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TABLE OF CONTENT

ABSTRACT

Today's main challenge for the designers and developers of protocols and applications for a group of WBANS is to design appropriate cross-layer protocol mechanisms allowing to benefit from inter/intra-WBAN cooperation and to limit inter/intra-WBAN interferences, while ensuring higher quality of (localization) service. This document is related to the subtask 3.3 of the CORMORAN project (Inter-WBAN networking), which focuses more specifically on inter-BAN communications and interactions.

In the context of WBANs group navigation, each node could need to send its position to other nodes in the group or to exchange data in a peer-to-peer manner through multi-hop communications, for instance to determine the location of each node in the network, or simply for application-specific traffic. However, end-to-end communications between the nodes require a set of optimized mechanisms (routing, scheduling, resource allocation, coexistence approaches between WBANs, etc.). This deliverable focuses on the PHY, MAC and routing layers, with the idea that these layers could collaborate and exchange information. Accordingly, we thus propose a new topology control algorithm and routing protocol based on self-organization approaches inspired from ad-hoc and sensor networks communities. The latter is adapted to the particularities of the inter-WBAN context. Our simulation results show an improvement of the positioning accuracy of all on-body nodes.

1. INTRODUCTION

Advances in wireless communications, semiconductors and physiological sensing have given rise to miniature, lightweight, low power, intelligent monitoring devices. These devices can be integrated into a Wireless Body Area Network. This kind of network is on the verge of fulfilling new market needs in a variety of application fields such as emergency and rescue (e.g. distant posture detection for institutional rescuers or victims), healthcare (e.g. physiological or activity monitoring, wireless medical actuators and implants, assistance to medical diagnosis, lab-on-chip chemical analysis), entertainment (e.g. motion capture for gaming or sports analysis), personal communications and multimedia (e.g. distributed terminals, personal consumer electronics), clothing applications (e.g. garments with electronic components, smart shoes) [ULLA12].

In the near future, WBANs are expected to be massively present in public areas (e.g. streets, shopping malls, train stations etc.), where direct Body to Body interactions and heterogeneous network access are likely to offer the highest at most promising potential in terms of cooperation. From a general localization-oriented perspective, cooperation is expected to provide information redundancy and spatial diversity to enable better service coverage, as well as higher precision and robustness [RENA08].

This document is related to the subtask 3.3 of the CORMORAN project (Inter-WBAN networking), which focuses on inter-BAN communications and interactions. As detailed in deliverable D1.1, CORMORAN has selected two main target application scenarios called Large-scale individual motion capture (LSIMC) and Coordinated group navigation (CGN). The reader is invited to refer to deliverable D1.1 [CORMORAN_D1.1] for an extensive description of both scenarios. Hereafter, we will focus mostly on CGN scenarios (inherent to inter-WBAN contexts), after quickly reminding the specificities of the LSIMC scenario that are expected to have an influence on the inter-WBAN communication process too.

One primary objectives of LSIMC is to achieve Motion Capture (MoCap) or mobility detection functions 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). For this purpose, several devices are located on a single body. Note that the interaction between close WBANs is not necessary, at least to perform relative on-body ranging and positioning tasks. However, in the last sub-scenario evoked in D1.1, nodes that are located on-body are supposed to be able to express their coordinates in a global system, either by converting the local coordinate system to a global reference, or by directly localizing each node within the global infrastructure.

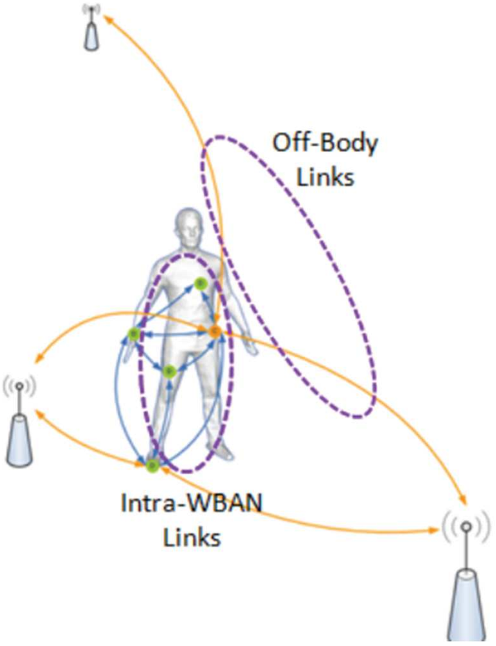


Figure 1.1: Generic deployment of LSIMC scenario, with short-range intra-WBAN links (blue), and large range off-body links (orange).

For the CGN scenario, multiple BANs will move together forming groups that have their own group trajectories, meeting and separating according to classical mobility models. Each individual in the group wears a few devices (typically < 10) that can have multiple interfaces: IEEE 802.15.6, Bluetooth LE or IEEE 802.15.4a could be utilized for instance for on-body and body-to-body opportunistic communications, whereas IEEE 802.15.4 or Bluetooth would be good candidates for inter-WBAN communications passing through gateways, such as mobile phones.

As depicted in Figure 1.2, the topology in a CGN scenario is characterized by three kinds of communications that may coexist at the same time: On-Body (or intra-body), Body-to-Body (or inter-body) and Off-Body links. The body-to-body communication is required to collect ranging measurement in order to improve the absolute body positioning in a group through spatial diversity and information redundancy techniques. In some considerations, the use of fixed and know elements of infrastructure around can be also required. In distributed localization schemes, on-body and body-to-body nodes exchange data together for both ranging measurements and positions exchange.

In comparison with the LSIMC scenario, the CGN scenario suffers particularly from interference and coexistence issues between neighboring WBANS. In addition, as the communication is sensitive to the LOS/NLOS conditions, the network density should not increase too much within this type of technology, except for highly crowded scenarios such as public transportation or manifestation. Hence, it is necessary to select or to design the MAC layer so that it can deal with interferences that appear between close networks when two devices that use the same schedule on the same channel get in mutual range. Moreover, it is important to create collaboration between the layers and introduce new cross-layer PHY/MAC/NWK mechanisms allowing to mitigate inter/intra-WBAN interferences, favor inter/intra-WBAN coexistence and hence improve the quality of service (e.g. ensure higher delivery packet rate).

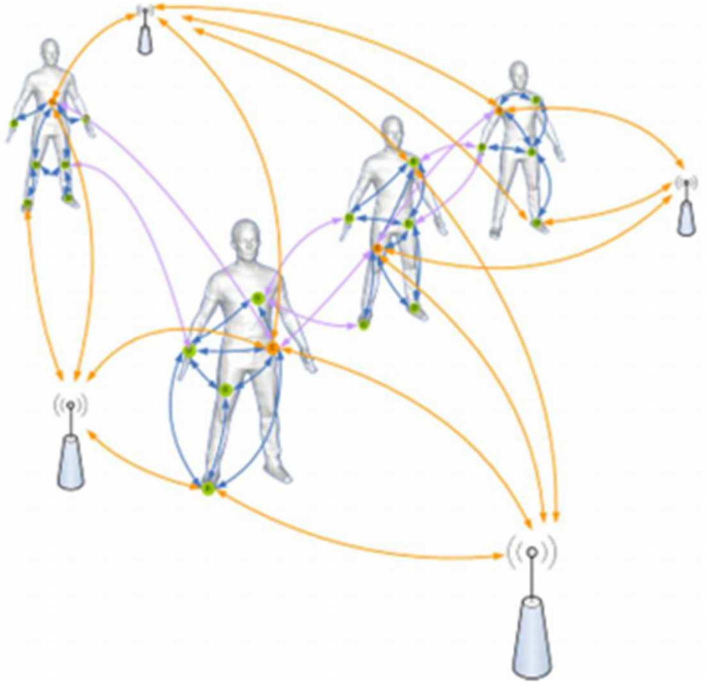


Figure 1.2: Generic deployment scenario for CORMORAN, with short-range intra-WBAN links (blue), medium-range inter-WBAN links (lavender), and large range off-body links (orange).

Because the MAC and upper layers protocols are strictly connected to the knowledge of the propagation mechanisms and channel models, this deliverable is related to some extent to the deliverables D2.2 and D2.3, which present the WBAN channel measurement campaigns carried out in the frame of Task 2, but also to D4.2, which describe another measurement campaign based on real devices.

This document contains two parts structured as follows: the first part is focused on a topology control approach inspired from multi-hop wireless network (e.g. WSNs, ad-hoc). This approach is described and detailed in Section 2.2. Section 2.3, then, describes the system model and gives the problem statement. We propose and evaluate a new topology control algorithm in Section 2.3 and Section 2.4. In the second part, we investigate the issues related to the routing of data in highly dynamic WBSNs. A new routing strategy based on clustering is thus explained in Section 3.3. Finally, Section 4 concludes this deliverable.

2. COOPERATIVE NETWORK TOPOLOGY CONTROL FOR WBAN-BASED COLLECTIVE NAVIGATION

2.1. INTRODUCTION

Nowadays, self-organizing wireless network deployments have become a necessity especially when the topology is dynamic, in which node-to-node links are established and broken quite often due to various reasons. Thus, maintaining a fully connected topology for such networks is a challenge and requires careful application of topology control. Before the concept of topology control is introduced, it is important to start by formally defining network topology which is necessary to understand the foundations and motivations behind topology control. The topology of a network defines the structure of links connecting pairs of nodes of the network. Each communication between two nodes of the network is routed based on the network topology. Usually, the network topology is represented by a communication graph. The primary goal of Topology Control (TC) is to restrict the network topology to a small connecting subset with the purpose of maintaining some global graph property (e.g., connectivity). The idea is to choose a connecting subset from all possible links such that the overall network performance remains good while routing on the topology is faster and easier thanks to the reduced number of links. Figure 2.1 gives a first example of topology control. The topology with grey color shows a unit disk graph with all possible communication links. The topology with red color depicts the resulting network after application of topology control. The resulting topology is still connected, but consists of much less links.

