

Reconfigurable Tactical Impulse Radio UWB for Communication and Indoor Localization

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Abstract—The paper is focused on the design of a new reconfigurable tactical UWB impulse radio enabling indoor communication and localization for military application. The proposed system contains both a physical and a MAC (Medium Access Control) layer. It proposes to answer military needs for information sharing and for indoor localization of infantry. The physical layer is based on IR-UWB (Impulse Radio Ultra WideBand). Its goal is to ensure communication and distance evaluation between the transmitter and the receiver. IR-UWB is necessary for constraints such as low power consumption, reconfigurability, through the wall propagation, fine resolution localization, low probability of detection and interception. These advantages come from the use of a very large bandwidth with very short pulses. The digital baseband implementation of a reconfigurable IR-UWB transceiver is based on a coherent Rake receiver and on a parallel search acquisition. Its synchronization accuracy is of 0.33 ns. This enables distance evaluation with a precision of 10 cm. The MAC layer deals with the multi user access and the positioning. TDMA is used for sharing the channel between users. WiDeCS, a master-slave TOA (Time of Arrival) cross layer mechanism is implemented for time synchronization. This algorithm can also determine the Time of Flight of the IR-UWB signal due to timestamps at the physical layer. This algorithm followed by triangulation and-or angle of arrival techniques leads to 3D positioning.

Index Terms—indoor ; IR-UWB ; localization ; Wireless Sensor Networks

I. INTRODUCTION

Positioning the infantry units is a strategic issue on a battlefield. For many years, Global Positioning System (GPS) has allowed teammates, as well as commanding officers, to know in real time the position of units taking part in a battle. This tactical advantage, as a consequence, is lost in indoor environments such as buildings, or caves. There is a need for indoor positioning equipment for ad-hoc networks. Although millimeter precision is not mandatory for such applications, a position error under 50 cm is sufficient in order to distinguish a teammate and other persons. The main requirements are

- indoor capability and through the wall positioning
- a fast acquisition of teammates' location
- a reliable tracking of moving partners
- a secure transmission channel hard to detect and to jam
- a communication channel for health monitoring

Recent researches have focused on a new way to localize team members in indoor environments. Most of them require the previous installation of reference base stations to locate units in absolute coordinates.

This work is focusing on the possibility for each unit to obtain the location of every other unit in both direct and indirect range. For that, a system based on Impulse Radio Ultra Wide Band is proposed. The IR-UWB allows an accurate timestamping of emitted and received packets. Over this physical layer, we propose to use a Synchronization and Localization protocol named WiDeCS[1]. WiDeCS uses timestamping at physical level, coupled with two-way ranging to obtain both the time reference offset, and the Time of Flight. The use of Smart antenna allows to obtain an information about the Angle of Arrival, and then determine the position of every node in range by combining ToF information and Angle of Arrival.

In the first section, this paper proposes a possible system using the proposed schemes for localization of moving units. Related works on this subject are then overviewed. The proposed system, and its two major parts - the physical layer, and the MAC layer with synchronization and localization - are detailed in a third part. The last part deals with theoretical performances of the system.

II. POSSIBLE INTEGRATION AND OPERATIONAL SYSTEM ASSEMBLY

The proposed system is based on the use of two techniques to determine the position of the nodes in range.

A. Smart antenna for fast rough localization

The first step towards a positioning of all the units is to determine roughly the position of neighboring units by the means of Time of Arrival and Angle of Arrival. This step has the main advantage of giving a first rough estimation to the user.

B. Map generation

In the same time, an array of distances and directions is computed with the help of WiDeCS and is stored inside the MAC layer. The MAC layer shares the information of distance between nodes with nodes in range. A map can then be determined owing to these information and a trilateration algorithm.

III. RELATED WORK

Indoor positioning is a challenging subject gathering resources from all around the world. Rough localization has been made possible in the case of widely used wireless networks

such as WiFi and Bluetooth. However, the achievable accuracy is limited by a major drawback of these technologies, the use of a narrow band, making event time stamping hard to improve [2].

