Towards Mobility Support in Wireless Sensor Networks

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Abstract—Wireless sensor networks have been the subject of intensive research over the last few years. Nevertheless, although the concept is now well defined, network operability, integrity and reliability are not yet at desirable levels. This paper focuses on the most basic requirements for the massive application of wireless sensor networks to real problems and environments. In it we propose a set of mechanisms to turn sensor networks into an adaptable and flexible solution, capable to answer most application needs. These mechanisms support dynamic node and service discovery, optimized native IPv6 mobility and mobile nodes soft handoff. All of the proposed mechanisms were implemented and evaluated in a realistic test-bed.

Index Terms—6lowPAN, Mobility, Node and Service Discovery, Wireless Sensor Networks.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are not a novelty in the electronic or communication areas. These networks of small devices, with limited capabilities, wireless communication, sensors and conventional batteries have led researchers, academies and companies to devise countless application scenarios worldwide. From military to health, from environment to security, WSNs have been pointed out as the missing concept to link the real world to the virtual world.

For sure, WSNs are not the ultimate in technology. However, the real application of the WSN concept requires a profound research and development effort, followed by a thorough, non-trivial engineering process. On one hand, all the possibilities provided by such networks, made up of very simple low cost devices, make them very appealing. On the other hand, constraints such as energy and processing require the design of proper operational modes and communication protocols.

An intrinsic property of sensor nodes is portability. Considering that they have small size, low weight, battery supply and wireless communication capability, sensor nodes are easily deployed on mobile entities, thus creating the potential for Mobile Wireless Sensor Networks (MWSN). Based on this potential, a large number of application scenarios were designed.

For instance, in the healthcare area, patients’ monitoring is extremely important. Heart rate, breath rate, blood pressure and body temperature are common variables that must be constantly monitored. Using portable systems based on WSNs makes it possible to constantly monitor these and other vital signs without restraining the patients, in addition to providing a more efficient and user-friendly medical service.

Additionally, mobility in WSNs will be the key to allow the monitoring of workers within hazardous areas. This scenario is being explored in the European FP7 Project GINSENG, and is one of the real scenarios where the solutions proposed in this paper are being deployed. Some examples of hazardous areas are oil refineries, chemistry and petro-chemistry industries, among others. In such places, workers can be under perilous and/or potentially health threatening conditions. Hence, constant real time monitoring of workers is highly desirable, in terms of position, movement and life signs (e.g., heart rate, breath rate). With mobility support in WSNs, workers can do their normal tasks while they are ensured that if any abnormality is detected an alarm will be triggered in real time.

Apart from hazardous areas, most common within industrial environments, the military area also demands such monitoring. For instance, in battlefields, soldiers must be also under monitoring, controlling their vital signs in order to detect injuries as fast as possible. To support such scenario, WSNs can be deployed in military vehicles and soldiers.

In general, all the scenarios above require mobility support, as well as reliability and quality assurances.

Based on the specific properties of WSNs, the requirements of Mobility and the demand for critical applications, we propose a model for the support and deployment of mobility-aware wireless sensor networks. Our main goal is to provide an energy-aware node and service discovery mechanism, which, in turn, is the support for the handoff mechanism that provides efficient mobility of nodes among different sensor networks.

Mobility has been approached in WSN from different perspectives, including the Sink, the Node, the User and also the Information mobility. In this paper our main focus is the node mobility, which can be intra-mobility when the node moves within the same network domain or inter-mobility when the node moves between domains. Inter-mobility is the crucial situation and therefore the one on which we are focused.

The remainder of this paper is organized as follows: Section 2 presents related work on node discovery, service
discovery and mobility. Section 3 describes the proposed model, detailing the node and service discovery mechanism and presenting a MIPv6 adaptation model. Section 4 presents evaluation results, in terms of energy consumption, network lifetime, cost and reliability. Section 5 concludes the paper and outlines the future work.

II. RELATED WORK

A. Node and Service Discovery

Node and Service Discovery in lowPANs has been integrated in duty cycle schemes, where nodes, synchronized or not, exchange information with their neighbors. S-MAC[1] and wiseMAC[2] are interesting examples of mechanisms that use different duty cycles. X-MAC[3] and B-MAC[4] are the most used duty cycle protocols, being integrated with the most popular platforms.

