this scheme the relay amplifies the received signal before transmitting. This operations correspond to the **analog domain** (phase shifting, power amplification, …)

- **Regenerative relaying:** In this case, the relay have to change the information on the message by making operations in the **digital domain** (channel coding, …)



3.3.1 TRANSPARENT RELAY PROTOCOLS

Amplify and Forward (AF) [21]**:** In this technique, **the received signal is amplified** (with the fixed gain (FG) or variable gain (VG)) and **retransmitted** (the frequency can also be translated). This technique is of easy deployment and it introduces less delay to cooperate.

Moreover, the multibranch channel performs diversity gain at fading level. However, this technique needs a good algorithm for partner choice and communication may suffer of noise propagation. Thus, the Multihop fading channel performed worse than the direct channel unless the fading (and shadowing) gains are taken into account (pathloss gain). Furthermore, for this technique we can find four kinds of topologies that change the performance of the communication:

- Single-Branch Dual-Hop AF (Typical AF),
- Single-Branch Multihop AF (Traditional relaying, Serial relaying),
- Multibranch Dual-Hop AF (Opportunistic Relay, Parallel relaying)
- Multibranch Multihop AF (SISO Topologies for BAN, MIMO possible but not for BAN)

Linear-Process and Forward (LF) [22]**:** In this technique, the received signal uses a linear operation such as a phase shifting (in the case of BAN we can imagine a BPSK shifting for cooperate)**. Non Linear-Process and Forward (nLF)**: This technique is not fully explored [3], it performs a non linear operation to the received signal such as the nonlinear amplification which minimizes the end-to-end error rate (SNR optimized by minimum mean square uncorrelated error MMSUE). These techniques meet a simple Linear Operation with the possibility to achieve high rates (but needs higher forms of modulation such as 64 QAM) but adding an error rate (tradeoff). Moreover, these techniques need a good partner choice algorithm.

3.3.2 REGENERATIVE RELAY PROTOCOLS

Decode and Forward (DF) [1]**:** In this technique, the relay detects the signal, decodes it and re-encodes it prior to retransmission. Then the destination uses a Maximal Ratio Combining to recover the message. This technique reduces noise propagation by decoding codewords and it is possible to separate optimization of Source-Relay/Source and Relay/Source-Destination links. However, if there is more than one transmitter, relays are interference-limited. For this technique we can find two approaches:

- Fixed F-DF: the message is received at the destination if the combined received signal from the source and relay is successfully decoded. However, if the relay's transmission contains errors, the destination will recover the message from the combined signal.

- Adaptive A-DF: the difference is that if the source-relay transmission is unsuccessful (errors in the decoded message), the relay does not forward the message and the source may retransmit the message
- Selective S-DF: those relays that can decode the received signals correctly use DF protocols to forward the signals to the destination and the remaining relays will stay in an idle state. Thus, this approach is power safe energy and finds diversity gain for multibranch hops.

Estimate and Forward (EF) [23] **/ Detect and Forward / Demodulate and Forward:** In this technique, the received signal is amplified and down-converted to baseband; the representation of the signal is estimated with some detection algorithms without decoding. After the relay estimates the modulated symbol, it retransmits the signal using the same or a different modulation order. This technique is a simple linear operation and for small values of relay constraint rate, EF performs better than DF in Gaussian relay channels. However, it is possible to find errors at the destination in high rates.

Soft information relaying (SIR): this technique performs the error propagation of the DF, SIR calculates and forward the corresponding soft information instead of making a decision on the transmitted information symbols at the relay. SIR based on log-likelihood ratios, derivation of the mean square errors of signal estimation at the relay, etc. Thus, forwarding soft information at the relays provides additional information to the destination decoder to make decisions, instead of making premature decisions at the relay decoder.

Adaptive relaying protocol (ARP) trades the advantages and disadvantages of DF and AF protocols. All the relays that fail to decode correctly use the AF protocol to amplify the received signals and forward them to the destination. On the other hand, all the relays, which can successively decode the received signals, use the DF protocol. ARP is based on CRC estimation. Moreover, it is not necessary the CSI to be feedback from the destination to the relays or the source.

Compress and Forward (CF) [3] [19]**:** This protocol relays a compressed version of the detected information stream to the destination. This technique involves a distributed source coding. Thus, it can find capacity/performance optimum for the compressing node being close to the destination. However, in practice it is usually hard to come up with a joint probability mass or density function in sensor network (or BAN). It is possible to use two coding approaches with this technique which leads to different problems:

- **Slepian – Wolf coding (Compression):** This essentially deals with the compression of two or more correlated data streams. This technique has been used independently by the relay directly to compress the binary sequence obtained by making a hard decision on the relay received signals. The seemingly source coding problem of Slepian-Wolf coding is actually a channel coding problem

- **Wyvner-Ziv Coding (Quantizer + Compression):** it consists of a quantizer followed by an index encoder (syndrome or parity-based). The quantizer converts the input analog signals into the digital signals, which are then processed by the succeeding index encoder to get further compression. However, Wyner-Ziv coding has a source-channel coding problem.

Distributed Space-Time Coding (DSTC): This technique provides more coding advantages by transmitting additional incremental redundancy with the relay. For this purpose, joint coding schemes may be used by the source and relay coding. In this topology, it is introduced the virtual antenna arrays (VAA). With DSTC, different parts of the codeword coding are transmitted by different nodes through different wireless links. Furthermore, there are three approaches for DSTC:

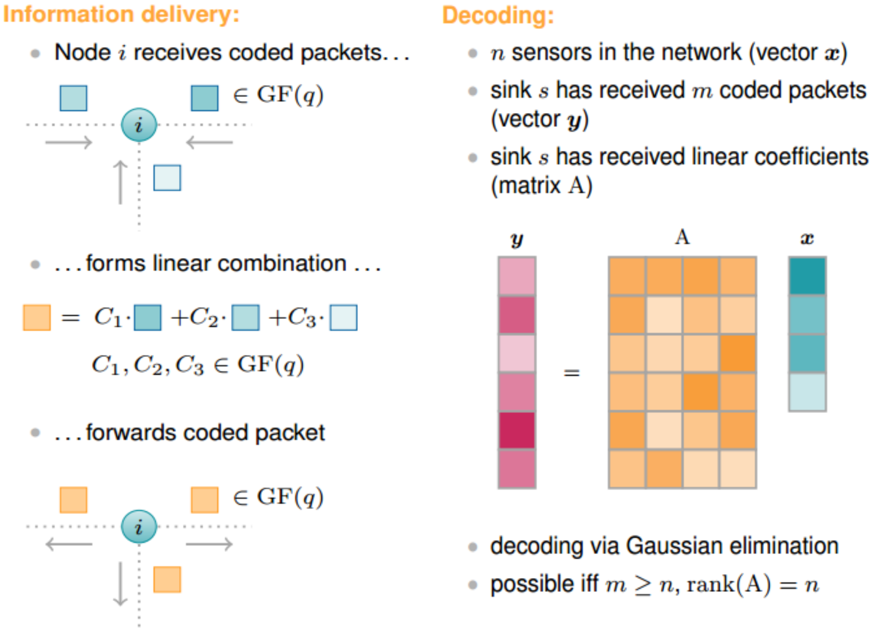
- **Distributed Space– Time Block Coding:** based on linear dispersion codes where each relay performs a linear transformation of the previously received signals and then forwards them simultaneously to the destination.
- **Distributed Space– Time Trellis Coding:** where the search for the optimum generator matrix has been based on design criteria adapted to the cascaded relaying channel
- **Distributed Turbo Coding STBC:** where we observed that the majority is based on some simple zero-forcing principles.

This technique, will create an additional freedom, but will also some practical issues in implementing these coding schemes (such as, decoding errors at relays, channel variations in different parts of codeword, and rate/power allocations at the source and relay), thus, it is preferable to use this technique with MIMO nodes [4], but it is not suited for BAN scenarios.

Distributed Network Coding: For this technique we have two approaches:

- **Distributed Network–Channel Coding:** The basic idea is to match the code-on-graph with network-on-graph. This is designed for the scenario where a single group of source nodes communicate with a single destination node. The coding schemes are based on the general graph codes, such as low density generator matrix (LDGM) codes, low density parity check (LDPC) codes, etc.

- **Network Coding Division Multiplexing:** This technique explore both network and channel coding gains as well as enabling multiple source groups to communicate with multiple destination nodes independently.



This is an effective technique to increase the network's spectral efficiency by using simple coding and routing process. It can also provide strong error correcting capabilities for packets flowing through lossy networks. It benefits from the broadcast transmit nature. However, it is an all or nothing decoding and it may leads to long delays, especially for the WBANs scenarios where there is not a good stability of links.

3.4. DESIGN DIRECTIONS FOR COOPERATIVE PHY LAYER DESIGN

If we summarize the discussion on this chapter, we can find the advantages and disadvantages of cooperation at the physical layer [5] in the following table:

	Advantages	**Disadvantages**
Supportive Relaying	• Pathloss gains • Balanced user QoS	• Increased interference • Complex schedulers
Cooperative Relaying	• Diversity gains • Balanced user QoS	• Optimum partner choice • Complex schedulers

Space-Time Relaying	• Diversity gains • Multiplexing gains • Available space – time codes • Balanced user QoS	• Increased overhead • Tight synchronization • More channel estimates • Complex schedulers

Moreover, independently of the strategy we may choose for the CORMORAN project, we may consider the following optimization for both transparent and regenerative techniques.

3.4.1 DISTRIBUTED SYSTEM OPTIMIZATION FOR TRANSPARENT RELAYING

- **Constant Output Power.** In this case, the transparent relaying node transmits at a constant output power that has been set during node manufacturing. **This is the simple way** but, it is also suboptimum.

- **Fixed Gain Amplification.** In this case, the node fixes the amplification factor over a given time window to a value (typically an inverse function of **the average channel gain** between source and relay). In poor channel conditions, this may lead to very large amplification factors and hence high output powers; in this case, the retransmitted signal is delimited to the maximum transmission power, leading to clipping effects.

- **Variable Gain Amplification.** The amplification gain is adapted to instantaneous changes in the channel and network. For instance, the amplification factor is typically an inverse function of the **instantaneous channel** gain between source and relay. Clipping effects may occur due to large amplification factors.

- **Choice of relays.** This is important to achieve better diversity gains with traffic management and power control. This can be achieved from the analysis of the channel stability of links over time [25] [26] by quantifying the effects and considering the variations for a relay selection protocol.

- **Opportunistic relaying:** this kind of strategy aims to provide an efficient way to cooperate during the communication by defining some rules at the relay node to know when to cooperate based on proactive or reactive relaying [27]. Proactive relaying anticipates the moment which a relay node has to cooperate, for that there is a distributed algorithm to choose the best relay among a set of possible candidates. In reactive relaying, relay nodes cooperate when they decode successfully the messages, however this can be seen as a best effort case which can lead to overhead. In [28], they propose an opportunistic relaying for WBAN to reduce the complexity by making one single relay with the best path towards the destination send a packet per hop.

3.4.2 DISTRIBUTED SYSTEM OPTIMIZATION FOR REGENERATIVE TECHNIQUES

- **Choice of Channel Code**: It basically trades encoding/decoding complexity and power with coding gains in form of transmits power reduction. Without channel code in a relay we reduce the complexity but also is the worst performing solution. If a channel code is used, then we can choose from a variety of block codes, trellis codes and concatenations thereof. Block codes can correct a fixed amount of error but not more and trellis codes can correct with a given probability a density of errors but difficult to achieve in WBAN.

- **Choice of Interleaver**: The role of the Interleaver is to break long sequences of errors so that they can be corrected more easily. Since it breaks long error bursts into several short ones, the application of Interleaver is useful in block fading environments where the channel remains constant over a few symbols. Inter-leavers trade performance gains against memory requirements.

- **Choice of Waveform and Modulation**: First, one has to decide between single carrier and multicarrier modulation schemes. Second, there is the choice between coherent and differential modulation. Third, the modulation order where higher modulation orders exhibit a higher spectral efficiency but more susceptible to noise and interference.

- **Power Control:** the regenerative relay may use adaptive amplification factors to facilitate power control and hence manage interference (tradeoff)

- **Choice of Receiver**: Available techniques include simple threshold detectors, zero forcing(ZF) and minimum mean square error (MMSE) receivers

4. COOPERATIVE COMMUNICATIONS FOR THE MAC LAYER

4.1. OVERVIEW

As we discussed on the last chapters, research in wireless sensors networks grew so fast in the past decade. We also discussed the differences between WSN and BAN, and the challenge to find innovative protocols for BAN to counter the communication problems on dense networks with heterogeneous nodes. In the last chapter, we explained that the PHY layer has to guarantee the links stability with a reliable connectivity via cooperative techniques. However, cooperative communication at PHY layer needs an adaptive MAC layer to ensure the cooperative gains, but also to reduce the detrimental effects of cooperation, such as extra overhead and enlarged interference area.