Recent advances on this subject have improved the spatial resolution of positioning systems. Most of the proposed systems use Ultra Wide Band (UWB) transceivers. The UWB technologies allow large band emission, which present fast changes in the time domain. These events can be used for measuring the Time of Arrival (ToA) or Time Differential of Arrival (TDoA). UWB makes it possible to implement low power and low complexity systems. The three most widely spread methods for UWB localization are [3]:

- Triangulation uses one distance and 2 angle informations to compute the position of a node when the 2 reference base stations have known positions. Its advantages are the small number of base stations necessary to determine the position coupled with no necessary synchronization between base stations. However, a high accuracy of the measured Angle of Arrival (AoA) is necessary.
- Trilateration is a method similar to triangulation with the difference that it uses a ratio between distances measured relatively to at least three base stations. This distance can be estimated from the ToA. However, a high synchronization is required between all the stations.
- Multilateration is derived from trilateration. Instead of using absolute ToA to determine the distance, the TDoA allows to not synchronize the localized node with the base stations. Those base stations, on the other side, still need to be synchronized.

A rough estimation of the relative position can be determined if an information of distance is coupled with the Angle of Arrival. The Received Signal Strength (RSS)[4] helps determining the approximate distance owing to the knowledge of the channel path loss. The other possible way to know the distance is based on a ToA measurement. However, this technique's performances are linked to the synchronization performances. UWB appears to be a solution to the ToA measurement issue. For example, Clarke et al. compared commercially available positioning systems based on different modulation (e.g. Wi-Fi, signal strength, radio frequency (RF), ultrasound, and UWB) [2]. Implementations based on IR-UWB have been proposed in the literature. Rahmatollahi et al. [5] described a solution using base stations coupled with IR-UWB. However, this system cannot be used without a previous deployment. The main challenge in such systems is to detect the shortest path among all the multipath pulses. Indeed, the most important pulse is not always the one carrying the greatest amount of energy. Recent publication show propositions based on the detection of the first pulse to arrive in the receiver [6] The proposed system embeds the localization protocol in every node in order to localize the nodes relatively to each other instead of positioning them relatively to a previously deployed infrastructure. It is then possible to localize persons equipped with such system even in the case of a first visit of the indoor

environment.

A. System view

The localization system is based on a network communication stack. Each node must gather Time of Flight (ToF) information regarding its data exchanges with the other nodes and compile them in an array. This array is the utilized at application layer to determine location of all the nodes. The figure 1 shows an example of deployed system.

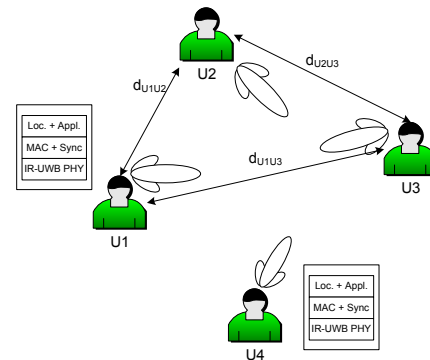


Fig. 1. Operational use case

A smart antenna is placed on the helmet to cover all the possible incoming directions. These antennas are connected to multiple instances of the physical layer. The first instance detecting the pulses and decoding them is supposed to be attached to the antenna pointed in the direction of the shortest path between the transmitting node and the receiving node. This shortest path is assumed to be the Line Of Sight path owing to the through the wall propagation performances of IR-UWB.

The physical layer used in this system is an Impulse Radio Ultra Wide Band protocol. This protocol is based on the use of short pulses spread over an ultra wide bandwidth. The possible achievable synchronization is then directly linked to the occupied bandwidth and the receiver resolution. Details about the use of IR-UWB in such systems are given in a first time.

Once the physical layers are synchronized, it is then important to synchronize the clocks of the discussing nodes in order to determine the Time of Flight (ToF) as precisely as possible. The WiDeCS synchronization scheme is used for this purpose [1]. The MAC layer also computes the ToF calculations and delivers them to the application dedicated to maintaining a map of neighboring teammates.

