Reduced overhead for intra-cluster and inter-cluster sensor-to-actor communications in IEEE 802.15.4 networks

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Abstract: This paper proposes a novel way to enable sensor-to-actor communications in Wireless Sensor and Actor Networks (WSANs) that only requires a simple modification to the IEEE 802.15.4 header. Although this standard includes the definition of sensor-to-actor communication, it does not address how to provide it. Our proposal is able to provide this sensor-to-actor communication at the 802.15.4 MAC layer, thereby reducing the overhead of the additional network header, and achieving an important reduction of the energy consumption. In addition, avoiding the need of a network layer with full routing capabilities in the sensors provides further memory, processing and communications saving. More-over, this paper considers two scenarios for sensor-to-actor communications: intra-cluster and inter- cluster. The former enables the communication among sensors/actors at the same wireless sensor and actor network, and the latter allows sensors/actors located in geographically separated cluster to communicate transparently as if they were in the same WSAN.

Keywords: WSAN; wireless sensor and actor network; IEEE 802.15.4; energy efficiency; bandwidth saving; Zigbee.

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1 Introduction

Wireless Sensor and Actor Networks (WSANs) have attracted the interest of both the industry and the research community in the last decade. This interest has resulted in the development of several commercial solutions. The research community has dedicated much effort to study every layer of WSANs, ranging from physical to application layer (Huo et al., 2011; Hussain et al., 2012), and passing through MAC, network and transport layers (Akyildiz et al., 2002; Akkaya and Younis, 2002; Cuevas et al., 2011). One of the most important topics studied in all sensor-related papers is the energy consumption issue, which ultimately seeks to maximise the life of the sensors. In a wireless sensor, the most expensive task in terms of energy is powering the radio device to send and receive bytes (Mclntire, 2006; University of Korea, 2005), a lot more than actually gathering and processing the information at the sensor. Therefore, many solutions propose how to process, aggregate or fuse the data in order to send fewer and shorter messages, leading to significant energy savings.

The IEEE 802.15.4 standard (IEEE, 2006) defines two network topologies: the peer-to-peer and the star topology. In the latter one, all nodes are directly connected to the coordinator of the network, and communications are from the coordinator to the sensors (coordinator-to-sensor communications) or from a sensor to the coordinator (sensor-to-coordinator communications). In the peer-to-peer topology, the nodes can communicate with each other directly (sensor-to-actor or sensor-to-sensor communications)[1], as long as they are in range.

The 802.15.4 PHY/MAC standard only details the sensor-to-coordinator and coordinator-to-sensor scenarios. However, it does not specify how to perform sensor-to-actor communications at the link layer. This problem is usually solved by routing at the network layer. This is the case if a Zigbee/802.15.4 stack is employed for sensor-to-actor communication, where the Zigbee specification (Zigbee Alliance, 2005) provides the network and application levels of the WSAN. This stack is being developed by the Zigbee Alliance, and currently there are several Zigbee-compliant commercial products.

Sensor-to-actor communication is a topic that has widely attracted the attention of the research community since the second half of the last decade (Akyildiz and Kasimoglu, 2004). Also, the Zigbee Alliance is focused on this type of communications, it has defined several application public profiles where sensor-to-actor communication is required. For instance, the Zigbee home automation public profile includes the definition to turn on lights located in a device from switches located in other devices using the IEEE 802.15.4/Zigbee stack. Therefore, sensor-to-actor communication is attracting the attention from the research and industrial communities.

This paper presents a novel and simple mechanism to enable this sensor-to-actor communication at the link layer. Our solution only requires a slight modification to the 802.15.4 header, but it avoids the need of an upper network layer in star and cluster-tree topologies. This feature has many advantages, including an important overhead reduction (since the network header is no longer included in each frame), thus saving bandwidth and energy. It also reduces the complexity of the sensors because a network layer would require additional storage, memory and CPU in order to perform network management and, specially, routing and path discovery mechanisms (i.e., Ad hoc On-Demand Distance Vector (AODV) in Zigbee).

In a nutshell, our solution for star topologies employs the coordinator of the star-topology network to relay frames from one sensor to an actor in a similar way than an 802.11 access point manages the same task. For this purpose, we propose an extension to the addressing field of the 802.15.4 header in order to include an optional extra address field. Since the standard addressing field has already a variable length, this modification should have a minor impact in practice. In addition, we extend the solution proposed for star topologies to be used in cluster-tree topologies (a particular type of p2p topologies) by just using two extra bytes. This extension allows using the proposed solution in multi-hop networks organised as a cluster tree.

Furthermore, this simple modification to the 802.15.4 header allows us to address a second open issue in WSANs: the communication between sensors/actors located on different 802.15.4 WSANs (called clusters in the rest of the paper). Dealing with this issue could greatly increase the scope of current applications because sensors/actors will be able to communicate transparently across different clusters as if they were on the same WSAN. For this purpose, it is only necessary to interconnect enhanced IEEE 802.15.4 coordinators to each other to exchange inter-cluster frames. Since these 802.15.4 frames can be sent encapsulated, any available technology, such as WiFi, ethernet, UMTS, WiMAX, etc., could be employed for cluster interconnection. For simplicity, we will illustrate cluster-interconnection across the internet using the IP protocol to encapsulate these 802.15.4 frames, but if both clusters were close enough, they could be connected using a WiFi tunnel.

We have evaluated our solution in front of Zigbee to measure the improvement provided in terms of energy savings. This evaluation is based on real energy consumption values (University of Korea, 2005) from MICA motes and WINS nodes. The results show that by using a single AA battery our solution is able to send/receive 3% more messages than Zigbee in the worst case, and 40% in the best case.

Finally, we have implemented our solution for star topologies in a simple testbed, where PCs are used as gateways to interconnect two 802.15.4 clusters. A simple Java software running on the PCs takes care of the inter-cluster communication.