In the literature, we can find several classifications of MAC protocols, especially for ad hoc networks and WSN. However, there are few cooperative MAC protocols proposed for Body Area Networks. Thus, this chapter will show a global scope of existing cooperative and non-cooperative protocols that could be used for BAN, and more especially for the CORMORAN project. The authors of [1] proposed to use cooperative MAC strategies in order to achieve PHY cooperative gains and they also divided MAC protocols in two families: contention and reservation mechanisms. However, this approach does not take into account the special issues of BAN. We can find the same classification of MAC protocols in[17] and [20], with an approach for medical applications, such as implants and in-body sensors. In this overview, they focus on energy efficiency and reliability without considering cooperative strategies.

In [21], another classification is proposed for WSN, MAC protocols are divided in scheduled protocols, protocols with common active periods, preamble sampling protocols and hybrid protocols. Then, each of them are sub-classified by specific solutions to deal with different problems such as resource allocation, controlling sleep delay, avoid overhearing or reducing idle listening. A more profound study about energy efficiency in WSN can be founded in [22], where authors classified MAC protocols depending on the mechanism used to minimize energy consumption.

Furthermore, in [23] we can find another approach of MAC solutions for Wireless Mesh Networks. The authors study MAC mechanisms that support dynamic traffic with heterogeneous Quality of Service. From this study, they classified the protocols in best effort service support, priority guarantee, resource reservation or fairness enhancement.

This chapter is organized as follows. First, section 4.2 gives a background of general requirements for a BAN MAC layer. Then, section 4.3 provides the classification of usual MAC families. After, in section 4.4 we show the existing non cooperative MAC protocols for BAN, classified according to the CORMORAN requirements. Finally, in sections 4.5 we discuss the strategies for cooperative communications by providing a classification of the existing cooperative MAC protocols.

4.2. MAC LAYER REQUIREMENTS

The design of the cooperative MAC layer on the BAN context is a challenge for recent research area to find new strategies ensuring the nodes communication. In the CORMORAN context, the diversity gain achieved at the physical layer should be correlated with specific advantages at the MAC layer, such as increasing throughput and transmission rate; reducing transmission power and nodes interference; improving spatial reuse and fairness to the medium; enhancing transmission reliability; and enlarging transmission range and network coverage. For this purpose, we need to consider the following requirements:

- **Energy saving ($r_{\text{energy saving}}$):** the energy cost to allocate resources (i.e. scheduling, duty cycle, logical channel allocation) must be less than that of the existing MAC

- **Mobility (r_{mobility}):** the protocol has to assess the different refreshment modes that could appear within the mobility of the BANs. Reducing at maximum packet collisions and relaying interference. And also, defining solutions to detect the most demanding nodes and make their update in priority.

- **Adaptability ($r_{\text{adaptability}}$):** the protocol must be self-adapt to the intra/inter BAN communication and the different kind of traffic appearing in the network (fast-varying, bursty and medium or low load traffic)

- **Reliability ($r_{\text{reliability}}$):** The communication reliability and precision of the system must be as high as possible. This is suitable for the location applications. It must be capable to reach all the nodes in the system i.e. with cooperative strategies (muti-hop and single-hop)

- **Fairness (r_{fairness}):** the protocol must grant a fair medium access to all nodes considering the load traffic and channel variations

- **Easy deployment ($r_{complexity}$):** the protocol must consider the complexity of its deployment by making a study of the performance tradeoff. We can assess robustness with respect to scalability (bit rate)

4.3. MAC PROTOCOL CLASSIFICATION

The goal of this section is to show the conventional MAC mechanisms which can be classified into three categories regarding the way nodes compete to access medium [17] [21] [20] [22]: reservation-based, contention-based and hybrid access. Furthermore, the MAC protocols proposed in literature for WBAN will be explained on the section 4.4.

4.3.1 RESERVATION-BASED PROTOCOLS

Reservation-based approach allows each node to access the channel with scheduled resources and communicate with other nodes; this technique requires the knowledge of the network topology to establish a schedule. For example, some reservation-based protocols use the Time Division Multiple Access (TDMA). This mechanism divides the time into frames and each frame is composed by slots. Each node is assigned a unique slot during which it has the right to transmit. As a consequence, transmissions do not suffer from collisions. There is no contention, idle listening and overhearing problems, so these protocols are energy conserving protocols However, the knowledge of topology and strict synchronization requires large overheads which needs extra energy for periodic time synchronization and/or expensive hardware and hence renders TDMA solutions more expensive. Moreover, there are few cooperative strategies for this protocol proposed for WBAN scenarios. Therefore, these mechanisms do not meet the $r_{complexity}$, $r_{reliability}$ and $r_{adaptability}$ while respecting $r_{fairness}$, $r_{energy\ saving}$ and $r_{mobility}$. Some reservation based protocols are TSMP, Arisha, PEDEMACs, GMAC, TRAMA, EMAC, and FLAMA.

4.3.2 CONTENTION-BASED PROTOCOLS

In this family, neither global synchronization nor topology knowledge is required. Nodes contend to access to the channel and transmit the data (i.e. Aloha, CSMA). In the case of Carrier Sense Multiple Access, each node listen the channel before sending. If the channel is busy, the node defers its transmission until it becomes idle to avoid interfering with the ongoing transmission. And if the channel is clear, the node starts the transmission. These protocols do not rely on a central entity and they are robust to dynamic traffic. Moreover, they do not need strict time synchronization. However, contention-based protocols suffer from degraded performance in terms of throughput when the traffic load increases, so this increases overhead, packets drop and power consumption. Therefore, these mechanisms do not meet the $r_{energy\ saving}$, $r_{fairness}$, $r_{reliability}$ and $r_{mobility}$ while respecting $r_{complexity}$ and $r_{adaptability}$.

These protocols can also be studied as two sub-categories based on CSMA mechanism [24]: unsynchronized and synchronized protocols. Unsynchronized mechanisms use the preamble-sampling mechanism [25] which is considered as energy efficient for low traffic applications in WSN. In these protocols, nodes do not need to be synchronized and they are almost all the time in sleep mode. If a node needs to send a packet, it has to perform a preamble to the channel before. Then the nodes in the network wake up for a short time, called Check Interval (CI), to verify if there is a transmission. The transmission is started only if the node listen the preamble during the CI. For this, the preamble duration needs to be at least as long as the CI. Thus, these protocols reduce synchronization overhead and realize larger energy savings at the cost of a longer preamble. However, the transmitter uses more energy to transmit long preambles and when a collision occurs; it implies retransmission which is costly. Moreover, collisions are frequent for applications with high traffic. These mechanisms do not propose cooperative strategies. Therefore, these mechanisms do not meet $\mathbf{r}_{\text{adaptability}}$, $\mathbf{r}_{\text{fairness}}$, $\mathbf{r}_{\text{reliability}}$, $\mathbf{r}_{\text{mobility}}$, $\mathbf{r}_{\text{energy saving}}$ for high traffic applications while respecting $\mathbf{r}_{\text{complexity}}$ and $\mathbf{r}_{\text{energy saving}}$ for low traffic applications. Some protocols based on Preamble Sampling Mechanisms are LPL channel poling, PS CSMA, PS ALOHA, 1-hop MAC, BMAC, Wise MAC and STEM.

In the other hand, synchronized mechanisms use the common active periods to maintain a certain level of synchronization to keep common active/sleep periods. The active periods are used for communication and the sleep ones for saving energy. For this approach the contention families achieves the best performances in industrial applications in which traffic is periodic such as monitoring and applications in which keep-alive packets are periodically exchanged to ensure network reliability. However, because nodes use contention inside periodic active periods, it is not suitable for applications with irregular traffic. Moreover, short or long active periods perform drawbacks: short active periods reduce idle listening, but contention and collision rates increase; and long active periods reduce contention at the cost of idle listening. Sleep periods do save energy at the cost of extra delay, especially for multi-hop networks. These mechanisms do not propose cooperative strategies. Therefore, such protocols do not meet $\mathbf{r}_{\text{adaptability}}$, $\mathbf{r}_{\text{fairness}}$, $\mathbf{r}_{\text{reliability}}$, $\mathbf{r}_{\text{mobility}}$ and $\mathbf{r}_{\text{energy saving}}$ while respecting $\mathbf{r}_{\text{complexity}}$. Some protocols based on Common Active Periods are SMAC, TMAC, NanoMAC, DSMAC and RMAC.

However, CSMA based protocols suffers from some known problems with IR UWB systems which makes these protocols not suitable for location scenarios. In fact, as CSMA needs an accurate channel sensing with energy detection, UWB transmission is highly low power and requires knowledge of the spreading code for effective reception, a node would check all possible spreading codes before declaring an idle channel. ALOHA is a simple protocol possible with UWB systems, because it allows transmitting whenever it has data to send and if a transmission collides, the packet is retransmitted after a random back off as suggested in [26] [27].

4.3.1 Hybrid Protocols

Hybrid mechanisms as in [24] and [28], achieve high performance by mixing both reservation and contention strategies. According to [21], contention-based approaches achieve a better performance in small-scale topologies. In the other hand, reservation-based approaches are better for large-scale topologies. For these reason, hybrid protocols may adapt their behavior according to the traffic load and topology size predictions. Some hybrid protocols as [29] allow cooperative strategies in order to improve communication in multi-hop networks. However, these protocols carry out different drawbacks depending on their behavior and they use more complex algorithms. Therefore, such protocols do not meet $\mathbf{r}_{\mathbf{complexity}}$ while respecting $\mathbf{r}_{\mathbf{adaptability}}$, $\mathbf{r}_{\mathbf{reliability}}$, $\mathbf{r}_{\mathbf{fairness}}$, $\mathbf{r}_{\mathbf{mobility}}$ and $\mathbf{r}_{\mathbf{energy\ saving}}$. Some hybrid protocols are IEEE 802.15.4, IEEE 802.15.6, SCP-MAC and CT-MAC.

4.4. NON-COOPERATIVE MAC

As described before, there are three main families for MAC protocols. Contention based protocols are less suited for WBAN scenarios, specially for IR-UWB location applications. Thus, in literature there is also said that schedule-based protocols (TDMA), compared with contention-based protocols, have their natural advantage, such as collision-free, low-overhearing, and low-duty-cycle operations. Moreover, TDMA protocols can effectively reduce the transmission latency and increase transmission determinism by guaranteeing dedicated time slots for each node periodically. These natural advantages of TDMA make it more energy-efficient and attractive for BANs, specially to ensure high reliability for QoS scenarios i.e. Emergency and on-demand traffic.

Moreover, we have to consider the cooperative nature of the MAC layer, the choice of a MAC family is not enough to ensure the reliability of BAN's communication. However, cooperative mechanisms may not be always desired in some real scenarios. For example, if the relay channel is of low quality, cooperation may not be beneficial or necessary, therefore, the source may prefer not to transmit to save energy. Another case is when the relays are moving constantly, because the source may not have the current information of the available relays to cooperate. This means that relays may not be always ready and willing to help. In this subchapter, we present some traditional MAC protocols for BAN which focuses on a single-hop link to coordinate the sharing of the channel by BAN nodes.

4.4.1 NON-COOPERATIVE MAC PROTOCOLS FOR BAN

Heartbeat Driven MAC protocol (H-MAC) [30]**.** This protocol is a **TDMA based protocol proposed for a star topology WBAN**. In H-MAC, biosensors extract the necessary synchronization information from their own sensory biosignals, which are correlated with or directly driven by the heartbeat pulsation, in a distributed way **to avoid the radio energy consumption for transmitting timing synchronization beacons**. The heart beat rate of human is usually within **60–200 b/min**, which makes the **peaks interval fall** in the range of **300–1000 ms (**Figure 4-1**)**. In H-MAC, **the peaks are used as synchronization beacons and use peak intervals as time slots** for data transmission. In this protocol we find two kinds of control packets:

- **One is very short and used for synchronization and resynchronization (CS):** It only includes the coordinators current peak counting number and one bit, indicating whether there are changes in time slot assignment scheme
- **The other is longer and used for time slot scheduling (CL):** CL includes the H-MAC frame length (total peak number in a frame), time slot assignment scheme (sensor ID and transmission start/stop peak number), and mandatory radio wake up cycle (peak number).

This protocol reduce the extra energy cost required for synchronization, however it does not support sporadic events, not traffic adaptive and it has low spectral/bandwidth efficiency in case of low traffic. In the case of location scenarios for CORMORAN, a refreshment rate of 10ms to 100ms is needed to locate all nodes on the body, which is impossible if the synchronization rate depends on the human bit rate which is higher than the expected latency. Moreover in the case of Inter BAN, each body may have different heart bit which made the synchronization impossible. Therefore, this protocol do not meet the $\mathbf{r}_{\text{complexity}}$, $\mathbf{r}_{\text{reliability}}$, $\mathbf{r}_{\text{mobility}}$ and $\mathbf{r}_{\text{adaptability}}$ while respecting $\mathbf{r}_{\text{fairness}}$, $\mathbf{r}_{\text{energy saving}}$.