Within IETF’s 6lowPAN WG, there are some interesting ideas to adapt the Neighbor Discovery protocol (ND) to WSNs. “Load adhoc routing”[5] defines a method called LOAD to provide route discovery, managing data structures and maintaining local connections. "Hierarchical-routing" [6] introduces the issue of dynamic address assignment for hierarchical routing and procedures to discovery and self-configuration. “LowPAN Neighbor Discovery Extension” [7] proposes optimization methods to Neighbor Discovery, minimizing the multicast of Router Solicitations and Advertisements, while [8] proposes the suppressing of the Neighbor Discovery Router Advertisements. This draft overcomes the unnecessary knowledge of the global address by the sensor node. Nodes should be configured with the previously defined anycast L2 address, which will be replaced when the node receives a Router Advertisement (RA).

In [9] a simple version of Neighbor Discovery Route-Over 6lowPAN Networks is described. It specifies a new mechanism that also includes the function of Duplicate Address Detection over entire 6lowPANs. It allows the use of stateless address assignment, Neighbor Discovery proxy (to allow the interoperability among all lowPANs) and optimization of Router Advertisements. This draft introduces the concept of a Router Edge (RE) per network.

B. Mobility

Due to the dynamic nature of lowPANs, some approaches to provide mobility support at the MAC layer have appeared.

The mobility-aware synchronized protocol (MS-MAC) [11] is an extension to S-MAC. This extension supports simultaneous stationary and mobile networks, and it is energy efficient. In MS-MAC, when a mobile node arrives at a stationary network, the surrounding nodes in the range area create an active zone where nodes wake up at shorter intervals. Those shorter intervals are useful to better monitor the movement of new neighbors. This extension was only tested by simulation and, as it is based on S-MAC, it suffers from the same inherent problems, such as the adaption needed in the active time to assure the reliability and also its dependency on the message transmission rate. MS-MAC defined a shorter period for S-MAC Neighbor Discovery Period (NDP) in the mobile nodes and increased the complexity of the nodes, introducing the link quality variable to detect movement. It also requires an extra listening time for neighbors, mainly for the boundary nodes, in order to detect mobile nodes. The drawback of this is the extra energy required.

Mobile Adaptive MAC (MAMAC) [12] gathers the best of two worlds: the synchronized and desynchronized MAC protocols. MAMAC proposes a simple mechanism where nodes, mobile or stationary, do not have a synchronized clock. Instead, each node wakes up at random points in time, sending always an acknowledgement beacon. When a node wants to transmit, it starts to listen until it receives the acknowledgement beacon of the destination. After that, the node starts the transmission. In terms of channel occupation, this protocol is efficient because each transmission only requires the ACK message and the data transmission, instead of the RTS and CTS used in S-MAC.

Recently another approach called Mobile Multimode Hybrid MAC protocol MH-MAC [13] has been proposed. MH-MAC aims to maintain the low energy requirements of asynchronous protocols and the high throughput of synchronous protocols, even when we are in the presence of mobile nodes.

Despite MAC Protocols capable to handle mobility, it is necessary to apply higher-level protocols to guarantee latencies and packet losses control.

At the IP level, some Internet Drafts have appeared in the 6lowPAN WG, defining the requirements for the support of mobility at the network layer. [14] is one of the latest drafts about mobility in 6lowPAN. It identifies mobility scenarios, main challenges and security issues. It also addresses the requirements of mobile networks, as defined in NEMO [15], an extension of Mobile IP, which considers the movement of entire networks.

From the MAC to IP level protocols, the support for mobility has not been seriously approached yet. Many protocols were introduced, but separately and incompatible between each other. For instance, MAC layer mobility protocols do not support 6lowPAN and therefore IP level mobility. To solve this problem we present in the next section our solution toward a complete mobility support.

III. PROPOSED MODEL

To support mobility in WSN, we need to combine a method for node discovery with a method for handoff management. The first is responsible for the integration of each mote in the network, including detecting whether or not the mote is within the network range. The second is triggered by the first and must assure smooth, fast and soft handoffs, within the same domain (intra-mobility) and between different domains (inter-mobility).

