Power Management in Wireless Sensor Networks with High-Consuming Sensors

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Abstract—Wireless Sensor Networks (WSNs), usually battery-powered, thus very energy-constrained, present energy efficiency as the main challenge. To reduce the overall energy consumption of the network, research community has been tackling power management (PM) techniques on different levels — sensing, communication, computation and energy harvesting. Usually in WSNs the communication consumes most of the energy. But recently wireless sensor nodes are introduced that comprise also energy-consuming sensors, apart from the ‘traditional’ ones like temperature, air pressure and humidity sensors. Therefore, besides the well explored PM techniques on the transceiver activity and wireless transmission, there is a necessity to introduce also the PM on the sensing unit, that reduces the power consumption of the power-hungry sensors. This paper presents state-of-the-art of the most important PM techniques both for transceiver and sensor activity, focusing on the context- and energy-aware multimodal heterogeneous WSNs with energy consuming sensors, designed for smart video surveillance and smart gas detection.

Index Terms—wireless sensor networks, power management, duty cycle, hierarchical sensing

I. INTRODUCTION

A Wireless Sensor Network (WSN) consists of small devices with very limited capabilities, called wireless sensor nodes, that collect information from the environment by sensors, process the information, locally make decisions and wirelessly communicate with other nodes in the network. A scheme of a WSN connected to the Internet is presented in Fig. 1. WSNs are implemented in a wide range of distributed, remote and wireless sensing applications in environmental monitoring, agriculture, production and delivery, military, structural health monitoring, ambient intelligence, medical applications, etc. Deployment of WSNs avoids installation costs due to wire depositions, introducing at the same time power efficiency as a main challenge. Wireless sensor nodes are mainly battery-powered, thus having restricted amounts of energy. Even if they are equipped with power harvesting units (retrieving e.g. solar, vibrational or wind energy), energy is a critical point and should be tackled wisely. A WSN should be autonomous and self-sustainable, able to function for several years with a battery power supply. A node’s lifetime is defined as the node’s operating time without the need for any external intervention, like battery replacement. A WSN lifetime can be defined as the lifetime of the shortest living node in the network, but, depending on the application, density of the network and possibilities of reconfiguration, it can be defined as the lifetime of some other (main or critical) node. Anyway, in order to prolong a WSN lifetime, it is required to reduce the energy consumption of the nodes as much as possible and form an energy- and context-aware system.

A wireless sensor node usually consists of a power unit, sensing unit, communication unit (transceiver) and a processing unit (MCU), as showed in Fig. 2. Each unit contributes to the node power consumption. The industry and research are still intensively trying to develop nodes that have power consumption as low as possible and that are appropriate for various types of applications. The first developed nodes that gained the community attention were from the MICA family. Some other popular and commercially available nodes are Imote, Telos, Tmote Sky, Shimmer, WaspMote… A node is built around a low-power microcontroller unit, most often around an MSP430 or an ATmega 1281.

Traditionally, the nodes have been monitoring scalar values like the temperature, atmospheric pressure, humidity. Those sensors are very low-power and the major energy consumer of the node was the transceiver. A significant issue of a node’s design has been the trade-off between the computation and the communication energy. Most power management (PM) strategies earlier proposed in the literature assume that...
data acquisition consumes significantly less energy than their transmission [1]. However, this assumption does not hold in a number of practical applications where the power consumption of the sensing activity may be comparable or even greater than that of the radio. In this context, effective PM strategies should include policies for an efficient use of energy-hungry sensors, which become one of the main components affecting the network lifetime [2].

This paper will further present the state-of-the-art in a part of the PM schemes that concern radio PM, with duty-cycling and a separate wake-up receiver as main approaches. We will also present sensing PM for high-consuming sensors, that includes techniques of hierarchical, adaptive and model-based acquisition and data processing. The focus will be put on the hierarchical, heterogeneous, multimodal WSNs for smart video surveillance and smart gas detection. The combination of low-cost, low-power and low-resolution sensor nodes that detect an interesting event and trigger the high-resolution, high-consuming sensors is a promising method for tackling the trade-off between prolonging the system’s lifetime and providing high quality of service.