Therefore, the main contributions of this paper are:

- A mechanism that enables intra-cluster sensor-to-actor communications in 802.15.4 WSANs with star and cluster-tree topologies.
- A mechanism which enables inter-cluster communications between 802.15.4 clusters. That is, communications among geographically separated sensors/actors.
- Both mechanisms are compatible with the 802.15.4 standard, have a minimum energy impact i.e., only 2 (for star topologies) or 4 (for cluster-tree topologies) extra bytes are sent by the sensors/actors, and do not require that sensors/actors implement an additional network layer.
- This paper shows that our solution outperforms Zigbee in terms of energy efficiency.

The rest of the paper is organised as follows: Section 2 provides a brief overview of the 802.15.4 standard. Section 3 details the proposed solution. A performance evaluation of our solution for star topologies as compared to Zigbee as well as the testbed used to prove the suitability of the proposed solution is presented in Section 4. We show the performance of our solution in cluster-tree topologies and compare it to Zigbee in Section 5. Section 6 reviews some related work. Finally, we present concluding remarks and future work in Section 7.

2 IEEE 802.15.4 overview

The IEEE 802.15.4 standard (IEEE, 2006) defines the PHY/MAC layer for low-power personal area networks. This standard is very well suited for use in WSANs.

Two kinds of devices are defined in the standard: Full Function Devices (FFDs) and Reduced Function Devices (RFDs). The former have more capacity and are able to create a network by being the coordinator of that network. An FFD is also able to route messages if there is a network layer over the 802.15.4 MAC layer. RFDs (i.e., sensors/actors), on the other hand, are more limited and they can only communicate with FFDs. Therefore, the standard does not allow an RFD to communicate directly with other RFDs.

Also, two communication modes are defined: the beacon-enabled mode and the non-beacon enabled one. In the first mode, the coordinator sends beacon frames periodically, and the sensors (also referred as end-devices in this paper) are synchronised with this beacon. This allows them to be in an idle state most of the time and awake just in time to receive the beacon, i.e., to determine the coordinator has any frame for them, gather data and send it at the specified time. In the non-beacon mode, the coordinator does not send beacon frames, thus nodes require from external solutions to synchronise among them and be able to enter in idle mode.

Finally, the 802.15.4 standard defines two topologies: the peer-to-peer and the star one (see Figure 1), and three data communication scenarios:

- *EndDevice-to-coordinator*: In the beacon-enabled mode, the node transmits only after listening to the beacon, either in a reserved slot or using the CSMA-CA-defined mechanism. In the non-beacon mode, the end device sends the frame as soon as it is generated, using the defined CSMA-CA mechanisms. If an ACK is required by the end-device, the coordinator sends it back. Both procedures are shown in Figure 2.
- *Coordinator-to-EndDevice*: as shown in Figure 3, in both modes the end-device first requests the data from the coordinator, the coordinator acknowledges this request and then it sends the data frame, which is finally acknowledged by the end-device. The main difference between both modes is that, in the beacon-enabled mode the coordinator announces via the beacon which end-device it is storing frames for. In the non-beacon mode, the standard does not define how an end-device could determine if the coordinator is storing a frame for the end-device. The access to the shared medium during this process is arbitrated using the contention access mechanisms defined for each mode.
- *EndDevice-to-EndDevice*: The standard defines this type of communication but does not specify how it could be established. Therefore, it is left as an open issue to be resolved by upper layers.

Figure 1 IEEE 802.15.4 topologies (see online version for colours)

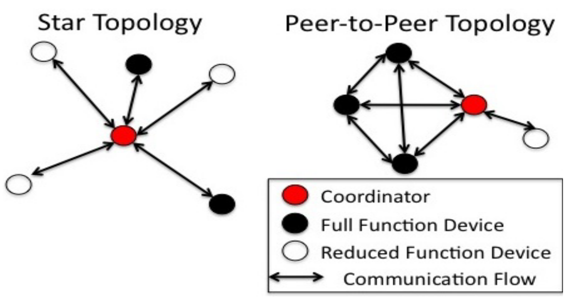


Figure 2 IEEE 802.15.4 data transmission from an end-Device to the coordinator: (a) beacon mode and (b) non-beacon mode (see online version for colours)

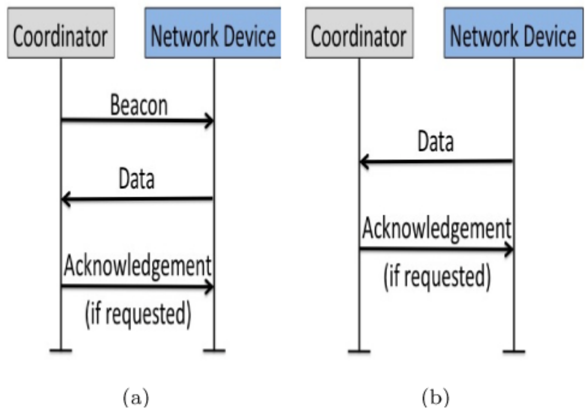
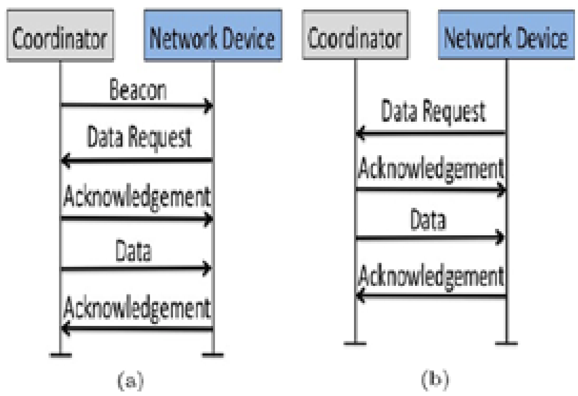


Figure 3 IEEE 802.15.4 data transmission from the coordinator to an end-device (see online version for colours)