As mentioned before, IETF’s 6lowPAN WG has been working on an adaptation model for the original Neighbor Discovery. On the other hand, our research group has been studying alternative solutions and developed the model presented in this section. Section A presents the node and service discovery mechanism. Mobility support is presented in section B. Section C presents the approach used to adapt MIPv6 mechanisms to lowPANs. It is an extension of the proposal in section B, aiming at a completely standardized solution [16].

A. NoDiS

In the initial models of 6lowPAN, nodes were completely static, without any special feature inherited from IPv6.
Consequently, the first step of our work was to implement a node and service discovery mechanism.

Wireless communication is identified as the main reason for energy consumption [17] in WSNs. Thus, the number of transmitted messages, mainly broadcast messages, should be minimized. However, solutions based on broadcast messages are very common, e.g. when establishing a network, or for discovering nodes, access points and neighbors. In conventional wireless networks there are access points broadcasting announcements. In addition, protocols, such as the Neighbor Discovery protocol, periodically broadcast advertisements.

Having in mind the constraints of WSNs, we designed and studied three different approaches to provide node and services discovery [10]. Based on the results obtained in [10], a complete registration protocol was developed. The complete mechanism is called NoDiS (Node Discovery and Services) and it is an alternative to Neighbor Discovery in 6lowPANs and consequently to the periodic broadcast of Router Advertisements messages. Fig. 1 presents an overview of the complete protocol. The entire mechanism is currently implemented in our lab using ICMP messages.

When a new node is deployed, it broadcasts a Router Solicitation. Then, all sinks in the area answer with a Router Advertisement, and the node selects the best one to connect based on the Received Signal Strength Indication (RSSI) value. The selection is confirmed by a unicast ICMP ACCEPT message. After receiving the ACCEPT message, the Sink Node computes a Time-to-Live value. Then, it sends this value to the mote, which, in turn, confirms the procedure with an acknowledgement.

During the Registration procedure, the ACK ICMP message contains the list of supported services in the data field. The format is:

SERVICES <service1> <service2> … <serviceN>

While performing this procedure, the Sink Node saves all information in a local database, so that it can be made available to applications if needed.

In turn, when it receives the TTL value, the mote self-configures its IPv6 address with the network prefix of the Sink Node, sent in the IPv6 packets’ header. This means that we are forcing the use of global addresses based on Router Advertisements. This procedure does not require an additional message to announce it.

Once registered in a network, we must guarantee the connections even for high mobility motes. Next section approaches this point.

B. Mobility Support

As previously presented, mobility is crucial to apply WSN in the most critical and demanded environments. Mobile nodes should not be physical constrained and we must assume the possibility to occur not only intra-mobility, but also inter-mobility where motes must reboot the transceiver during the handoff process.

Our main goal is to control the communication during the handoff, including latencies and packet losses. To do so, we firstly need to provide a mechanism to detect on time if the mote is moving away or if it is arriving.

In order to detect movement, we performed a study based on the RSSI value, which is the link metric [21] provided by IEEE802.15.4. Our objective is to detect when the mote is moving by comparing the RSSI of the exchanged messages. In [18] we concluded that independently of the environment conditions and the achieved distance, the lowest acceptable RSSI value is -88dBm. After that point the connection is lost. Therefore, we defined this point as the rupture point, R-point. However, nodes must connect to another Sink before reaching that point, at a point that we call the critical point, C-point. Naturally, the difference between C and R – which we denote \( \Delta c \) – depends on the average time taken by the handoff process and on the rate of RSSI degradation experienced by the mote. If the sensor node is experiencing a decrease in RSSI of \( \epsilon_i \) dB during a time interval \( T \) and it takes an average \( t \) seconds to perform the handoff procedures, then:

\[
\Delta c = k \times t \times \epsilon_i / T
\]

Where \( k \) is a constant used to adjust the handoff policy. Naturally, \( \Delta c \) is always an estimation, as there is no way to determine future RSSI values. A conservative approach would use \( k > 1 \), and an optimistic approach would use \( k < 1 \). Based on the above formula, nodes, or any other responsible entity, can decide if and when to handoff, according to their movement.

Once detected that the mote is within the critical area \( \Delta c \), the handoff process must start. Following the same concept of 6lowPAN we aim to use the well-known MIPv6 to support this process, including the return routability procedure. However, MIPv6 was not developed for WSN and therefore some adaptations must be carried on.

