ZigBee Wireless Dynamic Sensor Networks: Feasibility Analysis and Implementation Guide

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***Abstract*— The wireless sensor network (WSN) technology has attracted increasing attention considering its potential in many application fields. In most studies on WSNs, the network is assumed to cover several static devices over a fixed coverage area. As an extension of WSN capabilities, the devices mobility and the network dynamism provide a new chain of interesting applications defined as wireless dynamic sensor network (WDSN). The initial challenge in the WDSN is to investigate whether this dynamic imposed on the network will be supported, once the used network protocol must meet the requirements for WDSN applications, such as network formation and self-organization, route discovery and communication management with the input and output of devices on the network. In order to overcome these issues, specific wireless protocols have been developed to meet the applications with device mobility in the WSN. However, these specific protocols limit the development of the WSDN since, they are isolated and proprietary solutions, instead of using a standardized protocol for interoperability. This paper presents a feasibility analysis of the ZigBee protocol for the WDSN applications. A survey of application features and requirements, as well as a discussion of advantages and limitations, regarding the adoption of the ZigBee protocol in the WDSN is presented. An implementation guide for the ZigBee WDSN is proposed in order to assist a new application of this technology. Furthermore, a proof of concept using ZigBee devices validates the implementation guide and proves the ZigBee WDSN feasibility.**

***Index Terms*— Wireless dynamic sensor networks, ZigBee protocol, MANET.**

I. Introduction

EARLY research in Wireless Sensor Network (WSN) dates back to the project of Distributed Sensor Networks (DSN) in the Defense Advanced Research Projects Agency (DARPA), in USA, around the 80's [1]. According to [2], WSN is defined as "network devices, denoted nodes, spatially distributed that, in cooperation, carry out tasks of sensing and control of certain environment and communicate the information collected through wireless links, allowing the interaction between people or computers and the phenomenon under analysis".

The increasing interest of academic and industrial areas in this technology also cover new specific applications of WSN, such as the dynamic of these networks by the mobility of its components [3]. Defined as Wireless Dynamic Sensor Networks (WDSN), these networks with mobile components can be seen as a non-traditional WSN, where the previously specifications and expected performance are confronted against the capacity to support the dynamic imposed on the network. As a result, some authors have proposed new routing protocols or functionalities for wireless networks in order to optimize and/or enable new features to the WSN protocols existing on the market [4]–[6]. The goal was to fulfill the requirements for WDSN applications such as network formation and self-organization, route discovery and communication management with the input and output of devices on the network, among other characteristics. The disadvantage of this approach is the creation of proprietary protocols, with low level of interoperability and standardization.

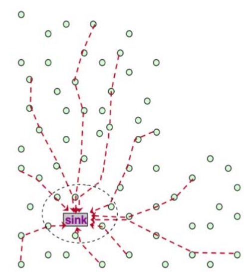

Fig. 1. Tree topology static WSN with a multi-hop communication network.

This paper is organized as follows. Section II presents a review of WDSNs, their types of mobility and existing applications. The feasibility analysis of using the ZigBee protocol, a worldwide accepted and standardized protocol, in WDSN applications is described in Section III. It describes the characteristics and requirements for WDSN application, as well as a discussion of the advantages and limitations relating to the adoption of ZigBee protocol in WDSNs. Section IV details an implementation guide for WDSN applications with ZigBee protocol. A proof of concept of a ZigBee WDSN is presented in Section V with further discussions about the paper results and contributions in Section VI and conclusions in Section VII.

II. WDSN

The primary goal of a WSN is to sense relevant data of an environment and transmit this data to a central processing node, usually defined as sink or base station. Currently, in most of the studies in WSN, it assumes that the network covers a large number of devices over an area of interest, forming a multi-hop communication network. Furthermore, sensors and the sink node conventionally remain fixed (static) in their network initial positions [2], as illustrated in the WSN of Fig. 1.

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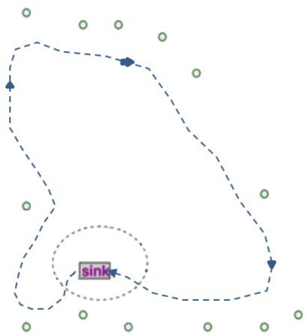

Fig. 2. WDSN with mobile sink and single-hop communication network.