3 Proposed solution

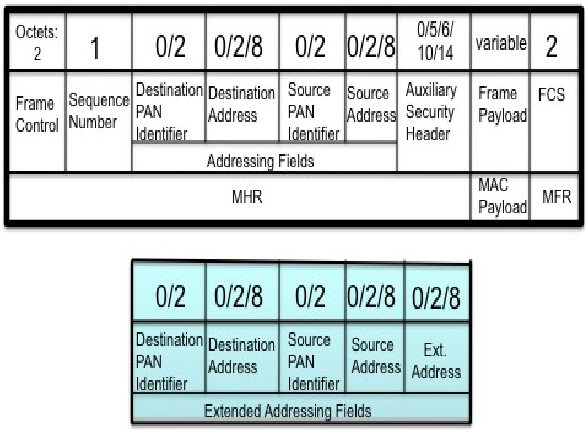
This paper proposes how to enable sensor-to-actor communication in two different scenarios: intra-cluster communication between sensors/actors in a single star or a cluster-tree topology and inter-cluster communication when the sensors/actors are located in different clusters. Our goal is to provide both types of communication by using only the mechanisms defined by the 802.15.4 standard, thus avoiding the need for an additional network layer.

The proposed solution does not modify any of the protocols or medium access mechanisms specified in 802.15.4 for sensor-to-coordinator and coordinator-to-sensor communication. In fact, it employs the coordinator (star topology) and some inter-mediate FFD (cluster-tree topology) to act as a relay of frames sent between sensors/actors.

3.1 802.15.4 header extension for star topology

Figure 4 shows the format of the 802.15.4 frame defined by the standard. The length of the addressing fields of the 802.15.4 header varies from 4 to 20 bytes and contains four fields: the destination personal area network identifier (DstPANID) and the source personal area network identifier (SrcPANID) are 2 bytes long each when they are used. The destination address (DstAddr) and source address (SrcAddr) could be either 2-byte short addresses, or 8-byte long addresses. Since sensors have severe energy and bandwidth constrains, short addresses are usually preferred over long ones.

Figure 4 IEEE 802.15.4 MAC frame and extended addressing fields (see online version for colours)



We propose to extend the addressing field by including an optional extra address field (ExtAddr) which contains a 2-byte short address or a 8-byte long address. The extended addressing fields are represented in Figure 4. This extra address is only needed for sensor-to-actor communication as it does contain the address of the sensor/actor node which is either the original source or the final destination of this frame.

In order to know whether an 802.15.4 frame contains the standard addressing fields or it also has an extra address field, one of the unused bits of the frame's control field (bits 7-9) could be defined for this purpose. Thus, when this ExtAddr flag is set to 1 this frame belongs to a sensor-to-actor communication and includes the extra address field. Otherwise, it is a standard 802.15.4 frame. Therefore, our solution is compatible with the standard. Furthermore, in case a routing layer is strictly required, we just need to set the specified flag to 0, and the routing layer will operate on top of the 802.15.4 native standard.

3.2 Intra-cluster sensor-to-actor communication in a star-topology

The IEEE 802.15.4 standard only specifies the sensor-to-coordinator and coordinator-to-sensor communication modes in star-topology networks. The sensor-to-actor communication is also defined. However, since no standard mechanism has been defined to enable it at the link layer, the only way left to provide it is by the peer-to-peer non-beacon transmission mechanism. However, this solution has two main drawbacks:

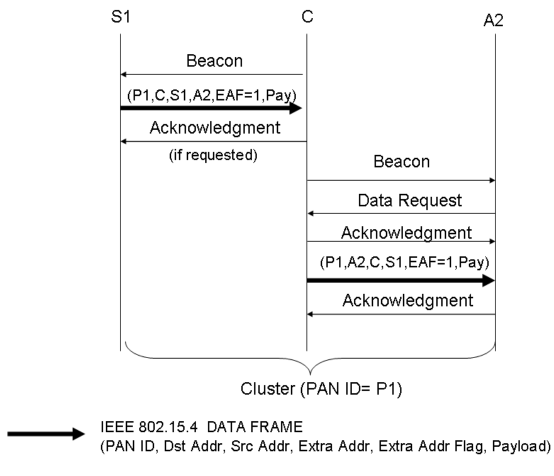
- it is energy-inefficient
- sensors must be in range.

Since there is no simple synchronisation mechanism for frame transmission/reception in this non-beacon peer-to-peer topology, this means that sensors cannot be in an idle state for too long as they could miss any frame sent to them during this idle period. Moreover, a sensor can only send a frame to another node that is inside its radio coverage. This means that a given sensor may not be able to communicate with all sensors/actors of its PAN.

Obviously these issues render this direct sensor-to-actor solution useless, or are at least quite limited. On the other hand, in our solution the coordinator acts as a relay of frames between sensors in a star topology, thus it does not suffer from any of the above problems. As the coordinator is the centre of the star, all sensors of the WSAN are able to send and receive frames from it, which means that any sensor is able to communicate with any other actor by employing the coordinator as a relay. Furthermore, the coordinator allows the PAN to employ the beacon-enabled mode, thus allowing the sensors/actors to be asleep for most of the time between beacons. The beacon frames are also employed to notify the destination actor that the coordinator has a relayed frame stored for it. The solution also works in non-beacon mode, even though this is less energy efficient since, due to the lack of beacon frames that synchronise sensors/actors, the coordinator must be awake most of the time in order to receive frames from sensors, and also every sensor/actor must periodically poll the coordinator to ask whether it has a frame stored for them.

A complete description of an intra-cluster sensor-to-sensor communication follows and it is also represented in Figure 5.