II. DUTY-CYCLING NODE’S ACTIVITY

One of the basic and most common used PM techniques is duty-cycling of a node’s activity. In duty-cycled operation, a node follows a sleep-wake-up-sample-compute-communicate cycle, where the majority of the cycle is spent in the low-power sleep state [3]. This process, which relies on hardware support for implementing sleep states, permits the average power consumption of a node \( P_{\text{avg}} \) to be reduced by many orders of magnitude. Duty cycle (\( D \)) of a node’s activity is defined as the fraction of time when the node is active:

\[
D = \frac{t_{\text{active}}}{T},
\]

\[
T = t_{\text{active}} + t_{\text{sleep}}\,.
\]

Power consumption of the node depends on the duty cycle:

\[
P_{\text{avg}} = \frac{P_{\text{active}} \cdot t_{\text{active}} + P_{\text{sleep}} \cdot t_{\text{sleep}}}{T}.
\]

Furthermore, power in inactive state \( P_{\text{sleep}} \) is usually significantly lower than the power in active state, so we can approximate the average power consumption as:

\[
P_{\text{avg}} = P_{\text{active}} \cdot D.
\]

Hence, in order to decrease the node’s power consumption, we are trying to reduce its duty cycle (\( D \)). To reduce the duty cycle, we should decrease the \( t_{\text{active}} \) time as much as possible and increase the period \( T \) as much as possible, taking into account some limitations. Duty-cycled operation is usually possible in WSNs due to the common requirement that they do not require continuous sampling or communication (WSNs are often defined by their low data-rate and communication frequency); hence, duty cycles of 1–2 % are common [3]. It is essential that events and packets are not missed while the node is asleep [4], requiring that careful thought is given to duty-cycled operation. A simplified graphics of the node’s power consumption with duty-cycled activity is shown in Fig. 3. The process of duty-cycled operation can also be applied to communications, whereby an active node only receives and transmits for a small portion of the active time. This form of duty-cycling is managed by the Medium Access Control layer (MAC) of the communication protocol, which is presented in the following section.

III. TRANSCEIVER POWER MANAGEMENT

A transceiver consumes generally the largest amount of a node’s energy. In TX and RX modes, it usually consumes about 20 mA. Most of the time, though, the transceiver is in idle state, listening to the channel if there is an incoming message, because the message can be received only if the radio is ON. Unfortunately, the idle state consumes almost as much as the RX/TX states. Since the node receives messages relatively rarely, lots of effort have been done to reduce the useless idle listening of the transceiver, usually by periodically switching the radio on and off. Another recent effort has been invested to wake the node (and the entire network) on a message reception.

When two nodes are to communicate, the receiver node must be awake when the sender initiates the communication, which is referred to as a rendez-vous [5]. There are three types of rendez-vous schemes:

a) Pure synchronous: The nodes’ clocks are presynchronized such that the wake-up time of each node is known a priori. This scheme requires recurrent time synchronization that consumes considerable energy. Moreover, the sensors wake up even if there is no packet to transmit or receive, which results in idle listening or overhearing.

b) Pseudo-asynchronous (or cycled receiver): Source nodes usually wake up and emit a preamble signal that indicates the intention of data transmission. The preamble time is long enough to coincide with the wake-up schedule of the destination node. Upon waking up and sensing the preamble, the destination node recognizes the intended packet transmission. In this scheme time synchronization is not required, but sensors still follow a duty cycle and consume considerable energy with preamble signaling.

c) Pure asynchronous: Sensor nodes reside in deep sleep and can be woken up by their neighbors on demand with very low-power wake-up receivers. Whenever a node intends to send a packet, first it wakes up the destination node and then sends the packet. Therefore, wake-up receivers are
a solution to the redundant energy consumption caused by rendez-vous.

Based on the previous research work, low power radio schemes can be roughly divided into two categories: the cycled receiver scheme and the separate wake-up receiver scheme. Since the primary difference between those schemes is whether there is a second wake-up receiver employed or not, the two schemes are also called one-channel wake-up radio and two-channel wake-up radio, respectively.