B. Physical layer specificities

The proposed physical layer is based on IR-UWB (Impulse Radio Ultra WideBand). Its goal is to ensure communication and distance evaluation between the transmitter and the receiver. IR-UWB uses pulse modulation for transmitting information. IR-UWB suits to constraints such as low power consumption, reconfigurability, through the wall propagation,

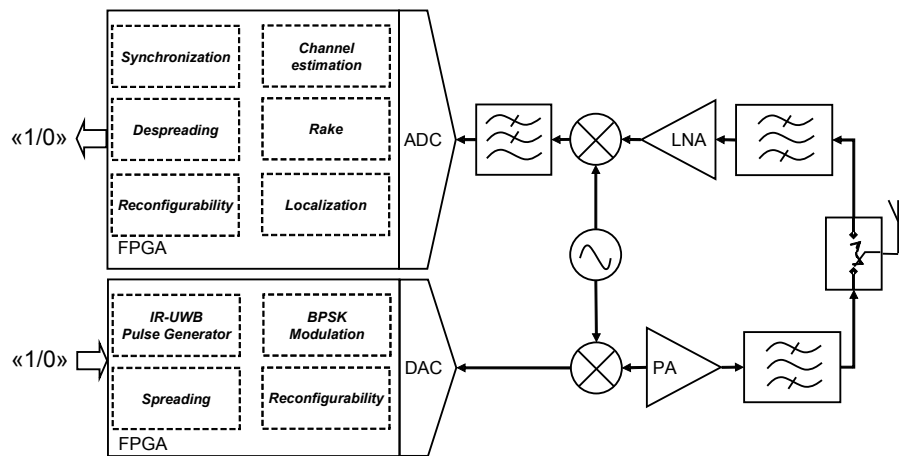


Fig. 2. Proposed IR-UWB transceiver implementation with localization capability.

fine accuracy localization, multi users scalability, low probability of detection and interception [7]. In addition, IR-UWB technique has a low probability of pulse collision enabling the support of multi user scenario with low complexity MAC-level mechanism. The use of very short impulse confers an excellent behavior regarding the fading caused by multipath in comparison with the classical narrow band techniques [8]. IR-UWB is a very promising technology for both low power communication and localization thanks to the use of a very large bandwidth with very short pulses[9]. The localization and the synchronization accuracy directly depend on the occupied bandwidth of the IR-UWB signal. This latter defines the resolution of the receiver, which is equal to the inverse of the occupied bandwidth. The finer it is, the more precise the synchronization and the localization are. Time of arrival (ToA) localization techniques suits to IR-UWB features [9]. The shorter the IR-UWB pulse is, and the better the localization accuracy is. The goal of ToA is to evaluate the time of flight of the pulse between the transmitter and the receiver, by measuring the time of arrival of the received pulse. Thus, the proposed system is able to evaluate the distance between the transmitter and the receiver. At this stage it is only a 1-D positioning. For achieving fine localization accuracy a fine estimation of the pulse time of arrival is needed, implying an efficient synchronization algorithm at the receiver. This performance requirement is also need for achieving IR-UWB communication. The localization is a classic IR-UWB communication. The better the IR-UWB communication performances are, the better the IR-UWB localization performances are.

The UWB occupied bandwidth is large and the UWB channel has a dense multipath behavior, these confer to the synchronization task a high level of complexity [10][11]. The receiver resolution is small and equal to the inverse of the occupied bandwidth. The number of multipath components resolved is then large. The short impulse duration, the large space search and the low power UWB signal levels are implied in the high complexity of the IR-UWB synchronization. An efficient synchronization technique has to be fast and precise

for, respectively, avoiding a large decrease of the signal to noise ratio and decreasing its cost. The synchronization criteria can be used for evaluating the localization technique. In IR-UWB many multipath components can be seen as solution of the synchronization even if they result from a NLOS contribution. This can imply an error in the distance estimation mechanism since a NLOS multipath is not directly linked to the distance between the transmitter and the receiver.

The proposed IR-UWB receiver, assuring both communication and distance evaluation, is based on a coherent BPSK Rake receiver and on a parallel search synchronization. The proposed IR-UWB transceiver allows fine localization at low cost and low power. It achieves reconfigurable performances in data rate, bit error rate, radio range, spectrum occupation, power consumption, synchronization accuracy, processing gain, transmitted power and pulse duration [12]. This reconfigurable behavior allows to efficiently fulfill the distinct applications needs and the evolutions of the environment at the best cost. [12] demonstrates that decreasing the synchronization accuracy implies a decrease of the power consumption. Thus in function of the localization accuracy requirement, defined by the application needs, the proposed reconfigurable IR-UWB transceiver can adapt its power consumption for increasing its life operating duration.

The synchronization technique used allows to determine the first multipath received. The proposed implementation of the IR-UWB transceiver is described in fig. 2. It is implemented according to the mostly digital implementation thus the performances directly depend on the digital to analog and analog to digital converters (DAC and ADC).

