Context-aware Low-energy Wi-Fi Sensor Networks for e-Health

Luís Carvalho
Faculdade de Engenharia
da Universidade do Porto
mpt10011@fe.up.pt

Rui Campos
INESC TEC
rcampos@inescporto.pt

Manuel Ricardo
Faculdade de Engenharia
da Universidade do Porto &
INESC TEC
mricardo@inescporto.pt

***Abstract*— Typical sensor networks are formed by low-end, battery operated devices, which rely on low-energy communication technologies, such as Bluetooth, Zigbee and ANT+, due to their energy efficiency. On the other hand, sensor networks increasingly need to be connected to the Internet, which implies adaptations of the TCP/IP stack to fit such wireless technologies. These adaptations bring additional complexity and imply new hardware, thus deployments are cumbersome and sub-optimal. Conversely, Wi-Fi is ubiquitous, can be seamlessly integrated with TCP/IP, and is energy-efficient with the right configurations; yet, its usage is still uncommon in e-health scenarios.**

For these reasons, we argue that a TCP/IP over Wi-Fi approach should be followed in e-health sensor networks. We propose a novel cross-layer, context-aware network configuration mechanism, which monitors the user and networking contexts and optimizes the configuration of the TCP/IP protocol stack accordingly. Our approach enables seamless integration between e-health wireless sensor networks and the TCP/IP backbone, while improving energy efficiency and reliability.

***Index Terms*—Wireless sensor networks, Context awareness, IEEE 802.11, Energy efficiency**

I. Introduction

The recent demographic changes are shifting the health care paradigm towards home care, causing the proliferation of e-health [1] and m-health [2] sensor devices. On the other hand, the increased usage of these devices is changing the personal networking scope, leading to the creation of a *Personal Area Network* (PAN) around the user. Apart from proprietary solutions such as ANT and ANT+, Zigbee and other IEEE 802.15.4-based solutions as well as Bluetooth-based solutions have been traditionally considered to enable wireless sensor communications in e-health scenarios; among these, Zigbee and Bluetooth are the most common. Despite both having large efforts towards their standardization as transport layers for e-health applications, the established frameworks are transport-agnostic and IP-compatible [3]. Among the advantages of using IP are [4]: (1) the support of multiple wireless technologies underneath and a wide range of applications on top; (2) the easy development and deployment of sensor applications based on traditional TCP/IP protocols and TCP/IP application development methodologies; (3) the possibility to run the IP stack on resource-constrained, battery-operated devices; (4) the fact that IP is stable, ubiquitous, and open.

The wireless technologies currently used in sensor networks are designed with energy efficiency in mind and define small frame sizes, which implies the design of adaptation layers to make them compatible with the traditional TCP/IP stack [5]. These adaptation layers hinder the seamless integration with the TCP/IP stack, and require a gateway to interconnect the wireless sensor network with the Internet.

An alternative is to consider IEEE 802.11 (Wi-Fi) as the underlying wireless technology. Wi-Fi has two major advantages over IEEE 802.15.4 and Bluetooth. Firstly, it is natively compatible with the traditional TCP/IP protocol stack. Secondly, it is ubiquitous and a well-established technology, with increasing market share. The former enables easy sensor integration with existing IP networks and legacy IP devices. The latter offers major cost savings and faster deployments, as existing Wi-Fi infrastructures can be reused and IT personnel is already familiar with managing Wi-Fi networks. Finally, economy of scale is another important advantage of Wi-Fi with an expected 22% annual growth rate between 2010 and 2015 [6], which will contribute to reduced hardware costs. Thus, thanks to its deployment advantages, increasingly smaller module form factors and costs, and low-power operation, Wi-Fi is gaining momentum within the wireless sensor communications domain; we believe it will become a standard wireless technology for sensors too, overcoming the disadvantages associated to IP-over-IEEE 802.15.4 and IP-over-Bluetooth solutions.