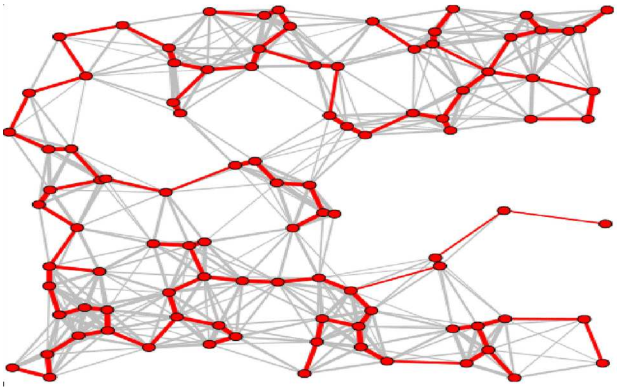


Figure 2.1 Topology control example: grey links present all possible communication links while red one depicts the resulting network after application of topology control

In wireless networks, topology control is used to reduce the cost of distributed algorithms. For instance, a Minimum Spanning Tree (MST) is used as a backbone to reduce the cost of broadcast in the network. This technique is extensively studied in particular in Wireless Sensor Networks (WSNs) and Ad'hoc networks to reduce energy consumption and to extend the network operational time or to increase the network capacity. A topology control algorithm is mainly composed of two subproblems, Topology Construction in charge of building a new reduced topology, and Topology Maintenance in charge of switching the reduced topology from time to time when the current one is not optimal anymore. Topology Control has directed impacts on network-level upper layer issues, such as routing and applications layers. To ensure end-to-end communications in the network through multi-hop routes, the network connectivity must be maintained at any time. However, due to radio channel problems (such as interference, shadowing, path-loss, etc.) some links with low quality links can impact the routing performance.

In this work we change and adapt the definition of topology control. We consider topology control as two processes that work in an iterative manner. On the one hand, there is the same process of Topology construction to build a reduced topology (called logical topology) based on physical layer and link quality measurements (in order to insure high-accuracy ranging estimation between peer-to-peer nodes). On the other hand, we introduce the concept of Topology Maintenance, which is the process in charge of updating the logical topology by reselecting the links with the best quality. Our definition differs from other topology control definitions that are conventionally adopted in the topology control field in the following respects. For example, many authors consider topology control as a technique whereby nodes dynamically change their transmission range to gain energy saving and/or improve throughput [BORB02], [BURK04], [LLOY05], [LHBW05].

In this work, we consider a scenario with a group of mobile WBANs in navigation application occupied with a set of wireless devices. The positioning of the on-body nodes consists in collecting the range measurements based on transmitted radio packets over Impulse Radio Ultra-Wideband (IR-UWB) links. This later allows high precision on the estimation of the Time of Arrival (TOA) of the transmitted signal.

In WBAN localization context, the cooperative localization consists in locating on-body mobile nodes by collecting peer-to-peer range measurements with respect to the on-body nodes as well as the anchors and body-to-body. As shown in Deliverable D3.5 [CORMORAN_D3.5], cooperative localization provides high positioning accuracy thanks to spatial diversity of nodes deployment, as well as to the measurement redundancy. The goal of this work is to exploit the advantages of topology control to construct a robust reduced topology in terms of high links quality which is very beneficial in the phase of ranging estimation. We combine the potential of topology control with the advantages of cooperative approach in delivering high positioning accuracy while exploiting cross layer information, i.e., channel measurements.

2.2. OVERVIEW OF TOPOLOGY CONTROL

2.2.1. RELATED WORKS ABOUT TOPOLOGY CONTROL

In the context of dynamic wireless networks, in which node-to-node links are established and broken quite often due to various reasons such as node failure or mobility, topology control techniques can play an important role in managing the complexity of such highly complicated and distributed systems through self-organization capabilities. The origin of topology control can be traced back to the 80s. Takagi and Kleinrock and later Hou and Li [TAKA84, HOU86] were among the first to study topology control in Packet Radio Networks (PRNs). With the inception of the Survivable Radio Network (SURAN) project, sponsored by DARPA, and with the advent of low cost portable communication devices, such as IEEE 802.11 network interface cards (NICs), the PRNs evolved into ad hoc networks in the 90s. With the work of [HU93, RODO99], there has been a renewed interest in the topology control community, for designing energy efficient ad hoc network topologies. In [RODO99], the authors propose a distributed algorithm for constructing minimum energy topologies on stationary networks. The work of Hu [HU93] was perhaps the first to draw upon geometric techniques in constructing energy efficient topologies. The specific technique used in [HU93] is the Delaunay Triangulation (DT), which forms a convex hull of a set of points under certain constraints. Among the well-known computational constructs are DT, Yao Graph (YG), Relative Neighborhood Graph (RNG) and Gabriel Graph (GG)—proximity graphs satisfying geometric properties such as optimum equi-angularity, uniform edge length distribution, maximum internal area: attributes useful in minimizing overall energy of a network. YGs, in particular, are well-suited for modeling network of radios with directional antennas. The use of these techniques in efficient topology design can be found in [GALI02, LI04].

2.2.2. TOPOLOGY CONTROL ALGORITHMS

In general, topology control can be classified as: (1) centralized and global vs. distributed and localized: and (2) deterministic vs. probabilistic. The localized algorithm is a special distributed algorithm, where the state of a particular node depends only on states of local neighborhood. That is, such an algorithm has no sequential propagation of state information.
Most protocols are deterministic. The work in [RAMA00] is concerned with the problem of adjusting the node transmission powers such that the resultant topology is connected or biconnected, while minimizing the maximum power usage per node. Two optimal, centralized algorithms, CONNECT and BICONN-AUGMENT, have been proposed for static networks. They are greedy algorithms, similar to Kruskal's minimum cost spanning tree algorithm. For ad hoc wireless networks, two distributed heuristics have been proposed, LINT and LILT. However, they do not guarantee the network connectivity.
Among distributed and localized protocols, a distributed and localized algorithm (LMST) for topology control starting from a minimum spanning tree is proposed [LIHS03]. Each node builds its local MST independently based on location information of its 1-hop neighbors and only keeps 1-hop nodes within its local MST as neighbors in the final topology. The algorithm produces a connected topology with maximum node degree of 6. An optional phase is provided where the topology is transformed to one with bidirectionl links. An extension is given in [LIHOU04], where the given network contains unidirectional links. Among probabilistic protocols, the work by Santi, Blough and Vainstein [SANTI00] assumes all nodes operate with the same transmission range.

2.2.3. TOPOLOGY CONSTRUCTION ALGORITHMS

There are many different algorithms that can be used in the topology construction and maintenance phases. The main concern of the topology construction algorithm is building a "quality" and efficient topology. In such topology, efficiency refers to minimal energy usage, minimum computational and information exchange complexity, and so on. Topology construction can be exercised in different ways. The initial topology can be reduced by solving the Critical Transmission Range (CTR) problem, which reduces the transmission range of all nodes by the same minimum amount, or by solving the Range Assignment Problem (RAP), which sets the minimum transmission range for each node [SANT05]. Other techniques are based on the assumption that nodes have information about their own positions and the position of their neighbors [LIHA01]. Other topology construction algorithms are based on the Connected Dominating Set (CDS) paradigm. Here, the idea is not to change the transmission range of the nodes but to turn unnecessary nodes off while preserving important network properties, such as connectivity and communication coverage. The CDS approach has been utilized in several papers [WIGH08], [RAMA00], [VIKAS03]. Most CDS-based mechanisms work in two phases: in phase one they create a preliminary version of the CDS, and in phase two they add or remove nodes from it to obtain a better approximation to the optimal CDS.

Many of the clustering approaches construct the virtual backbone using the connected dominating set (CDS) concept. A CDS has been widely used as a topology control to conserve network energy resources. A dominating set (DS) is defined as a subset of nodes in a graph such that each node not in the subset has at least one direct neighbor that belongs to the subset [DUPA11]. If the nodes in the dominating set form a connected graph, the set is called a CDS. Figure 2.2 shows an example of a CDS generated in a network that consists of fourteen nodes. In this figure, nodes u, v, w, x, y and z form the backbone to perform data forwarding while the remaining nodes do not participate in data forwarding. This strategy reduces the communication overhead and energy.

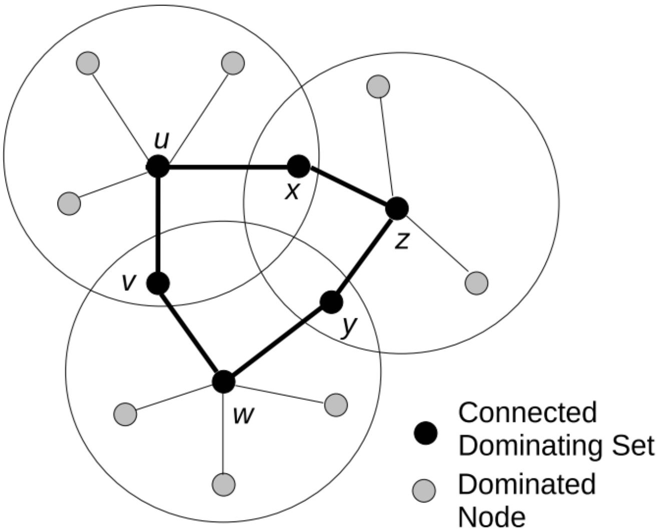


Figure. 2.2 A backbone in the network built using a connected dominating set

2.2.4. TOPOLOGY MAINTENANCE ALGORITHMS

Topology maintenance techniques can be subdivided as static, dynamic, or hybrid, according to the time when the new reduced topologies are built. Static topology maintenance techniques calculate all different topologies during the first topology construction process. These topologies are built and stored in memory and switched when needed. As such, static techniques have "pre-planned" topologies. The best example to describe these techniques is making the analogy with the lights of a Christmas tree: the entire set of lights contains a number of pre-defined subsets that cover the entire tree and take turns over time. As it can be inferred, static techniques take additional time during the initial topology construction phase to calculate all additional topologies, but once this process is finished, the switching process is faster than if a new topology construction phase had to take place. Further, the communication overhead of each subsequent topology construction phase is also saved. Static topology maintenance techniques may have some drawbacks too. For example, it is difficult to know a priori how each of the topologies and their nodes will consume their energy. Therefore, the mechanism may choose to use some nodes in more than one topology that may not be available or will make the topology to last shorter than expected.

Dynamic topology maintenance techniques, on the other hand, calculate a new reduced topology 'on the fly', triggering the topology construction mechanism when necessary. Dynamic topology maintenance mechanisms have the advantage of having more and better information about the network to find a better new reduced topology. The disadvantage of these mechanisms is that they consume additional resources every time they are run, therefore, it is extremely important that the topology maintenance and the topology construction mechanism be both efficient in term of resources consumption (i.e. traffic, energy, etc.). Finally, hybrid topology maintenance techniques use both, static and dynamic techniques. Hybrid techniques calculate all different reduced topologies during the first topology construction phase (static approach) but if the coming topology cannot be established because the sink has no connectivity with the nodes (dead topology), the mechanism finds a new topology on the fly (dynamic approach). This approach inherits some of the advantages and disadvantages of the static and dynamic techniques.

In order to maintain robust reduced topology, it is crucial to use some Link Quality Estimation (LQE) mechanisms. High quality links allows to maintain the stability of the reduced topology and hence avoiding unwanted transient topology breakdowns. Next subsection focus on the fundamental concepts related to link quality estimation.