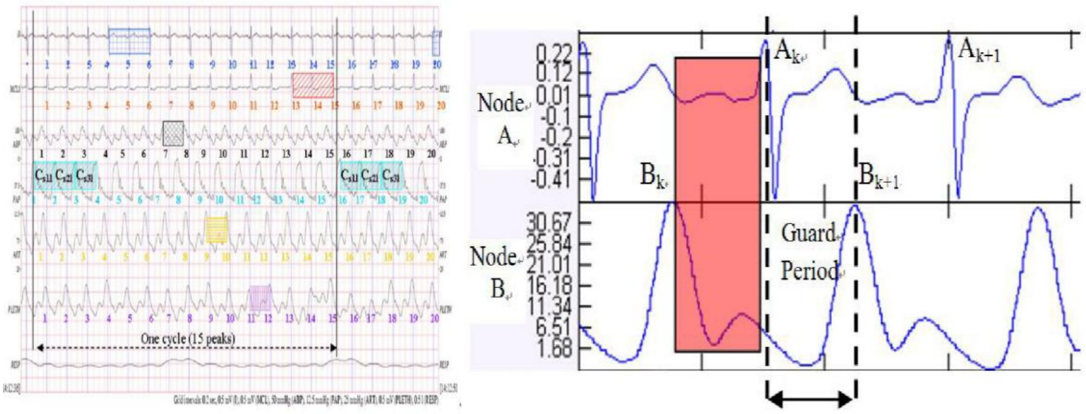


Figure 4-2: H- MAC synchronization

Reservation-Based Dynamic TDMA (DTDMA) [31]**.** This protocol is a hybrid protocol proposed for normal (periodic) WBAN traffic where slots are allocated to the nodes which have buffered packets and are released to other nodes when the data transmission/reception is completed. The channel is bounded by superframe structures.

Each superframe consists of a beacon used to carry control information including slot allocation information. CFP period is a configurable period used for data transmission. CAP period is a fixed period used for short command packets using slotted-ALOHA protocol. And a configurable inactive period used to save energy. The duration of an inactive period is configurable based on the CFP slot duration. In DTDMA protocol the CFP duration is followed by CAP duration in order to enable the nodes to send CFP traffic earlier than CAP traffic. If there is no CFP traffic, the inactive period will be increased.

This protocol provides more dependability in terms of low packet dropping rate and low energy consumption for normal (periodic) traffic when compared with IEEE 802.15.4, i.e. localization applications. However, it does not support emergency and on-demand traffic. This protocol could operate on one sub-channel but cannot operate on ten sub-channels simultaneously. Therefore, this protocol do not meet the $\mathbf{r}_{\mathbf{reliability}}$, $\mathbf{r}_{\mathbf{mobility}}$ and $\mathbf{r}_{\mathbf{adaptability}}$ while respecting $\mathbf{r}_{\mathbf{complexity}}$, $\mathbf{r}_{\mathbf{fairness}}$ and $\mathbf{r}_{\mathbf{energy\ saving}}$.

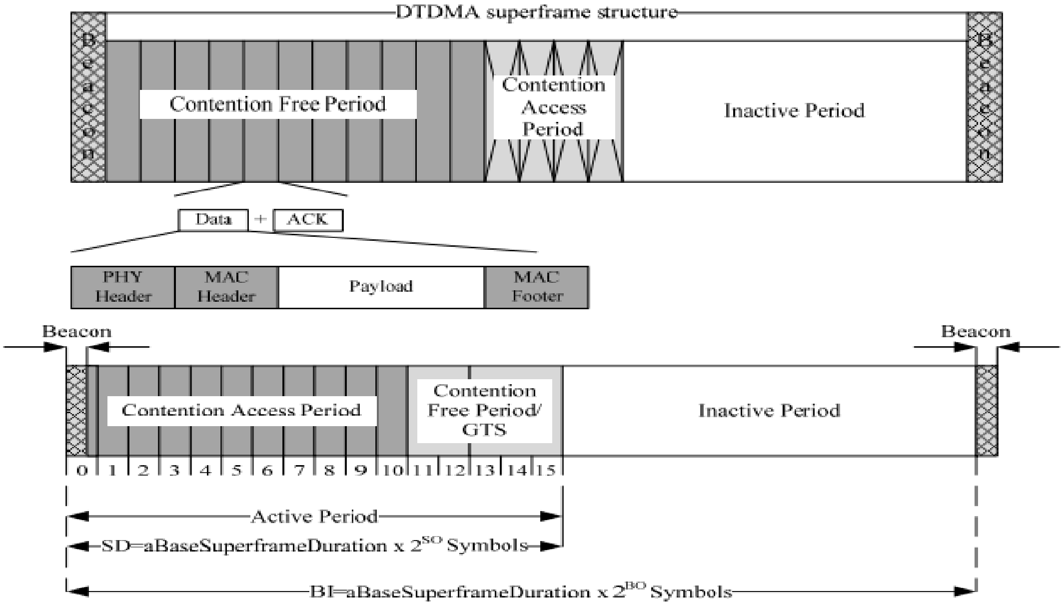


Figure 4-3: Comparison of DTDMA and IEEE802.15.4 MAC frames

Body MAC [32]. This protocol is a Hybrid protocol where the channel is bounded by TDMA superframe structures with downlink and uplink subframes. The downlink frame is used to accommodate the on-demand traffic and the uplink frame is used to accommodate the normal traffic.

The downlink part is reserved for the transmission from the gateway to the nodes. It can be either unicast data for a specific node or broadcast data for all the nodes in the network. The uplink frame is further divided into CAP and CFP periods. The CAP period is used to transmit small size MAC control packets which are based on CSMA/CA. The CFP period is used to transmit the normal data in a TDMA slot. The duration of the downlink and uplink superframes are defined by the coordinator.

The advantage of the Body MAC protocol is that it accommodates the on-demand traffic using the downlink subframe. It could be useful for location algorithms if the Downlink is reserved for schedule the resources and the Uplink CFP for the traffic needed for positioning and localization. However, there is no proper mechanism to handle the emergency traffic and it uses the CSMA/CA protocol in the CAP period which is not reliable for dynamic scenarios in a WBAN, or with UWB systems. In case of low-power implants the coordinator has to wake up the implant first and then send synchronization packets. Therefore, this protocol do not meet the $\mathbf{r}_{\text{reliability}}$, $\mathbf{r}_{\text{complexity}}$, $\mathbf{r}_{\text{energy saving}}$ and $\mathbf{r}_{\text{mobility}}$ while respecting $\mathbf{r}_{\text{fairness}}$ and $\mathbf{r}_{\text{adaptability}}$

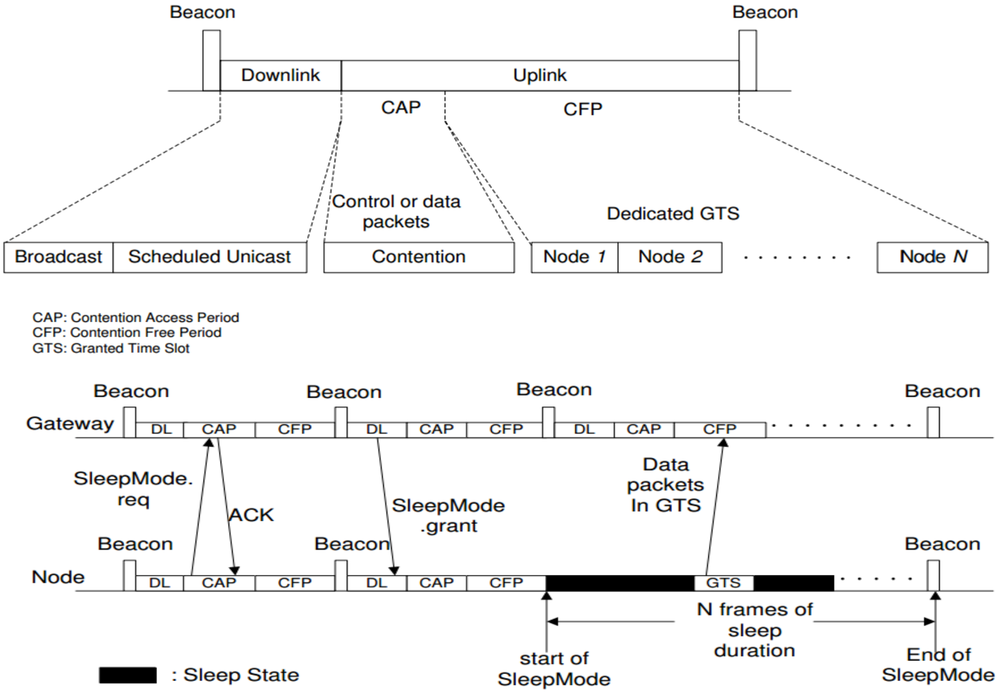


Figure 4-4: Body MAC frame

Wise MAC [33]**. This protocol is based on the LPL mechanism**. In this protocol, a **non-persistent CSMA and a preamble sampling technique is used to reduce idle listening.** The preamble is used to alert the receiving node of a packet arrival. All the nodes in a network sample the medium periodically. If a node samples a busy medium, it continues to listen until it receives data or the medium becomes idle.

The periodic sampling is efficient for high-traffic nodes and performs well under variable traffic conditions. It could be interesting for Body to Body applications. However, it is ineffective for low-traffic nodes, especially in-body nodes, where periodic sampling is not preferred due to strict power constraints. Since the WBAN topology is a star topology and most of the traffic is uplink, using LPL mechanism is not an optimal solution to support both in-body and on-body communication simultaneously, especially for UWB systems. Therefore, this protocol do not meet the $\mathbf{r}_{\mathbf{reliability}}$, $\mathbf{r}_{\mathbf{fairness}}$, $\mathbf{r}_{\mathbf{adaptability}}$ and $\mathbf{r}_{\mathbf{mobility}}$ while respecting $\mathbf{r}_{\mathbf{complexity}}$ and $\mathbf{r}_{\mathbf{energy\ saving}}$.

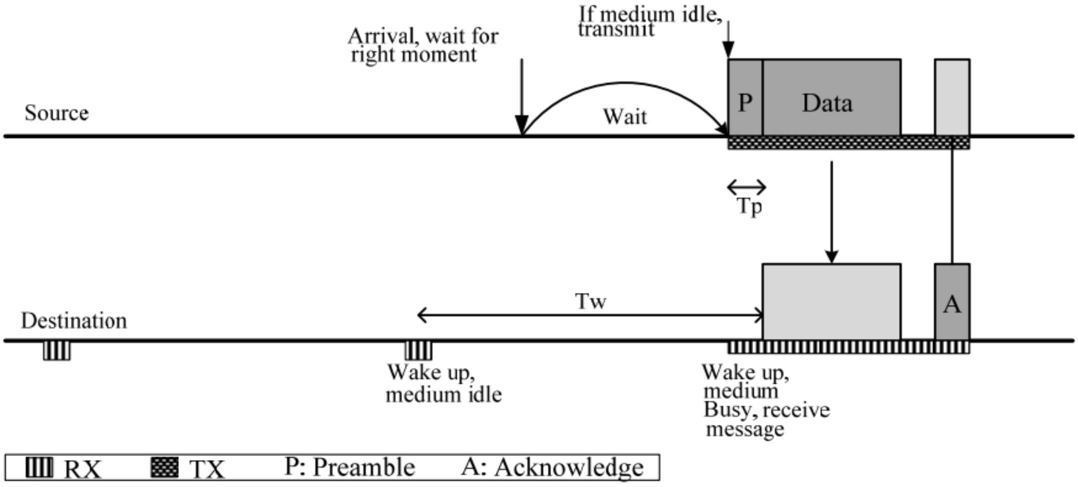


Figure 4-5: Wise MAC LPL mechanism

Preamble based TDMA Protocol (PB TDMA) [34]**.** This protocol is based on the TDMA mechanism. The nodes are assigned specified slots for collision-free data transmission. These slots are repeated in fixed cycle. A complete cycle of these slots is called a frame.

In this protocol, each TDMA frame contains a preamble and a data transmission slot. A node always listens to the channel during preamble and transmits in a data transmission slot. The preamble contains a dedicated subslot for every node. These subslots are used to activate the destination node by broadcasting the destination node ID of outgoing packet.

After receiving the preamble, the destination node identifies the source node. Each node turns off its radio when it has no data to transmit. This mechanism avoids unnecessary power consumption of sensor nodes. The radio is turned on when the node finds its ID in the preamble or when the node has data to transmit.

PB-TDMA protocol outperformed S-MAC and IEEE 802.15.4 protocol in terms of energy efficiency. The results are valid for normal traffic only and do not consider the behavior of emergency and on-demand traffic. However, it has preamble overhearing and limitation of handling sporadic events. This protocol is suitable for localization algorithms (i.e. LSIMC application) because it is easy to deploy. Therefore, this protocol do not meet the $\mathbf{r}_{\text{reliability}}$ and $\mathbf{r}_{\text{mobility}}$ while respecting $\mathbf{r}_{\text{complexity}}$, $\mathbf{r}_{\text{fairness}}$, $\mathbf{r}_{\text{adaptability}}$ and $\mathbf{r}_{\text{energy saving}}$.