One major disadvantage of Bluetooth, Zigbee, and Wi-Fi is the definition of static pre-defined configuration profiles to establish links between devices. In e-health scenarios, as the user moves, the networking environment will change, which means these configurations may need to be updated, so that the user can keep taking full advantage of his devices and optimal performance achieved. Yet, the state of the art configuration approach is rather static. Each node is pre-configured according to a set of rules, which remain mostly untouched, independently of changes in the networking environment. There are protocols that adapt to the changing network conditions [7], but they only take into account limited networking context (e.g., number of nodes, type of nodes, network topology), ignoring user context (location, status). We argue that by using additional context information, we can increase the energy efficiency of a Wireless Sensor Network (WSN), ensuring that each node uses the available resources adequately. For instance, in a given situation a particular sensor may be considered critical. This means we need to keep packet delay to a minimum and enable reliable communication, so that packets are not lost. On the other hand, in a non-critical situation, these restrictions may not apply, so we can skip the acknowledgments overhead (e.g., by switching to UDP). Even still, some scenarios may require guaranteed delivery, but accept high delay. All these different contexts imply a dynamic configuration of he TCP/IP protocol stack.

Our proposal is to address this problem by defining a novel context-aware, cross-layer mechanism for Low-energy Wi-Fi sensor networks, in order to enable energy-efficient and reliable communications. Our contribution is two-fold:

1) **A distributed cross-layer optimization mechanism** that optimizes the parameters in each layer of the TCP/IP stack in e-health sensor networks for a given context;
2) **A distributed context-aware configuration algorithm** for e-health sensor networks based on low power Wi-Fi that adapts the TCP/IP stack for each context.

This approach enables seamless integration with the ubiquitous Wi-Fi backbone, while improving energy efficiency and enabling reliable communications as needed.

II. State-of-the-Art

Wireless sensor networks are currently based on energy-efficient technologies, either proprietary (ANT, ANT+), or open standards-based (Zigbee, Bluetooth) [6], [8]. Zigbee and Bluetooth are of particular importance due to the current efforts in standardization of these technologies in healthcare solutions, with specific healthcare profiles defined. The Zigbee Healthcare Profile [9] and the Bluetooth Health Device Profile [10] have been considered by the ISO/IEEE 11073 Personal Health Data (PHD) working group [3] and the Continua Health Alliance [11] as possible transport layers for data exchange between healthcare sensors and a sink (e.g., mobile phone, laptop).

However, IEEE 11073 PHD WG defines a framework that enables transport-independent data transfer, and support for TCP/IP as the transport layer has already been considered in practice [12]. On the other hand, wireless sensor communications solutions increasingly consider IP-oriented communications on top of IEEE 802.15.4 and more recently on top of Bluetooth Low Energy too, towards the Internet of Things vision [13]. In order to support transmission of IP packets over IEEE 802.15.4 and Bluetooth Low Energy links a standard adaptation layer has been defined in IETF, named 6LoWPAN [5]. This adaptation layer copes with the limited 802.15.4 and Bluetooth frame sizes (128 bytes and 27 bytes, respectively), and significantly reduces TCP/IP overheads by employing two major techniques: fragmentation and header compression. Still, the definition of such adaptation layer introduces changes in the traditional TCP/IP protocol stack that preclude direct communication between 6LoWPAN sensors and any legacy TCP/IP device, besides the additional complexity incurred by packet fragmentation and header compression.

Given the drawbacks of a 6LoWPAN-oriented solution, a new paradigm is emerging which considers IEEE 802.11 for wireless sensor communications. It has been shown that with appropriate system design and usage models, Wi-Fi devices can operate in a power-efficient fashion, and achieve multi-year battery lifetimes [6], with a set of low-power Wi-Fi modules from multiple companies already available in the market. In addition, researchers have recently demonstrated the feasibility of low-power Wi-Fi technology to enable IP connectivity of battery-powered devices.