2.2.5. RADIO LINK QUALITY ESTIMATION

In wireless networks, the propagation of radio signals can be affected by several factors (i.e. obstacle, multi-path, interference, etc.) that contribute to the degradation of its quality. Thus, their quality fluctuates over time and space. Radio link quality estimation in has a fundamental impact on the network performance and affects as well the design of higher layer protocols. For instance, LQE allows for routing protocols to maintain correct network operation by limiting packet loss and avoiding route reselection triggered by link failures. LQE also plays a crucial role for topology control mechanisms to maintain the stability of the topology.

In the literature, various link quality estimation metrics have been proposed to cope with the vagaries of the wireless channel, which can be classified in two categories: hardware-based and software-based, as illustrated in Figure 2.3. Three LQEs belong to the family of hardware-based LQEs: LQI, RSSI, and SNR, which can directly read from the radio transceiver. While software-based LQEs can be classified into three categories: (i.) PRR-based: either count or approximate the PRR, (ii.) RNP-based (Required Number of Packet retransmissions): Counts the average number of packet Retransmissions required before a successful reception, and (iii.) Score-based: provide a score identifying the link quality. We give some related works about this issue in the following observations:

In [FARK08], the authors showed that the deployment of a typical multi-hop WSN based on low power radios results in a network with a large percentage of very poor link characteristics. A pattern based link estimation scheme is presented which allows to rate the link quality in an energy-efficient way during the initialization phase in order to construct optimal neighbor tables from the beginning. Srinivasan and Levis in [SRIN06] showed that for new transceivers the RSSI above the sensitivity threshold is a promising link quality indicator. A RSSI above the sensitivity threshold results in a packet reception rate (PRR) of at least 85%, whereas around the sensitivity threshold the RSSI does not have a good correlation with the PRR.
Expected Transmission Count (ETX), proposed by De Couto et al. [COUT03], is based on measuring packet losses between a pair of neighbors. Four-Bit (4B), proposed by Fonseca et al. [FONS07], exploits the radio channel quality information from physical layer, combines it with the ETX estimate and information from the network layer for better path quality estimation. Cerpa et al. [CERP05] proposed the Requested Number of Packets (RNP), which considers the temporal characteristics of wireless links while estimating link quality. Given links with identical packet reception ratios, RNP prefers links with discrete losses as they require less number of retransmissions than a link with consecutive losses.

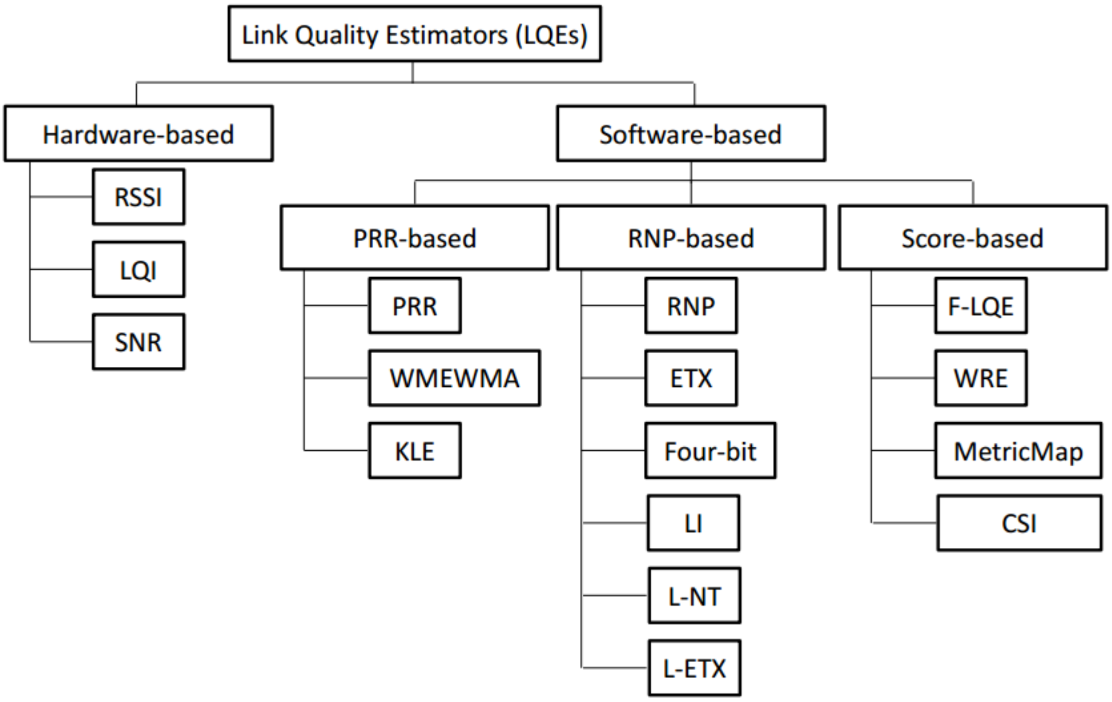
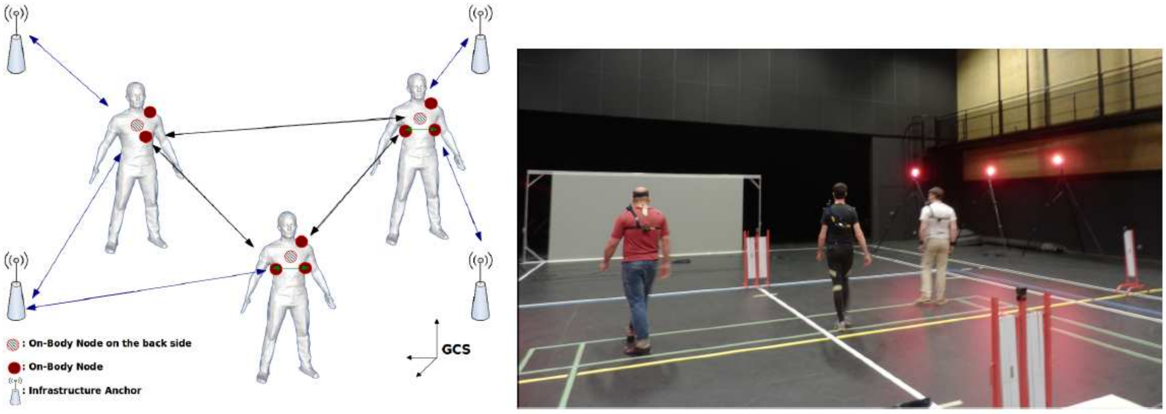


Figure. 2.3 Taxonomy of Link Quality Estimators

2.3. SYSTEM MODEL AND PROBLEM FORMULATION

2.3.1. SYSTEM MODEL

We consider a group of mobile WBANs and a set of fixed anchors (reference nodes) placed at known positions (position has been hard-coded into each anchor) with respect to a global 3D coordinate system. Each WBAN is defined by a set of on-body wireless devices, which are called on-body nodes. These on-body nodes are attached to the human body that evolves in an indoor and outdoor environment. The positions of all these on-body nodes are unknown and must be estimated relatively to the anchors. Since we assume a mesh topology network, we distinguish three kinds of links: either belonging to one single body network (on-body links), between distinct equipped users at reasonably short transmission ranges (inter-WBAN links), or even with respect to fixed elements of infrastructure (off-body links), as depicted in the figure below. In this paper, all anchors and on-body nodes use an IR-UWB physical layer and operate with a single-channel frequency. In order to avoid the interference between communications, a TDMA-based MAC layer is used by all the nodes. We assume that the nodes positions are mapped into a stable Cartesian Local Coordinate System (LCS), which is defined by the fixed anchors and can be easily referenced to any Global Coordinate System (GCS). All the on-body nodes are then located in this coordinate system using peer-to-peer range measurements with the anchors or even between them, by performing TOA and 3-Way Ranging (3-WR) handshake protocol transactions. We refer to non-cooperative localization (resp. cooperative localization) when a node perform the 3-WR with the anchors only (resp. with the anchors and the other on-body nodes).



(a) (b)

Figure 2.4 Typical deployment scenario of group of WBANs in navigation application. There are three kinds of links: on-body links (green color), inter-body links (black color) and off-body links (blue color). The on-body nodes (red color) must be positioned relatively to the fixed anchors.

2.3.2. RANGING MEASUREMENT

The peer-to-peer range information is derived from RT-TOF estimation, which relies on 2-Way Ranging (2-WR) or 3-Way Ranging (3-WR) handshake protocol transactions and unitary TOA estimates for each involved packet [MAMAN08]. The classical exchange for two-way ranging is represented on Figure 2.5. Two guaranteed packet transactions are necessary to evaluate the time of flight between two nodes *i* and *j*. Node *i* starts by sending its request packet inside the assigned packet at time T_{i0}. Once this packet is received by node *j* at time T_{j0}, node j sends its response back to the requester node *i* inside its own dedicated packet at time T_{j1}, after a known time of reply. Node *i* will receive this packet at time T_{i1}. Hence, the estimated RT-TOF through 2-WR is simply given as follows:

$$\boldsymbol{TOF} = \frac{\mathbf{1}}{\mathbf{2}}\left[(\boldsymbol{T_{i1}} - \boldsymbol{T_{i0}}) - (\boldsymbol{T_{j1}} - \boldsymbol{T_{j0}})\right]$$

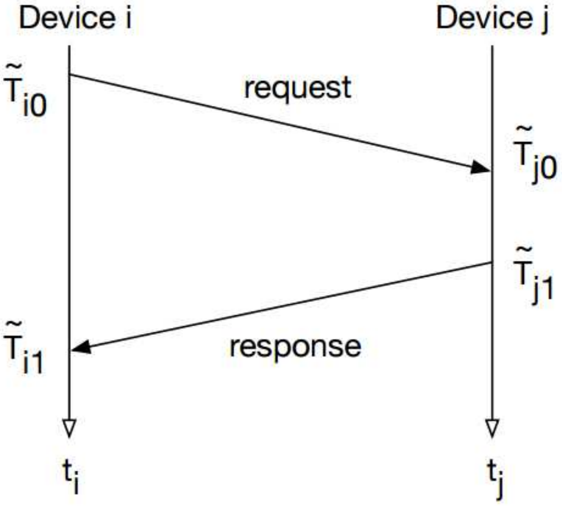


Figure. 2.5. Example of two-way ranging exchange

Considering the time frame of a typical request-response exchange, the clock drift of the requesting node cannot be neglected and has an effect on the ranging accuracy. To compensate this effect, the responding node j can transmit a third packet at time T_{j2}. This packet will be received by node *i* at time T_{i2}. This exchange, called three way ranging, is illustrated on Figure 2.6. The resulting time of flight estimate can be expressed as follows:

$$\boldsymbol{TOF = \frac{1}{2}\left[(T_{i1} - T_{i0}) - (T_{j1} - T_{j0})\right] - \frac{1}{2}\left[(T_{i2} - T_{i1}) - (T_{j2} - T_{j1})\right]}$$