Our first proposal includes a set of operation procedures for MIPv6 similar to the ones used in IPv6 for 6lowPANs, i.e. compressing, suppressing and coding fields of the original packets, in order to decrease each message size and therefore the energy and time required to send each one over IEEE802.15.4. The next section summarises our work on 6LowPAN and presents some concepts proposed in an Internet draft that we submitted to the IETF [16].

C. lowMIPv6 for 6lowPAN

MIPv6 is an extension of IPv6, constituted by a specific header, eight main messages and several mobility options. Each component has a specific format, considered too large for use in lowPANs. The original and the compressed header that we proposed are presented, respectively, in Fig. 2 and Fig. 3 [16].
We propose the compression of the 6 bytes MIPv6 header into just 1 byte. Payload Proto identifies the next header. Being equal to the original IPv6 header, we propose to compress this field in the same way that RFC 4944 [19] compressed it for 6lowPAN, reducing it to only 2 bits. Bit L represents the header length and can assume two values: 0 means that the length is obtained via the MAC Layer, and 1 means that it is carried in line. Since currently there are only 8 known types of mobility messages, we propose to reduce the MH Type field from 8 bits to 4 bits, allowing the maximum of 16 types. The last bit, C, signals if the checksum is carried in line or is included in the packet checksum.

The submitted draft [16] proposes a set of compression rules for all MIPv6 messages and mobility options. For instance, in order to analyze the real impact, let us consider the original Binding Update (BU) Message. Without considering mobility options, the original BU is composed of 6 bytes, plus 6 bytes of the Mobility Header, amounting to a total of 12 bytes. Our proposal reduced the BU from 6 bytes to 2 bytes, which means that with the 1-byte Compressed Mobility Header we get a BU with just 3 bytes.

Our proposal also includes advanced features, as the return routeability mechanism. To support that, the Mobile Node (MN) notifies both the Home Agent (HA) and the Correspondent Node (CN) about its new Care-of Address (CoA) during the handoff. This mechanism is composed of several mobility messages used to guarantee the integrity of the Mobility Binding Update.

Performed at the same time of the handoff process, the return routeability procedure starts with the Mobile Node sending a Home-Test Init (HoTI) to the CN via HA and a Care-of Test Init (CoTI) directly to the CN. When the CN receives both messages, HoTI and CoTI, it generates two keygen tokens based on a pre-generated key (random number of 20 octets) and a pre-generated nonce (random octet string with any length), namely: home keygentoken and care-of keygentoken, respectively. Then, via the same paths, the CN sends back the generated keygen tokens in Home Test (HoT) and Care-of Test (CoT) messages, respectively. When the MN receives both HoT and CoT, it computes a binding message key (bmK) to sign the Binding Update (BU) message that it then sends directly to the CN. Finally, the CN checks the signature, updates the Mobility Binding Table and sends back a Binding Acknowledgement (BA).

Our proposal, at this stage, does not intend to alter this procedure. However, as mentioned before, we proposed in [16] the compression of all mobility messages: HoTI, CoTI, HoT, CoT, BU and BA.

Accordinly, we propose in this paper the extension of NoDiS, with the handoff triggering method and therefore with the Return Routeability procedure, along with the proposed compressed messages: HoTIC, CoTIC, HoTC, CoTC, BUC and BAC. Fig. 4 illustrates the entire handoff process proposal.

### IV. PRACTICAL EVALUATION

#### A. NoDiS performance

In order to evaluate the NoDiS model, we implemented the node code in nesC for TinyOS-2.x, and included it in the 6lowPAN implementation [20]. The code for the Sink Node was implemented in C language running on Ubuntu-9.04. We used micaZ motes from Crossbow,Inc.

The first tests aimed at measuring the time necessary to register the mote in the best available network. 20 tests were performed and, for each one, the time since the node sent the Router Solicitation until the reception of the Acknowledge from the selected Sink was registered. TABLE 1 presents the results.

<table>
<thead>
<tr>
<th>N</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>time</td>
<td>20</td>
<td>0.60379</td>
<td>0.63172</td>
<td>0.62090</td>
</tr>
</tbody>
</table>

As it is possible to observe, the mean is approximately 620ms and the standard deviation approximately 6.9ms. These values mean that the registration procedure of NoDiS requires an acceptable time, taking about 620 ms for any deployed node to become integrated in the network, with a valid IPv6 address and the responsible Sink to save its services list.