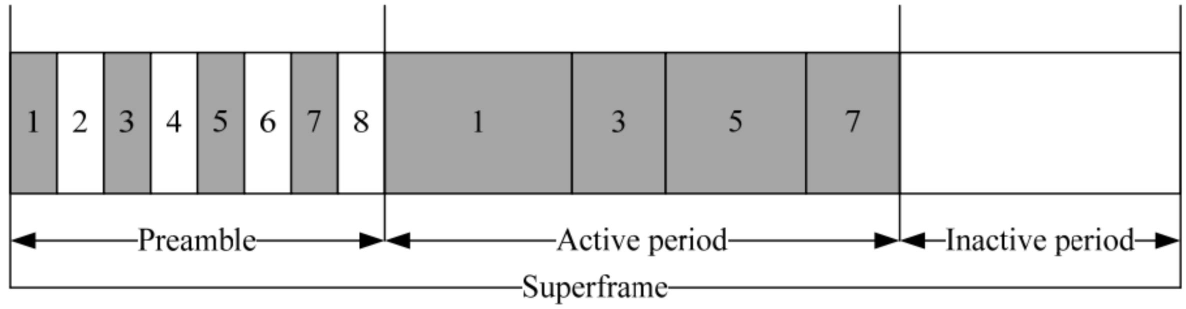


Figure 4-6: PB-TDMA frame structure

4.5. COOPERATIVE MAC

4.5.1 STRATEGIES FOR COOPERATIVE COMMUNICATION

As explained in subchapter 4.4, cooperation may not be necessary for all scenarios [35]. In literature, we can find some non cooperative MAC protocols for specific applications. In the CORMORAN context defined in D1.1, LSMIC and CGN applications needs a high reliability within specific refreshment to ensure positioning and localization. Thus, in order to design a cooperative MAC layer for the CORMORAN goal, it is necessary to address three problems:

When to cooperate? This means to look for the conditions when cooperation can be used or be beneficial. As WBAN links are instable because of the shadowing and the body movements, cooperation can be possible by detecting the moments when connectivity with relays is possible. In the D2.4, we prove that repetitive and regular movements imply that correlation matrices do not vary significantly over time, opening up the possibility for realistic protocols with relaying strategies. However, random movements can yield to a variation of the correlation along time; in this case opportunistic strategies may be more efficient.

Whom to Cooperate with? After finding the moment to cooperate, it is necessary to know the best and the available relays to cooperate. For this purpose, we may define the policy to choose the number of relays in the network and the strategy to select the relays. We can imagine a relay selection strategy that takes decisions based on instantaneous measurements of channel gain and achieved throughput, this decision will also depend if we have a centralized or distributed topology (see How to cooperate?). In the case of choice of the number of relays, we have to consider if we want single or multiple relaying. The single relaying consist in choosing one node to assist the communication, i.e. by choosing the best cooperating relay to ensure reliability in despite of some latency; or by choosing the available relay with opportunistic strategies in despite of reliability. The multiple relaying consist in choosing many relays for a transmission, however this is not suited for WBAN communication since there is the possibility of enlarged interference, overhead and complexity for the reception.

How to cooperate? The last task is to define the way we want to cooperate. This decision may also depend on the topology: decentralized or centralized. In the centralized case, there is a central controller which defines the scheduling and relaying strategies, however it needs significant feedback messages to send the quality of links to the central node and then to send his final decision to the whole network, this may be difficult for dynamic networks like WBANs. The decentralized case improves the cooperation capabilities by defining a utility function to select the relays, i.e. busy tone, best instantaneous quality of link or a simple timer. Then, the decision of relaying can be proactive by predicting the optimal moment to assist or reactive by retransmitting when needed. Moreover, we have to define the mechanism of cooperation [36] i.e. multi-hop or dual-hop which is more suited for WBAN; scheduling of relaying communication and opportunistic strategies [37]. Finally, it may be interesting to stimulate our nodes to cooperate with some incentives to find an optimal cooperation. Such stimulation may be possible with known schemes i.e. reputation based, remuneration based or game theory. In this subchapter, we present some cooperative MAC protocols designed for BAN and that could be interesting for the CORMORAN project.

4.5.2 COOPERATIVE MAC PROTOCOLS

CoMAC[38] **.** It is a cooperative preamble sampling protocol which aims at spreading the preamble emission over a set of nodes in a WBAN, in such a way that each node can comply with the LDC limitation. With CoMAC, the source sends a burst, whose duration is less than the 5 ms limit. It indicates the coming emission of a data packet at a given time. This burst is relayed one time after another by nodes, which wake up during a burst. As a consequence, the destination node is woken up by one of the relays and can learn the time left before data (see the next section). Hence, depending on this value, the node may go back to sleep and wake up to receive the data, minimizing the power consumption.

This protocol considers three configuration options which depend on the application: 0) low priority data, 1) alert-type data and 2) low latency data. In the case of CORMORAN, the option 2 is more suitable since the LSIMC is more a low latency data application. The Mode 2 (Emitter supervised preamble) enables the possibility for the packet initiator to monitors each relay to have the knowledge of the relaying chain. When the destination node is awake by one of the bursts, it relay the same burst, triggering the emission of the data packet leading into a reduction of latency. Therefore, the relays only participate in the wake up period but once the destination is awake, the relays do not relay the data packet. Therefore, this protocol do not meet the $\mathbf{r}_{\mathrm{reliability}}$, $\mathbf{r}_{\mathrm{fairness}}$, and $\mathbf{r}_{\mathrm{mobility}}$ while respecting $\mathbf{r}_{\mathrm{complexity}}$, $\mathbf{r}_{\mathrm{adaptability}}$ and $\mathbf{r}_{\mathrm{energy\ saving}}$.

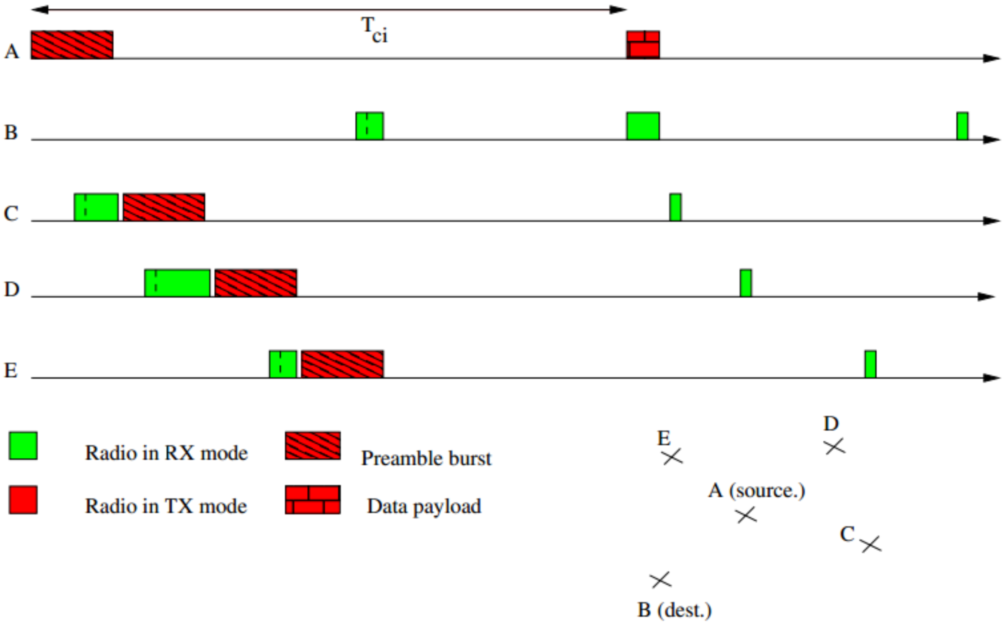


Figure 4-7: CoMAC principles of burst relaying

BAN Adaptive TDMA (BAT MAC) [29]**.** This protocol automatically detects the shadowing effect and adjusts its communication protocols and the parameters of the IEEE 802.15.4 superframe:

In the **Beacon Period (BP)**, the first slot is allocated to the coordinator to send beacons periodically and entirely specify the SF and the following slots are used by Relays. Beacons contain useful BAN information such as the relay list and the respective beacon slot index. **In the Indicator Period**, each device has an attributed minislot for sending back an ACK to the originator of the first received beacon. The indicator slot index is the same than the monitoring slot index. This period permits the MAC to use the beacon period as a channel sensing period for the links from the coordinator and relays. **The Monitoring Period:** The coordinator reserves slots for guaranteed communication GTS with each device for the data transmission. The slots indexes attributions are sorted as a function of the estimated reliability of the link. The first indexes will be reserved to the weakest link in order to enable the best device to relay in the same SF. **During the Priority Access Period (PAP),** devices contend to get access especially for life critical and emergency traffic. During **the Contention Access Period (CAP)**, devices contend to get access to communicate with the coordinator or with other devices. This contention period is mainly used for uplink GTS requests or other management packets using a slotted Aloha or CSMA/CA. The Optional Contention Free Period (CFP) is an optional period used for the exchange of other data than monitoring data.

This protocol mitigates shadowing effect thanks to relaying for human monitoring applications. Beacon provides a set of tool to schedule relaying reinforcing links from each device. However, it doesn't consider the Inter BAN communication (interoperability). It increases the power consumption of the nodes elected as relays. Therefore, this protocol do not meet the $\mathbf{r}_{reliability}$ and $\mathbf{r}_{mobility}$ while respecting $\mathbf{r}_{complexity}$, $\mathbf{r}_{fairness}$, $\mathbf{r}_{adaptability}$ and $\mathbf{r}_{energy\ saving}$.

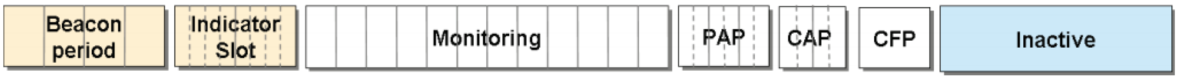


Figure 4-8: BATMAC super frame structure

Cooperative Scheduling for Coexisting Body Area Networks [39]**.** The goal of this work is to decrease inter-BAN interference by cooperative scheduling, hence increasing packet reception rate (PRR) of intra-BAN communications. The scheduling issue is divided into two sub-issues: **single-BAN scheduling** as an optimization issue and **multi-BAN concurrent scheduling** as a game.

For the first sub-issue, they assume that one BAN actively designs strategy to maximize its own benefit, while the other BANs fix their strategies. They apply two well-known combinatorial optimization algorithms, i.e., Hungarian algorithm and greedy algorithm, for comparison. Then, it is proposed a new scheme called horse racing scheduling, which is originated from an ancient Chinese horse racing story. This scheme is simple, fast and let the active BAN achieve near-optimum packet reception rate (PRR).

For the second sub-issue, they prove two theorems for the existence of Nash Equilibrium (NE). Then, based on the knowledge that horse racing scheduling performs very good for the active BAN for single-BAN scheduling, they propose a distributed cooperative scheduling scheme, which achieves higher PRR than the always existing mixed strategy NE for all the BANs.

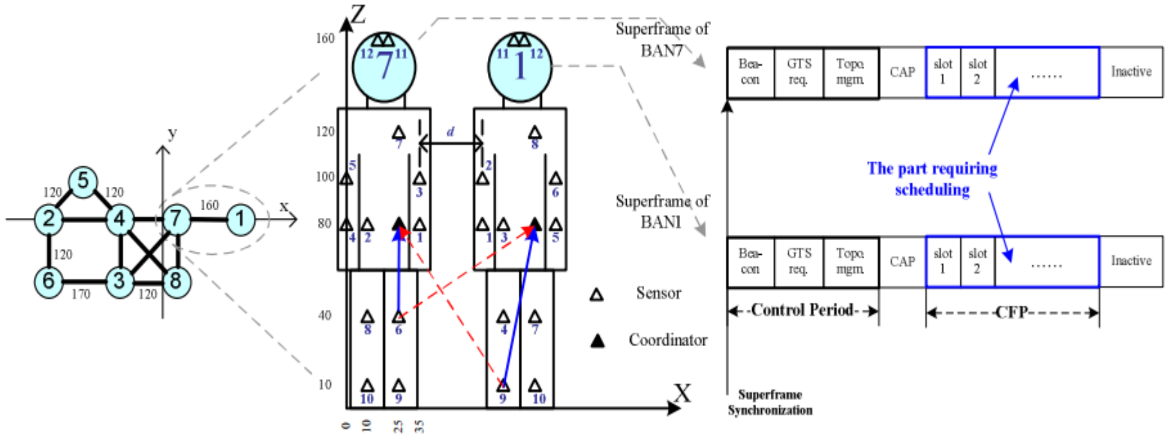


Figure 4-9: Multi BAN coexistence scenario

5. COOPERATIVE COMMUNICATIONS FOR THE NWK LAYER

The network layer's goal is generally to provide mechanisms that make end-to-end communication between hosts possible, without consideration of the communication properties (reliability, congestion control, etc.). This section examines solutions (i.e. protocols and standards) that could be considered for the two CORMORAN applications.