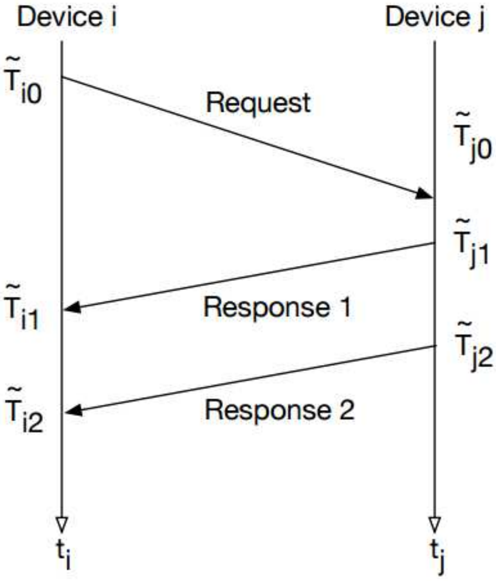


Figure. 2.6. Example of three-way ranging exchange

The node *i* can thus estimate its distance to node *j* as: $d_{ij} = TOF_{ij} * c$, where *c* denotes the speed of radio waves, i.e. $c = 3*10^8 m/s$. Once all the distances separating the on-body nodes with the anchors and/or with the other on-body nodes are extracted, the on-body nodes positions can be estimated using a localization algorithm. Given that these procedures have to be realized for each couple of devices, the traffic sent over the wireless medium quickly increases with the number of devices. To reduce the volume of control traffic, Macagnano et al. [MAC07] have proposed a procedure called Aggregate-and-Broadcast (A&B) to limit the number of required handshake transactions to perform all the possible pair-wise measurements in a mesh configuration. They propose to mutualize control packets by letting each node initiates specific ranging transactions by broadcasting a request packet to all the other nodes, instead of querying a single node. Each node then aggregates and broadcasts a packet, which can play different roles (i.e. response 1, or even response 2). Their method limits the number of transmissions required to evaluate all distances between n devices to 3n+2m transmissions instead of $2n(n+m-1)$. In our simulation environment, ranging is performed using the 3-Way ranging protocol with the A-B procedure.

2.3.3. PROBLEM FORMULATION

In localization and positioning context, several challenges are met such as the need of high ranging accuracy. In fact, in order to estimate on-body nodes positions, each node have to collect its range measurements with respect to fixed anchors. The range estimation through several transactions, as well as of the range collection from devices conducts for latency. However, as it is shown in [HAMI13], the main source of ranging error is related to the involved WBAN channel, in which the signal may suffer from NLOS propagation effects and dense multipath situation. These errors source, if not properly mitigated, generally yield severe degradation of positioning accuracy.

In deliverable D3.5 [CORMORAN_D3.5], the localization performance as a function of the packets error rate PER (the PER affects only the range measurements with respect to anchors) is studied. It is shown that the cooperative scheme keeps rather important gains in comparison with the conventional non-cooperative localization scheme. However, at high PER values, the number of the observed distance measurements between nodes and on-body anchors is relatively smaller, and then the robustness of the localization algorithm becomes smaller. For this purpose, it is very important to compute the localization nodes using only the links with high ranging accuracy (use the links with high channel quality), which is the main reason that motivates us to use a topology control approach.

2.4. APPROACH DESCRIPTION

2.4.1. OVERVIEW

Our approach is characterized by some basic steps as presented in Figure 2. 7. The first step consists to start by constructing an initial topology containing all peer-to-peer links. This can realized based on neighborhood discovery algorithm which consists to exchange Hello packets between nodes within a single hop. To achieve an accuracy peer-to-peer ranging estimation, we propose then to construct a "high quality" and an efficient logical topology based on physical layer and link quality measurements. The idea is to choose a subset from all possible links characterized by high channel quality in order to reduce the ranging error. Note that the links selection can be made on various criteria as explained in Section 2.2.5. Without loss of generality, we are based in this work on a Line Of Sight (LOS) links selection mechanism which consists in selecting only the links with directed view without any obstacle. This is explained by the fact that NLOS links are generally characterized by low channel quality inducing more errors in the ranging estimation. Once the logical topology is built, the mechanism of ranging measurement is started based on 3-WR handshake protocol transactions and TOA as explained in Section 2.3.2.

Since the node localization algorithm needs a minimum number of ranging measurements (generally at least 4 distances are needed in 3D environments), we propose a virtual cooperative algorithm to compute the rest of required distances based on geometric and mathematical approach (we don't requires any packet exchange or transaction between nodes in this step) as descripted in next subsection. Once all ranging measurements are available, the last step consists to estimate each node position using EKF algorithm with cooperative mode explained in deliverable D3.5 [CORMORAN_D3.5].

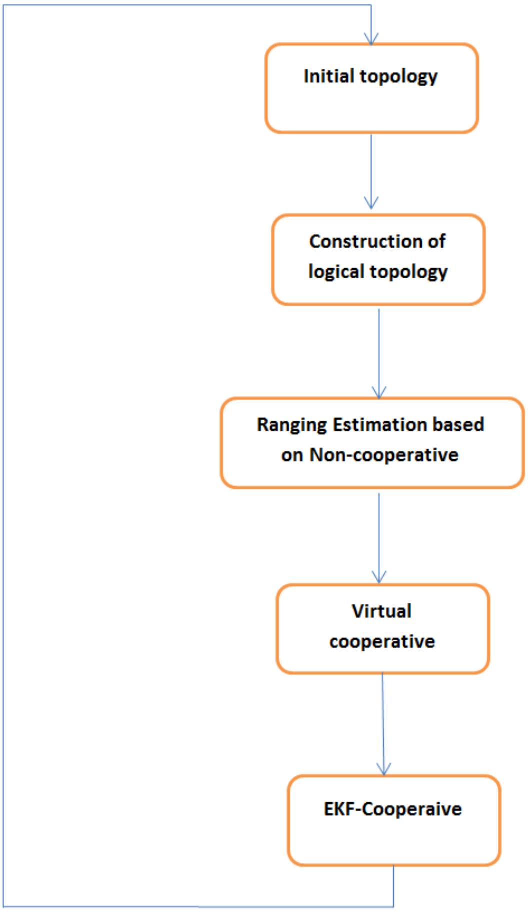


Figure 2.7. State transitions representing the different steps from logical topology construction to nodes localization.

2.4.2. VIRTUAL COOPERATIVE APPROACH

In group of WBANs navigation context, different kinds of cooperative links can be involved, such as on-body and body-to-body links. Generally, over each physical link, the measurement of location-dependent radio metrics for localization purposes (e.g. TOF, TOA, etc.) needs underlying communication capabilities (i.e. radio transactions based on 3WR). However, the distances estimation phase needs resources allocation at the MAC layer and high channel quality in order to well estimate the TOA value.

The idea of Virtual Cooperative Approach is to calculate the distances of a set of links, characterized with poor channel conditions, by utilizing the topology information such as the anchors positions and a kind of peer-to-peer distances which are estimated by the 3WR algorithm (third step in figure 2.7). According to 2D or 3D coordinate system, we propose two approaches detailed in the following.

2.4.2.1. GEOMETRIC RANGE-FREE APPROACH FOR 2-D COORDINATE SYSTEM

In order to calculate node localization in 2D coordinate system, at least 3 distances (i.e. with 3 different anchors) are needed. Herein, we assume that an on-body node has only 2 distances estimated by the 3WR algorithm, the third one (or more other required distances) will be computed by geometric range-free approach. Figure 2.8 illustrates an example of scenario where distance X ∈ R^+, between nodes *n1* and *n2*, have to be computed. Distances d11, d12, d21, d22 and A11 are known.

$$(d_{12})^2 = (d_{11})^2 + (A_{12})^2 - 2d_{11}A_{12}\cos\beta 1 \quad \text{(Eq.1)}$$
$$(d_{22})^2 = (d_{21})^2 + (A_{12})^2 - 2d_{21}A_{12}\cos\beta 2 \quad \text{(Eq. 2)}$$

$$(X)^2 = (d_{11})^2 + (d_{21})^2 - 2d_{11}d_{21}\cos\alpha \qquad \text{(Eq. 3)}$$

Where

$|\alpha| = |\beta 1 - \beta 2|\ if\ nodes\ n1\ and\ n2\ are\ in\ the\ same\ side\ with\ respect\ to\ line\ A1 - A2$,

$|\alpha| = |\beta 1 + \beta 2|$ Otherwise

As illustrated by Figure 2. 9. The value of α determines the distance X, which equals to X0 if the nodes n1 and n2 are on the same side with respect to the anchors A1 and A2. Otherwise, X equals to X1. Note that X1 is always bigger than X0. Thus, it is easy to estimate the value of distance X if we assume for example that n1 and n2 are always on the same side (the case of on-body nodes or when the anchors are deployed at the border of the scene). Next Section presents another approach to estimate the value of distance X based on last position of nodes n1 and n2.

The values of β1 and β2 can be deduced from equations (Eq. 1) and (Eq. 2):

$$\beta 1 = \cos^{-1}\left(\frac{(d_{11})^2 + (A_{12})^2 - (d_{12})^2}{2d_{11}A_{12}}\right)$$

$$\beta 2 = \cos^{-1}\left(\frac{(d_{21})^2 + (A_{12})^2 - (d_{22})^2}{2d_{21}A_{12}}\right)$$

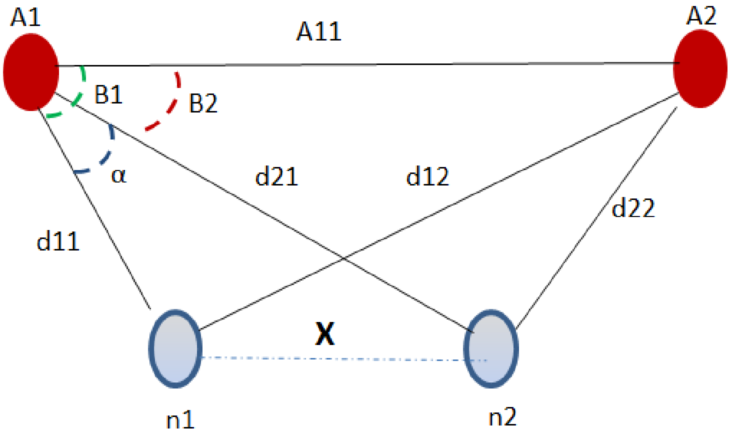


Figure 2.8 Illustration of distance estimation problem between two nodes. The unknown distance X have to be computed based on geometrical information.