Despite the initial proposal of WSNs have been based on statically distributed sensor networks, recent applications have focused on WSNs with mobility of components [3], [5], [7]. These new applications break the paradigm of limited coverage area of static WSNs, thus enabling the exploration of low cost and low power WSNs in large areas and in a new range of applications. This mobility aspect of WSNs is defined in this paper as Wireless Dynamic Sensor Networks (WDSN). As a result, the WDSN can be seen as a specific type of MANET (mobile Ad hoc network) and even also as a specific type of VANET (vehicular ad hoc network). The term VANET is a subgroup of MANETs. The movement and self-organization of the nodes characterize WDSN, VANET and MANET. Nevertheless, they are also different in some ways [8]. MANET can contain many nodes that have uncontrolled moving patterns and usually the routing is a main issue. Since VANET is consisted mainly by vehicles, the mobility is restricted by transportation issues like road path and traffic rules but usually higher in average speed. Finally, the WDSN consists specifically of low cost and low power devices with a simple communication stack and single routing protocol.

WDSN implies that the sink node, the sensor node and/or the variable under analysis is (are) in motion. A conventional WSN generates a data transmission path between interest variable (analysis phenomenon) and the base station (a PC or sink) under static conditions, i.e., nodes remain always in their network positions. In the particular case of WDSN, the path of collected data from the interest variable to the base station can provide multi-hops under dynamic conditions. Usually the data transmission path is formed when the sensor nodes receive a request from other node, i.e., the sensors transmit their collected data only when they receive a request from a managing node. This request can be in a direct way (sink–sensor) or indirectly (through router nodes), depending on the distance between the sink and the analysis phenomenon, and their respective positions. Fig. 2 illustrates a WDSN with a mobile sink and single-hop communication network.

The potential and benefits of WDSNs can be seen in different application areas in recent years such as precision agriculture [9], field mapping [7], VANETs [5] and MANETs [10]. Mostly of the papers addressing the mobility challenges in WSN are theoretical or based on simulation. The mobility aspect in WSN was initially discussed in [11]. Gabriele and Giamberardino [12] investigated the effects of communication constraints on the computation of an optimal mobile sensor trajectory to collect the required WSN data. Vlajic*et al.* [4] examined the path-constrained problem for WSN with mobility and proposed improvements to the ZigBee standard specifically targeted for WSNs with mobile sinks.

The mobility support of ZigBee protocol was investigated using simulation in [13] and [14]. In [13], an initial ZigBee layer was implemented in the NS-2 tool to enable the simulations. The results indicate that the delivery rated decreases and performance deteriorates when there are multiple instances of mobility in the network, and when mobile nodes are traveling at high speed. The packet delivery ratio, throughput and end-to-end delay has been examined in [14] using OPNET. The results shown that the tree topology provided the best performance in terms of packet delivery ratio and throughput. The performance of the ZigBee protocol considering realistic VANET mobility models have been investigated in [15]. Results shown (as in [13]) that the ZigBee protocol is only suitable for low speed VANETs.

Considering experimental papers, Valente *et al.* [9] presents the development of a WDSN with a mobile sink for crop monitoring. The solution uses a remote controlled aerial vehicle (drone) as the collector device for the data acquisition of sensors allocated along the winery. The main characteristic of the system is a mobile sink on a drone that assures the communication between groups of sensors (clusters) in the crop and the base station. As a result, the WDSN originates an extension of the coverage area of the traditional IEEE 802.15.4 WSN used for the winery data acquisition. An animal health monitoring system based on a ZigBee mobile WSN is presented in [16] and [17]. The mesh topology was used in [16] with multi-hop communication providing a reliable communication with a low percentage of data loss (14.8%).

III. ZigBee WDSN – Feasibility Analysis

In order to develop a WDSN, a wireless protocol have to be applied (or created) to carry out the application. The choice of this protocol has important conditions for the proper operation of the network, interoperability between the devices, self-organization of the network elements, possibility of future expansion, and other related features. In addition, the protocol must have a set of capabilities and resources, which allow the proper operation of the network with the imposition of mobility of its components as required by WDSNs [11].

There are inherent challenges in WDSN that must be considered such as the dynamic and arbitrary localization of devices, the constant need for network formation and route discovery as well as frequent communication intermittency between devices. Therefore, it is important to analyze the feasibility of using any wireless protocol in face of the WDSN requirements. The feasibility analysis in this paper seeks to confront the real functional needs of WDSN against the ZigBee protocol functionalities, investigating the possibilities, advantages and disadvantages of ZigBee application in WDSN.