Figure 5 Intra-cluster sensor-to-actor communication



Let us suppose that a sensor with address S1 wants to send a frame to an actor with address A2, and that both of them are in the same star-topology network, although A2 is outside the radio coverage of S1. Therefore, the coordinator, with address C, must be employed as a relay. S1 begins the communication by sending the frame for A2 to the coordinator (after the next beacon or directly if in non-beacon mode). This frame has S1 as source address, C as destination address and the extra address contains A2 which is the final destination of this frame. When the coordinator receives a frame (and acknowledges it if required), it must check the ExtAddr flag to determine whether it is the final destination of the frame or it contains an extra address with the real destination. In the latter case, the coordinator stores all of these relayed frames, until the destination actors request them. When A2 requests the frame (either by periodic polling or after being notified by the last beacon frame), the coordinator forwards the frame to the destination node. This time, the source address is C, the destination address is A2, and the extra address is S1. Hence, when A2 receives this frame and checks the ExtAddr flag, it is able to know that this frame comes from S1 and that it has been relayed by C. Finally, A2 acknowledges the received frame to the coordinator.

All the steps of this communication have strictly followed the semantics and procedures of the 802.15.4 standard, including the appropriate SrcAddr and DstAddr values for each hop. In fact, without looking inside the header frame, we would not be able to tell whether this exchange of frames has been a sensor-to-actor communication between S1 and A2, or a sensor-to-coordinator communication between S1 and C followed by a coordinator-to-actor communication between C and A2. The only differences that expose this as a sensor-to-actor communication is the ExtAddr flag set to 1, and the addition of an extra address field.

Hence, this solution provides 802.15.4-compatible sensor-to-actor communications in star topology WSANs. This goal has been achieved by adding just 2 extra bytes to the header (or 8 bytes if long addresses are used). If Zigbee had been employed for the same purpose and even if no route discovery mechanism was used (i.e., by using hierarchical routing), exactly the same number and kind of messages would be employed, but the Zigbee network layer would add at least 8 bytes to each frame. Therefore, even when compared to the optimal case in Zigbee, our solution saves 8–2 = 6 bytes per data frame.

Finally, it must be highlighted that the proposed extra address is an optional field, to be used in any direct sensor/actor-to-coordinator or coordinator-to-sensor/actor communications (as opposed to Zigbee). This means that our solution is fully compatible with all communication modes specified in the current IEEE 802.15.4 standard.

3.3 Inter-cluster sensor-to-sensor communication

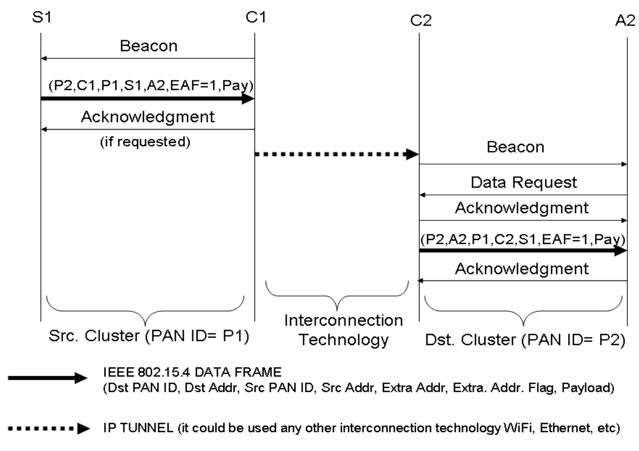
In this section the previous mechanism is extended in order to communicate sensors/actors located in geographically separated star-topology clusters. Again in this solution, sensors/actors only employ the 802.15.4 standard, and the inter-cluster communication is transparent for the sensors, because they maintain the same behaviour as in the intra-cluster case: sensors send their sensor-to-actor communication frames to their local coordinator, which in turn encapsulates and sends them to the coordinator of the destination cluster to complete the forwarding process.

Another useful property of our solution is that it is fully independent of the underlying technology employed for the coordinator interconnection. 802.15.4 frames could be encapsulated inside other ethernet, WiFi or WiMAX frames, or even employ a network protocol like IP, in order to connect WSANs across the internet.

Obviously, in an inter-cluster scenario, it is necessary to solve more issues than in an intra-cluster case. Perhaps the most important question to solve is how does a local coordinator know to which cluster a given sensor/actor belongs to? A possible solution could be to implement a dynamic address-learning mechanism into the coordinator, as ethernet switches do, and just broadcast the unknown frames to all remote clusters until a response arrives from one of them. While this is a simple and well-known mechanism, it should not be applied to this case because bidirectional traffic is required to obtain a good performance (which is not always the case in sensor networks). Moreover, sensor/actor addresses must be unique. We propose to use the PAN identifier fields of the standard 802.15.4 header to explicitly identify to which cluster the destination sensor belongs to.

To illustrate the intra-cluster scenario, a detailed description of the example in Figure 6 follows:

Figure 6 Inter-cluster sensor-to-actor communication



A sensor S1 belonging to the cluster with PANID P1, wants to send a frame to the actor A2, at the cluster with PANID P2. Therefore, as in the intra-cluster case, S1 just sends an 802.15.4 frame to its coordinator C1 with the following addressing fields: source address S1, source PANID P1, destination address C1, destination PANID P2 and A2 in the extra address field. When the C1 coordinator receives this frame, it knows that this is a sensor-to-actor communication frame because of the ExtAddr flag. Now it must decide whether this is an intra-cluster frame that should be relayed locally, or an inter-cluster one that must be sent to a remote coordinator. Since the DstPANID (P2) is different from the SrcPANID P1, the coordinator knows that the frame must be encapsulated and sent to the coordinator of the P2 cluster, in this case both coordinators exchange 802.15.4 frames through an IP tunnel. Thus, when the IP packet arrives at the remote coordinator, the 802.15.4 frame is decapsulated and stored until the remote actor A2 requests it. Finally coordinator C2 transmits the frame to the destination actor, but changes the addressing fields: source address C2, source PANID P1, destination address A2, destination PANID P2 and S1 in the extra address field. Therefore, S1 and A2 employ exactly the same mechanisms as in the intra-cluster scenario, and the only way to know that this is an inter-cluster communication is the use of the optional PANID fields.