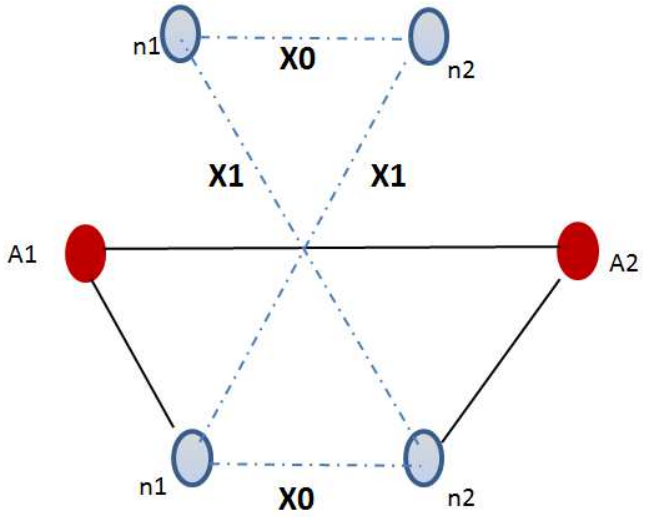


Figure 2.9 The distance X equals to X0 if the nodes n1 and n2 are on the same side with respect to the anchors A1 and A2. Otherwise, X equals to X1.

2.4.2.2. GEOMETRIC RANGE-FREE APPROACH FOR 3-D COORDINATE SYSTEM

In 3D coordinate system, at least 4 ranging measurements are needed to estimate a node position. In this work, we assume that an on-body node is not able to collect all these required ranging or some distances are not accuracy estimated because channel conditions. The aim, herein, is not only to compute the rest of needed distances, but to create implicit cooperation between nodes by measuring the distances between them without any cost (i.e., without any resource allocation and packets exchange). To achieve this, we are based on equations system which is similar to a classical NLLS formulation. Figure 2.10 illustrates an example of this problem, where the distance, denoted X between nodes n1 and n2, have to be computed. The nodes n1 and n2 have, respectively, the coordinates (x1, y1, z1) and (x2, y2, z2, and the distance X at time t can be written as $X(t) = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}$. To resolve the problem with only 3 ranging measurements by node, we assume that the last position of the two nodes is known a priori. This allows us to estimate the last distance between them, denoted X(t-1). The idea consists to minimize the following cost function:

$$X(t) = argmin\, C(t)$$

Where

$$\begin{cases} C(t) = |X(t) - X(t-1)| \\ X(t)^2 = (x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2 \\ d_{12}^2 - d_{11}^2 = (x_1 - x_{A2})^2 + (y_1 - y_{A2})^2 + (z_1 - z_{A2})^2 - (x_1 - x_{A1})^2 - (y_1 - y_{A1})^2 - (z_1 - z_{A1})^2 \\ d_{13}^2 - d_{11}^2 = (x_1 - x_{A3})^2 + (y_1 - y_{A3})^2 + (z_1 - z_{A3})^2 - (x_1 - x_{A1})^2 - (y_1 - y_{A1})^2 - (z_1 - z_{A1})^2 \\ d_{22}^2 - d_{21}^2 = (x_2 - x_{A2})^2 + (y_2 - y_{A2})^2 + (z_2 - z_{A2})^2 - (x_2 - x_{A1})^2 - (y_2 - y_{A1})^2 - (z_2 - z_{A1})^2 \\ d_{23}^2 - d_{21}^2 = (x_2 - x_{A3})^2 + (y_2 - y_{A3})^2 + (z_2 - z_{A3})^2 - (x_2 - x_{A1})^2 - (y_2 - y_{A1})^2 - (z_2 - z_{A1})^2 \end{cases}$$

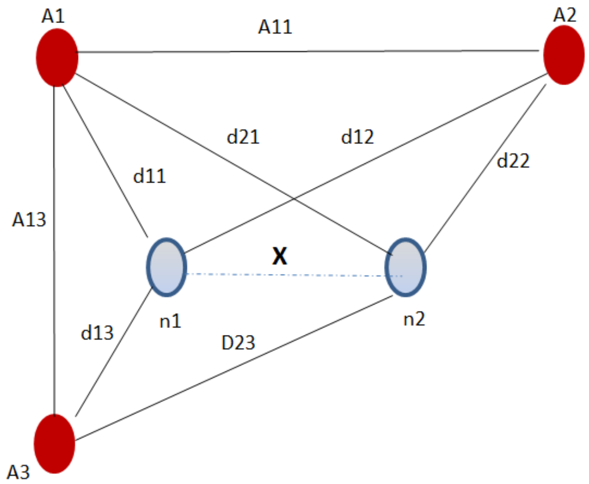


Figure 2.10 Illustration of distance estimation problem between two nodes in 3D coordinate system.

This system can be linearized and solved as described in Deliverable D3.4 [CORMORAN_3.4].

Note that the ranging measurements estimated by 3WR and used to compute the variable X(t) generally contain some errors. For this purpose, there is no always a solution of this problem. To deal with this problem, it is recommended for each node to cooperate implicitly (with virtual cooperation) with the most possible of nodes. Note also that the use of EKF algorithm after this step allows to reduce the positioning errors compared for example to another localization algorithm like NLLS which the impact of ranging errors is very important on the localization phase.

2.5. PERFORMANCE EVALUATION

2.5.1. SIMULATION ENVIRONMENT

2.5.1.1. WSNET Simulation Environment :

WSNET is a discrete-event simulator which provides an advanced and complete simulation environment to investigate and evaluate networking protocols and wireless systems. This simulation environment simulates all the tasks of real device wireless node (i.e. application, MAC, radio and antenna layers), the radio medium (interferences, pathloss, shadowing, etc.), as well as all the network functionalities such as data exchange, network queue management and packets loss, etc.. For more details, we invite the readers to refer to [HAMI14]. Since the original WSNET simulator has been drawn for large-scale wireless networks (e.g. ad hoc, sensor, mesh, etc.), the WBANs operating conditions are not well suited, particularly, in terms of physical layer, mobility and channel models. Thanks to its modularity and its flexibility, WSNET offers the opportunity for developing and integrating our own modules and protocols, which could be in compliance with our WBAN context. At the radio layer stage, we implemented an IEEE 802.15.6 PHY UWB with OOK modulation and data rate of 0.4875 Mbps. Since we are based on the TOA estimation for delivering the distance between two nodes, we assume that the radio of the receiver node is able to detect the first path of IR-UWB. At the MAC layer stage, we implemented a typical TDMA protocol. In order to reduce the TDMA-frame duration, we evolved a dynamic slotted TDMA approach, where the duration of each slot depends on the size of the transmitted packet.

At the algorithmic level, all the localization algorithms (i.e. virtual and conventional cooperation and non-cooperative EKF) are implemented at the application layer. Since the WSNET's mobility models are not basically defined for describing the human body movement, we implemented our own realistic BAN mobility traces, which will be illustrated in details in the next subsection. For more information about simulations tools, reader is invited to refer to the Deliverable D2.5 [CORMORAN_D2.5].

2.5.1.2. Realistic Mobility Model

In this work, we use a real mobility traces obtained from our measurement campaign described in Deliverables D4.1 and D4.2 [CORMORAN_D4.1, CORMORAN_D4.2]. A Vicon optical motion capture system provides us the motion of people in a 13mx8m area. This system records all the markers positions thanks to 16 cameras surrounding the scene, and produces a C3D motion capture file containing all markers positions over time. Figure 2.4 illustrates this process, showing an image from the real scene with three persons in random navigation with the presence of four fixed anchors. Two subjects are equipped with four radios devices each, while the third subject is equipped with three devices (due to the limited number of devices). The devices are placed at the chest left, the chest right, the shoulder and the back. We equipped each wireless device with a marker in order to record its exact position alongside in addition to the movements of each subject.

2.5.2. SIMULATION PARAMETERS

In our simulation results, we consider a scenario of 3 bodies as described in Section 1.1.2 and illustrated by Figure 2.4. Each device (on-body node and anchor) uses an omnidirectional antenna and transmits at -10dBm in order to insure a full mesh network. Concerning the localization algorithms and settings, each estimated body position is updated each T period that is equal to the requested TDMA-frame duration for making and delivering all the range measurements between devices. We apply the EKF algorithm described in Deliverable D3.5 [CORMORAN_D3.5]. Similarly to [HAMI14], we empirically and a priori determine the state-space noise covariance matrix Q, relying on the variation of the true simulated on-body locations over a long period of time. In details, we apply the state-space equation onto these real positions, aggregate the noise residuals over each state component (i.e. computing, $\mathrm{u(k)} = \mathrm{S(k)} - \mathrm{A} * \mathrm{S(k-1)}, \forall \mathrm{k}$) over a long period and finally compute the variance over each state component in S, leading to the following numerical values:

$$Q = I_n \oplus \begin{pmatrix} 0.004 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.002 & 0 & 0 & 0 & 0 \\ 0 & 0 & 10^{-4} & 0 & 0 & 0 \\ 0 & 0 & 0 & 4.3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2.25 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.1253 \end{pmatrix}$$

Simplifying further the ranging error model in [HAMI13], our simulations are carried out using a synthetic and constant σ_n equal to 10 cm, independently of the instantaneous signal to noise ratio, but still in the range of the values observed and characterized in [HAMI13] based on real measurements.

Since our algorithm is based on LOS links selection, the all NLOS of each kind of links (i.e. on-, inter-, and off- body links) are identified at each time stamp. Figure 2.11 illustrates the variation of NLOS percentage of each kind of links: the obstructions status between nodes are superposed on the evolution of the ground truth quantity for illustration purposes. This status has been retrieved based on motion capture acquisition after simplifying the body as a set of 11 cylinders, thus determining intersections of the LOS path by one of these cylinders at any time. For more information, the reader is refer to read the Deliverables D.2.5 [CORMORAN_D2.5].

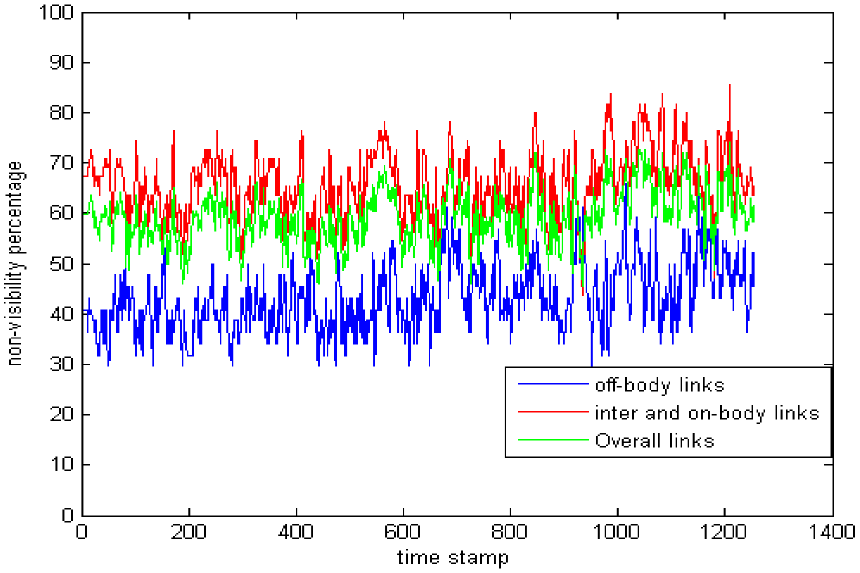


Figure 2.11 variation of non-visibility percentage of different kinds of links: on-, off- and inter-body links.