A. WDSN Functional Needs

A proper WDSN application must consider some operational requirements such as:

- Energy management: WDSN devices have to realize when to transmit data (only if in communication coverage with another node) in order to manage the power consumption to prolong the battery life;
- Self-organization: devices have to connect automatically one each other, creating communication links without the user's need. Likewise, with the mobility of the nodes, they have to support the rearrangement of routes and network topology. Each WDSN node have to be able to associate, dissociate and re-associate, whenever necessary;
- Reliability: the WDSN communication protocol must provide mechanisms for the creation of reliable data links and transmissions. With the devices mobility in WDSN, it is required a way to indicate that a message was received. In addition, it is important to have a proper network throughput in face of the reduced communication time due to the limited coverage usually found on low power WSN;
- Permissible associations: WDSN devices must allow the automatic association of several neighboring nodes since one node may have to communicate with different nodes at different coverage areas with the devices mobility;
- Node independence: the WDSN operation has not to be dependent of any network node. The WDSN has to continue operating in case of any node failure or network dissociation and if the node is out of communication range;
- Interoperability: WSDN must use a standardized network technology in order to be flexible and to enable the use of different devices and producers.

B. ZigBee Protocol Features

The ZigBee-2007 protocol specification [18] (last revision in 2012) defines two high-level layers (Network Layer – NWK – and Application Layer – APL) to the basic structure predetermined by the IEEE 802.15.4 standard [19], creating a low cost and low power wireless communication protocol with robustness and interoperability.

The ZigBee devices features are defined by the function of "type" and "role" of the device on the network. The device type is related to the amount and capacity of tasks that a ZigBee device can take in the network, as well as their level of association. There are two types of ZigBee devices: Full Function Device (FFD) and Reduced Function Device (RFD). FFDs have a complete instructions stack on their layers and can be associated with any other device on the network, being these devices called parent node. RFDs have limited functions on their stack layers, enabling better power management, and can be associated only with FFD devices, being these devices called child node. The device role on the network is related to the assignments that these nodes will have when in operation. There are three roles that a device can take in a ZigBee network: coordinator (ZC), router (ZR) and end-device (ZED). ZigBee Coordinators are responsible for network formation and managing (routing, operating channel selection and Personal Area Network identification). The ZC is a single device in a ZigBee network, and its presence is mandatory for the formation of the communication among network devices. ZigBee Routers have the capacity to provide routing paths to data packets, performing data retransmission by extending the communication range of a ZigBee network. Finally, ZigBee End-devices (only ZigBee RFD type) have the role of send and receive information to/from FFDs (ZC and/or ZRs). ZEDs are usually connected to sensors and actuators. ZigBee devices can be configured in any of the three network assignment roles, with a diversity of parameters configuration and operating modes.

According to the ZigBee protocol features, there are certain requirements for obtain a communication between ZigBee devices, performing the permissible network topologies and managing data exchange. Among these requirements, there are two important parameters to WDSNs: "maximum association per device" and "parent node communication timeout".

The "maximum association per device" describes the number of permissible neighboring nodes that a ZigBee device can own in its "Child Table". Moreover, it is related to the "Number of Remain Children (NC)" parameter in ZigBee devices configuration. This parameter specifies the number of children nodes that a ZigBee FFD can assign in its "Children Table". In the case of a ZC device, the NC parameter has a maximum value at 10, and in the case of a ZR, it is 12 [18].

The "parent node communication timeout" describes the maximum time that a child node can remain without communication with its parent node. If this period is exceeded, the parent node removes it from the Child Table. By the ZigBee specification, this requirement relates to "End Device Poll Timeout" parameter, and follows the rule as (1), where SN (Number of Sleep Periods) and SP (Sleep Period) are parameters set by the Sleep Mode ZED setting [18].

$$End\ Device\ Poll\ Timeout = 3.SN.(SP.10) \quad (1)$$

The ZigBee access control rules is another important feature for WDSN. The functions of "network formation", "network discovery" and "network joining" enable the automatic association, dissociation and re-association procedures of ZigBee devices. Using incorporated tasks such as energy scan per channel, network scan, PAN ID filter, among others, the ZigBee protocol may be able to automatically manage the constant input and output of devices of WDSNs.

Another important feature present in the ZigBee protocol is the routing function, or "Route Discovery". Routing is the process of identifying a path to a destination address whose route is unknown. The route discovery in a ZigBee network is based on the Ad Hoc On-Demand Distance Vector (AODV) algorithm, a recipe for flood the network with frames until reaching the address destination. The route discovery is stored in a table of neighboring nodes, and such route discovery entries on all the nodes are expired after a time specified by the ZigBee protocol: 10 seconds [18].

Other key feature for the application of ZigBee in WDSNs is its power management capability. The simplified ZED communication capability enables the suppression of certain functions of the MAC and NWK layers, resulting in lower processing and power consumption. Additionally, ZED has its own resource of energy saving: sleep mode. The sleep mode puts the device in standby, entering a state of low power consumption (few micro amps), and waking up periodically to probe (polling) any buffered message. The sleep period is defined using the SN (Number of Sleep Periods) and SP (Sleep Period) parameters.