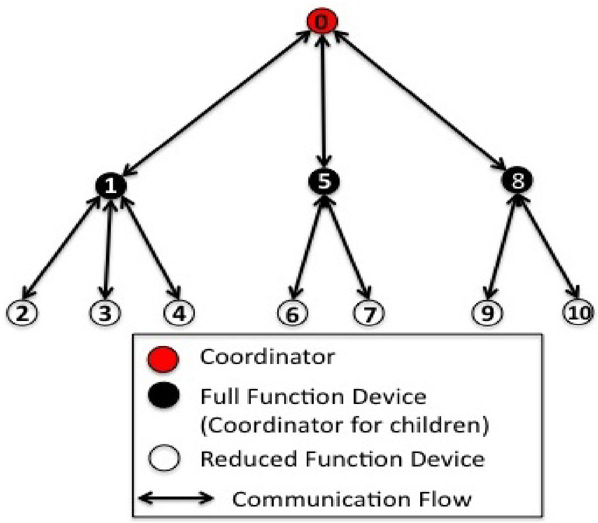
In order to simplify the description of the above example, some issues have been omitted but they should be discussed in more detail:

- How a sensor is able to obtain the DstPANID and the DstAddr of the destination actor in a remote cluster is not an 802.15.4 issue, thus it should be solved by the upper layers (e.g., the destination could be manually pre-configured at the application layer). Therefore, this issue is out of the scope of this paper.
- Due to the use of PANIDs, the cluster coordinators do not need to learn where each individual sensor/actor is, but they still need to know what the IP address of the coordinator associated with a given PANID is. There are many possible solutions to this problem, and choosing the best one mostly depends on the interconnection technology employed, and on the total number of clusters.
- The PANID mechanism allows sensors to keep using 2-byte short addresses for local communications because, even though there could be two sensors/actors with the same short address in different clusters, the inter-cluster address is formed by the concatenation of the PANID and the local address, thereby solving all the possible collisions of short addresses. However, this requires all PANIDs to be unique. Again, there are different approaches to solve this issue: a central DHCP-like entity assigning sequentially PANIDs to authorised coordinators, a random PANID creation plus a database of PANIDs in use, etc.

3.4 Adapting IEEE 802.15.4 header extension to cluster-tree topologies

Figure 7 shows an example of a cluster-tree network. In this topology a node just knows who are its parent and children in the network. Then, it uses its parent to forward upstream messages and is able to decide who is the right children to forward downstream messages towards a particular destination.[2] In this topology, parent nodes act as coordinators for their children, and thus the cluster-tree topology can be perceived as a set of hierarchical star topologies. For instance, Zigbee specification defines how to form a cluster-tree to-pology as one of its scenarios to realise multi-hop communication.

Figure 7 Cluster-tree topology (see online version for colours)



The current proposed solution for star topologies is not valid for cluster-tree ones, since it only allows identifying either the source or destination node of a message, but not both together (i.e., there is only one extra address field), which is required in the case of a cluster-tree topology. Then, in order to extend our solution to cluster-tree topologies, we just need to add an extra 2-byte address field. Figure 8 shows the IEEE 802.15.4 extended header to be used in cluster-tree to-pologies. In this case, we need two extra address fields: Src. Ext. address and Dst. Ext. address of 2 bytes (or 8 bytes in case of using long addresses) for each one. In order to differentiate which solution is being employed, we make use of another flag. This implies that we will have two flags: star flag (SF)[3] and cluster-tree flag (CTF). Then, we find three possibilities as combination of those flags:

- if SF = 0 and CTF = 0, the nodes will use the native 802.15.4 standard, thus being compliant with standard communication mechanisms such as rout-ing protocols.
- If a message includes SF = 1 and CTF = 0, it means only one extra address is being used, and thus the communication is happening in a star topology network.
- Finally, if the cluster-tree flag is active, i.e., SF = 0 and CTF = 1, the nodes will be using two extra address fields in a cluster-tree topology.

Figure 9 shows an example where node 2 in Figure 7 sends a message to node 10. For simplicity, we have avoided including IEEE 802.15.4 specific messages (e.g., beacon frame, acknowledgement, etc). As we have already denoted, intermediate nodes (e.g., nodes 1, 5 and 8 in the example) act as coordinators for their children using beacon frames (if required) to synchronise them.

Figure 8 IEEE 802.15.4 header extension for cluster-tree topology (see online version for colours)

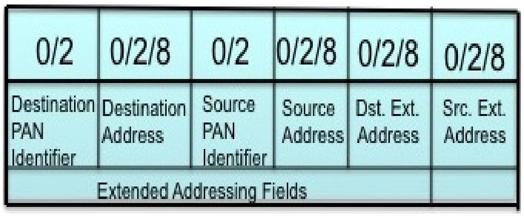
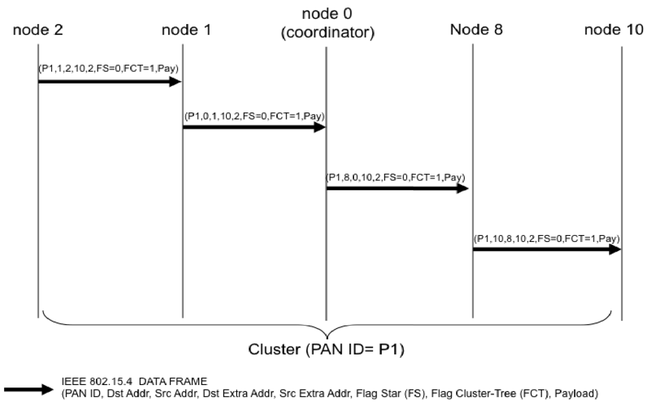


Figure 9 Communication from node 2 to node 10 in Figure 7 cluster-tree topology network



4 Performance evaluation for star topology

Our proposal enables several improvements in sensor-to-actor communications when compared to the current solutions based on the network layer for this kind of communication:

- It reduces the number of overhead bytes sent per data frame. To the best of our Knowledge, there are no WSANs routing protocols which define a routing header with only 2 bytes.
- It avoids the need for any path discovery mechanism used by many routing protocols (e.g., AODV in Zigbee) in order to establish a route from sender to destination for the simple, but commonly used, star topology. These mechanisms are usually very expensive in WSANs because they imply sending broadcast messages that are processed by all nodes within the network, and then forwarded by some of them.
- The use of a network layer implies memory costs (e.g., routing tables), processing costs for routing and network management tasks, etc., which are avoided if the proposed approach is used.
- When the sensor stack includes a network layer, it is used for all its communications. This means it must be also used for direct sensor-to-coordinator and coordinator-to-sensor communication, whereas our solution does not add any overhead to these communication types, and the 802.15.4 protocol could be used directly as defined in the standard.

