Abstract—A wireless network architecture is suggested to support the increasing demand of low-power, short-range ubiquitous, ad-hoc (self-configuring) communication for fixed, embedded or portable devices. It is envisaged that the proposed communication network architecture supports applications like wireless sensor networks and smart environments. We describe a network architecture and topology capable of integrating different wireless transmission technologies – suitable to support dense network of communication devices (nodes). The network is heterogeneous as nodes can have different wireless communication means, tailored to their individual role in the network and other constraints (e.g., power consumption), and thereby allow different communication patterns (e.g., bi-directional, uni-directional). To optimize power consumption and network latency, a new addressing mechanism at the MAC level is combined with a novel “always on” receiver architecture.

Keywords—wireless sensor networks; network architecture; addressing; medium access control

I. INTRODUCTION

Wireless sensor networks are a recent R&D topic in multiple fields: healthcare (patient monitoring), intelligent household, industry (e.g., production), military and other areas. A vital component in wireless sensor networks is a low-power, robust radio link, which must be able to operate with a power consumption of the order of miliwatts to ensure an acceptable lifetime (e.g., >1 year). Wireless sensor networks are in general very heterogeneous (e.g., many simple nodes, some complicated nodes) and may have a very sporadic communication pattern.

Current wireless sensor networks (both research systems like MIT’s or µAMPS [1], as well as commercial systems [2]) adapt conventional low power radio sub-systems (Bluetooth, IEEE802.11), or consider new standards like 802.15.4/ZigBee. All these solutions still require a substantial amount of energy for radio transmission and reception. Therefore, even if the traffic pattern is very sporadic, both units (receiver and transmitter) are turned on from time to time, need to be synchronized and finally exchange information (if there is any information to be exchanged). Typically the reception unit requires the same power (or even higher power) as the transmission unit; so even if no information needs to be received, substantial power is wasted just to be able to receive data. In order to save as much power as possible, complex duty cycle radio protocols are employed. However, duty cycling raises another two problems:

1. Information can only be exchanged during the ‘on’ time, therefore in typical duty cycle protocols (e.g., with 1% duty cycle the transceiver is switched on for 0.1s and turned inactive/off for 9.9s) messages may therefore need to be delayed substantially.

2. With such long radio inactivity times, synchronization between transmitter and receiver is not easily achieved and maintained in a distributed wireless sensor networks. A common solution is to use beacons, which are transmitted periodically from every node, and convey useful information like node address or listening pattern. However transmitting those beacons wastes a valuable amount of power.

Some alternative solutions can be found in the literature to solve this problem through new MAC protocols based on preamble sensing (WiseMAC) [3][4].

Furthermore, when conventional low power radio technology is used in a wireless sensors network, even the leaf nodes (which maybe deployed massively and hence it is desirable to use low hardware cost) use the same kind of radio technology as the aggregator or sink nodes. In this sense, unbalanced radio complexity solutions, where the radio complexity is moved to these last node types as much as possible, are more suitable. In the wireless sensor network presented in this paper we have reduced the power consumption by tackling all aspects mentioned above. The outcome is a novel network architecture combining different types of nodes, which implement various communication units by using different radio technologies. This new network architecture is presented in the following sections.

II. RADIO TECHNOLOGIES

A. Modulated backscatter

A suitable radio technology for ultimate simple wireless sensor applications is the ‘modulated backscatter’ (MBS) technology. A backscatter device absorbs or reflects RF radiation by switching its antenna impedance between the matching value (for absorption) and open (for reflection). When this switching is controlled by a modulating signal, the backscattered signal is called “Modulated Backscatter”.

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A simple backscatter system consists of a RF CW (Continuous Wave) source, a receiver, and the backscatter device. The source is continuously radiating RF energy at a predefined frequency. The backscatter device influences the electromagnetic field by absorbing or reflecting the electromagnetic radiation according to the modulation signal that controls the switch. The observed effect at the receiver is a change in the CW signal amplitude according to the modulating signal. The received modulated carrier is demodulated to gather the information from the backscatter device. The backscatter device can be passive (it gets the energy from the incident wave), semi-passive (it has its own energy storage for operation and antenna switching but there is no conversion gain added to the incident wave) or active (a positive conversion gain is added). The simple nodes in our system are semi-passive nodes operating at 2.45GHz. The maximum communication distance from the simple nodes is up to 5m and the data rate is in excess of 100kb/s.