Finally, the ZigBee protocol provides resources to perform protected and reliable communications between devices. The communication safety is guaranteed by data encryption (Advanced Encryption Standard) of 128 bits, network keys management and devices authentication. The message delivery confirmation (ACK) helps on the communication reliability.

C. ZigBee × WDSN Analysis

Considering the functionalities in the ZigBee standard layers, it is possible to match it against the functional needs of WDSNs. This analysis supports determining the ZigBee protocol feasibility for WDSN application.

First, in terms of energy management, the ZigBee protocol presents a well-developed hibernation feature of sensor nodes (sleep mode). This feature is an important point for ZigBee application in WDSN. While the mobile device is out of communication coverage with other devices, they may remain in a state of low energy consumption with temporary check for any communication request (presence) of the mobile device. If the energy consumption is crucial, it is important to consider the impact of the periodic channel energy scan on the ZigBee device consumption.

The self-organization is an essential functionality for WDSNs. It provides rapid device and network reorganization and the rearrangement of routes and network topology in accordance with the devices mobility and constant association on the network. The ZigBee protocol has built-in functions for network discovery and formation, joining procedure and network routing, consequently providing adequate management of input and output of devices in the WDSN. The ZigBee AODV routing protocol supports the dynamism of constant devices association with the minimum time of route discovery equal do 10s. It automatically enables different routes discovery in accordance with the devices mobility and association with other devices.

The reliability and security requisites in WDSN are included on ZigBee with the data encryption, network keys and devices authentication. On the other hand, the network speed transmission and throughput, as well as the required time for input and output devices on the network (10s), may limit (or do not guarantee the communication) the ZigBee use in WDSN applications with high speed mobility among the devices. Even with this limitation, the ZigBee protocol provides packet delivery confirmation (ACK) for the cases in which it can be used for WDSN.

The maximum permissible association is another requisite that may limit an application of a ZigBee WWDSN. This parameter is defined in the ZigBee network discovery process, through the NC parameter. The maximum permissible association (simultaneous) for Coordinator devices is set to 10 children nodes, and for Routers, 12 children nodes. These values impose certain restrictions on the ZigBee use in WDSN in cases of agglomeration (cluster) of sensors nodes in a central node (usually the router type) and/or communication of multiple routers with the Coordinator node at the same time. However, applications of WDSN with simultaneous associations below these values are suitable with the ZigBee protocol, until the limit number of nodes on a ZigBee network (65,000 devices). Bear in mind the existence of the “End Device Poll Timeout” parameter, which defines the withdrawal period of children nodes of devices Children Table in accordance with the equation (1). This parameter allows periodic rotation of children nodes for the same device, allowing the association of different children nodes at different times (and locations) and it should be related with the maximum permissible association (NC) parameter for a good performance of the WDSN.

The node independence is the only requisite not satisfied in the ZigBee protocol. Once the ZigBee Coordinator (ZC) is responsible for the network management functions, it is mandatory the presence of the coordinator node in any ZigBee network. Nevertheless, this node dependence in ZigBee WDSNs can be overcome with the use of a mobile ZC node on the network. In this situation, every time the mobile ZC enters the communication coverage of other nodes, the functions of network formation, joining and discovery are initialized, enabling the dynamic communication required by the WDSN. As a result, the ZigBee WDSN applications with mobile routers (ZR) and/or mobile sensors (ZED) are only possible if the mobile devices move until the communication coverage of the ZC and only transmit data to it.

Finally, the use of an international and worldwide-accepted standard protocol is one of the biggest advantages of the application of ZigBee to WDSNs. It provides flexibility and allows the use of any ZigBee compatible device for WDSN applications.

Considering the required functional needs expected for WDSNs, the ZigBee protocol acceptably deals with the requisites of energy management, self-organization and interoperability. The criteria of reliability and permissible associations of devices impose some constraints for ZigBee WDSNs. Finally, the only criteria not fulfilled by ZigBee WDNSs is the node independence, as any ZigBee network must have an active coordinator node.

The Table I provides a resume of this feasibility analysis through the comparison of ZigBee features and WDSN requisites. In general, the analysis proved that the ZigBee protocol acceptably accomplishes to a wide range of applications of WDSNs, and the main limitations were discussed.

IV. ZigBee WDSN Implementation Guide

The application of a WDSN is given by the movement of one or more modules, called dynamic modules, within the coverage area of other physically static and/or mobile modules. Many papers can be found on the WDSN or mobile WSN literature providing different analysis and applications. However, none of them explains in detail how to implement the WDSN. As a result, if anyone is interested in this new application of WSN (WDSN), he will have to study and discover how to implement the WDSN solution.