Energy-efficiency is a crucial aspect for battery-powered sensors and experimental analysis has shown that data communications are a major contributor for energy consumption when compared to data processing [14]. As such, a myriad of techniques and mechanisms have been proposed in the state of the art for wireless sensor communications, with the ultimate purpose of improving data communications energy efficiency. Still, most of these solutions either employ IEEE 802.15.4 as a basis or define yet another MAC protocol [15]. Also, they mostly consider duty cycling and data reduction techniques.

A different approach to increase energy efficiency is to use context-aware techniques to optimize resource usage. By using contextual information from the network and the user status, nodes can be tweaked to save energy, for instance, by reducing duty cycle of sensors [16], reducing frequency rate of unimportant or unused sensor nodes [17], or by employing context-aware QoS techniques [18]. While notable, these approaches are specific to the sensors the authors considered for their networks in [16]–[18] and require specific changes in the firmware of each particular sensor. Furthermore, the scope of context information used is limited to a fixed set of positions or mobility patterns from the user.

Instead of tweaking the algorithms and routines of sensors, one can tweak the networking protocols instead. One such approach is to optimize the MAC layer by recurring to cooperative relaying techniques. Although the main focus of such schemes is ad-hoc networks, these have also been applied in WSN scenarios [19]. In this case, by combining cooperative relaying with network coding schemes, the authors can increase the energy efficiency by 50%. However, in the e-health scenarios we are considering, there are less nodes and less spatial diversity, so these techniques would not be as effective. Focusing on health scenarios, in [20] the authors consider that different sensors have different relevance at each time instant, and the time slots of a TDMA-based MAC protocol are decreased for sensors with less relevance. This leads to and overall increase in efficiency, while increasing the reliability of the most important sensors, however, this scheme is limited in scope (only two scopes: emergency, normal). Furthermore, redefining the MAC layer can be cumbersome, as each node needs significant firmware changes and legacy nodes will not benefit from these gains. Conversely, in [21] a cross-layered architecture is proposed to configure the whole wireless communication stack in order to minimize redundancy and increase efficiency. However, only networking parameters are taken into account, ignoring user context.

There is currently no state of the art solution that combines Wi-Fi with a context-aware approach to optimize resource

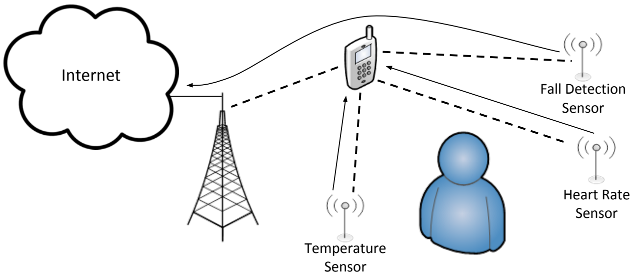

Fig. 1. Outdoor scenario. Some sensor nodes carried by the user connect directly to the smartphone; others connect to endpoints on the Internet.

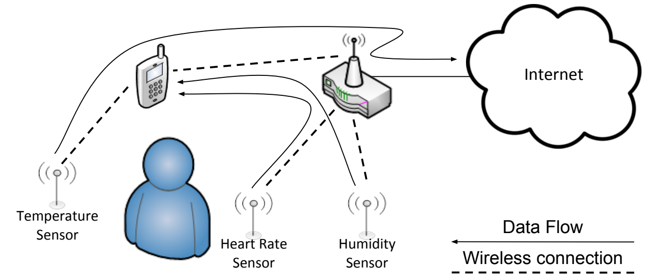

Fig. 2. Indoor scenario. Some sensors are distant from the smartphone, communicating through the gateway. Others still reach for the Internet.

usage in e-health sensor networks.

III. Use cases and Problem Statement

To better illustrate the problems addresses in this paper, Figures 1 and 2 depict two typical e-health scenarios, which we believe are both the most significant, as well as the most explicit and simple to understand.