2.5.3. IMPACT OF NUMBER OF ANCHORS

Generally, we assume that there always at least 4 anchors in to localize nodes in 3d coordinate system. However, due to the channel conditions this assumption is not always valid. The goal of this study is firstly to quantify the localization error according to the number of available anchors where a node uses only the ranging measurement with the anchors to estimate its own position (Non-cooperative scenario) and then to evaluate the gain due to cooperative approach between different kinds of links (on- or/and inter-body links). Figure 2.12 presents the empirical Cumulative Density Function (CDF) of the estimated location of all the nodes in the presence of 1 and 2 anchors. We show that even using cooperative approaches between different types of links, the positioning errors are very important (of the order of some meters) which is not acceptable for navigation purposes. This can be explained by the fact that the ranging measurements with the anchors are very accurate compared to the ranging incorporated with cooperative links. Hence, in 3d coordinate system, the number of accurate ranging measurements with 1 and 2 anchors are insufficient (even using cooperative links). However, as expected by Figure 2.13, the cooperative approach is very beneficial in the presence of 3 and 4 anchors, in particular using full cooperative localization scenario (incorporate on-body and inter-body ranging measurements): around 70% of estimated nodes positions are less than 72cm (resp. 130cm) of errors with full-cooperative (resp. non-cooperative) scenario. Since in 3D coordinate system only 4 anchors are needed to estimate nodes position, the gain of cooperative approach is less important. Compared the results of full cooperative in the presence of 3 anchors (red curve with bold line) with the non-cooperative in the presence of 4 anchors (black curve with dotted line), we point out that the cooperative approach can replace an anchor and gives more accurate localization thanks to spatial diversity and measurements redundancy.

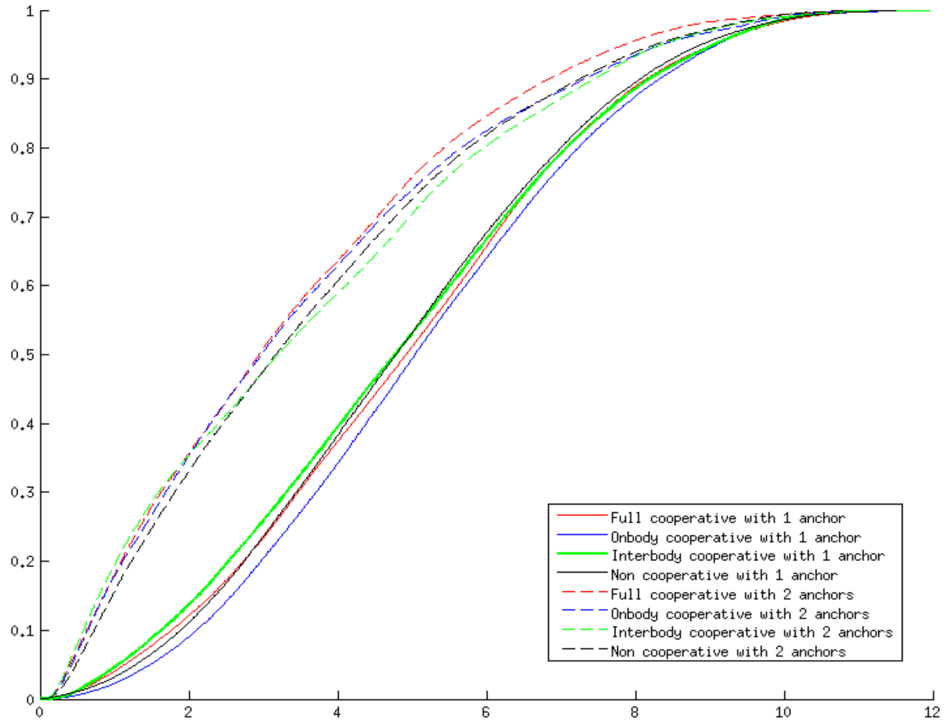


Figure 2.12 CDF of the estimated location over all the nodes, in the case of non-cooperative and various cooperative scenarios, in the presence of 1 and 2 anchors.

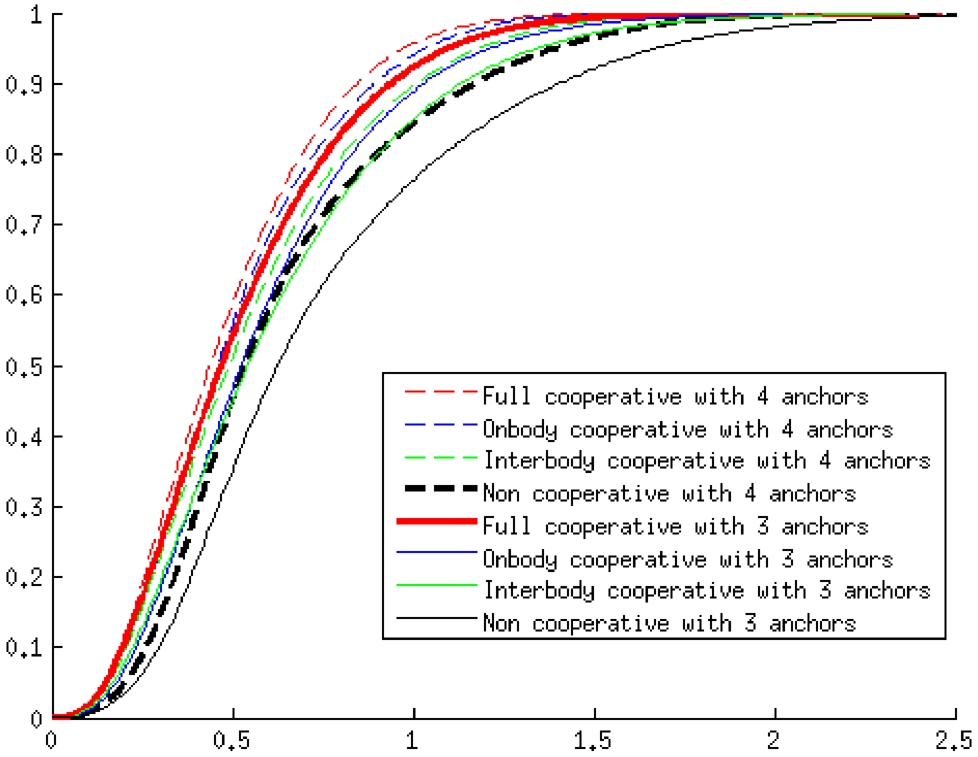


Figure 2.13 CDF of the estimated location over all the nodes, in the case of non-cooperative and various cooperative scenarios, in the presence of 3 and 4 anchors.

2.5.4. GAIN DUE TO TOPOLOGY CONSTRUCTION APPROACH

In this study, we lead to evaluate the gain due to the use of Topology construction algorithm. As detailed in Section 3.4, the idea is to choose a subset from all possible links characterized by high channel quality in order to reduce the ranging error. Without loss of generality, we are based in this study on LOS links selection mechanism which consists in selecting only the links with directed view without any obstacle which are generally characterized by high channel quality. Others criteria of links selection can be used as explained in Section 2.2.5.

Figure 2.14 presents the CDFs of localization errors of all nodes with full cooperative localization scenario. Four localization approach are used:

- Conventional EKF: classical EKF algorithm without any improvement,
- Biased EKF: EKF algorithm with NLOS mitigation technique proposed in [HAMI14].
- EKF with LOS-Links selection: EKF algorithm is used with topology construction approach.

- Adjusted and Biased EKF: two improvements of EKF are used: (i) NLOS mitigation technique and (ii) adjustment of the noise covariance matrix, see Deliverable D3.5 [CORMORAN_D3.5] for more information.

As expected, Figure 2.14 shows that the LOS-links selection approach gives rather important gains of localization accuracy in comparison with conventional EKF and biased EKF thanks to the elimination of the ranging measurement with high error. Despite the important gain due to the use of LOS-links selection, the green curve shows that keeping NLOS-links with a good adjustment of the covariance matrix with biased approach allows to improve more the nodes localization accuracy.

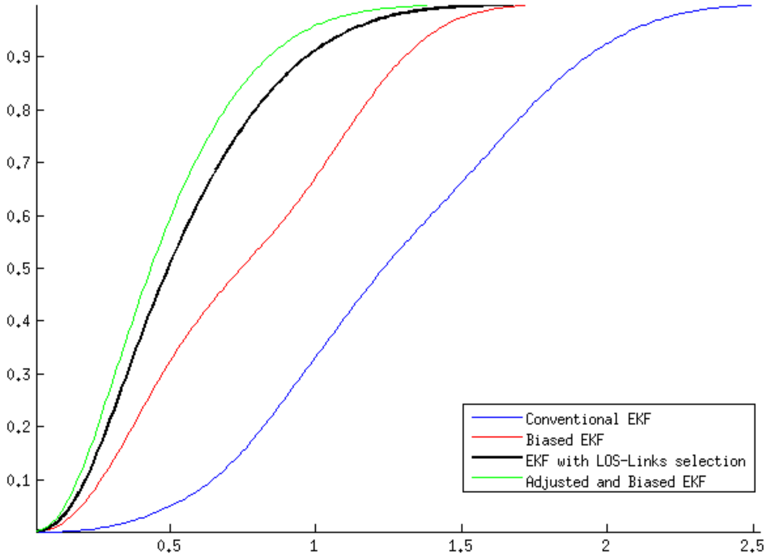


Figure 2.14 CDF of the estimated location over all the nodes, in the case of full cooperative scenario, in the presence of 4 anchors.

2.5.5. GAIN DUE TO VIRTUAL COOPERATION APPROACH

In this study, we consider a scenario with only 3 available anchors. The first step is to construct a logical topology containing only LOS links with high radio quality. Each on-body node, then, have to estimate its position based on the ranging measurement collected with the 3 anchors (based on the logical topology) and can perform the virtual cooperative approach explained in subsection 2.4.2 in order to compute the inter-body nodes distances using the mathematical method detailed in subsection 2.4.2.2.