TABLE I
OVERVIEW OF FEASIBILITY ANALYSIS OF THE ZigBee PROTOCOL APPLICATION IN WDSNs

WDSN Requisites	ZigBee Protocol Features	Analyses
Energy Management	• Sleep Mode • Polling Request	Considerable reduction in energy consumption of devices with verification of communication requests and standby operation mode;
Self-Organization	• Routing AODV • Network Formation • Network Discovery • Network Joining	Satisfactory management of devices input and output on the network, with automatic creation of networks, topology and communication routes; Possibility of automatic node discovery in network coverage. Timing of children nodes entries (End Device Poll Timeout) may limit certain applications;
Reliability	• AES 128 bits and network authentication • ACK confirmation	Satisfactory encryption feature along with device authentication for secure communication and confirmation of message transmissions; Limitation for applications with high-speed of node mobility;
Permissible Associations	• NC (Number of Remain Children) • Number of devices	Values specified for maximum association per device may limit certain applications; Satisfactory maximum number of devices on the network;
Node Independence	• Coordinator node dependence	Network management functions are exclusive for the ZigBee Coordinator (ZC); ZC dependency bypassed with the use of mobile sink (ZC) in WDSN;
Interoperability	• International standard; • Worldwide acceptance	Standard layers and functions provide flexibility and interoperability of equipment

The proposed implementation guide seeks to assist and details the use of ZigBee networks for applications that require the mobility of devices. This guide is based on a specific procedure of message exchanging (communication sequence) between the devices required to enable the ZigBee use on WSDN. It is important to realize that without this specific procedure, the ZigBee protocol itself will not permit the intermittent communication among the devices as required by WSDN applications. Bear in mind that the guide does not cover optimal procedures for specific ZigBee WDSN applications. Therefore, any ZigBee WDSN solution implemented (using or not the guide) will have to be further analyzed and investigated against its development requirements.

This guide is based on the ZigBee-2007 specification [18]. The messages contained on the procedure are standard ZigBee frames. As a result, any ZigBee compatible device becomes able to understand the messages and to operate as required by the WSDN application. It enhances the contribution of the implementation guide presented and the potential of WDSN using ZigBee.

The communication procedure detailed in this paper is based on a peer-to-peer communication model, or star topology. The star topology has only direct communication between ZigBee modules, i.e., coordinator modules communicating directly with end devices, without the intermediation of routers. ZigBee WDSN structures with star topology can be set with two types of devices:

- **Data acquisition devices (sensors) - *ZEDs*:** modules responsible for reading and acquiring sensors data. They are arranged at different points in the application, which can be fixed or movable type. In applications with data storage structure, these modules are coupled to a micro-controlled, with features of processing, storage and data organization;
- **Collector devices - *ZC*:** single network module, responsible for creating and managing the network and for collection of the data from ZEDs. It is a mobile type module, and it is coupled to a microcontrolled structure with features of processing, storage and data organization. Eventually, these devices may be able to transfer the collected data to a final station of data processing, monitoring and storage;

In this model, the collector device (ZC) moves between coverage areas of data acquisition devices (ZEDs) of the WDSN network, thus expanding the low cost and low power WSN coverage. In case of request, the ZED transmits the accumulated data to the ZC. The ZEDs are prepared to support intermittent communication with the ZC, i.e., remain outside the ZigBee network for an unlimited period without causing any data loss, and with capacity to network reintegration.

The implementation guide considering the required communication (ZigBee frames) between ZC and ZED in a ZigBee WDSN with peer-to-peer communication is detailed in the diagram of the Fig. 3. The direction of each arrow indicates the flow of information between sender and receiver.

In accordance with the Fig. 3, the data transmission (ZigBee frames) is enabled only when the ZC and ZED are on the same network coverage area. The transmission initiates according to a ZC request. While the ZC is out of coverage, the ZED remains in low consumption operation (sleep mode) and the microcontroller structure samples and stores the data. If the ZE and ZED are in network coverage, a communication link is created through the channel verification, association procedure and route discovery of ZigBee networks. With the communication link enabled, the ZC may be able to request the data from the ZED. It is done using standard ZigBee Transmit Request frames (0×10). In this case, the ZED receives this solicitation by a standard ZigBee Receive Packet frame (0×90) and confirms it returns to the ZC using a standard Receive Confirmation or ACK frame (0×8B).