Our main use case is that of a PAN composed of e-health wireless sensors, which the user takes with him. Furthermore, we consider the inclusion of static nodes, which are not carried by the user, but are a part of the environment he is in. We then consider two scenarios: user is outdoor, on the move (Figure 1); user is indoor, at home (Figure 2).

We consider the user to be carrying a smartphone or similar device with a high processing power and Internet access. The sensors are low-end devices, with little processing capabilities, and are assumed to be monitoring the user's vital signs (e.g., temperature, respiratory rate, cardiac output) and other environment variables (e.g., movement, location, fall detection). Some of the sensors send their data to an application running on the smartphone, which keeps track of his/her health, while others communicate directly with an online service, using the smartphone as an IP gateway to the Internet.

A. Outdoor Scenario

This scenario is simpler in terms of network topology. As the user is carrying the smartphone and the sensors, they are all within transmission distance, thus a star topology is formed, with the smartphone in the center, acting as an IP gateway.

Although simple in topology, this setup is more dynamic due to the user mobility. So, the network conditions, such as the interference levels, will change. Furthermore, as the user is moving, performing different activities and triggering different actions on the sensors, the traffic patterns generated may change as well.

Due to this dynamic environment, the state of the art static configuration approaches referred in Section II will yield sub-optimal performance.

B. Indoor Scenario

In the indoor scenario we consider that (1) the user may move the smartphone apart from some of the sensors, precluding direct communication between them, (2) there may be other, stationary sensors that are part of the network, and (3) the user has a Wi-Fi Access Point at home. These assumptions are consistent with (1) the habit of everyone not carrying their smartphone when at home, (2) the Internet of Things vision, and (3) Wi-Fi as a ubiquitous home network technology.

Sensors communicating with the smartphone may be placed out of its range, thus requiring some relay to reach its destination. This creates a multi-hop scenario and induces a more complex topology (multi-hop, potentially multi-technology), leading to a more complex configuration.

As a result of the IP-incompatibility of the state of the art e-health sensor networking approaches, these communications are required to pass through specific nodes (gateways). This makes them more restricted in terms of topology, thus hindering optimal energy efficiency and ease of deployment.

C. Problem Statement

In dynamic scenarios, sensors will have different network requirements. Sensors such as fall detectors and cardiac output monitors have stringent specifications; their data must reach its destination with minimal delay and high reliability. Less critical sensors such as temperature and movement will have more flexible requirements: there is no need for guaranteed delivery and a high delay can be tolerated.

The combination of these delay-tolerant characteristics with the specific traffic types and patterns of each sensor, and patient mobility patterns, results in nodes having different duty cycles that maximize energy efficiency; for instance, while the patient is moving sensors may buffer data and transmit a burst when the patient stops, in order to avoid transmissions over an unreliable link, leading to energy inefficiency.

Also, the choice of transport protocol has a big impact on energy efficiency. Considering the scenario of Figure 1, where source-sink communication is a one-hop direct link, we need to take into account that (1) TCP and 802.11 MAC may implement redundant functions in terms of reliable data communications and flow control, (2) TCP may be useful to complement the MAC functions in terms of reliability and congestion control, and (3) UDP may be preferred over TCP, since the latter introduces further signaling (e.g., acknowledgments, connection establishment) and processing overheads (e.g., congestion control algorithm, flow control algorithm).

As described in Section II, the current network configuration approaches do not properly solve the problem in these dynamic environments.