B. “Always-on” receiver

To solve the synchronisation problem between wireless nodes, our network utilizes a radio link to remotely activate the destination node, which in turn will activate the data reception (‘always-on’ receiver network architecture). The RF wake-up receiver unit designed for this propose is an essential means to allow communication based on this “always-on” concept. The basic idea behind this unit had been already proposed by Rabaey in [5].

The RF wake-up circuit is “on” all the time and therefore its power consumption is very crucial. In order to have a low power consumption, a bias-free diode detector is used followed by a low power filter and tone detector. Furthermore the maximum frequency or bandwidth of the wake-up signal is limited to several kHz to reduce the probability of signals from other wireless systems causing false wake-up events. The Fig. 1 shows the architecture of this unit which works in two phases:

1. The activation sequence starts with a very narrow band wake-up signal called whistle tone, which is passed through a narrowband filter centered at 2 KHz. The output of this filter feeds a digital circuit (tone detector), which checks the frequency and duration of the received signal. If they match with the expected values, the tone detector commutes the switch at the input and prepares the unit for the reception second phase.

2. For a successful unit activation a valid ID sequence must follow the whistle tone. For the ID sequence we use FSK modulation with two tones at 8 and 12 KHz as it is shown in Fig. 1. The digital ID detector after the wideband filter compares the received ID with three values stored in memory: the unicast ID, and the multicast and broadcast IDs. If they match the ID detector switches on the modules needed for the data communication, which in fact can use any kind of radio technology like standard RF or the already mentioned modulated backscatter.

With this design is it possible to achieve power consumption values for the first stage of the wake-up unit (diode detector and narrowband filter) which are lower than a standard alkaline battery leakage power. In our implementation with discrete components we measured 12µA, but values around 4µA are possible in a more integrated solution. For the ID detection phase the measured current was in the range of 100µA.

When one node wants to activate a remote node it sends first a 2KHz tone for about 16ms, followed by a silence gap of 4ms and an ID sequence of 20 bits (2 bits preamble, 10 bits ID and 8 bits CRC), which takes another 10ms (Fig. 2). The destination node’s ID is known in advance at the transmitter node by the new addressing mechanism explained in section IV.B. If the node with the transmitted ID is within the transmitter’s range, it will now be ready for the data communication phase.

III. NETWORK ARCHITECTURE

A. Node types

In the proposed wireless network, the nodes are characterized by their role within the network, their communication capabilities and the employed/supported wireless communication technologies. There are three different types of nodes, namely PU (Polling Unit), SA (Simple Active) and SP (Simple Passive) nodes. A short description of each node, the communication units they integrate, and their graphical representation are provided in Table I.

B. Communication units

The nodes are different in hardware resources (CPU speed, memory size etc.), power consumption constrains and, as indicated in Table I, in the communication units they integrate:
A transmission unit capable of transmission is a radio transmitter capable of sending a radio signal. One of the types of transmission units is a passive receiver which is tuned to receive signals. This communication unit allows different types of communication based on the type of node it is connected to.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Com. Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PU</td>
<td>Polling Unit</td>
<td>Active Tx, Active Rx, Ether Provider, WU-Whistle</td>
<td>A PU can send and receive data by its own. It can demodulate backscattered signals coming from a simple passive node (SP), and signals from active transmitters in others PU or SA nodes. It can use its active transmitter to provide the electromagnetic field necessary for the MBS communication (PU is acting as Ether Provider). With the Wake-Up Whistle unit it can wake-up any device with a Wake-Up Listener unit within its range.</td>
</tr>
<tr>
<td>SP</td>
<td>Simple Passive node</td>
<td>Passive Tx, Passive Rx, WU-Launcher</td>
<td>It has a passive transmitter (MBS) and a passive receiver (diode detector). It uses backscattered technology to receive and then reflected back to the PU. As the Wake-Up Listener unit is active all the time, it can be awakened by any device with a Wake-Up Whistle unit if the SP is within its range.</td>
</tr>
<tr>
<td>SA</td>
<td>Simple Active node</td>
<td>Active Tx, Active Rx, WU-Launcher</td>
<td>A SA node includes an active transmitter, a passive receiver (diode detector) and a passive transmitter (MBS). It can transmit data either actively or using backscattering technology.</td>
</tr>
</tbody>
</table>