5.1. OVERVIEW

The network layer's requirements generally influence two main tasks: routing and addressing.

Routing ensures that paths are available between sources and destinations that want to communicate together, and that these paths updated in case of node failure, changes in channel conditions, or in case of mobility. Routing has been widely studied in the classical Internet, and the behavior, performance and properties of the general algorithms classes such as distance vector routing or link-state routing are known, thanks to the resulting experience. More recently, the contributions in the ad-hoc networking, sensor networking and delay-tolerant networking domains have proposed alternatives to address situations unknown in the classical Internet and closer to the WBAN context such as terminals-based routing, in-network mobility, or the usage of a wireless channel. Even though the WBAN context is different from these networks, inspiration should come from the related literature.

Addressing is dominated by the Internet Protocol (IP) and, as WBANs can be considered as a part of the Internet of Things, they should theoretically use IPv6. However, the problem is far from simple, as IPv6 has not been designed for constrained devices. The size of the address, for example, is too large compared to the size of a frame and the full IPv6 header represents an unacceptable overhead. Solutions have been proposed in the wireless sensor networks domain that suffers from similar limitations and that could be suitable to the WBAN scenario.

5.2. NWK LAYER REQUIREMENTS

The two classes of scenarios identified by CORMORAN produce very different network topologies and impose very different constraints on the end-to-end transmission. If that shouldn't have a great influence on addressing matters, it could however have a great impact on routing. Some routing algorithms may be adapted to one of the scenarios and perform poorly in the other category of networks.

The discriminant parameter is the network topology, and more specifically its density (i.e. nodes degree) and its dimension (i.e. network diameter):

- In the LSIMC scenario, we essentially consider a single WBAN surrounded by an infrastructure. This suggests all the WBAN nodes will form a star-like network organized around a master node (anchor) and that there will be direct connections between a subset of the nodes and the infrastructure anchors. The paths diversity should remain manageable and the main goal of the network layer should be to distinguish between routes of various qualities (regarding QoS parameters) and their stability. Mobility is such that the group of on-body nodes moves together and that these nodes could share information in order to predict changes in the connections to the infrastructure, predicting disconnections and helping to keep routes up-to-date.

- The CGN scenarios are more complex for the pure network layer's point of view. As BAN-to-BAN connections are possible, there could be multiple paths alternatives for end-to-end communication and in-network mobility is higher. This essentially means that the routing updates should be more frequents indicating a different class of relevant algorithms. However, as the applicative QoS constraints are less stringent, it should be possible to select or to build a suitable routing algorithm.

In this chapter, we will give a general description of different strategies proposed in the literature for the routing and addressing problems. As shown in Figure 1-1, routing protocols can be divided in three categories: temperature aware, cluster algorithms and cross layer.

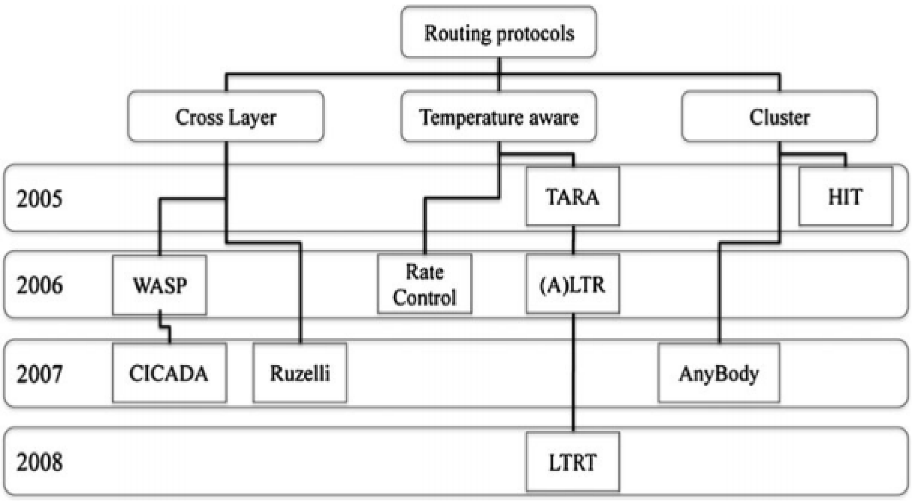


Figure 5-1: Routing protocols overview

5.3. TEMPERATURE AWARE ROUTING

Temperature-aware routing constitutes a WBAN-specific class of routing algorithms that build on classical routing algorithms, but incorporate in the choice of the routes a health-related metric: the heat produced by the electronics that should be kept as low as possible in order to reduce the effects of WBAN on health. A survey on this category of algorithms has been published in 2013 in the Sensors journal [40]. This survey essentially concerns WBANs that are organized as a tree around a single gateway, which is the only node able to communicate with the external infrastructure. In this sense, its conclusions may be a bit restrictive with respect to the LSIMC scenario, in which all off-body links are potentially active, and even more with respect to the CGN scenario that explicitly includes inter-BAN links. However, they list and detail all major proposals that fall in this category.

5.3.1 LTRT

Least Total-Route Temperature Routing [41] simply uses the temperature metric as the cost function of a shortest path algorithm. It uses a link-state like protocol to feed a simple Dijkstra algorithm. The main critic that could be addressed to this strategy concerns the volume of control traffic. Indeed, temperature could evolve rapidly in presence of irregular traffic, which would result in an increase of the necessary control traffic, further increasing the devices temperature.

5.3.2 TARA

TARA (Thermal-Aware Routing Algorithm) [42] considers that heat comes from the antenna and from the electronics. The goal of the protocol is therefore to reduce as much as possible communications and processing in individual WBAN nodes. They operate by delaying the packets that are targeted to a node whose recent activity is considered too important and buffering these packets in the previous node on the route. When a relay node is too active, they propose to get around the overheating nodes when an alternate path is known. When no detour is possible, TARA forwards the packet backwards.

TARA has been one of the first attempts to include temperature in the routing metrics and is therefore not adapted to the actual WBAN context, especially in a UWB scenario. Indeed, the algorithm supposes that all routes are identified in a first phase and do not change over time, which is unlikely considering body shadowing. Moreover, applying TARA in our scenarios would probably result a systematic selection of the off-body links, which would be counter-productive with respect to localization objectives.

5.3.3 LTR

LTR (Least Temperature Routing) [43] is a greedy evolution of TARA. Packets are forwarded to the neighbor that has the lowest heat and LTR tries to avoid using always the same next hop node towards a given destination by maintaining a history of recent forwarders.

The critics addressed to TARA also apply to LTR, as the basis of the protocol is similar. Moreover, LTR will eventually select long routes, which may be result in QoS violations for individual packets in our constrained applications. In this case, it would be more efficient to directly discard the packet. Moreover, LTR, as well as TARA, require to precisely identifying the neighbors temperatures, as an emitter node takes a forwarding decision based on its neighbor's status. The resulting control traffic could be too important considering the channel capacity and could also have a negative impact on the nodes heat generation.

5.3.4 ALTR

ALTR (Adaptive Least Temperature Routing) [43] is an evolution of LTR that tries to avoid long routes. The classical LTR algorithm is applied until a packet has travelled a pre-defined number of hops. When the packet has travelled too far, a simple shortest path routing is used. This enhancement improves a little bit the QoS-related critics of LTR, as it is possible to control the detours lengths with respect to delay constraints by playing on the threshold. However, in addition to the critics to LTR and TARA that pertain, ALTR only solves the problem close to the data sources. If there are traffic concentration points in the network (i.e. anchors, gateways, ...) the devices close to these particular nodes will be overloaded anyway and will therefore overheat.

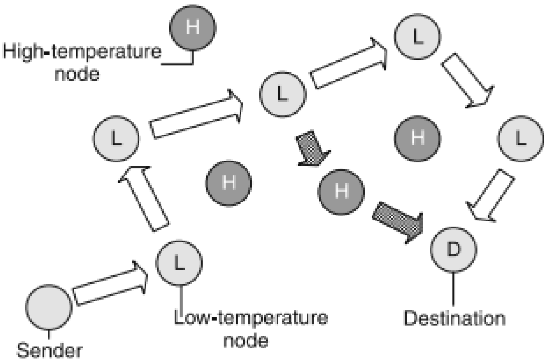


Figure 5-2: LTR and ALTR algorithms. The white arrows indicate the LTR-path. The shaded arrows show the adapted path of ALTR. When the path has three hops, the routing algorithm switches to shortest path routing. Remark that if the maximum hop count were limited to five or less, the packet would have been dropped

5.3.5 HPR

Hotspot Preventing Routing [44] is yet another evolution of LTR that considers both the path length and the temperatures, as ALTR, but reverses the relative importance of both criteria. Nodes try to select the shortest possible paths, but choose alternate paths when temperature of a neighbor rises above a threshold that depends on all neighbors temperatures. As this solution favors QoS, it could be more suitable to the CORMORAN applications. However, the question of the volume of control traffic remains open.

5.3.6 TSHR

Thermal-aware Shortest Hop Routing [45] improves HPR by combining two temperature thresholds. They add to the dynamic HPR threshold an absolute limit on each node's temperature that should not be crossed. When a node intends on forwarding data through a neighbor that is strongly overheating, it buffers the packet instead. It synthesizes all previous contributions, but does not really provide strong support to applications, as it does not take decisions based, for instance, on packets deadlines.

5.4. CLUSTER BASED ROUTING

Clustering is a classical way to manage wide network scalability. It separates the network in several zones, whose exact shape depends on the expected performance, and tries as much as possible to confine traffic and data manipulation inside each zone. This way, the traffic that crosses the borders of each cluster are reduced, which improves overall QoS and network consumption. This divide and conquer approach is the key element behind the scalability of the Internet, which is separated in several AS based on pure administrative criteria. Besides, cluster heads can manipulate data, e.g. by filtering or aggregating, to reduce the global data flow.

In distributed wireless networks, the question of the shape of the clusters has been under discussion in various contributions. Several algorithms try to build a dominant set (connected or not) on the connectivity graph that represent the network, each dominant node acting as a cluster head. Other contributions allow deeper clusters [46] (for example limiting the maximum number of hops between any node and its clusterhead), and let each node associate to the closest cluster head, forming a Voronoï diagram on the network topology. Finally, some contributions propose to rotate the cluster heads in order to reduce these nodes load and energy consumption [47].

There could be both an interest and a natural way to build clusters in WBAN: a cluster could naturally be composed of all the nodes that belong to the same body, and the cluster heads role could fall on the anchors shoulders. An arbitrary node could then distinguish between other nodes that belong to the same group and nodes that do not. A node would exchange relative localization data with nodes that are in its group and absolute localization information with external nodes. However, there is no need to rely on a specific mechanism to form this structure. A node can identify which nodes are located on the same body, either by explicit identification (pairing), or by distinguishing between technologies (e.g. UWB inside clusters and IEEE 802.15.4 outside clusters). In a totally unmanaged network, they could also deduce this categorization by learning based on history.

Besides clusters formation, one of the key issue that has been addressed by the literature is how routing happens between clusters. Several protocols dedicated to wireless sensor networks make the unrealistic assumption that cluster heads are able to communicate directly at large distances, increasing their transmission power if required[47]. This over-simplifies the problem by forgetting about regulations that limit the transmission power. In other contributions, the philosophy is generally to use a classical routing algorithm (Dijkstra or Bellman-Ford) on the graph of cluster heads rather than on the full graph. Each couple of cluster heads then bears the responsibility of maintaining a communication path between end points.

Indeed, in the CORMORAN scenarios, clustering has limited flexibility and advantages when it only concerns the network layer. If routing is built independently from the application and the MAC layer, there is not much latitude that allows to divide the network in original zones. In the LSIMC scenario, the most immediate clustering consists in forming a cluster with all the BAN nodes and maybe a cluster that comprises all the nodes that constitute the infrastructure anchors. In the CGN scenario, clusters would either be limited to single BANs, or would comprise, at a higher hierarchical level, all the BANs that move together, forming a group. However, when considering that clustering should help the MAC layer and the application, and if we relax the classical hypothesis that a node belongs to a single cluster, there could be interesting optimizations.

5.5. CROSS LAYER PROTOCOLS

Cross-layer optimization has been popular since wireless sensor networks. Most of the contributions published so far explored the close collaboration between two layers, often the PHY and MAC or MAC and network layers in a mutual optimization objective. Such approaches are particularly appealing in WBANs, as they allow to take into account the specificities of the physical layer in upper layers algorithms that were often designed with light but real assumptions on the links stability, on their reliability, or on other criteria. Besides, the additional data exchanged with this approach eases multi-objectives optimization and allows to find a good compromise between performance and energy aspects.

5.5.1 TICOSS - RUZELLI

TImezone COordinated Sleep Scheduling (TICOSS) [48] was one such cross-layer approach designed with wireless sensor networks energy optimization in mind. The authors couple the IEEE 802.15.4 medium access protocol with classical shortest path routing in order to take into account the intermittency of the radio links introduced by the duty cycling mechanism (i.e. when nodes put their radio interfaces to sleep). The approach separates a multi-hop network in time zones, which are groups of close nodes sharing the same duty cycle scheme. They base routing on the induced scheduling, and try to avoid problematic situations such as the hidden node scenario with the help of the time zones.