The following subsections compare the proposed solution with the use of the Zigbee network layer. Zigbee offers two routing mechanisms: an AODV-like mechanism which is very costly since it uses broadcast messages to discover the routes, and a hierarchical routing in which any node forwards the message to its parent if the destination is not one among its descendants. In particular, the latter is the most suitable for star topologies, and so we will compare our solution with the hierarchical routing one. It must be highlighted that our solution would provide a much higher improvement if the AODV-like routing was used by Zigbee. A Zigbee network header is 8 bytes long. Therefore, our solution saves 6 bytes per data frame if it is used rather than Zigbee. This improvement has a direct impact on two important aspects: bandwidth and energy consumption.

4.1 Bandwidth evaluation

The maximum length of an 802.15.4 MAC frame is 127 bytes. Eleven of these bytes are part of the 802.15.4 MAC header (assuming short addresses and including source and destination PAN IDs). Also, there are 2 extra bytes at the end of the frame, the FCS (frame check sequence) field. Therefore, 13 out of 127 bytes are not payload bytes. Thus, the total header and FCS bytes length for sensor-to-actor communication only increases up to 15 bytes if our solution is employed. On the other hand, the sum of the Zigbee network and MAC headers plus the FCS field represents 21 bytes of overhead for every data frame. Moreover, our solution allows up to 112 bytes of frame payload, whereas Zigbee is limited to 106 bytes at most. However, it must be highlighted that sensors usually employ just few bytes to transmit their measurements.

Figure 10 shows the bandwidth saved by our solution as compared to using Zigbee as function of the frame length. Since our solution reduces the overall overhead, it is straightforward to see that the lower the frame length, the greater the bandwidth saved. Thus, the maximum bandwidth saved is over 25% for the shortest frame allowed in Zigbee (21 bytes), whereas the minimum saved bandwidth is almost 5% if the longest 802.15.4 frame (127 bytes) is sent.

4.2 Energy evaluation

There are some studies that have evaluated the energy consumed by a sensor for each transmitted/received bit. These values are highly dependent on the transmission power, the range, the bit error rate, the binary rate, etc. In Mclntire (2006), the energy cost per transmitted bit is briefly summarised as 979 nJ/bit when 802.15.4 is used. In University of Korea (2005), a cost of 710 nJ/bit for transmission and 110 nJ/bit in reception is defined for MICA motes. This work also specifies 6600 nJ/bit in transmission and 3300 nJ/bit in reception when WINS nodes are used. Taking these values into account, and considering that a standard AA battery provides 12,900 J (2400 mAxh, 1.5 Volts), we will evaluate the number of sensor-to-actor messages that can be sent and received using a single AA battery when using both, our solution and Zigbee, utilising as reference WINS and MICA nodes. We consider just the energy consumed by the source sensor in order to send the data frame and by the destination actor receiving it. Figure 11 shows the total number of messages that can be either sent or received using a single AA battery,[4] represented in front of the 802.15.4 frame size, taking into account that the frame size is 6 bytes shorter when using the proposed solution than Zigbee. Figure 11(a) shows the results when WINS nodes are used while Figure 11(b) does the same for MICA motes.

Figure 10 Percentage of bandwidth saving applying 802.15.4 header extension instead of Zigbee (see online version for colours)

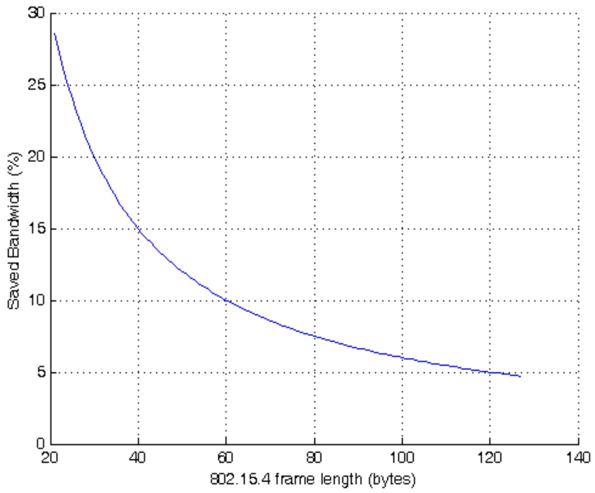


Table 1 summarises the results showing the number of extra messages, expressed in millions, generated using our solution instead of Zigbee, when all the AA battery energy is used either for transmission or reception. This table shows the values for the shortest frame when the payload is 0 bytes (21 bytes for Zigbee,15 bytes for our solution), for a medium size frame (74 bytes for Zigbee, 68 bytes for the proposed solution) and for the longest frame (127 bytes for Zigbee that is compared with 121 bytes for our solution).

Our proposal clearly outperforms Zigbee, since in the best case our solution is able to receive 279 million messages more than Zigbee for MICA motes and 4.6 million for WINS nodes. Even in the worst case, the proposed solution outperforms Zigbee by receiving 5.7 million extra data frames of maximum length in MICA motes and almost 200 thousand in WINS nodes.