By considering the ADC sampling frequency F_s , the achievable synchronization accuracy ϵ , in seconds, of the receiver is defined by:

$$\epsilon[s] = \frac{1}{F_s} \quad (1)$$

The localization accuracy β , in meters, is obtained as follow:

$$\beta[m] = v_{UWB} \times \epsilon \quad (2)$$

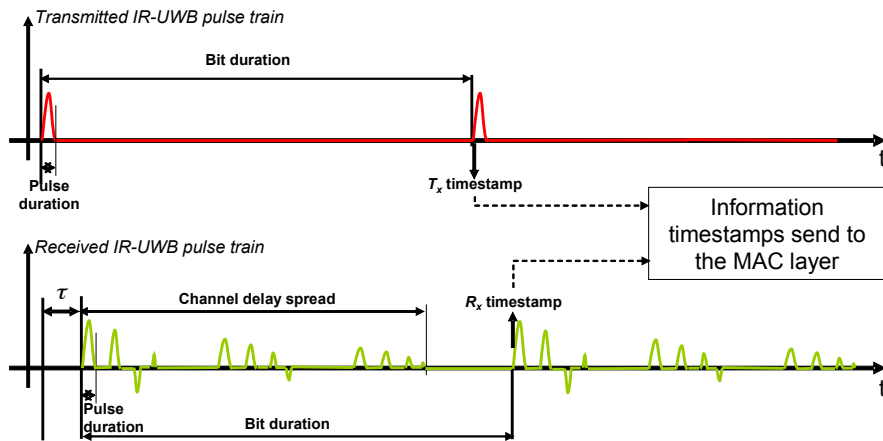


Fig. 3. First multipath component timestamp

where v_{UWB} is the propagation speed of the IR-UWB in the considered environment. The proposed receiver is implemented on FPGA Virtex 4 board with a 3 GPS time interleaved ADC. In this case, the synchronization accuracy is equal to $\epsilon = 0.33ns$. This enables distance evaluation with a precision of $\beta = 10cm$. The information conveyed by the proposed PHY to the MAC layer allows only 1-D positioning, i.e. distance estimation between the transmitter and the receiver as described by the figure 2. For 2-D or

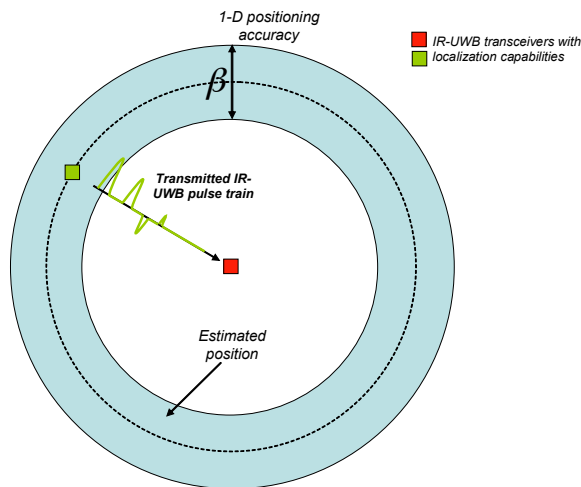


Fig. 4. Illustration of the 1-D positioning offered by IR-UWB transceivers.

3-D positioning high level algorithm must be used such as triangulation, trilateration, or multilateration. The PHY layer sends to the MAC layer two timestamps information. At the transmitter side, the PHY layer warns the MAC layer when the first pulse containing information is sent. Whereas at the receiver side, the PHY layer warns the MAC layer when it detects the first multipath component of the first received pulse of information. Even in case of NLOS communication the use of the first multipath component is required for reducing the average distance estimation accuracy as illustrated in the figure 3.

C. MAC Layer and cross layering for distance evaluation

The MAC layer used for this system is based on a static TDMA frame with pre-assigned slots which includes an implementation of the Wireless Deterministic Clock Synchronization (WiDeCS) scheme. WiDeCS is a protocol allowing high performance synchronization in wireless sensor networks while keeping a low power consumption.

The proposed synchronization protocol takes advantage of the restrictions linked to the application to make strong assumptions and simplify the development of both the MAC layer and the synchronization protocol.

1) General description: The Wireless Deterministic Clock Synchronization (WiDeCS) protocol is based on the planning of transmissions, and the respect of this planning. It is designed for propagating the master time reference of a star network to all the slaves.