After the data request from the ZC, the ZED starts transmitting its acquired data using one or more ZigBee frames. The data transmission to the ZC uses ZigBee Transmit Request frames (0×10). In addition, the ZC receives them using

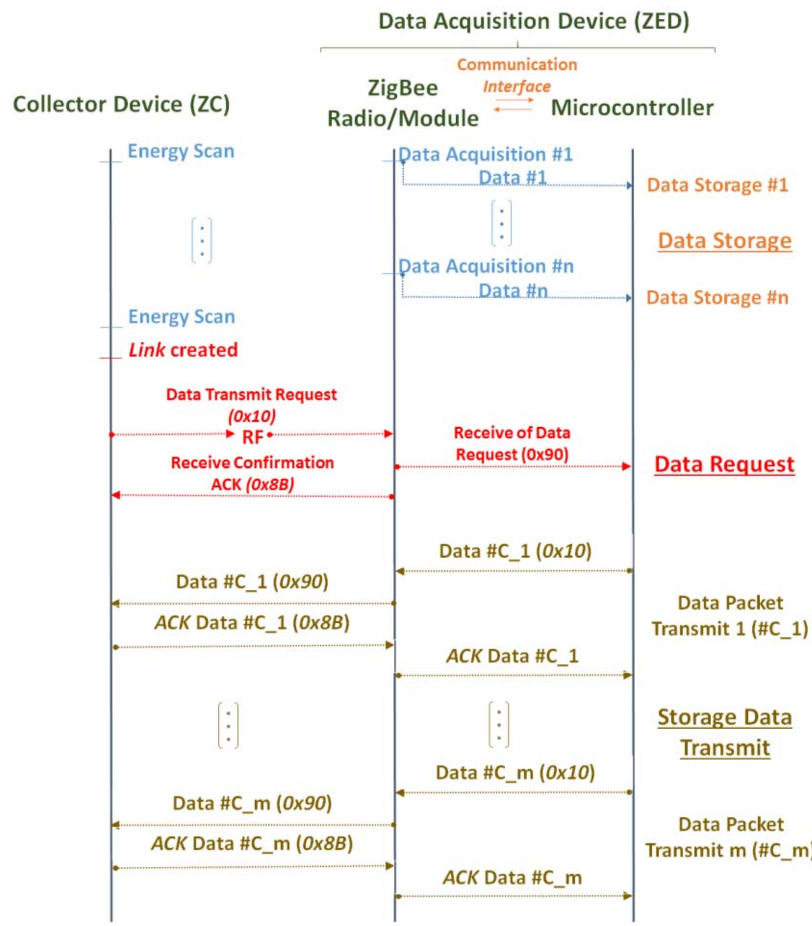

Fig. 3. Implementation guide: communication diagram of peer-to-peer WDSN.

ZigBee Receive Packet frame (0×90). All the transmission procedure is confirmed using Receive Confirmation or ACK frames (0×8B). The entire transmission uses standard ZigBee frames, which makes the implementation guide compatible to ZigBee devices.

The implementation guide also involves the configuration of the ZigBee network and ZED and ZC modules:

• PAN ID name and configuring the ZEDs to transmit data to the ZC;

• ZED setting of the sleep mode with polling request verification;

• ZED setting of data sampling period (user defined);

• Structuring of data storage (user defined);

V. Proof of Concept

A proof of concept is a demonstration of a method or idea with the purpose of verifying that certain concepts or theories have the potential for real-world application. This section focus on a realization of the ZigBee WDSN implementation guide using hardware and software solutions compatible to industrial applications in order to demonstrate the feasibility of the ZigBee protocol for WDSN. The purpose of this proof of concept is the experimental validation of the guide, proving that it can be used as a reference guide to assist new developments of ZigBee WDSN.

The proof of concept is based on a ZigBee WDSN in which the sink or collector device (ZC) has mobility in order to cover a route and to communicate (intermittently) with the ZEDs. When in communication coverage with the ZC, the ZEDs are able to transmit their measurement data in accordance with the communication diagram of the guide in Fig. 3.

For this ZigBee WDSN proof of concept, it was deployed a mobile collector device (ZC) and three sensor devices (ZEDs). The ZEDs used for the experimental validation consisted of ZigBee modules of the Digi International (XBee Series 2 PRO with whip antenna), and an Arduino UNO as microcontrolled structure as shown in Fig. 4. Temperature sensors were used to provide measurement test data.

The ZC in the ZigBee WDSN is a main component as it has all the network management functions and is required for network formation. In this experiment, the ZC is consisted by the same ZigBee module used in ZEDs, which performs the necessary functions to manage network and to communicate with the ZEDs. A PC (laptop) with a data acquisition system in LabVIEW was connected to the ZC, aiming to embed the required communication procedure for WDSN. The ZC was arranged in a vehicle as shown in Fig. 5 for mobility in such a way that it can perform a route in order to communicate with all ZEDs spatially distributed.

