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On reliable communication in transmit-only networks for home automation

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ABSTRACT

Home-automation applications such as intelligent illumination, heating, and ventilation allow reducing the overall energy consumption and improve comfort in our everyday lives. To implement such applications, multiple sensors and actuators often need to be connected into networks typically communicating over radio signals, i.e., wireless sensor networks (WSNs). Many available technologies are based on bidirectional devices with the capability of acknowledging packets and performing retransmissions if necessary. However, home-automation devices mostly report data to a sink for which they do not need any feedback channel or external control, thus, unidirectional devices can be used instead reducing costs and energy consumption. On the other hand, since unidirectional nodes are unable to perform carrier sensing or acknowledge packets, the resulting networks are often unreliable. To overcome this problem, we propose a medium access control (MAC) that consists in making each transmit-only node send a sequence of redundant packets. The proposed method guarantees reliability, i.e., at least one packet of each sequence reaches its destination within a specified deadline by carefully selecting inter-packet times. In contrast to similar approaches from the literature, our MAC is based on a more general model that allows describing arbitrary deadlines and packet sizes for each node in the network and can accommodate considerably more nodes into a reliable network as the ratio between the longest and the shortest deadline increases. We illustrate these and other benefits of the proposed MAC by means of extensive simulations based on the OMNeT++ framework.

1. Introduction

There is an increasing interest in home automation with the aim of improving comfort and energy efficiency in modern homes. As illustrated in Fig. 1, applications such as heating, ventilation and air-conditioning (HVAC), appliance management, etc. are typical of this domain. To this end, embedded devices need to be interconnected, which puts emphasis on wireless sensor networks (WSNs), since communication has to be flexible, reliable and cost-effective at the same time.

Home-automation WSNs are normally based on bidirectional nodes that are capable of transmitting and receiving data. However, the focus recently shifted towards unidirectional (i.e., transmit-only) protocols, as these allow reducing the energy consumption by avoiding the high overhead of bidirectional MAC protocols and do not require to monitor the communication channel (Blaszczyszyn and Radunovic, 2008; Lin et al., 2016; Zhao et al., 2013). Another important aspect of unidirectional networks is the reduced complexity as sensor nodes forgo the receiver circuitry and, hence, can use smaller batteries, less powerful processors, etc. (Blaszczyszyn and Radunovic, 2008). This results in lower hardware costs, which is especially interesting for networks with high numbers of nodes. For example, a simple transmit-only light switch from HomeEasy,2017 costs around 10 euros, whereas the price of its bidirectional equivalent from Z-Wave,2017 is about 50 euros. Considering that home-automation networks typically contain 30–50 devices, using unidirectional nodes can result in considerable cost savings.

However, this comes at the cost of an increased unreliability, i.e., data is more likely to be lost; no carrier-sensing or synchronization is possible, hence, established solutions like CSMA (Carrier Sense Multiple Access) or TDMA (Time Division Multiple Access) are not applicable. To overcome this problem, most commercial available transmit-only systems send their data multiple times to increase the probability of a successful delivery. For example, HomeEasy nodes send up to 12 redundant copies of their packets upon activation depending on the type of node. However, no special care has been taken on choosing inter-packet times and packets are rather sent subsequently with a fixed separation not always leading to good results.

To overcome this problem, MAC techniques based on sending a sequence of redundant data packets have been proposed in the literature (Andersson et al., 2007a; Parsch et al., 2014). Neglecting external interference – home automation nodes are well shielded by

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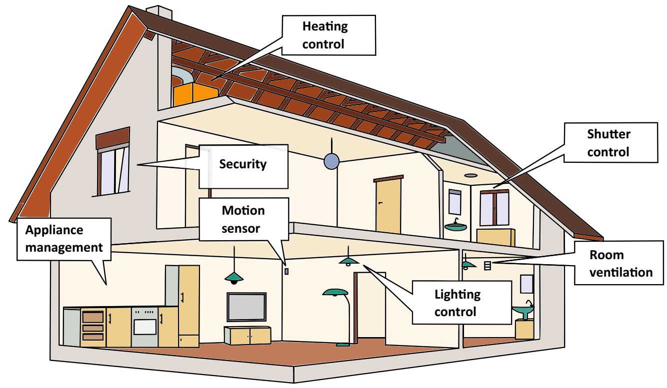

Fig. 1. Example of a home-automation network and its typical application areas: heating, ventilation, air-conditioning (HVAC), appliance control and security (Gomez and Paradells, 2010). More elaborate applications can further be realized. For example, lights can be automatically turned on at night when a user enters a room. Similarly, appliances, e.g., TV, radio, coffee machine, etc., can be switched off when a user leaves home, etc.

walls (Parsch et al., 2014) – these methods guarantee that at least one packet of each sequence reaches its destination within a specified deadline in the worst case. To this end, suitable inter-packet times need to be found for each transmit-only node in the network.