Hence, if our micaZ mote takes an average of 620ms to perform the registration procedure, requires 22.6mA while sending and receiving messages, and considering a required voltage of 2.6V, the energy consumed by NoDiS during registration is 36.4312mJ.
Considering the same evaluation for the update method, we also measured and calculated the average of the required time. TABLE 2 presents the results of these tests.

<table>
<thead>
<tr>
<th>N</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.059794</td>
<td>0.064598</td>
<td>0.0626</td>
<td>0.001842</td>
</tr>
</tbody>
</table>

As it is possible to conclude, the three update messages required an average time of approximately 62.5 ms, which represents a spent of 3.6725mJ.

The total energy consumed by NoDiS per hour will depend on the TTL value, which determines the update frequency. Fig. 5 presents the results for different TTL values.

The smallest the TTL value, the highest the required energy. Usually, highly dynamic applications require shorter TTLs. Using the proposed mobility model, nodes become aware of network conditions and are not dependent on registration updates to select new and better sinks.

Comparing the energy required by NoDiS with the conventional solution, in which sinks periodically broadcast advertisements, we concluded that NoDiS is more efficient when \( t = \text{TTL} < 50 \), i.e., considering the most reasonable values. Fig. 6 shows the result of this practical evaluation.

According to the experiments, the time it takes since the node detects a bad connection until it connects to a new Sink and sends the Care-of Address, through the Binding Update, to the Home Agent, is approximately 2.106 seconds.

For handoff time this is a considerable long period, in which several packets might be lost. Therefore, even considering soft-handoff mechanisms, we must improve this value in the future.

### C. lowMIPv6 benefits

As presented before, MIPv6 defines a specific header format, several messages and additional mobility options. In [16] we proposed a model to compress, suppress and code some fields in order to reduce the MIPv6 message length.

Based on the example presented in this paper related to the compression of a Binding Update message, from 12 to 3 bytes, we analyze in this section the real impact in terms of energy consumption. To measure it, we used the same micaZ mote, requiring the same 22.6mA to transmit and the 2.6V of the circuitry. The time each message took to be sent was measured implementing a nesC module. In the compressed mode we considered that the length was inherited from the MAC Layer and the Checksum was calculated as part of the entire packet. TABLE 4 summarizes the results.
The difference of 9 bytes in the message length is visible at a millisecond scale. Although both ranges are slightly overlapping, the obtained average stresses the difference. Looking at the energy consumption, in just one message we saved about 0.23mJ as a result of the 9 bytes suppression. Considering that in the entire Return Routability procedure (Fig. 4) we proposed to save 62 bytes [16], we can conclude that in this process we are able to save, under the same conditions, 1.58mJ.

The total amount of energy saved with our proposal will be determinant for the lifetime extension of the entire network.

V. CONCLUSION

Nowadays, applications require that WSNs have dynamic features, including mobility support. Plug-and-play solutions are highly desirable in these environments, guaranteeing the efficiency of a reliable and self-adaptable network structure.

In this paper we proposed and evaluated a comprehensive set of mechanisms essential to assure the support of mobility in WSNs, composed of a) a dynamic energy-efficient mechanism for node and service discovery, b) a mechanism for soft handoff, based on the determination of the link quality, and c) an MIPv6 adaptation model for lowPANs.

All these proposals were studied on test-bed implementations, which also served as proof-of-concept. In addition, some of the proposed mechanisms are already deployed in critical scenarios, such as in intensive care units and in hazardous environments, the latter in the scope of the work of the IST FP7 GINSENG project.

Although the presented mechanisms will assure the required mobility support, we aim to improve them, in order to optimize the handoff time and therefore to control latencies and packet losses.

Future work comprises the evolution of the adaptation model for MIPv6, in line with the latest work of the 6lowPAN WG. Also, NoDiS will be further evaluated and possibly integrated in one of the solutions proposed in the scope of the 6lowPAN WG. Besides this, we are introducing a new concept of proxies to support the heavier procedures on behalf of motes. Those extra entities might bring some further benefits but will be only possible to deploy in controlled environments.

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