The ideas behind TICOSS are interesting, even though they are quite natural. However, in the CORMORAN context, the specificities of the physical layer and the use of IEEE 802.15.6 for intra-BAN communication make these results difficult to apply as is. Besides, duty cycling is not suited to the QoS constraints of CORMORAN in the general case. Considering the expected end-to-end delays, duty cycling should indeed happen at a very fine scale and would be closely related to TDMA scheduling, leaving few space for optimization.

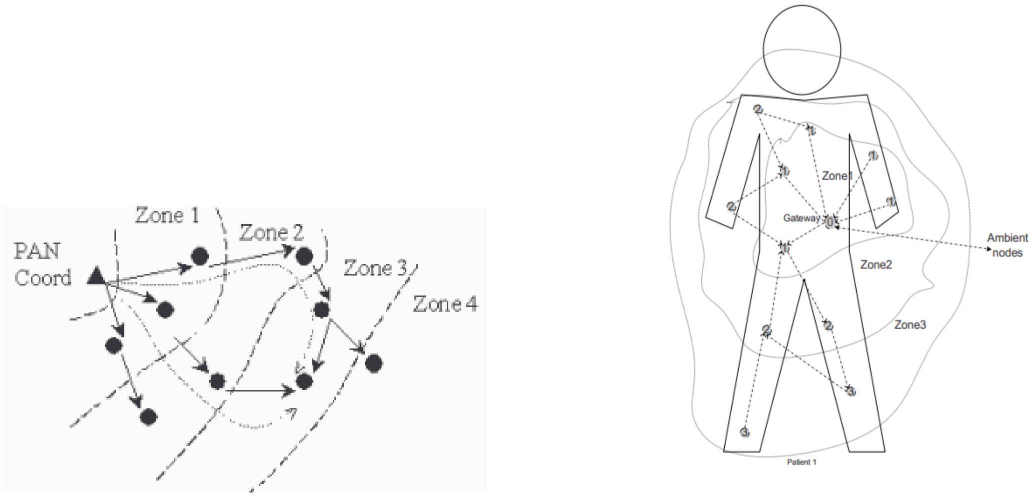


Figure 5-3: **TICOSS-Ruzelli algorithm. The initial timezone setup by flooding and different path generation**

5.5.2 WASP

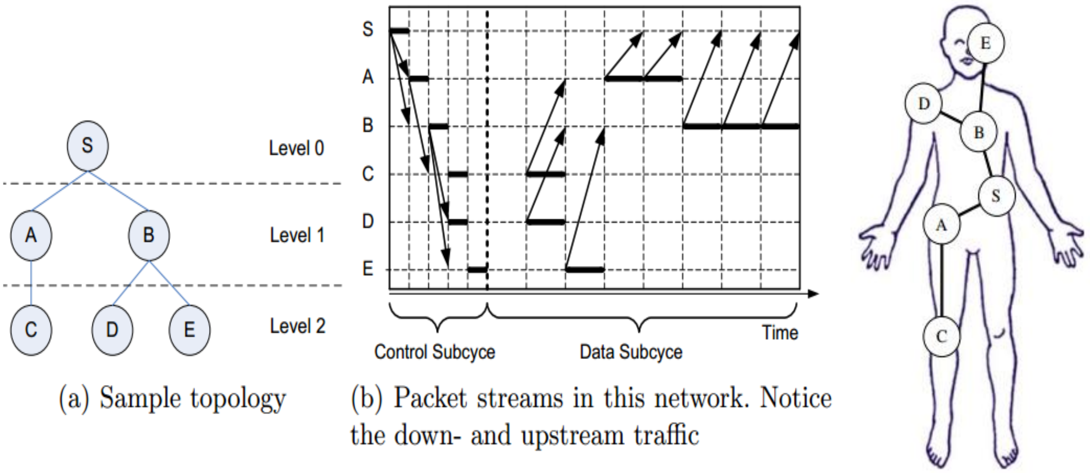
Wireless Autonomous Spanning tree Protocol [49] sets up a spanning collection tree and derive a TMDA slot allocation scheme based on this structure. It is, in this sense, a cross layer protocol, as control packets are shared between the routing algorithm that builds and maintains the collection tree in presence of mobility, and the MAC layer, allocating the time slots accordingly.

Tree-based approaches are relevant in large-scale networks and could be fruitful when it comes to the CGN scenario. However, for intra-BAN communication, such approaches are difficult to articulate with classical IEEE 802.15.6 or IEEE 802.15.4-like random behaviors.

5.5.3 CICADA

Cascading Information retrieval by Controlling Access with Distributed slot Assignment [50] is an evolution of WASP that reserves time slots for control traffic. The control part of a transmission cycle allows handling mobility (detecting nodes movements, selecting new parents in the tree, ...) and hence allows to sort out connectivity issues before transmission. The paper shows that this approach tends to lower delays and loss rates.

CICADA suffers from the same scenario-related issues as WASP. In the scenarios envisioned by CORMORAN, delay constraints are more important than energy consumption issues and the goal of these protocols, which treat QoS as a secondary objective, is therefore not fully in line with the project objectives.



(a) Sample topology

(b) Packet streams in this network. Notice the down- and upstream traffic

Figure 5-4: Communication in CICADA for a sample network of 5 nodes and a sink. The arrows indicate the transmission direction. The bold lines show when the node is transmitting.

5.6. DTN BASED ROUTING

Delay tolerant networks have been a very active research area since more than a decade. The early works in this domain essentially addressed transport and routing protocols operation on links that appear and disappear regularly.

The Interplanetary Networking initiatives, which aim at allowing transmissions using relay satellites orbiting around planets, have examined scenarios in which links between two satellites were active and inactive following regular patterns, which is close to the situation encountered in WBANs, but at a much larger time scale. At the time frame of the revolution around a planet, store-and-forward schemes are easier to schedule than at the speed of arms movements. However some results could inspire WBAN protocols. More recently, DTN have addressed human-level mobility scenarios (vehicles, pedestrians, ...), extending to different and irregular mobility patterns.

The classical approaches concerning routing consist in duplicating packets to increase the delivery probability, and to forward packets probabilistically, according to a history of encounters for example. The whole difficulty of these approaches lies in a correct definition of the forwarding probabilities and of the number of replicas to generate. Which criteria should be considered to select the next hop that will bring a packet closer to its destination at a given time and introducing a minimum delay?

DTN-like operation has been examined for data transmission from a WBAN to the infrastructure. In this scenario, explored in [51], a node collects data inside the WBAN with a classical scheme and transmits this data to an infrastrcuture (database, ...) when links are available. It builds on DTN [52], an adaptation to the sensors context of the bundle layer, which handles store-and-forward operation in interplanetary networks.

In [53][54] [55], the authors propose a probabilistic routing algorithm that takes into account the specificities of the body movements and its implication on the links appearance and disappearance. They address short range links, with an unpredictable on/off pattern, which result in frequent network partitioning and optimize delivery delay.

5.7. ADDRESSING ISSUE

Addressing is, as in every distributed wireless network, an important issue. Addressing should be unique and should be as organized as possible to let the network scale. However, in the two applications that are envisioned by CORMORAN, the network size is reasonable enough to let the network operate with flat addressing. This essentially means that communication inside the network (a single BAN as well as a group in the CGN scenario) can rely on a flat addressing space. It is only when numerous BANs form a wide scale network that addressing may need to be hierarchical.

In an IPv6 scheme, the problem can be solved by allocating a 48 bits prefix to a large-scale multi-BAN, leaving the 16bits of the Site-level aggregator free for each individual BAN or for each group of BANs depending on the regularity of the neighborhood.

For individual nodes addressing, the interface identifier can be derived, as usual, from the MAC address if any, or from the node ID inside the BAN, that can be hadcoded in the node's firmware, set at the node deployment, allocated dynamically by the anchor node with a lightweight DHCP, or decided in a distributed manner. From this interface identifier, nodes within a BAN can communicate together using a link-local address.

5.7.1 6LOWPAN

The 6LowPAN IETF group has been addressing issues regarding the integration of wireless tiny devices, such as sensors, in a large IPv6 network. They specify how functions such as fragmentation / reassembly, auto-configuration or mobility should be handled, and they also specify a header compression mechanism.

The idea behind header compression is that the IPv6 header would represent a very high overhead it it were fully inserted in every IEEE 802.15.4 frame. Header compression consists in selecting which fields should be included in the reduced IPv6 header that is used within the sensor network (or within the BAN in our context). The gateway of the sensor network then translates addresses from and to IPv6.

6LowPAN defines two levels of compression. The first level reduces the IPv6 header to 7 bytes, while the second level reduces it to only 2 bytes, but limits communication to the link-local scope.

6. TOWARDS CROSS LAYER STRATEGIES FOR CORMORAN

6.1. INTRODUCTION

As explained on the introduction, the objective of the Task 3.1 of the CORMORAN project is to propose new cooperative algorithms in order to collect information to achieve enhanced communications and location, to enable Individual Motion Capture applications. In the last case, the posture of On-Body nodes is expected to be estimated with an Impulse Radio-Ultra Wide-band (IR-UWB) system [56].

In the literature, the considered challenges on Individual Motion Capture using IR-UWB are mainly the clock synchronization, the NLOS case (Non Line of Sight), the interference and multipath [57]. When considering mobility, some nodes located in the body moves always and the positions of the nodes changes at each frame transmission, thus introducing error in the estimation [58]. In [59], the authors have considered the mobility issue, for the localization of a pedestrian in a room. They present the issues of ranging error, position update latency and calculation algorithms under mobility. But, no rigorous analysis was provided. Besides, the considered speed is much lower than the one in a BAN. They show the impact of MAC allocation resources on the capacity of the tracking system for Wireless Sensor Networks (WSN) scenarios. Therefore, it is necessary to understand the drawbacks between the mobility and channel constraints before the design of any protocol at the upper layer.

In terms of protocols, the PHY layer considered for the LSMIC scenario is the UWB proposed in the IEEE 802.15.6 group. We will consider the cases when we are in the ideal case for the localization (i.e. study of the mobility impact on localization with Line of Sight) and the case with realistic channel models with enhanced localization algorithms. For the MAC layer, we will study the protocol defined by the standard but depending on the final application, we will propose to adapt some MAC features, especially to comply with constraints for cooperative transmissions and localization applications. Then, considering the co-simulator between WSNET and Pylayers presented in the Deliverable D2.5, we will be able to implement the protocols and algorithms in order to study the behavior and performances under realistic scenarios, as the one performed during the measurement campaign at ENS Cachan Bretagne, Deliverable D4.1.

The chapter is organized as follows. First, section 6.2 gives the basics and the requirements to perform a cross-layer design for the LSIMC scenario. Then, section 6.3 shows the different points and drawbacks to consider at the upper layers in order to design cooperative strategies. Finally, we came with the conclusion.

6.2. LOCALIZATION AND POSITIONING REQUIREMENTS

6.2.1 IR-UWB LOCALISATION BASICS

As explained before, Impulse Radio Ultra Wideband (IR-UWB) systems [58] are a good solution thanks to the high time resolution using the Time of Arrival (ToA, i.e., the propagation duration) which can be accurately estimated for precise range measurements between two nodes.

For this study, we consider a mesh of IR-UWB WBAN under full connectivity containing N_T nodes of two kinds as in [58] , on-body mobile nodes that do not know their own position (i = 1…N) and on-body anchor nodes that know their own position (j = 1…M), N_T = N + M. A set of anchor nodes define a Local Coordinate System (LCS) to localize nodes under mobility. We define the instantaneous distance of the node i with the anchor j as $d_{ij}(t)$ and the estimated distance as $\hat{d}_{ij}(t)$ which is calculated through Toa estimation. Moreover, the instantaneous position for a node is defined as $P_i(t)$ and the estimated position is defined as a function of estimated distances $\hat{P}_i(t) = f(\hat{d}_{i1}(t), \hat{d}_{i2}(t), \ldots, \hat{d}_{iN}(t))$.

The distance $\hat{d}_{ij}(t)$ between two nodes is deduced with the Three-Way Ranging (3WR) protocol (resp. Two-Way Ranging 2WR) by combining the typical timers obtained from 3 transmissions (resp. two slots) [59], corresponding to one Request Q_{ij} send by a node i to an anchor j and two Response packets $R1_{ij}$ and $R2_{ij}$ from anchor j to node i, as shown in **Figure 1-1**. We define $\Delta t1$ (resp. $\Delta t2$) as the time difference between the reception of a request packet and the transmission of a response 1 packet (resp. the time difference between the transmission of the responses packets).

$$\hat{\mathrm{d}}_{\mathrm{ij}}(\mathrm{t}) = \frac{1}{2}\,\mathrm{c}\left[\underset{\text{Time of Flight}}{\left((\mathrm{T}_4 - \mathrm{T}_1) - (\mathrm{T}_3 - \mathrm{T}_2)\right)} - \underset{\text{Clock Drift}}{\left((\mathrm{T}_6 - \mathrm{T}_4) - (\mathrm{T}_5 - \mathrm{T}_3)\right)}\right] \qquad (1)$$

, where c is the light speed.