- **Active transmitter**: transmission unit capable of transmitting a modulated radio signal by its own.
- **Passive transmitter**: transmission unit not capable of transmitting a radio signal by its own. It can only modulate and reflect external radio signals using modulated backscatter technology (MBS).
- **Passive receiver**: reception unit based on a diode detector. It is a very low power consumption but also low sensitivity receiver.
- **Active receiver**: reception unit with high sensitivity that can demodulate backscattered signals as well as any transmission from an active transmitter.
- **Wake-Up Whistle**: a radio transmitter capable of sending a wake-up signal to the nodes in its vicinity. This signal is received by a passive receiver (Wake-Up Listener).
- **Wake-Up Listener**: a passive receiver which is tuned and capable of receiving/identifying wake-up whistle signals.

### C. Link capabilities

The combination of different node types and communication units allows different types of communication links:

- **Active-to-Active (A2A)**. The first communication technique is the standard active wireless communication where the source is using an active transmitter and the destination is using an active receiver. The symbol used for this link is shown in Table II. Since a PU node is the only device integrating an active receiver, a PU must always be at the reception side of an A2A communication scenario, but the transmitter can be either another PU or a SA.

- **Active-to-Passive (A2P)**. This communication technique is used to activate and send management or configuration information to nodes operating a passive receiver (SP or SA). A passive receiver is based on an analogue diode detector that, since it consumes very low power, can be active (listening) all the time, while the digital parts of the receiver are inactive. Therefore, nodes with a passive receiver can be remotely activated by nodes with an active transmitter. The symbol used for this link is shown in Table II.

- **Modulated Backscattered link (MBS)**. One of the unique network features is the use of backscatter technology to transmit information. Devices with a passive transmitter (SP and SA) can modulate, with the data they want to transmit, and reflect (backscatter) an electromagnetic field (Ether) received in its antenna. Since the reflected signal is very weak, an active receiver is necessary to demodulate it. A PU node is the only device capable to generate the Ether and also the only implementing an active receiver, so at least one PU must be always part of an MBS communication. The process of reading a SP device is done in two phases (Fig. 3):
  - **Activation phase**. As SP nodes are inactive by default (only its Wake-up Listener is active), a PU must first activate the SP by sending a Wake-up signal by means of an A2P link.
  - **Response phase**. After activating the SP, the PU starts to generate the Ether, which the SP modulates with the data to be transmitted.

### D. Topologies

These nodes can be deployed in a star or mesh topology (or in a hybrid combination of both). SP nodes can only be deployed in a star topology as they cannot initiate a communication on their own. Furthermore, they need a PU to be able to transmit their sensor or identification data. The PU acts as the center of the star topology (Fig. 4). The area a PU covers with its active transmitter is called “Aura”, and it can only demodulate MBS signals if they are coming from a SP/SA within its Aura. Also, the Wake-Up whistle works only for nodes inside the Aura of the PU.

![Image](image_url)
A PU is responsible of polling the SP and SA nodes within its range by using an interrogation algorithm that is executed periodically. The PU may uniquely address a SP, or globally (broadcast) all the SPs in its Aura to receive an answer. In the first case the SP requested will answer immediately but, in the second case, a distributed anti-collision algorithm running in the SPs ensures that the access to medium is achieved in an organized way. A third option could be to address only those SPs which share some common features (e.g. only temperature sensors) by coding the SP type as part of its own address.

It is important to note that A2A link in a SA→PU communication is an unidirectional link. Therefore it could happen that a SA node can reach a PU by using an A2A link, but the reverse A2P link is not possible because the SA is not within the PU’s Aura. Therefore the PU would need to hop over some intermediate SA nodes to send data back to the SA. Fig. 5 shows an example of this situation.