Table 1 Number of extra messages (in millions) when IEEE 802.15.4 header extension is used in a star topology instead of Zigbee

	Shortest frame (21B)	*Medium size frame (74B)*	*Longest frame (127B)*
MICA tx	43.2596	2.7861	0.8868
MICA rx	279.2208	17.9829	5.7236
WINS tx	4.6537	0.2997	0.0954
WINS rx	9.3074	0.5994	0.1908

Looking at the results for transmission, when MICA motes are used, our solution allows to send more than 43 million messages than Zigbee when the payload is 0, and 880 thousand for the longest 802.15.4 frame. On the other hand, the results using WINS nodes confirm the goodness of our solution since in the best case more than 4 extra million messages can be sent than when using Zigbee. In the worst case this quantity is reduced, but still almost 100 thousand extra frames are forwarded using the IEEE 802.15.4 extension in front of Zigbee.

4.3 Implementation

Our solution has been implemented using Jennic motes that include the IEEE 802.15.4 stack. However, since Jennic does not provide open source code (just an API to use all IEEE 802.15.4 functionalities), we had to implement our solution including the extension address field in the two first payload bytes. Our goal is to demonstrate the suitability of the proposed solution in commercial motes.

Jennic motes can only communicate with an external device using the serial port. Therefore, the interconnection between clusters was developed using two PCs that were running on Java program that sends/receives IEEE 802.15.4 frames to/from the coordinator using the serial port. That Java daemon also implemented the communication between clusters. The source PC receives the IEEE 802.15.4 frame from the coordinator in the source cluster and encapsulates it into an UDP/IP packet. The destination PC decapsulates the frame and sends it to the coordinator in the destination cluster via the serial port.

We ran a testbed with two clusters interconnected using two PCs through the internet. The source cluster has two end-points and one coordinator while the destination cluster has one end-point and one coordinator.

A light-switching application was used to check the testbed functionality. One mote in the source cluster generates an IEEE 802.15.4 frame when a user presses one button on the mote. Since the motes have two buttons, one of them generates an intra-cluster communication by sending a frame to the other mote located in the source cluster, and the other button generates an inter-cluster communication by sending a frame to the end-point located in the destination cluster. The destination motes turn on a light when the frame is received.

Using this testbed, we have validated that both inter-cluster and intra-cluster communication are possible by means of the proposed solution. The most important conclusion is that it was a very simple implementation that required very slight modifications.

4.4 Results summary

The proposed IEEE 802.15.4 header extension is valid for WSANs implementing a star topology. For those networks, we have demonstrated that our solution is more efficient than standard routing solutions like the one implemented by the Zigbee protocol stack. The improvement of our solution is inversely proportional to the size of the frame. That is, our solution achieves the best performance as compared to Zigbee for the shortest frame length (no payload), since in this case the overhead introduced by MAC+Routing layer has a major influence in the transmission/reception of the frame. On the other hand, when we use the longest frame (i.e., 127 bytes), our solution presents a lower benefit, but it is still better than Zigbee. Finally, we have implemented our proposal in commercial motes. This implementation is a proof of concept that demonstrates the suitability of our solution in real sensor/actor nodes.

5 Performance evaluation for cluster-tree topology

In this section we briefly evaluate the benefits of our solution when it is used under cluster-tree topologies. We remind that in this case, our solutions use 4 extra bytes (2 for Ext. Src. Addr and 2 for Ext. Dst. Addr). We repeat the methodology used in the previous section and compare our solution to Zigbee for MICA and WINS motes. We notice that since our solution in the cluster-tree topology uses 2 bytes more than in the star topology, we expect to obtain a slightly smaller benefit when comparing our solution to Zigbee.

Figure 12 shows the bandwidth saving that our solution offers for cluster-tree topologies when it is used instead of Zigbee. As it happened in the case of star topologies, the shorter the frame the larger is the improvement achieved by the IEEE 802.15.4 header extension approach. In particular, for the shortest frame, the saved bandwidth is around 19% and this value reduces until 3% for the longest IEEE 802.15.4 frame.

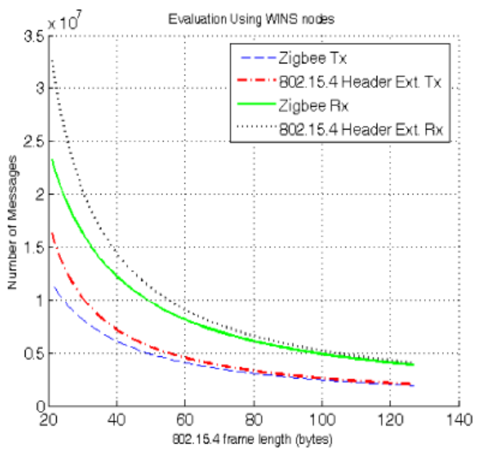
Table 2 shows the extra number of messages that can be transmitted or received by a MICA and a WINS mote when our solution substitutes Zigbee in cluster-tree topologies. Again the results show that the benefit of our solution is in-versely proportional to the frame size. In the worst case, i.e., WINS motes only transmit, our solution is able to send more than 60K extra messages as compared to Zigbee. Moreover, in the best possible scenario, i.e., a MICA mote only receives frames, our proposal receives more than 160 million messages as compared to Zigbee.