IV. Our Approach

Our approach relies on Wi-Fi as the underlying technology, and runs a full TCP/IP stack over it. In order to optimize resource usage, we employ a dynamic configuration mechanism that enables reliability as needed and optimizes energy savings according to context information. This mechanism relies on the Configuration Mechanism and the Context Manager, depicted in Figure 3. The Configuration Mechanism takes input from the Context Manager and applies a set of configurations to the nodes. For each scenario described in Section III, we determine the optimal values for the parameters at each protocol layer, such as maximum transmission power, frame size, retransmission timeouts, duty cycle, and link speed by taking into account the following aspects:

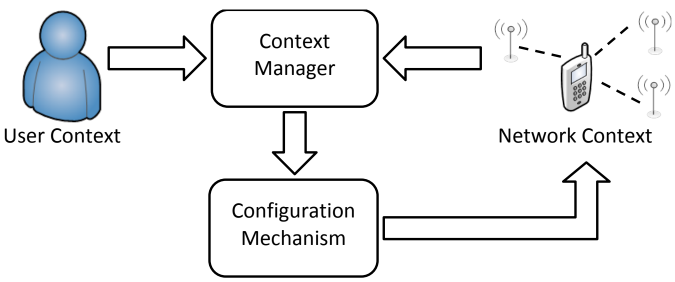

Fig. 3. System architecture. Context information from user status and networking environment is input to the Configuration Context, which computes the optimal settings and configures the TCP/IP stack accordingly. These settings, in turn, become part of the networking context.

- the dynamic environments wherein the sensors operate;
- the specific traffic types and traffic patterns;
- the communication distances involved;
- the type of sensor (wearable, in-home) involved;
- the reliability and delay requirements.

The optimization of these parameters may lead to significant reduction in energy consumption, since each sensor will (1) transmit just at enough power, (2) consider the frame size that maximizes MAC transmission efficiency and minimizes frame error ratio and frame retransmissions, (3) reduce the idle time between frame transmissions, and (4) select the transport layer that satisfies the reliability and delay requirements with minimum energy waste.

Other parameters could be taken into consideration and provide even better results. However, only those parameters that can be tuned and techniques that can be implemented using off-the-shelf low-power Wi-Fi modules are considered.

The Context Manager infers context information from network parameters, as well as from user behavior and status. From the network perspective, context is characterized by information readily available from the communication protocol stack, such as network topology (single/multi hop), connectivity, interference level, number and type of nodes, as well as information from the node itself, such as traffic patterns and link requirements. These parameters change with time and nodes adapt to them. For instance, in high interference situations, non-critical nodes queue packets and refrain from sending them in order to avoid wasting energy on retransmissions. On the other hand, nodes with crucial data switch to a reliable transport, in order to avoid packet loss, even though there will be redundancy with the MAC layer, and sub-optimal resource usage may take place.

User context is inferred by the behavior of the nodes as well as from the data they are collecting. We take into account information on user location (indoor, outdoor), movement (walking, stopped), and status (sensors collecting vital parameters can detect if the user is at rest or having a crisis). When at home, there are some static, trustworthy, nodes which can be used as packet relays, so we can configure multi-hop paths. When the user is outside, stopped, we can trust the environment to remain stable for a bit, so if interference levels are low, nodes take a chance to transmit queued packets to avoid wasteful retransmissions. In a critical situation, sensors are more stringent, thus will switch to a setting that can offer more reliability at the expense of energy efficiency.

By constantly monitoring these parameters and feeding them to the Configuration Mechanism described previously, we provide the nodes with the necessary resources to comply with their needs, while at the same time maximizing the lifetime of the battery-operated sensors.

V. Gains of the Proposed Approach

In order to estimate the gains of our approach, we detail how the choice of transport and MAC layers affects the performance of the network. Our scenario considers a single sensor connected to a server in a direct, one-hop, link. This sensor will periodically transmit a new measurement to its destination (for instance, it can be a measurement of body temperature). Typically, these will be small packets, with a few bytes for the measured values, a timestamp and possibly other signaling options.