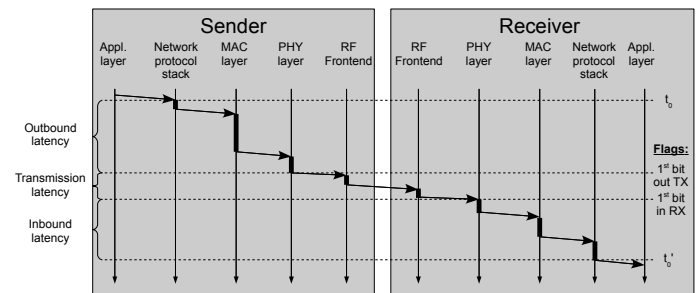


Fig. 5. Latencies involved and flag positioning for WiDeCS

For first experiments, a Time Division Multiple Access MAC layer is used. This MAC layer divides time in slots attributed to the nodes. The figure 5 details sources of delays in the network link. Delays are measured on the first effective bit (events linked to preambles and serialization have to be de-embedded). Efforts have been made to place this time stamping as close as possible to the effective channel, thus reducing uncertainties on the characterization of the propagation time on the channel. WiDeCS uses time stamping at the time of the first effective bit at the output of the PHY layer in emission, and the

first effective bit in input of the PHY layer in reception. These flags then enable precise measurement of the propagation time except for the jitter linked to RF front-ends. We name these flags TX_ONGOING for the first bit of effective data out of the PHY transmitter, and RX_ONGOING for the first bit of effective data entering the PHY receiver.

Owing to this MAC layer, each node of the network is supposed to talk at precise moments. Measuring delays between expected receiving times and actual ones helps determining the clock offset and the propagation time. WiDeCS Synchronization protocol uses possibilities relative to time division to determine the clock offset between each node and the master. The figure 6 shows the different informations gathered on different sides, and sent to the slaves by the master. The

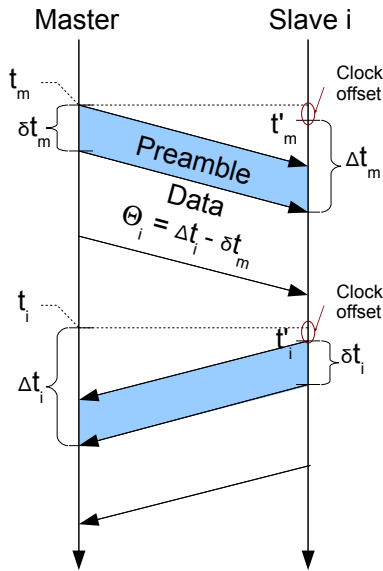


Fig. 6. Exchange of timing information

complete synchronization is based on 2 steps.

Phase 1: Pre-synchronization

This step is performed by every slave when joining the network.

The master has the same communicating hardware the slaves have. The function of the master is to create a frame, and regularly send a preamble of the TDMA frame. The slaves, when reset, or desynchronized, switch to reception only mode, and wait for the master node to indicate the beginning of the frame. When this message is detected, the slave resets its *frame counter* to a predefined reset value in order to begin transmitting data in the dedicated slot. When this step is passed, the slave switches to phase 2 of the synchronization process.

Phase 2: Fine-synchronization

Once pre-synchronized, the nodes have a clock offset of 1 μ s compared to the master clock.

This step consists in determining the offset with the greatest precision possible. When the slave is allowed to transmit data, it does it at one precise moment t_i of the slot. This date

is coded in the protocol and is known by every slave, and more importantly by the master. Data is sent to the PHY layer when $t = t_i$ and a capture of the timer is done when the TX_ONGOING flag is set. t_i is then subtracted to this date, and the result is stored as δt_i . Note that small deltas (δ) are used for delays in transmitted packets, whereas capital deltas (Δ) are for delays in received packets. The following equations can be deduced from fig 6. The equation 3 represents the clock offset correction applied to the slave node in WiDeCS scheme.

$$\Delta t_{clk} = \frac{(\Delta t_i + \delta t_m) - (\delta t_i + \Delta t_m)}{2} \tag{3}$$

In the case of distance evaluation, the Time of Flight is necessary to determine the distance between the nodes. The variant equation 4 deduces this Time of Flight information from the same captured deltas.

$$ToF = \frac{(\Delta t_i - \delta t_m) + (\Delta t_i - \delta t_m)}{2} \tag{4}$$

WiDeCS can be used in every frame to maintain a clock as precisely synchronized as possible for all the length of the measurements. Another possibility is to train the slave with an optimal number of frames, and then turn the reception module in sleep mode for as long as blindness is allowed in the network.