Table 2 Number of extra messages (in millions) when IEEE 802.15.4 header extension is used in a cluster-tree topology instead of Zigbee

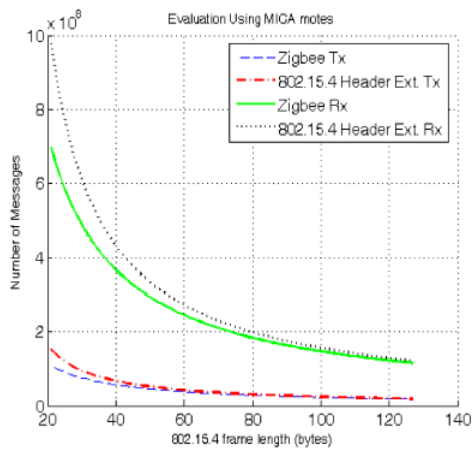
	Shortest frame (21B)	*Medium size frame (74B)*	*Longest frame (127B)*
MICA tx	25.4468	1.8036	0.5816
MICA rx	164.2475	11.6411	3.757
WINS tx	2.7375	0.1940	0.0626
WINS rx	5.4749	0.3880	0.1251

Therefore, as we expected, the improvement of our solution in the cluster-tree topology is a bit worse than for star topologies, but in both cases our solution presents much better performance when it is compared

Figure 11 Number of sent/received messages using Zigbee and 802.15.4 header extension with MICA and WINS motes: (a) WINS evaluation and (b) MICA evaluation (see online version for colours)



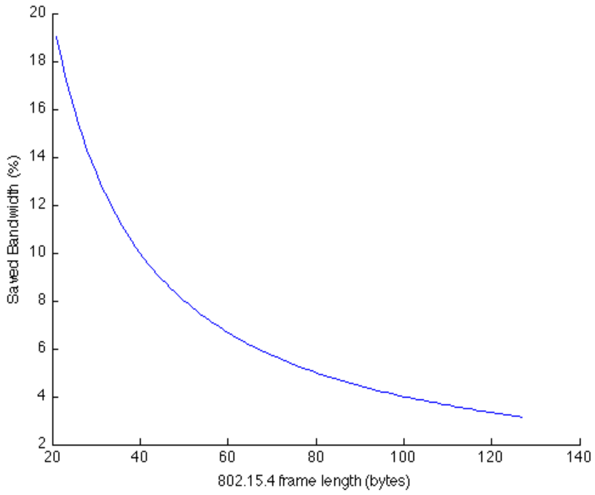
(a)



(b)

to Zigbee and by extension with traditional routing protocols.

Figure 12 Percentage of bandwidth saving applying IEEE 802.15.4 header extension in cluster tree topologies instead of Zigbee (see online version for colours)



6 Related work

We can find several recent work in the literature that model the performance of IEEE 802.15.4. For instance, authors in Ayoub (2012) try to predict the lifetime of an IEEE 802.15.4 WSN using an analysis of energy consumption. In addition, we can find an exhaustive evaluation of IEEE 802.15.4 standard for cyber physical systems in Xia et al. (2011). Finally, authors of Kumar and Tiwari (2011) evaluate the performance of three well-know routing protocols (i.e., AODV, DYMO and XMESH) in top of IEEE 802.15.4 networks using the beacon-enabled mode.

We can also find several work that discuss different IEEE 802.15.4 network topologies. In Bykowski et al. (2011) authors present a solution to select the right network topology for wireless body area networks. Authors in Martalo et al. (2011) try to find the optimal topology in IEEE 802.15.4 clustered networks. Finally, (Theoleyre and Darties, 2011) presents an analysis to optimise the capacity and minimise energy consumption in IEEE 802.15.4 cluster-tree topologies.

There are many work focused on connecting a WSAN with the external world by using middleware entities, but they do not consider the possibility of transparent sensor-to-actor inter-cluster communication. A previous work (Cuevas et al., 2007) proposes an approach similar to the inter-cluster communication, but using Zigbee as the interconnection layer. The advantage of that proposal is that it also allows multi-hop intra-cluster communication in mesh topologies. The drawback is that in the case of clusters using the common star topology, this solution is a lot more complex and implies more overhead than our proposal because in this simple case, an additional network layer in not really necessary.

Furthermore, there is a very interesting research line (Misic, 2006; Misic and Udayshankar, 2007; Misic and Fung, 2007) that studies how to interconnect two or more 802.15.4 clusters employing a shared node called bridge. A bridge could be a node that is in the coverage area of two coordinators (Misic, 2006; Misic and Udayshankar, 2007) (this schema is defined as slave-slave access mode) or a node that is a child of the main or sink coordinator, and coordinator of a cluster at the same time (Misic and Fung, 2007) (the authors call this master-slave access mode). A bridge in slave-slave mode is able to switch its radio on to listen and communicate with both coordinators, while in the master-slave mode the bridge listens to the sink coordinator and switches its radio on when necessary to manage its cluster. In both cases, the bridge is employed to relay messages from one cluster to another. Although this is a very interesting research line, it does not explain how the bridge is able to act as an 802.15.4 relay and capture frames that are not directed to itself. Therefore, the 802.15.4 header extension proposed in this paper could be also useful in order to explicitly send frames to these bridge nodes.

7 Conclusions and future work

This paper presents a novel approach to enable transparent intra-cluster and inter-cluster sensor-to-actor communication in 802.15.4 star and cluster-tree topology networks that are commonly used. Towards this end we propose a minor extension to the addressing field of the 802.15.4 header in order to add one extra address field (2 bytes) for star topologies and two extra address fields (4 bytes) for cluster-tree topologies. With this small change we are able to provide the sensor-to-actor communication model directly at the 802.15.4 link layer, without requiring an additional network layer. This leads to bandwidth, energy, processing, storage and memory savings, as it has been shown when comparing our solution to the Zigbee network layer. Finally, we present in this paper a testbed that implements both intra-cluster and inter-cluster communication.

In the near future we plan to use our testbed to obtain performance measurements.

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Notes

[1] In this paper we use sensor-to-sensor and sensor-to-actor communication indistinguishably referring to the same communication type.

[2] We assume that either addresses are statically assigned and thus each intermediate node knows the addresses of all its children, or there is a pre-defined and well-known mechanism to assign the addresses that allows each intermediate node knowing the addresses of all its children

[3] star flag was denoted as ExtAddr flag in the star topology case. We use a new name now for better readability

[4] For this evaluation we assume that the whole AA battery is exhausted by either sending or receiving messages.

Website

http://www.jennic.com