Figure 2.15 illustrates the CDFs of each scenario while assuming that each node can virtually cooperate with 1, 2 and 3 nodes. Note that the simulation time increases with the number of virtual cooperative nodes since the equations system have to be resolved for each one.

As expected, the virtual cooperative scheme outperforms the localization precision: the localization error of all nodes decreases while increasing the number of virtual cooperative nodes. In fact, the non-cooperative scenario integrates only off-body measurements with 3 anchors which are insufficient to properly estimate the nodes localization. However, by exploiting the peer-to-peer range measurements between nodes (computed with the virtual cooperation approach), the information redundancy and the spatial redundancy increases which achieves more significant gain in comparison with the non-cooperative scenario. Note that the gain of the third cooperative nodes seems to be not significant in comparison with the first and the second one. In 3d coordinate system, with 4 distances we can accuracy estimate a node position. For this purpose, the first cooperative links are the most important to give useful information to limit the research area around the node location and hence reduce the position error.

It is important to note that virtual cooperative approach also allows to reduce the size the frame duration (which defines the refreshment rate of nodes positions) at MAC layer since the approach does not require resource allocation to compute the peer-to-peer ranging between nodes in comparison with classical cooperative scheme. Figure 1.16 shows that the frame duration increases with the network size. Moreover, due to the extra over-the-air traffic that has been introduced in the classical cooperative scheme, by exploiting the peer-to-peer range measurements between nodes, the cooperative frame duration is more important than the virtual cooperative one.

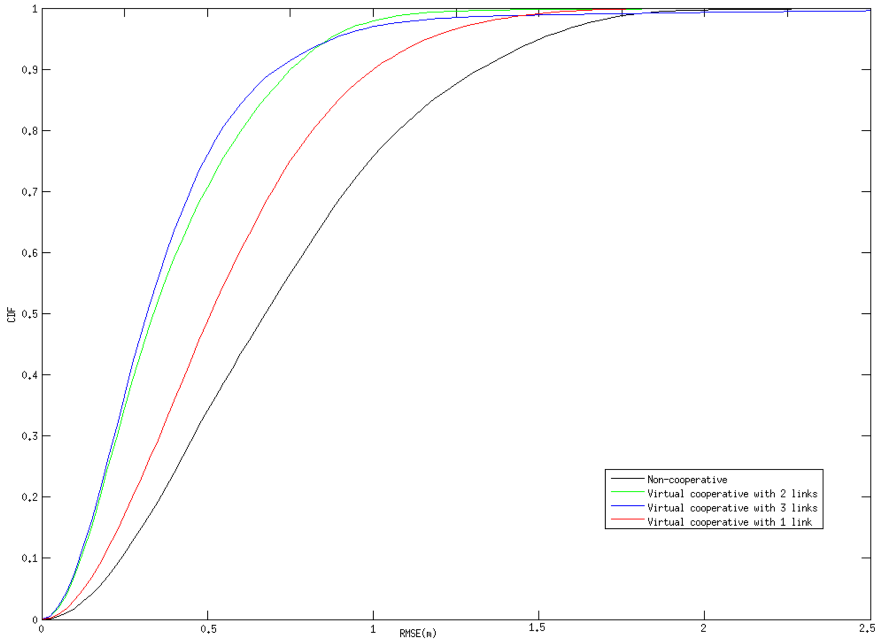


Figure 2.15 CDF of the estimated location over all the nodes, in the case of virtual cooperative scenario, in the presence of 3 anchors.

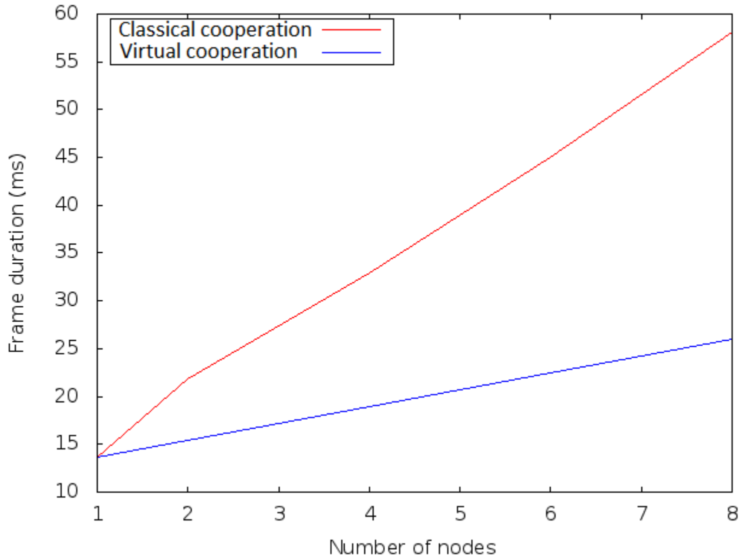


Figure 2.16 TDMA frame duration as a function of the network size, for both of classical cooperative and virtual cooperative localization schemes.

3. ADAPTED ROUTING STRATEGIES IN GROUPS OF WBANS

3.1. INTRODUCTION

Today's main challenge for the designers and developers of protocols and applications for a group of WBANS is to design appropriate and new cross-layer PHY/MAC/NWK mechanisms allowing to mitigate inter/intra-WBAN interferences, favor inter/intra-WBAN coexistence and ensure high quality of service. During the past decade, many MAC and routing protocols are designed and presented for wireless sensor networks (WSNs) where the network is very dense (i.e. comprises hundreds to thousands of nodes). The exponentially increasing complexity with the number of nodes and the need to exchange large volumes of link-state information make such algorithms prohibitive. Unlike WSNs, a common network architecture used in WBAN is a star-topology, where the central node gathers and records the sensing information around the human body. Hence, in the context of a single WBAN, the type and size of the on-body topology (i.e., limited number of nodes) makes the routing problem less difficult. However, in group navigation context where multiple WBANs move together many problems appear: the topology is very dynamic, interferences and coexistence problems between neighbors WBANS appear, network size is variable, etc. As explained in Deliverable D3.3 [CORMORAN_D3.3], the performances of MAC and routing protocols are highly dependent on the type of network and infrastructure. For instance, the shape and dynamics of the topology have a strong influence on the efficiency of the various techniques and the best techniques for static networks could exhibit poor performance in dynamic network. That's why, new requirements and constraints are imposed over the MAC and routing protocol design, and thus, we cannot use the same WSNs or Ad'hoc protocols to WBANs in same way.

Collaboration and exchange information between layers is very important to deal with these problems. For instance, some information like network density, or the composition of each node's neighborhood are very beneficial to the medium access control layer. How many neighbors or contenders does each node possess? Is the density uniform across the network or are there variations from area to area? Brought at the routing level, the network density influences the path diversity, but a finer grain of description may be required to optimize the routing operation, and more specifically the stability of the routes. For example, a routing protocol may benefit from knowing which proportion of the neighbors of a node belong to the same BAN, which proportion belong to a close BAN that belongs to the same group (in the sense of group navigation). In addition, a routing protocol can take benefit from such link quality estimations to optimize the routing process in terms of latency, reliability and stability.

The main goal of this work is to investigate the issues related to the routing performance in highly dynamic WBSNs, where the inherent body mobility and posture introduce frequent time and space variations in the observed link reliability and network connectivity. Moreover, the impact of the routing on the resource allocation at MAC layer and on the performance of the localization algorithm is also one of our objectives.

3.2. RELATED WORK

Numerous protocols have been proposed for routing and MAC layers for various traditional wireless networks (ad-hoc, WSNs, etc.). Section 5 of deliverable D3.1 [CORMORAN_D3.1] presents a selection of routing algorithms and protocols coming essentially from the DTN and sensors worlds, which could be adapted to be suited to the specific WBSNs application requirements and constraints. In the context of WBAN, traditional routing strategies are generally based on the selection of reliable long-term links [BANG14]. However, given the highly dynamic nature of the Wearable BSNs radio channel and network topology, links may appear and/or disappear very frequently, thus impacting the performance of the routing process. More recently, opportunistic and posture-aware routing mechanisms have been investigated to better take into account the inherent properties of such dynamic networks. For example, in [MASK11], the authors propose an opportunistic routing algorithm to exploit the body movements to increase the network lifetime and relaying performance. In the proposed scheme, relaying nodes are optimally placed around the body (e.g. on the waist), while the best relaying strategy is dynamically selected based on successfully received Request to Send (RTS) signals. A similar opportunistic routing mechanism was evaluated in [ABBA13] using Log-Normal and IEEE 802.15.6 CM 3A path-loss models. The obtained results show that reliability and energy efficiency can be improved up to 16% and 25% respectively. In [YANG13], the authors introduce a probabilistic routing protocol that aims at better exploiting the short-term and long-term topological behavior, through the fusion of inertial sensor data and historical link quality estimations. The obtained experimental results show that the proposed routing schema outperforms existing approaches in terms of packet delivery ratio and delay performance. In [LIAN12], the authors propose a joint secure and prediction-based routing framework for Wearable BSNs, where each node maintains a local Auto-Regressive (AR) prediction model based on smoothed link quality measurements (i.e. received signal power). At every time instant, any node can predict the quality of every incidental links and thus can make the best forwarding decision accordingly. Obtained simulation results show the reliability and effectiveness of the proposed routing schema.

As explained in Section 1, CORMORAN has selected two main target application scenarios LSIMC and CGN. In the motion capture scenario (LSIMC), a BAN is a two hops star centered on a gateway and classical routing could be implemented between gateways if the application requires or benefits from multi-hop communication. However, in most situations, the gateway would either be directly connected to the infrastructure (via Wi-Fi for instance), or have access to a cellular network (LTE), or could dispose of sufficient storage space. The CGN scenario is indeed more relevant to an evolved routing, as it involves multiple devices that belong to different BANs, connected through multiple technologies.

3.3. ON THE WBANS ROUTING PROTOCOL

We propose a hierarchical self-organizing routing protocol based on the clustering approach which is extensively used in sensors networks. This approach consists to construct a topology with hierarchical structures that are scalable and simple to manage. As depicted by Figure 3.1, our proposal can be divided into four phases:

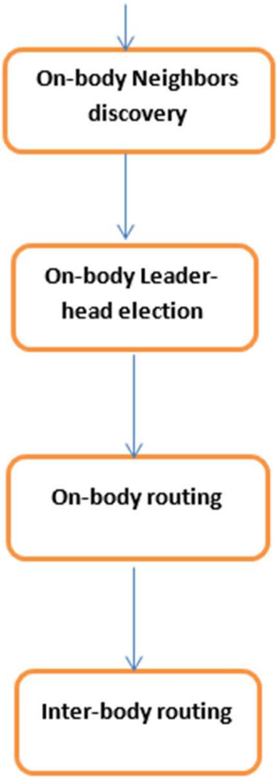


Figure 3.1: State transitions representing the different steps of self-organizing routing protocol

On-body Neighbors discovery

Neighbor discovery is a critical component of proactive routing protocols largely used in multi-hop wireless networks like Ad'hoc and sensors networks. We reminder that nodes are neighbors when they are within communication range. Note that based on this process, each node can estimate and save the list of neighborhood, e.g. based on the RSSI measurement or PER. A classical neighborhood discovery algorithm consists to exchange Hello packets between nodes within a single hop. In our approach, only the on-body nodes in the same body can exchange Hello packets between them. Due to the high mobility of the on-body nodes and that the links can appear and disappear, all nodes have to update periodically its list of neighbors. It is important to note that a significant increase in the transmission rate of Hello packets consumes much of the available bandwidth, leaving little bandwidth available for delivering data. Thus, there a tradeoff between the overhead from Hello packets and the quality of neighborhood estimation or the credibility of the neighbors list.