A. Cycled receiver

The one-channel wake-up scheme employs duty cycle control on the main radio to decrease the power consumption, while suffering a penalty on the latency performance. The cycled receiver schemes can be classified into two groups, depending upon who (transmitter or receiver) initiates the rendez-vous. These schemes are called ‘Transmitter/Receiver Initiated Cycliced Receivers’, respectively, or TICER and RICER in short and are shown in Fig. 4 [6]. In TICER scheme, as soon as a node has a data packet to transmit, it wakes up and monitors the channel. If it does not hear any ongoing transmissions on the channel, it starts transmitting request-to-send (RTS) signals to the destination node, and monitors the channel for responses. The destination node, upon waking up according to its regular wake-up schedule, immediately acquires and receives the RTS’s, upon which it responds with a clear-to-send (CTS) signal to the source node. After reception of the CTS signal, the source node transmits the data packet. Similar to the TICER scheme, in RICER a sensor node with no data packet to transmit wakes up with period T. It then proceeds by transmitting a short wake-up beacon to announce that it is awake, and by monitoring the channel for a response. If there is no response, the node goes back to sleep. A source node with data to transmit stays awake and monitors the channel, awaiting a wake-up beacon from the destination. Upon reception, it starts transmitting the data packet.

A practical implementation of a simple transceiver duty-cycling (TICER scheme) is presented in [7]. The wake-on sensor network uses the Wake-On Radio (WOR) capability that enables the radio to periodically wake up from sleep mode and listen for incoming packets without MCU interaction.

There are several MAC protocols that use low-power listening to reduce the energy consumption (e.g. S-MAC, B-MAC, X-MAC) and many various optimization approaches to further reduce the idle listening of the radio, e.g. for IEEE 802.15.4 MAC [8] and a newly proposed MAC protocol that outperforms the IEEE 802.15.4 and B-MAC [9]. STEM (Sparse Topology and Energy Management) optimizes the duty cycle of a secondary (wake-up) receiver and efficiently wakes up nodes from a deep sleep state without the need for an ultra-low-power wake-up receiver. The designer can trade the energy efficiency of this sleep state for the latency associated with waking up the node [10].

B. Separate wake-up receiver

The two-channel wake-up radio implements an additional wake-up receiver to monitor the communication channel continuously, and keeps the main radio in the sleep mode for most of the time. When a node wishes to communicate with a neighbor, it sends a wake-up call, containing the wake-up code or address of the target to awake only the desired neighbor. For this mode of operation to be effective, the power consumption of the wake-up device must be quite low. When the latency requirement of a certain application is not strict, the cycled receiver can apply a very low duty cycle. In that case, the power consumption resulted from the second wake-up receiver in the two-channel scheme might counteract the anticipated improvement. Therefore, the choice between the two typical wake-up schemes is not straightforward [11].

Gu and Stankovic [12] present in 2004 the following design goals for wake-up radios: low power consumption, high sensitivity, resistance to interference and fast wake-up and also propose the idea of passive ‘zero-powered’ wake-up radios that harvest energy from the received EM signal. Lin et al. [6] estimated a more realistic consumption value that the wake-up radio must have. According to their simulations, if the wake-up radio power consumption is greater than 50 µW, the overall performance of the purely asynchronous communication protocol will be worse than that of pseudo-asynchronous schemes.

Besides the advantages of the two-channel wake-up radio — virtually eliminates idle listening on the primary radio (presuming that only the desired node wakes up), reduces latency (as receivers are woken up when they are needed) and reduces collisions (as transmissions are no longer scheduled into discrete communication periods) — there are several crucial challenges. Problems encountered in design and implementation of wake-up radios include: limited reception range or very high transmission energy requirements, higher than desired receiver power consumption and false wake-ups caused by interference from other sources of transmission in the chosen frequency bands. Thus, trade-offs expected in

Fig. 4. Pseudo-asynchronous rendez-vous schemes [6]
networks with wake-up receivers are wake-up range vs. energy consumption, wake-up range vs. delay (due to multihops) and in-band vs. out-of-band wake-up radio (whether to implement the wake-up radio in the same channel as the main data radio [5, 13].