Especially original in our network is the operation of the SA nodes. They may act as independent nodes in a mesh topology, but also like a SP nodes when the presence of a PU is detected (star topology). The mutation between SA and SP nodes operation and between star and mesh topologies is driven by the protocol and illustrated in the Fig. 6.

### IV. COMMUNICATIONS PROTOCOL

#### A. Medium access

As the SPs do not implement an active transmitter, their transmission has to be managed by the PU, which is transmitting the Ether that the SPs need for communication. The only medium access problem appears when more than one SP is requested by a PU to transmit data, but this is solved by using the already mentioned anti-collision algorithm, which runs partially in the SPs and the PU.

A SA needs access to the medium to talk with another SA or with a PU. For the first case the SA senses the medium and, if it is free, the SA just sends a wake up signal selecting the destination SA, followed with the data it wants to transmit. In the second case there is no need to send a wake up signal (section IV.C), so the data is sent immediately. If the medium is busy, the SA will back-off for some random time before trying again.

The PU is the most complete node and also the one that will make a more intensive use of the physical medium. Although sleeping times for the PU nodes may be used for power saving reasons, a PU has its active receiver on (listening) when it is not transmitting. The medium access in a PU is also based on a listen-before-talk mechanism, similar to the one used in the SAs nodes. During the polling procedure of the SPs (and SAs operating like SPs) within its Aura, the PU must synchronize the utilization of its Active Tx, Active Rx and Electromagnetic Field generator. The PU divides the polling time in two phases (Fig. 7), mapping the activation and response phases of Fig. 3:

- **Selection phase.** In this phase the PU generates the wake-up signals for the nodes it wants to interrogate.
- **Response phase.** During this phase the PU generates an electromagnetic field (Ether) that the SPs and SAs modulate with their data. As it was already mentioned, an anti collision algorithm needs to be used in this phase.

### TABLE II. COMMUNICATION LINKS DESCRIPTION

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2A Link</td>
<td>Medium range communication that requires an active transmitter and an active receiver (PU→PU, SA→SA).</td>
<td></td>
</tr>
<tr>
<td>A2P Link</td>
<td>Short range communication (&lt; 3 meters) that requires an active transmitter and a passive receiver. The wake-up signals to activate a SP or SA node are transmitted in this link before the data (PU→SP, SA→SP).</td>
<td></td>
</tr>
<tr>
<td>MBS Link</td>
<td>Short range communication that requires an active transmitter (to provide the Ether), a passive transmitter (MBS) and an active receiver (SP→PU).</td>
<td></td>
</tr>
<tr>
<td>Ether</td>
<td>Electromagnetic field generated by a PU to provide the signal necessary to be used by the passive transmitters (MBS).</td>
<td></td>
</tr>
</tbody>
</table>

![Figure 4. Star and mesh topologies](image)

![Figure 5. A2A asymmetric link](image)

![Figure 6. Mutation between SA and SP nodes operation and between star and mesh topologies](image)
When the number of passive nodes to interrogate is high, the polling procedure (and the channel occupancy) will last for a relatively long amount of time, compared with the duration of one peer to peer transmission. To avoid collisions with other PUs in its vicinity, the PU transmits a beacon at the beginning of the polling time, which informs other PUs about the duration of the polling procedure. PUs receiving the beacon will back-off for at least the duration of the polling time before trying to get access to the medium again (Fig. 7).

**B. Selective node activation (Addressing)**

The ‘always-on’ receiver architecture saves power and reduces the latency, since the transmitter is able to selectively wake up the destination node before transmitting the data. The question is: how to identify the target node to wake up? The use of a node identification number is obviously necessary, but how long this number should be? To speed up the wake up procedure, it should be kept as short as possible, but then the node assignment should be done in advance (statically) to avoid duplication, or dynamically, by using some central controller or some distributed assignment protocol. Furthermore, the size of this number would depend on the number of nodes within the network, which would complicate the design of the ID detector in the wake-up unit. A better solution is to use two addresses: a short identification number for wake-up purposes and one protocol address for data communication. The protocol addresses can be chosen to avoid address duplicity and allow network extension.