For this body temperature example, we anticipate that relying on TCP for transport will involve high overhead. Figure 4 depicts the sequence of messages needed to transmit 1 data packet to the server, using TCP (left) and UDP (right). As

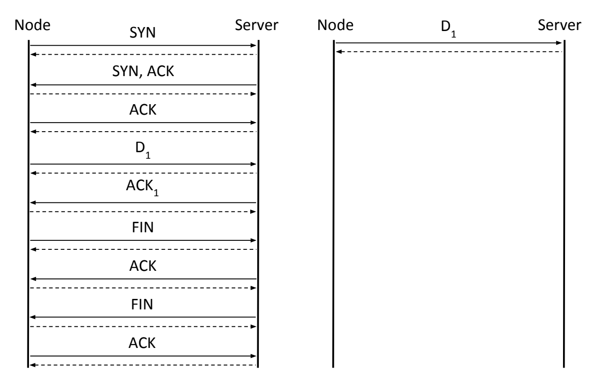

Fig. 4. TCP vs UDP sequence diagrams of 1 data packet being sent from a sensor to its endpoint. Connection establishment and termination steps incur additional overhead and the increased reliability might not always be necessary. The dashed lines represent MAC acknowledgment frames.

mentioned above, in a one-hop setting, the TCP and 802.11 MAC protocols will have redundant functionalities, such as acknowledgment packets, thus even if we need some degree of reliability, TCP might be unnecessary. In this situation, and assuming a worst-case scenario of 1 data packet being transmitted, we can expect UDP to send only 11% of the messages. This means that we can reduce the time the node has its radio on by an order of magnitude.

On the other hand, if we don't need any kind of reliability, we can switch to broadcast mode on the MAC layer, so that not even MAC-level acknowledgments are sent, further reducing the time our sensor needs to keep its radio on. Using this scheme, we reduced the number of frames exchanged from 18 to just 1: a 95% reduction. Of course this reduction comes at the cost of lower reliability, but that is why we use the Context Manager to know when we can enable these mechanisms.

VI. Discussion

From the scenarios presented and the analysis in Section V, we can highlight the following advantages in our approach:

- **Seamless integration with TCP/IP backbone.** There is no need to define new adaptation layers, as the sensor network is already running over TCP/IP;
- **Energy efficiency optimization.** By analyzing each scenario, we can make the most of the available resources in order to decrease the overall energy expenditure;
- **Context-aware dynamic configuration.** Real-time monitoring of context variables allows us to adapt the network to different conditions and requirements;
- **Compatibility with legacy devices.** Because we do not define our own MAC layer, we can integrate with legacy nodes and use our optimizations whenever possible.

As we are increasing the complexity of the system, the following disadvantages can be identified:

- **Computational overhead.** By forcing nodes to constantly monitor the environment to detect context changes, we are increasing the processing load of each node. However, we argue that the reduced time in transmitting/receiving packets will save more energy than that needed to perform the additional computations;
- **Configuration switching overhead.** There is an energy cost associated with the reconfiguration of a node (e.g., in terminating and starting connections), thus in highly dynamic scenarios where nodes are quickly switching settings, energy can be wasted in this process. Nevertheless, by defining hysteresis values, we can minimize this effect.
- **Important information loss in undefined contexts.** As we are dealing with health sensors, if a sensor is labeled as non-critical in a situation where it is critical, we could face unacceptable packet loss. To address this, sensor configurations will be performed conservatively, i.e., when in doubt, prefer reliability over energy efficiency.

Nonetheless, the advantages mentioned above, coupled with the gains estimated in Section V will be enough to outweigh these drawbacks, and result in greater energy efficiency and reliability as needed.

VII. Conclusion

In this paper we proposed the concept of TCP/IP over Wi-Fi for e-health IP-based sensor networks. This approach, coupled with our context-aware configuration mechanism is envisioned to enable energy-efficient, reliable e-health sensor networks.

The proposed approach still remains to be validated with real-world data. As future work we propose thorough simulations, benchmarking this approach against the solutions in the literature, and the development of a proof-of-concept prototype with off-the-shelf devices.

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