Because of these challenges, there have been very few practical designs and implementations of the wake-up receivers. Just recently (since 2008), a significant progress has been recorded. Le-Huy and Roy present a 2.4 GHz wake-up radio design with simulated average power consumption below 20 μW, but the physically implemented device is yet to be fabricated [14]. Pletcher et al. present an implemented prototype of the wake-up radio that consumes 52 μW [15]. Mathews et al. assembled a wake-up transceiver using Free Space Optical (FSO) communications, that consumes 317 μW and is applicable in indoor WSNs with line of sight connectivity [13]. Gamm et al. present a 868 MHz wake-up receiver that consumes only 2.78 μW [16]. In 2010, IMEC implements a 2.4 GHz/915 MHz wake-up receiver which consumes 51 μW power [17]. The wake-up radios have not been widely used in WSNs yet, but these reported designs are promising for the wake-up circuitry to become an indispensable part of WSN nodes.

IV. INFORMATION DISSEMINATION

There are four established techniques for information dissemination in WSNs:

- continuous/periodic dissemination: The sensor node continuously reports data following a periodic schedule. In this way, packets are proactively pushed from the network (and an energy cost incurred) even when the sensed parameter has not significantly changed, hence containing little useful information since the previous transmission.
- query-driven dissemination: The user or application initiates data transfer by querying data from the network. Qualifying nodes reply to these queries with packets.
- event-driven dissemination: The intelligent ‘sensor node decides for itself what data are worth reporting to a sink node. In that way, redundant transmissions can be minimized (using the principle that: ‘it is not news if one can predict it’).
- hybrid dissemination: Algorithms that are an amalgamation of the above techniques.

In continuous reporting, the choice of period duration has a considerable effect on network performance. If a short period is chosen, a large proportion of the packets are likely to be redundant (containing little useful information), while still consuming energy. If a long period is chosen, the network is likely to suffer from latency issues and the missing of events. While the missing of events can be avoided by locally aggregating the average-max-min sensed values (when using a sampling rate that is greater than the dissemination rate), this does not avoid the issues with latency or the information smoothing that aggregation introduces. Hence, while continuous dissemination is suited to applications with random or uncharacterizable signals, in most cases it does not maximize energy consumption or information throughput. Event-driven dissemination approaches provide more suitable techniques, and are discussed in the following subsection [18].

A. Event-driven dissemination

Event detection systems can be classified into two categories: those that report only the ‘digital’ occurrence of an event (such as smoke or motion detectors), and those that detect the occurrence and magnitude of an event (such as a seismograph which reports the magnitude of any vibration above a certain threshold) [19]. Event detection can be used in systems to manage the operation of energy-hungry sensors, where low-power (but less accurate) sensors detect the occurrence of an event and subsequently sample power-consuming (or lifetime- and sample-limited) sensors [3]. Event-driven algorithms require a form of intelligence inside the network, however simple, to ascertain when events occur. Rule-based approaches generate events whenever specific criteria are fulfilled or features detected in the sensed environment.

Manjeshwar et al. [20] proposed APTEEN, an event-based dissemination technique for WSNs that is based upon the concept of two thresholds: the Hard Threshold $H_T$, and the Soft Threshold $S_T$. Data is sent from the sensor node if the sampled value either exceeds $H_T$, or changes by more than $S_T$. A smaller value of $S_T$ maintains a more accurate picture of the network at the expense of power consumption. In this way, APTEEN is able to provide a customizable balance between temporal resolution and power consumption (hence network lifetime). In addition to hard and soft thresholds, periodic messages are transmitted if the sensor node has not reported for a period $\Delta t_{tr}$. APTEEN also introduces the possibility of the user querying the network at any node for ‘on-the-fly’ information retrieval. Hu et al. [21] propose an algorithm based upon APTEEN, which adaptively adjusts the value of $S_T$ (essentially controlling the resolution of disseminated data) through attempting to keep the ratio between the number of packets disseminated as a result of $\Delta t_{tr}$ and $S_T$ constant.