However, these methods from the literature make restrictive assumptions to reduce the complexity of the problem and are, hence, not suitable for a wide range of applications. In particular, the deadlines, by which at least one packet of each sequence must reach its destination, and the packet sizes, i.e., the amount of data bytes to transmit, are enforced to be the same for all nodes (Andersson et al., 2007a, 2007b; Parsch et al., 2014; Zhao et al., 2013). Further, nodes are either assumed to be activated once within a sufficiently long time interval such that all sequences of packets finish before the next activation of any node, or to implement a transmission pause – equal to the longest deadline in the system – after each sequence of packets (Andersson et al., 2007a, 2007b; Parsch et al., 2014).

These assumptions do not reflect the actual requirements of home-automation applications, since networks typically contain different types of nodes with varying packet sizes and/or deadlines requirements (Gomez and Paradells, 2010). For example, a light switch should turn on/off lights within 500 ms. Greater delays would negatively impact the quality of the system. In contrast, temperature sensors periodically transmit their data within a relatively long time interval in the order of minutes. In addition, temperature sensors usually require multiple data bytes, whereas light switches can encode their data within one byte.

The methods presented in Andersson et al. (2007a) and Parsch et al. (2014) consequently incur in great pessimism when adapted for heterogeneous networks. On the one hand, this results in increased communication delay and, on the other hand, there will be more packet collisions as the number of nodes increases. As a result, less nodes can be accommodated in the network for a specified deadline – more details follow in Section 5.

1.1. Contributions

In this paper, we propose a reliable MAC for unidirectional (i.e., transmit-only) home-automation WSNs. Our technique consists in making each transmit-only node send a sequence of k_i redundant packets with constant inter-packet times p_i. Neglecting external interference and carefully selecting k_i and p_i, the proposed technique guarantees *full* reliability, i.e., at least one packet of each sequence reaches its destination in the worst case.

In contrast to existing approaches from the literature (Andersson et al., 2007b; Parsch et al., 2014; Zhao et al., 2013), the proposed MAC is based on a more general model that allows for modeling arbitrary deadlines and packet sizes. It also eliminates the need for transmission pauses after a sequence of packets, which reduces the communication delay and therefore increases the maximum possible network size.

In addition, we analyze the effect of practical factors such as external interference and clock drift on our MAC. In practice, whereas clock drift has almost no effect on reliability, it is not possible to guarantee *full* reliability in the presence of a high external interference. However, our MAC still shows a robust behavior.

We finally analyze the effect of sending less than k_i redundant packets with the aim of reducing the protocol's overhead while still guaranteeing a desired reliability. This allows designing heterogeneous networks with mixed reliability levels and enables nodes to dynamically adapt their energy consumption depending on the type of data to transmit.

1.2. Structure of the paper

The rest of this paper is structured as follows. Related work is discussed in Section 2. Next, Section 3 explains our system model and assumptions. Section 4 introduces the proposed MAC technique for home-automation WSNs with transmit-only nodes. Section 5 presents our simulation results, while Section 6 studies the effect of practical factors such as external interference and clock drift on the proposed MAC. Section 7 concludes the paper.

2. Related work

There are many different approaches from the literature that are concerned in making WSN more reliable and energy-efficient. Most of them use bidirectional nodes that implement elaborate protocols such multi-hopping, automatic retransmission and routing of data packets. However, in scenarios, where simplicity and cost-efficiency are key factors, unidirectional communication has been used many times in the past: environmental monitoring (Lazarescu, 2013), body area networks (Keong et al., 2013; Santagati et al., 2015; Yi et al., 2015), Internet of Things (Han and Huang, 2017; Lazarescu, 2013) and RFID systems (Han and Huang, 2017).

The simplicity of unidirectional nodes, however, comes at the cost of increased unreliability; no carrier-sensing or synchronization is possible, hence, generated traffic is completely uncoordinated (Blaszczyszyn and Radunovic, 2008). As a consequence, established solutions like CSMA and TDMA cannot be used and special MAC protocols must be applied instead that do not rely on feedback from the sink node.

The two protocols presented in Blaszczyszyn and Radunovic (2008) and Radunovic et al. (2005) use a hybrid approach, i.e., they are composed of a high number of transmit-only nodes forming clusters for cost reduction and so-called *cluster heads* with reception capability. Cluster heads collect packets from their corresponding transmit-only clusters and forward them to receivers. Since they can acknowledge packets and perform carrier sensing, more sophisticated communication schemes can be implemented upon them. For example in Radunovic et al. (2005), cluster heads use a configurable receiver that only collects data packets complying with a pre-specified signal strength. By this, the strongest signal can be received at the event of a collision whereas otherwise it would be lost. However, if many cluster heads are used, costs and energy consumption increase rapidly. Moreover, these methods cannot provide any reliability guarantees and packets may potentially never reach their receivers due to collisions, in particular, within a transmit-only cluster.

Another hybrid approach presented in Zhao et al. (2013) also consists of two sensor node types: low-priority, transmit-only nodes (LP-nodes) and high-priority, bidirectional nodes (HP-nodes). Both node types are triggered periodically and transmit a number of redundant data packets with constant inter-packet times. These times