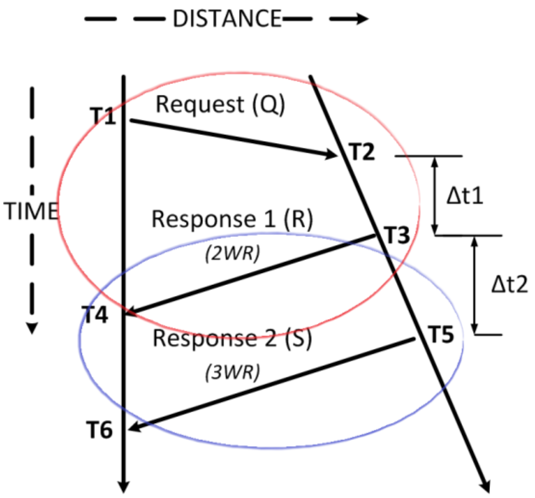


Figure 6-1: IR-UWB 2WR and 3WR protocol

From these first assumptions, we can notice that there are several parameters that may affect the 2WR and 3WR based ranging errors. Such parameters can be the speed of nodes, the variation of Δt1 and Δt2, the number of nodes/anchors and the scheduling of the 3WR (2WR) packets. In fact, the speed of nodes depends on the kind of human activity and it may have an impact on the capacity of the BAN system to estimate accurate positions for Motion Capture. Moreover, the physical channel between anchors and mobile nodes depends on the speed of nodes and we can have high packet loss rate under high speeds. Furthermore, we can also observe that the position of a mobile node evolves during the 3WR packets transmission, so the delay of Δt1 and Δt2 needs to be as smaller as possible to achieve accurate positioning estimation.

$$\hat{d}_{ij}(t) = \frac{1}{2}\, c \left[\left((T_4 - T_1) - \Delta t1\right) - \left((T_6 - T_4) - \Delta t2\right)\right] \qquad (2)$$

Therefore, we can also assume that the delay of Δt1 and Δt2 can also be affected by the number of nodes/anchors; the order of the slot allocation for the nodes; but also by the strategies used to schedule the 3WR packets. This means that the system needs a MAC protocol as flexible as possible to consider all this parameters and adapt the system to different human activities. Thus, the study of these parameters is important for a cross layer protocol design and it will be more discussed by the next subchapters.

6.2.2 LOCALIZATION APPLICATION ALGORITHMS

As explained before, benefiting from the TOA estimation, we can provide ranging measurements for each pair of nodes of a WBAN. Thus, each mobile node Ni collects the distances ($\hat{d}_{i,j}$) and positions (P_j) from all the anchors nodes to perform its own position estimation ($\hat{P}_i(t)$). The Deliverable 3.2 will provide an enlarged scope about the different techniques and algorithms for positioning estimation, but in this subchapter we will give some basics for the cross layer design.

$$\hat{d}_{i,j} = \sqrt{(x - x_j)^2 + (y - y_j)^2 + (z - z_j)^2}, \quad \hat{P}_i(t) = \{x, y, z\} \qquad (3)$$

The position $\hat{P}_i(t)$ of a node is estimated with the Time Difference of Arrival (TDOA) technique [56], where the position is determined as the intersection of hyperboloids in a tridimensional space. For this purpose, each node communicates with at least four anchors for a distributed localization, which is the minimum needed for a tridimensional positioning, as described by the following equations:

$$\begin{aligned}
{d_2}^2 - {d_1}^2 &= (x_2 - x)^2 + (y_2 - y)^2 + (z_2 - z)^2 - (x_1 - x)^2 + (y_1 - y)^2 + (z_1 - z)^2 \\
{d_3}^2 - {d_2}^2 &= (x_3 - x)^2 + (y_3 - y)^2 + (z_3 - z)^2 - (x_2 - x)^2 + (y_2 - y)^2 + (z_2 - z)^2 \\
{d_4}^2 - {d_3}^2 &= (x_4 - x)^2 + (y_4 - y)^2 + (z_4 - z)^2 - (x_3 - x)^2 + (y_3 - y)^2 + (z_3 - z)^2
\end{aligned}$$

Then, we use a Linear Least Square (LLS) approach to estimate the position of the node by reorganizing the equations into a linear equation and an intermediate variable is added (linearization function) to estimate the source position:

$$d_2^2 - d_1^2 = (x_2^2 - x_1^2) + (y_2^2 - y_1^2) + (z_2^2 - z_1^2) - 2\,[\,x\,(x_2 - x_1) + y\,(y_2 - y_1) + z\,(z_2 - z_1)\,] \quad (4)$$
$$d_3^2 - d_2^2 = (x_3^2 - x_2^2) + (y_3^2 - y_2^2) + (z_3^2 - z_2^2) - 2\,[\,x\,(x_3 - x_2) + y\,(y_3 - y_2) + z\,(z_3 - z_2)\,] \quad (5)$$
$$d_4^2 - d_3^2 = (x_4^2 - x_3^2) + (y_4^2 - y_3^2) + (z_4^2 - z_3^2) - 2\,[\,x\,(x_4 - x_3) + y\,(y_4 - y_3) + z\,(z_4 - z_3)\,] \quad (6)$$

Alternatively, we define the following expressions (with $j \neq k$ as different anchors) to simplify the equations before the linearization:

$$r_{k,j} = (x_k{}^2 - x_j{}^2) + (y_k{}^2 - y_i{}^2) + (z_k{}^2 - z_j{}^2) \qquad (7)$$
$$a_{k,j} = x_k - x_j\,; \qquad b_{k,j} = y_k - y_j; \qquad c_{k,j} = z_k - z_j \qquad (8)$$

Then, substituting the expressions (7,8) into eq. (4-6) yields:

$$d_2{}^2 - d_1{}^2 = r_{2,1} - 2\left(x * a_{2,1} + y * b_{2,1} + z * c_{2,1}\right) \qquad (9)$$
$$d_3{}^2 - d_2{}^2 = r_{3,2} - 2\left(x * a_{3,2} + y * b_{3,2} + z * c_{3,2}\right) \qquad (10)$$
$$d_4{}^2 - d_3{}^2 = r_{4,3} - 2\left(x * a_{4,3} + y * b_{4,3} + z * c_{4,3}\right) \qquad (11)$$

Finally, the matrix form for eq. (9-11) is then:

$$A = -2\begin{vmatrix} a_{2,1} & b_{2,1} & c_{2,1} \\ a_{3,2} & b_{3,2} & c_{3,2} \\ a_{4,3} & b_{4,3} & c_{4,3} \end{vmatrix}; \qquad b = \begin{vmatrix} d_2{}^2 - d_1{}^2 - r_{2,1} \\ d_3{}^2 - d_2{}^2 - r_{3,2} \\ d_4{}^2 - d_3{}^2 - r_{4,3} \end{vmatrix}; \qquad P = \begin{vmatrix} x \\ y \\ z \end{vmatrix}$$

$$A\,P = b \qquad (12)$$

Where vector P is the position $\widehat{P}_i(t)$ of the node we want to estimate and $\hat{d}_{i,j}$, $r_{k,j}$, $a_{k,j}$, $b_{k,j}$ and $c_{k,j}$ are known values. For the TDOA technique, we assume that the anchor nodes have a common time reference, but not with the mobile nodes. Therefore, the clock drift between the anchors and mobile nodes is mitigated with the 3WR packets. This technique is good in the case of WSN, where the node has a regular motion and the coordination between anchors and mobiles nodes is easy to achieve and maintain. However, the introduction of errors in the ranging estimations will cause an error on the position estimation. This is possible in the case of WBAN, during the transmission of 3WR packets the mobile nodes are always moving and the estimated distances with the anchors are not performed at the same time for the position of the node, which can lead into an error estimation on the positioning **Figure 1-1**.

Moreover, if we consider a bigger topology of N mobile nodes performing 3WR transactions for localization with M anchors, the positioning error can also be a problem for the Motion Capture. Therefore, it is necessary to find new cooperative strategies at MAC/NWK layer to mitigate the positioning error within an acceptable latency.

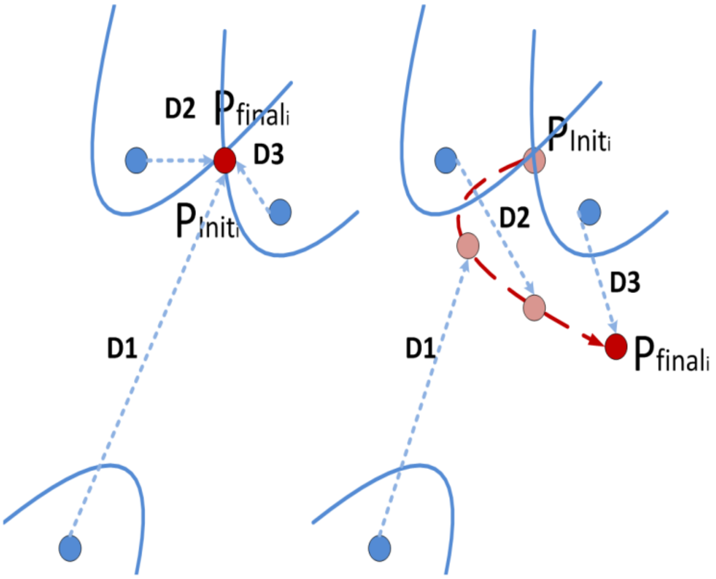


Figure 6-2: Error on ranging estimation with TDOA (static node vs mobile node)

6.3. CROSS-LAYER DESIGN FOR LOCALIZATION

6.3.1 MAC/NWK DESIGN FOR LOCALIZATION APPLICATION

As explained on the last chapters, the design of the MAC/NWK layer has to be seen as an independent black box offering the service of enhanced communications for the localization applications. In this view, the adoption of new cooperative algorithms have to match with the use of the IR-UWB PHY layer defined on the standard IEEE802.15.6. A cross-layer design will led to strategies for system optimization considering the throughput, the delay, the degree of fairness, the energy consumption and the positioning accuracy. The recent works in localization with WBAN focused on the radio issues and localization algorithms performances without rigorous scope on MAC or NWK strategies.

Previous works focusing on MAC design for localization with UWB systems proposed protocol strategies based on beacon-enabled Time Division Multiple Access and evaluated the performance in terms of accuracy and latency. In [60], they proposed cooperative ranging with Aggregated and Broadcast schemes to reduce the delay of 3WR transactions. In[61], they focus on better resource management with priority levels for communication. In [62], they focus on the relation between MAC delay and UWB accuracy related to the number of anchors and the communication range of nodes under mobility. However, all these works focuses on localization applications for WSN which do not present the same problems of WBAN and they do not consider the impact of the scheduling of localization packets on the positioning estimation nor more accurate routes for enhanced communication between the nodes. In [63], they proposed scheduling schemes for cooperative distributed localization with two different policies (node neighborhood and links quality) to reduce positioning convergence, latency and overhead. However, they consider a 2D Positioning for WSN which again is not realistic for WBAN location-aware applications.

Typically, the main functions on MAC design that we have to consider for localization purposes are the following [64]:

- **Medium sharing** aims on how nodes access the medium. As explained on Chapter 4, this depends on the application and the PHY layer. In the case of LSIMC, a hybrid multi-channel approach based on TDMA is more suitable for the IR-UWB WBAN since we need to adapt its behavior according to the channel state, traffic load and topology size predictions. In the case of CGN scenarios, we have to study the behavior of contention, reservation and hybrid protocols depending on the PHY layer since there are few works considering multi BAN medium sharing e.g. a network based on NB PHY Layer may work with contention and reservation protocols, but in the case of UWB PHY layer, reservation protocols are more suitable for enhanced communications.

- **Topology organization** includes the algorithms to coordinate the nodes for resource sharing. In the case of CORMORAN scenarios, we have to consider the order of the slot allocation for the nodes to communicate and study if there is an impact on ranging estimations depending on the position of the nodes on the body e.g. we have to be able to know which node should communicate first with anchors (distributed localization), the nodes positioned on the wrists or the ones positioned on the legs. For that, it would be interesting to look for correlations between channel states of links and estimated distances to perform an organization algorithm.

- **Admission control** deals with the management of access to avoid congestion and interferences. In the case of LSIMC, there is a problem of connection with nodes under high mobility because they are not in a regular LOS with the anchors. Cooperative strategies with one-hop algorithms can help to adapt the medium access for the mobile nodes and enhance the communication with the anchors. Moreover, this is important for the CGN scenarios in order to mitigate interference between the nodes i.e. multi BAN coexistence.

- **Packet Scheduling**: several algorithms have been proposed to determine the order of packets for transmission, based on channel models and interference mitigation. In the case of the LSMIC scenario, as said on chapter 6.2.2, there is a ranging error on estimation of distances related to the scheduling of Three Way Ranging packets under realistic WBAN scenarios. Therefore, we have to consider a specific study of the impact of scheduling strategies for positioning estimation.