To solve the outlined problem, we propose to use a pair of addresses in every node related by a Hash function: a protocol address of 48-bits (long range or MAC address) and a short identification number of 10-bits (short range or PHY address). Only the long range address needs to be globally unique. Hash functions are also called one-way functions because it is easy to determine the hash value from the message, but mathematically infeasible to determine the message from the hash value. This kind of functions are common in authentication protocols and recently they are also being used in wired network switches to directly map the MAC addresses with the correspondent port number in the switch, avoiding storing in the memory [6].

By using a Hash function that generates a 10-bit number from a 48-bits number, every node obtains its own PHY address from its MAC address. The PHY address is then used by the wake-up unit in the radio hardware, which activates the data receiver if the received address matches its own one.

Fig. 8 uses an example to show the proposed working principle. As part of the initial configuration procedure in every node, the MAC layer protocol in node B uses its globally unique long range address to generate a short range address by passing that address through a Hash function $H()$. The generated number is used in the PHY layer to configure the hardware Wake-Up Listener unit. On the other side, the MAC layer of node A has some data to transmit to the node with protocol address 0x0123456789AB, which is effectively node
The protocol calculates the result of the Hash function for this destination address, and triggers the Wake-Up Whistle unit in its PHY layer, to generate a wake-up signal with the obtained node address. The data is transmitted afterwards.

The main advantage of this addressing mechanism is that every node can obtain the PHY address of any other node by just passing the node’s protocol address through the Hash function being used. This avoids the need for an address resolution protocol like the one used in IP networks, which consumes power and bandwidth [7].

C. PHY address format

As the PHY address is only necessary for remote activation purposes, it is used only in A2P links (PU→SP, SA→SP and SA→SA). It is important to note that only the PHY address of the destination node is important, hence the PHY address of the sender is not transmitted at all. If this address is necessary for sending and acknowledge or for replying, it can be calculated from the MAC source address inside the received frame. The frame format at the PHY layer is shown in the Table III. The PHY address of the destination node is added to the payload received from the MAC layer.

In a MBS link the active receiver in the PU is already on, because it is ready to receive the backscattered signals coming from the PU nodes. The PHY address is therefore useless in this case. The other possible link in our network is the A2A link, which can be established between PU→PU or SA→PU. In both cases the active receiver in the PU and the active transmitter in the PU or SA have to be tuned in frequency and time, which implies that the receiver must be on before the communication starts. Therefore the PHY address is also not necessary here.

The PHY layer address of a PHY frame consists of an initial bit indicating whether the frame contains a higher-layer (MAC) command, which must be received and evaluated by all SP nodes, or whether the frame is related to the PU-data polling process. In the latter case, only those nodes that actually wish to transmit data to the PU need to wake-up to receive this frame. The SP nodes change the first bit of their PHY address depending on whether they intend to transmit data or not. By comparing this bit and the first bit of an incoming frame, the wake-up hardware can determine if the frame needs to be processed or not (Table IV).

V. IMPLEMENTATION

The ideas presented above have been implemented in a real hardware demonstration system. Although a complete network solution including all the features is not yet available, all the ideas proposed have been physically verified.

The Wake-Up unit has been implemented by using discrete components and showed to run over distances up to 5 meters. The protocol stack (including addressing mechanism, anticollision algorithm and routing protocol) has been implemented and tested using low cost micro-controller development boards and a low power 2.4GHz ISM radio chip. The MBS was not integrated, but the proposed PU receiver architecture and modulation scheme was tested separately over distances up to 7 meters.

VI. CONCLUSIONS

Nowadays it is commonly claimed that wireless sensor networks key to make ubiquitous computing or context awareness applications become reality. However, this will not happen without an efficient network power management allowing the nodes to operate in an user-unattended mode for an acceptable lifetime (eg. several years). This can only be achieved by tackling the power consumption issue as a global task, and not only as a radio or communication protocol aspect.

In this paper we have investigated these issues and proposed a complete network solution combining a low power consumption radio technology, a remote wake-up mechanism and a communications protocol specifically designed to efficiently use all those features. The new addressing mechanism is a good example of a cross-layer integration between PHY and MAC layers.

The network architecture is novel, formed by a heterogeneous combination of different node types and communication capabilities that allows the network to operate differently in various topologies, or even change between different modes if that topology changes.

REFERENCES