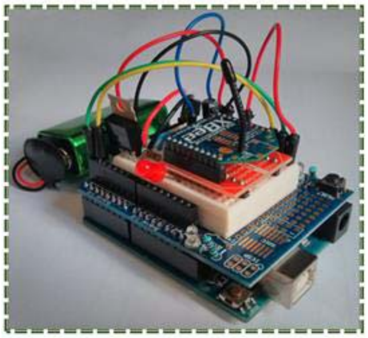

Fig. 4. ZED developed for the ZigBee WDSN proof of concept.

Fig. 5. ZC developed for the ZigBee WDSN proof of concept.

Fig. 6. Mobility route of the ZigBee WDSN experimental validation.

In the validation experiment, the developed ZEDs were distributed at three different points in the city of Sorocaba - SP – Brazil, remaining fixed in chosen points and collecting periodic temperature readings. The ZC device performs a route, of approximately 7 km, entering in the ZigBee coverage area of each ZED, intermittently. The Fig. 6 shows a possible route that the ZC device performed to get into communication with ZED devices.

When the ZC device enters the coverage area of any of the ZEDs, it verifies the network joining conditions. If these are okay, the ZC creates automatically a ZigBee communication link. Following the guide of Fig. 3, at this time the ZC may be able to transmit the request frame (polling request). In response, the ZED transmits one or more ZigBee frames with the acquired data. This frame is interpreted by the ZC supervisory system according to the specifications of ZigBee frames [18]. The ZigBee frame enables the monitoring system to identify the receipt of frames, the ZED sender and the data contained on it.

VI. Result Analysis

Among the great benefits of using ZigBee in WDSN, it can be cited the capabilities of energy management considering the device operation and intermittent communication, self-organizing of the network through automatically network formation and joining procedures according to nodes mobility, as well as the restructuring of data routes due to constant association, dissociation and re-association of the network components. In addition, the application is improved in terms of compatibility and robustness using a standard protocol such as ZigBee.

On the other hand, it was also observed certain limitations for the ZigBee use in specific applications of WDSNs. There is a limitation in the number of simultaneous permissible association (10 for ZigBee Coordinators and 12 for Routers), which constrains applications with agglomeration of devices (clusters). The required period (10s) for the devices input and output and route discovery may limit the ZigBee use in WDSN applications with high-speed mobility among the devices. Finally, the node independence was the only functional requisite not satisfied for ZigBee WDSNs, as the presence of the ZigBee Coordinator (ZC) is mandatory for network operation.

In order to fulfil a gap verified in the WDSN literature review, this paper presented an implementation guide for assisting the creation of ZigBee WDSN. This guide comprises the mandatory procedure without which the ZigBee protocol itself will not permit the intermittent communication among the devices as required by WSDN applications. An important verification is that only standard ZigBee messages are used on the communication procedure defined by the guide. The great benefit is that it enables using any ZigBee compatible device for WSDN applications.

The experimental proof of concept of a ZigBee WDSN, composed of fixed ZEDs at different points and a mobile ZC, enabled the validation of typical conditions foreseen for implementing a ZigBee WDSN, such as the mobility of devices and the permanence of devices without communication coverage for long periods. Further analysis and tests are necessary in order to relate the dependency between the mobility speed with the required period for network and route restructuring of the ZigBee protocol in WDSN applications.

Another result validated in the proof of concept, and a great benefit proposed by WDSNs, is the solution for the limitation of the coverage area of low power and low cost wireless communication networks such as ZigBee. The mobility of one or more nodes of the network can be seen as an extension of the coverage area of these WSNs.

As future work, the authors expect to implement comprehensive case studies in order to evaluate the ZigBee WDSN performance when using the implementation guide as well as to confront simulation and experimental results.

VII. Conclusion

The application of the ZigBee protocol in WDSNs brings a reasonable alternative to avoid the development of complex solutions and proprietary protocols for low cost and low power WDSN applications. The ZigBee protocol provides worldwide acceptance and devices interoperability, enhancing the potentials of this new feature of WSN with node mobility.

In general, it could be concluded that the ZigBee protocol is feasible and acceptably accomplishes the functional requirements for low cost and low power WDSNs applications. The feasibility analysis summarized and explained in details the most important points to consider as well as the advantages and limitations regarding the use of the ZigBee protocol for WDSN. Even though there are specific drawbacks, they do not unable the use of ZigBee for several applications of WDSN.

The major contribution of the paper is the implementation guide for using ZigBee devices in WSN applications with mobility of components on the network. The guide compiles and describes in details the required procedure of messages exchanging (communication sequence) between devices to enable the ZigBee use on WSDN with peer-to-peer communication (star topology).

A proof of concept allowed the experimental validation of the guide using hardware and software solutions compatible to industrial applications. It also proved that it could be used as a reference guide to assist new effective developments of ZigBee WDSN even though further performance analysis will have to be done for each application developed.