Phase 3: Distance evaluation sharing As explained in phase 2, WiDeCS scheme does estimate the distance only between the master and every slave. A modification to this scheme is then necessary to allow distance evaluation between every node. This modification consists in measuring every delay between planned reception and effective reception of every node's packet. An array of such delays can be integrated in every node's packet in order to calculate the ToF between all the nodes.

The equation 5 shows the information transmitted between slaves

$$\Theta_{ij} = \Delta t_j - \delta t_i \tag{5}$$

where i is the node transmitting the Θ_{ij} , and j the node whose delays are spoken of.

2) *Application specific improvements and simplification:*

Usually, a network is composed of nodes coming and leaving the network. The number of nodes changes with time. In the context described before, the network is planned and parametrized before its deployment. Simplifications are then allowed, without risking uncontrolled behavior. The simplifications used in this paper are listed below, and reasons are given for their existence.

- Fixed number of nodes per piconet and pre-programmed time slots:
As we explained before, the network architecture is fixed, and planned before deployment of the team. The number of nodes for each network is then decided upon the number of persons to localize.
- No jamming between neighboring networks:
IR-UWB has a low pulse collision probability. The use of directive smart antenna - implying Spatial Division

Multiple Access (SDMA) - reinforces this fact. This modulation then allows multiple TDMA networks to exist on the same frequency band. This is possible by the means of a tradeoff between number of networks, and each network's data rate.

- Symmetrical links:
Every node of the network is fabricated using the same hardware. Delays in RF front-ends are then similar from one node to another.

IV. PROPOSED SYSTEM'S PERFORMANCES

The IR-UWB modulation is based on the emission of short pulses covering an Ultra Wide frequency Bandwidth. These short pulses are then a very precise means of getting the information of when it left the transmitter, and when it entered the receiver. Considering that the physical layer described previously allows a synchronization with the first received pulse. The resulting first pulse detected is then the one that followed the shortest possible way from the transmitter to the receiver. The proposed PHY layer uses a synchronization technique not based on the acquisition of the highest energy multipath component. This approach reduces the error due to NLOS scenario. The proposed PHY layer is synchronized on the first viable multipath component assuring communication.

The proposed transceiver achieves reconfigurability in data rate (from 4 to 125 MBits/s), chip duration (from 8 to 32 ns), pulse duration (from 1 to 4 ns), bit duration (from 8 to 256 ns), processing gain (from 1 to 8 pulses/bit), occupied bandwidth, radio range, BER performance, synchronization accuracy (from 0.33 to 2.64 ns), transmitted power density, duty cycle (from 3 to 50 %), power consumption, spectrum occupation, and maximum supported UWB channel delay spread (from 4 to 31 ns) [12]. These performances depend on the used FPGA and DAC/ADC. In our implementation, a FPGA Virtex 4 is used and DAC/ADC at 3 GSps. Reconfigurability allows to support a large range of operating scenarios with distinct requirements.

WiDeCS scheme [1], on the other hand has reached synchronization accuracies of 1 clock period in simulations, and of 3 clock periods on a specific testbench. The deductible accuracy for the synchronization is then $\Delta t = 0.33 \text{ ns} \times 3 = 1 \text{ ns}$. The distance evaluation accuracy is then of : $\Delta d = c \times \Delta t = 30 \text{ cm}$ in vacuum.

The Smart antenna adds an information of Angle of Arrival. However, directional antennas often have radiation patterns with main lobe's angle above 15° . The angle error is then $\pm 7.5^\circ$.

The localization performances are linked to the communication performances. The proposed system achieves a 30 cm resolution 3-D positioning when using triangulation.

V. CONCLUSION

This paper proposed a physical and a MAC layer adapted to localization of nodes without pre-deployed spatial references. The estimated distances are measured for every node and can be transferred through the data link for each node to calculate a

map of partners' positions. As an opening, a possible system integration including the use of Smart Antennas for rough localisation of neighboring nodes is proposed.

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