On-body leader-head election:

The idea is to select, for each WBAN, a node, called body-leader, among the on-body nodes which will be responsible to collect all the traffic of the WBANs to forward it directly to the destination (e.g. access point, anchors, gateway, etc.) or using the inter-body routing protocol. The selection of the body-leader can be made on various criteria like high degree node (the node which has the higher number of neighbors), links quality (each link is characterized by a weight reflecting its radio quality and, then, the node which have the highest value of the sum of its links weights will be selected). To select the best body-leader a cooperation with the low layers to exchange information (e.g. links quality) is very beneficial. If a node is not directly connected to the body-leader, it can select a common neighbor which plays the role of relay node. Note that all the required information as node degree, links quality or neighbors list can be obtained through periodic exchanges of Hello packets.

After this step, a one or 2-hops star topology, centered on the body-leader node, will be created for each WBAN, an example is illustrated by the Figure 3.2. Since the radio conditions of on-body links change over the time, this process has to be repeated periodically.

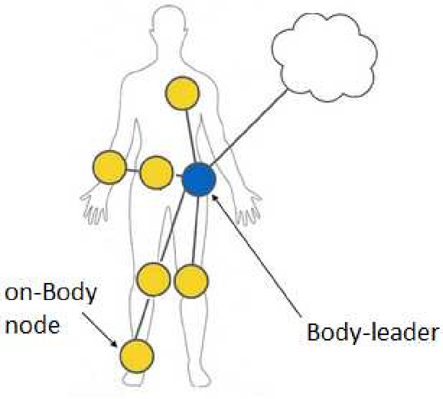


Figure 3.2: illustration of on-body hierarchical topology: body-leader node is represented with blue color while simple on-body node is with yellow color. A simple on-body node can relay traffic to the Body-leader

On-body routing:

Once the on-body topology is created, a routing protocol has to be running in order to ensure high delivery packet rate from on-body nodes to the body-leader. Since the path length of the on-body topology is around one or two hops, a classical relaying protocol can be used. The goal is to send the packet directly to the body-leader if it is neighbor node, else transmit the packet to a relay node (which is directly connected to the destination). At this step, all the on-body traffic can be collected at the body-leader to will be routed to the final destination through inter-body routing protocol.

Inter-body routing:

With our strategy of clustering (each WBAN is a cluster), each WBAN can be seen as a single entity. With this approach, from network layer of view, the group of bodies can be represented/modeled by mobile ad hoc network (MANET) where a WBAN is modeled with a single node (i.e. the body-leader node). Hence, as depicted by Figure 3.3, a backbone network composed from body-leader nodes is created. As the number of bodies is low, the inter-body routing is very simple: we can use any MANET routing protocol like Inter-zone Routing Protocol (IERP). The inter-body routing could require an inter-body neighborhood discovery phase. In this case, each inter-body transmits a second type of Hello packets received only by the backbone nodes: each Hello packet can be target (adding a field *type*) to indicate it type. Note that in order to reduce routing control traffic, an optimized random or broadcast routing protocol is a good candidate since the size of the backbone network is generally very low.

Note that one advantage of our clustering approach is to reduce the interference between the WBANs and ensure low human exposure by reducing the transmitted power of the on-body nodes since it can only communicate with nodes on the same WBAN and hence don't need to large coverage.

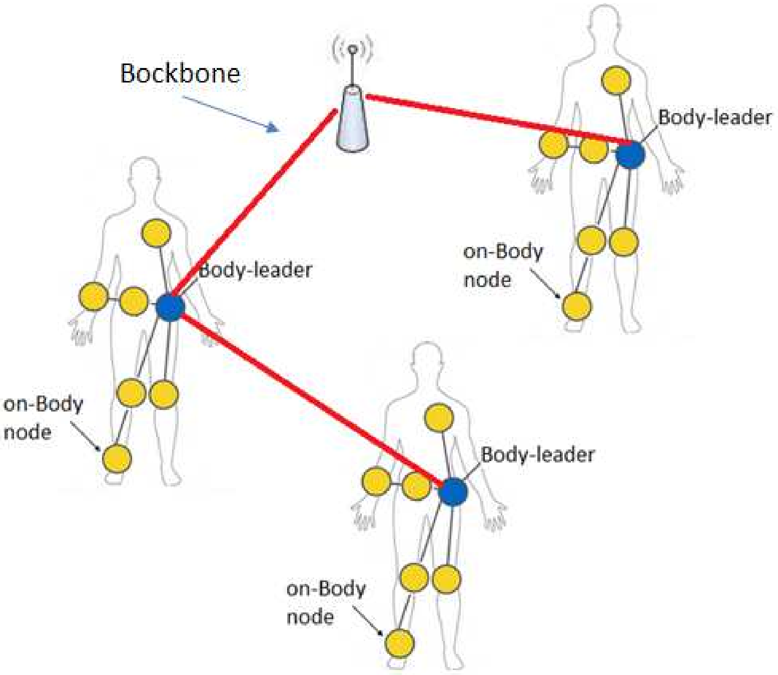


Figure 3.3: illustration of on-body routing infrastructure (black color) and inter-body routing infrastructure (red color).

3.4. IMPACT OF ROUTING ON MAC LAYER AND LOCALIZATION ACCURACY

In the context of nodes localization application, the nodes have to exchange several data (e.g. peer-to-peer ranging measurement, estimated positions, etc.) between them in the case of distributed localization approach or to send them to specific node in the centralized approach case. This traffic generated by each node has to be taken into account, in particular, by the MAC layer in order to reserve resource and by the network layer in order to flow the traffic between the source and destination nodes. In addition, the setting or design of the L2/L3 protocols, to serve this traffic, can influence the performance of the localization algorithm. To quantify this influence, we assume in this study a centralized localization algorithm with TDMA MAC layer. Hence, all the ranging measurement have to be transmitted to an external node in charge of computing all nodes positions.

Figure 3.4 presents the CDFs of on-body nodes' positioning error in group navigation involving on-body links (on-body cooperation, green curves) or on-body and inter-body links (full-cooperation, red curves). The results with continuous line are obtained assuming a dedicated channel (e.g. other interface like 802.15.4) to transmit and to forward/route these traffic, while the dotted curves are obtained assuming an extended TDMA frame with specific time-slots reserved to flow these data. As expected by this figure, the cost to transmit this traffic is significant, for instance, the full-cooperative can lose around 18% of its localization accuracy. This observation refers to the effect that the frame duration increases with the routing data, and thus the location updates is longer and the localization precision become lower. For this purpose, booking a dedicated channel to route these data could be a good strategy.

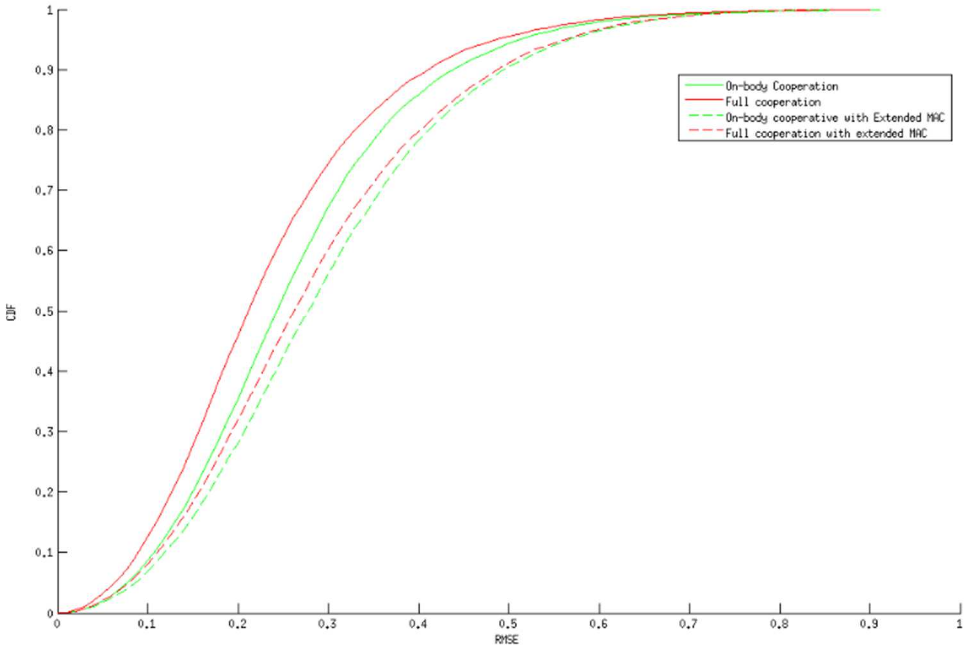


Figure 3.4: CDFs of on-body nodes’ positioning error in group navigation involving on-body links (on-body cooperation, green curves) or on-body and inter-body links (full-cooperation, red curves).

4. CONCLUSION

This document is related to the subtask 3.3 of the CORMORAN project (Inter-WBAN networking), which focuses on inter-BAN communications and interactions. In this context, each node could need to send its position to other nodes in the group or to exchange data in a peer-to-peer manner through multi-hop communications, for instance to determine the location of each node in the network, or simply for other application-specific traffic purposes. In order to ensure high localization accuracy and high packets delivery rates between end-to-end nodes, we firstly proposed a new approach exploiting the advantages of topology control to construct a robust reduced topology (in terms of high links quality), which is very beneficial in the phase of ranging estimation. We combine the potential of topology control with the advantages of cooperative approaches in delivering high positioning accuracy while exploiting cross layer information, i.e., channel measurements. Then we have investigated issues related to the routing performance in highly dynamic WBANs, where the inherent body mobility and posture introduce frequent time and space variations in the observed link reliability and network connectivity. Thus we have proposed a new hierarchical self-organizing routing protocol based on a clustering approach in order to reduce the interference between the different WBANs and ensure low human exposure by reducing the transmitted power of the on-body, while ensuring high packets delivery rate.

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