- **Power control** is important for WBAN networks for longer autonomy and reduction of interference, specially for UWB networks. Moreover, cooperative strategies can be used to adapt the power of transmission depending on the channel and mobility variations.

- **Quality of Service** management is important for both LSIMC and CGN scenarios with adapted policies according to the requirements described on chapter 1.2. The strategies have to be as flexible as possible to adapt the network behavior depending on the channel links and the ranging estimations.

While the MAC layer attempt to decide whether or not cooperation is necessary and select the optimal relaying entities among the network, the NWK layer defines a the routing protocols to deliver the TWR packets between the mobile node and the anchors with cooperative strategies. In this case, the NWK has several challenges to be addressed:

- **Specific Link Definition:** for localization purposes, mobile nodes and anchor nodes exchange 3WR packets with an end-to-end route, however it is possible that in some cases there is not LOS between them and therefore, a new cooperative route needs to be defined considering the localization aspects. Hence, this cooperative link can be seen as a multi-terminal link or a sequence of one or more cooperative links. In the case of WBAN, this cooperative links can be seen as virtual MISO or MIMO, since one or many mobile nodes will attempt to localize a set of anchor nodes in a cooperative context. Thus, the NWK layer faces the challenge of constructing optimal routes.

- **Cost of Route establishment and maintenance:** route establishment aims to find the optimal routes for communication and its construction should not consume much energy and latency. Moreover, route maintenance depends on the periodic route discovery to update the status of links. The discovery can be updated when a path fails leading to overhead or when all paths fails leading into throughput degradation and service interruption. Hence, we have to determine an optimal value of paths through one-hop cooperative nodes to balance the QoS degradation for the localization.

- **Multi-Flow Throughput and multi path interference:** cooperative transmission has multiple traffic flows which increase the path interference. Therefore, the network throughput is reduced and the probability of collision becomes important. This problem has to be considered especially in the case of Multi-BAN coexistence. Moreover, in the case of aggregated and broadcast techniques, it is necessary to select independent paths to reduce the path interference e.g. coupling metric between joint and disjoint paths which is the average number of nodes that are blocked from receiving data along one of the paths when a node in another path is transmitting [73].

- **Delay differences:** this is a common problem in multi-path routing, because each path present different end-to-end delays. Therefore, the cooperative protocol have to optimize over the achievable bandwith and the differential delays.

In Chapter 4, we analyze different protocols attempting to enable the CORMORAN scenarios. However, it is necessary to quantify their behavior and compare their performance on positioning estimation under realistic WBAN scenarios. For the following studies, we need to consider the impact of mobility and the channel state (Deliverable 2.2, 2.3, 2.4) for ranging purposes. Then compare both impacts in order to propose an adapted cooperative protocol at MAC and NWK layers.

6.3.2 MOBILITY IMPACT ON POSITIONING ESTIMATION

When considering mobility for localization applications in WBAN, we explained in Chapter 6.2.2 that the distance between a pair of node and anchor changes at each transmission of the 3WR packets, thus introducing error in the ranging estimation [58]. There are few works considering this issue, in [59] the authors have considered the mobility issue, for the localization of a pedestrian in a room. But, no rigorous analysis was provided. Besides, the considered speed is much lower than the one in a BAN. For this reason, we propose a preliminary study for Individual Motion Capture to quantify the impact of mobility on the ranging estimation [65].

To this aim, we analyze the distance estimation between 2 nodes, a mobile sensor and an anchor attached to a human body. We defined a physical (PHY) Layer based on the IEEE802.15.6 PHY UWB [28] in default mode (OOK modulation, data rate 0.4875 Mbps) and we consider a Line of Sight (LOS) channel without packet loss. Therefore, we assume that our radio is capable to detect the first path of IR-UWB to detect the precise TOA at the receiver. At the Medium Access Control (MAC) Layer, we define a protocol based on the TDMA protocol and we assume that it is beacon enabled. Then, we reserve three transmission periods corresponding to the 3WR (2WR) protocol and we considered two types of parameters: (i) the speed of nodes; (ii) the values of Δt1 and Δt2 as defined in chapter 6.2.1.

The anchor has a known position with respect to a global 3D coordinate system while the sensor does not have any knowledge of its own position. We assume that the sensor follows a back-and-forth linear motion. Then, we quantify the impact of mobility by using the Root Mean Square Error (RMSE).

$$RMSE = \sqrt{\frac{\sum_1^N \left| d_{ref} - d_{est} \right|^2}{N}} \qquad (13)$$

The RMSE compare the estimated distance d_{est} with three reference distances d_{ref} as follows: d_{ref1} is the distance at the beginning of the first request, d_{ref2} is the distance at the reception of the last response, and d_{avg} is the average of d_{ref1} and d_{ref2}.

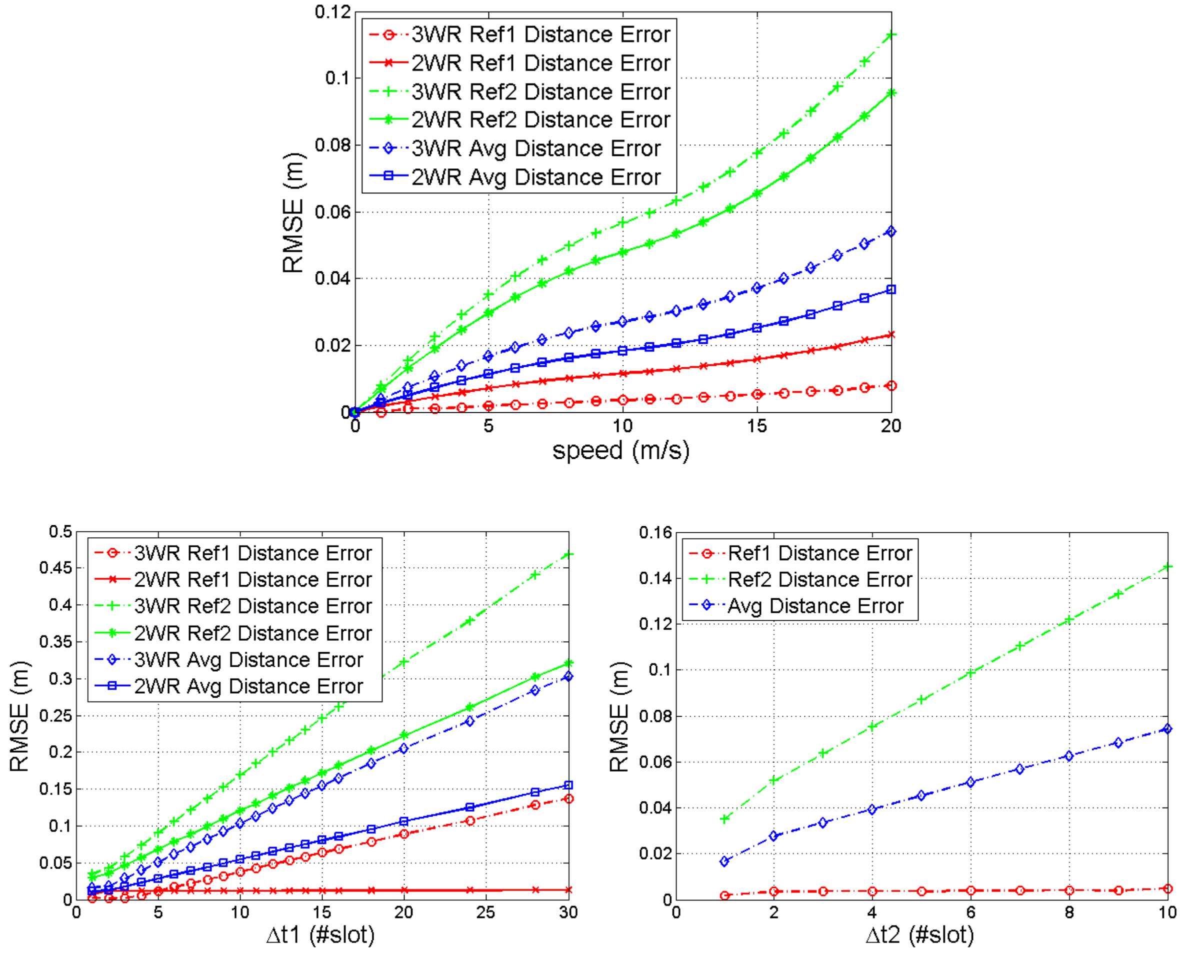


Figure 6-3: (a) RMSE of estimated distance between 2WR/3WR as function of speed. (b) RMSE of estimated distance between 2WR/3WR as function of $\Delta t1$. (c) RMSE of estimated distance with 3WR as function of $\Delta t2$.

Figure 1-1 shows that RMSE increases with the speed and the response time Δt1 and Δt2. This means that increasing one of these parameters leads to a higher distance between the nodes due to the node mobility, and hence an error in the ranging estimation is introduced. The results show that depending on the speed and the chosen reference point, the 2WR can be better than 3WR if only mobility is taken into account. This would mean that the channel would be less used since sends a packet less. Moreover, the results show that $\Delta t1$ has more impact on the ranging estimation than the speed since the RMSE can reach an important ranging error (>50cm) while with 20m/s (i.e. human fist speed) of speed RMSE do not exceed 12cm of error. This leads us to investigate more in the optimization of the scheduling problem (3WR) in order to reduce the response time at $\Delta t1$.

Moreover, we can find the same problem for the positioning estimation, if we consider the case of one node sending 3WR packets to at least four anchors in order to find its position in a tridimensional space as in **Figure 6-4**. As explained before, the position of the node may not be the same between the moment it send the first request packet and at the moment it receive the response packets of the last anchor. This positioning error can be reduced by proposing the most appropriate scheduling scheme at the MAC layer. Therefore, we propose to extend the study to evaluate the impact on positioning estimation with different scheduling strategies to minimize the ranging and positioning error in order to enable the human motion capture. Then, we want to enlarge the study with channel models under Realistic short-term and long-term pedestrian mobility models, i.e. from the CORMORAN measurement campaign which has been realized during the project June 2014 at ENS Cachan Bretagne, France. Finally, we will make a study of the ideal case for both LSIMC and CGN scenarios and compare with enhanced localization algorithms as proposed on D 3.2.

7. CONCLUSIONS

Throughout this Deliverable, we gave the basics, taxonomies and foundations of cooperative communications for enhanced communications in the context of localization purposes, as described on Deliverable 1.2. Most notably, we have distinguished PHY, MAC and NWK layers design for cooperative purposes, as well as the challenges and key milestones for the CORMORAN project.

In Chapter 1, we have briefly presented the selected scenarios and applications for the CORMORAN project. Considering the different needs and requirements for localization purposes, we alluded to the role of cooperative strategies to perform better performances for the LSIMC and CGN applications as described on Deliverable 1.2.

In Chapter 2, we presented an overview and taxonomy of cooperative communications, as well as their pros and cons at different levels. Then we discuss about the differences between WSN and WBAN in terms of requirements to enable cooperation strategies. For this purpose, we show the different challenges to consider for the LSIMC and CGN scenarios. Moreover, we introduced the canonical strategies proposed in literature and we highlight that the choice of the strategies depends on the application.

In Chapter 3, we discuss about the relaying cooperation at the PHY Layer which has several benefits in terms of capacity and performance under realistic WBAN channels. We introduce the performance bounds to quantify the gains of cooperative relaying systems. where we looked at capacity over ergodic channels and outage over non-ergodic channels. We also discuss about the transparent (AL, LF) and regenerative (DF, CF, EF) relaying techniques, for each of these, we discussed about the design parameters, as well as the pros and cons to consider for the CORMORAN scenarios.

In Chapter 4, we alluded to the role of the cooperative strategies at the MAC layer. We defined six specific requirements to consider for the CORMORAN project: easy deployment, fairness, adaptability, reliability, mobility and energy saving. Then we presented a list of cooperative and non-cooperative protocols interesting for the project and we give a qualitative analysis according to the defined requirements.

In Chapter 5, we introduce the cooperative approaches at the NWK layer. We discuss about different cooperative protocols and we presented their pros and cons. Moreover, we highlight that routing techniques will want to minimize time network discovery, and maximize the knowledge of the neighborhood of each node so that the road used to pass the information to the central equipment is the most efficient in terms of time and energy spent by each node.

Finally, in Chapter 6, we presented the preliminary studies necessary for the LSIMC and CGN scenarios. We briefly described the application assumptions and challenges to consider for the design of cross layer protocols for localization. We also defined a system model considering the LSIMC scenario for the study on the impact of mobility for positioning estimation. Thus, we highlight that the cooperation strategy for localization purposes should be based on cross-layer design. PHY layer provides to the MAC layer the channel measurements and TOA estimates to help on the cooperative decision. NWK layer will help to find cooperative path in order to mitigate interferences between inter/intra BAN flows and the application layer will seek to aggregate and compress on the fly the information detected by the sensors to reduce traffic

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