REFERENCES

[1] Q. Wang and I. Balasingham, “Wireless sensor networks—An introduction,” in *Wireless Sensor Networks: Application—Centric Design*, Y. K. Tan, Ed. Rijeka, Croatia: InTech, 2010, doi: 10.5772/13225.

[2] C. Buratti, A. Conti, D. Dardari, and R. Verdone, “An overview on wireless sensor networks technology and evolution,” *Sensors*, vol. 9, no. 9, pp. 6869–6896, Aug. 2009.

[3] M. Di Francesco, S. K. Das, and G. Anastasi, “Data collection in wireless sensor networks with mobile elements: A survey,” *ACM Trans. Sensor Netw.*, vol. 8, no. 1, p. 7, Aug. 2011.

[4] N. Vlajic, D. Stevanovic, and G. Spanogiannopoulos, “Strategies for improving performance of IEEE 802.15.4/ZigBee WSNs with path-constrained mobile sink(s),” *Comput. Commun.*, vol. 34, no. 6, pp. 743–757, May 2011.

[5] K. Park, H. Kim, and S. Lee, “Mobility state based routing method in vehicular ad-hoc network,” in *Proc. IEEE Int. Conf. Mobile Services (MS)*, Jun./Jul. 2015, pp. 473–474.

[6] M. Khelifi, I. Benyahia, S. Moussaoui, and F. Nait-Abdesselam, “An overview of localization algorithms in mobile wireless sensor networks,” in *Proc. Int. Conf. Protocol Eng. (ICPE) New Technol. Distrib. Syst. (NTDS)*, Jul. 2015, pp. 1–6.

[7] H. M. La, W. Sheng, and J. Chen, “Cooperative and active sensing in mobile sensor networks for scalar field mapping,” *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 45, no. 1, pp. 1–12, Jan. 2015.

[8] A. Singh, M. Kumar, R. Rishi, and D. K. Madan, “A relative study of MANET and VANET: Its applications, broadcasting approaches and challenging issues,” in *Proc. 1st Int. Conf. Adv. Netw. Commun.*, vol. 132, 2011, pp. 627–632.

[9] J. Valente, D. Sanz, A. Barrientos, J. del Cerro, Á. Ribeiro, and C. Rossi, “An air-ground wireless sensor network for crop monitoring,” *Sensors*, vol. 11, no. 6, pp. 6088–6108, Jun. 2011.

[10] R. Kaur and N. Sharma, “Dynamic node recovery for improved throughput in MANET,” in *Proc. 1st Int. Conf. Next Generat. Comput. Technol. (NGCT)*, Sep. 2015, pp. 325–330.

[11] E. Ekici, Y. Gu, and D. Bozdag, “Mobility-based communication in wireless sensor networks,” *IEEE Commun. Mag.*, vol. 44, no. 7, pp. 56–62, Jul. 2006.

[12] S. Gabriele and P. Di Giamberardino, “Mobile sensors networks under communication constraints,” *WSEAS Trans. Syst.*, vol. 7, no. 3, pp. 165–174, Mar. 2008.

[13] L.-J. Chen, T. Sun, and N.-C. Liang, “An evaluation study of mobility support in ZigBee networks,” *J. Signal Process. Syst.*, vol. 59, no. 1, pp. 111–122, Apr. 2010.

[14] A. Kaur, J. Kaur, and G. Singh, “Simulation and investigation of ZigBee sensor network with mobility support,” in *Proc. IEEE Int. Adv. Comput. Conf. (IACC)*, Feb. 2014, pp. 176–181.

[15] M. A. Ramteke and R. K. Krishna, “Realistic simulation for vehicular ad-hoc network using ZigBee technology,” *Int. J. Eng. Res. Technol.*, vol. 1, no. 10, pp. 1–5, Dec. 2012.

[16] E. S. Nadimi, R. N. Jørgensen, V. Blanes-Vidal, and S. Christensen, “Monitoring and classifying animal behavior using ZigBee-based mobile ad hoc wireless sensor networks and artificial neural networks,” *Comput. Electron. Agricult.*, vol. 82, pp. 44–54, Mar. 2012.

[17] A. Kumar and G. P. Hancke, “A ZigBee-based animal health monitoring system,” *IEEE Sensors J.*, vol. 15, no. 1, pp. 610–617, Jan. 2015.

[18] *ZigBee-2007 Specification Incorporating Errata Described in 11-53778-r13 and 12-0030-01; ZigBee Alliance*, document 53474r20, ZigBee, Sep. 2012, p. 622.

[19] *Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Network (WPANs)*, IEEE Standard 802.15.4, 2006.

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