Wermer-Allen et al. [22] present a WSN used to monitor the behaviour of an active volcano, using an event-based mechanism to control data dissemination. In this system, each node runs an event detection algorithm that computes short-term and long-term exponentially-weighted moving averages over the sampled data. When the ratio between the two averages exceeds a preset threshold, the node transmits an event report to the base station. If the base station receives triggers from at least 30% of the active nodes within a ten second window, the event is considered to be well-correlated and data collection is initiated from all nodes.

Predictive approaches to event detection use a prediction model at both the node and the sink. Packets are reported whenever sensed data differs from the node’s prediction by more than a preset value (as the data will therefore also differ from the sink node’s prediction by the same amount). This reduces the packet transmissions (and hence energy consumption) while maintaining information throughput, but requires a powerful sink node that is able to maintain independent predic-
tion models for every node in the network. A variety of models have been suggested for use with predictive event-detection, e.g. a scheme inspired by MPEG video compression [23].

V. SENSING POWER MANAGEMENT

For the WSNs comprising energy-consuming sensors, PM schemes aimed at minimizing the radio activity are insufficient to fully address the energy savings issue and need to be complemented with techniques for energy-efficient management at the sensor level.

Two approaches are considered to reduce the energy consumed by a sensor: duty-cycling and adaptive sensing. Duty-cycling consists of waking the sensing system up only for the time needed to acquire a new set of samples and powering it off immediately afterwards. This strategy allows us to optimally manage energy, provided that the dynamics of the monitored phenomenon are time-invariant and known in advance. The (fixed) sampling rate is computed a priori. As a consequence, the sampling rate is larger than necessary (oversampling), inducing, in turn, energy wasting. A better approach would require an adaptive sensing strategy able to dynamically adapt the sensor activity to the real dynamics of the process. It is obvious that an efficient sensing strategy, by reducing the number of samples, also reduces the amount of data to be processed and (possibly) transmitted to clusters and/or the base station. In designing the sensor drivers for the operating system, some aspects must be considered to grant an effective handling of the duty-cycle issue: failing in doing that might result in invalid acquired data, and/or energy dissipation larger than that associated with the always-on mode. Each sensor is characterized by a set of functional characteristics, e.g. wake-up latency and break-even cycle, impacting on the PM of the sensor. The wake-up latency is the time required by the sensor to generate a correct value once activated. Clearly, if the sensor reading is performed before the wake-up latency has elapsed, the acquired data is not valid. Thus, the time that the sensor has to be active ($t_{on}$) needs to be long enough for the sensor to wake up ($t_{wakeup}$) and to acquire the measured information ($t_{acquire}$) [3]:

$$t_{on} \geq t_{wakeup} + t_{acquire}. \quad (5)$$

The break-even cycle is defined as the rate at which the power consumption of a node with a PM policy is equal to that of not power managed node. Such value is in inverse proportion with the power consumption overhead introduced by the non-ideal on/off sensor transition and represents the highest sampling rate for which applying a power management is worth.

Adaptive sensing can be implemented by exploiting three different approaches: hierarchical sensing, adaptive sampling and model-based active sensing (Fig. 5).

A. Hierarchical sensing

Hierarchical sensing techniques assume that multiple sensors are installed on the sensor nodes, each characterized by its own accuracy and power consumption, to measure the same physical quantity. In most cases, simple sensors are energy-efficient, but provide a very limited resolution. On the other hand, complex sensors can give a more accurate characterization of the sensed phenomenon at the cost of higher energy consumption. Thus, accuracy can be traded off with energy efficiency. At first, low-power sensors are considered to provide a coarse-grained characterization of the sensing field or trigger an event. Then, accurate, but power-hungry, sensors can be activated with measurements used to improve the coarser description.

1) Triggered sensing: The activation of the more accurate and power-consuming sensors after the low-resolution ones, after some activity within the sensed area has been detected, is referred to triggered sensing. An example of triggered sensing is presented in [24] for structural health monitoring and damage detection of a civil structure (i.e. a bridge). A central node, which supervises all the activities of the WSN, is endowed with a triggering system: sensor units are activated when the passage of isolated, large payload vehicles are detected by an imaging system. Initially, in each sensor unit, only accelerometers are activated to collect data and perform a local assessment of the potential damage. Whenever a potential danger is detected, strain gauges are activated to get more accurate information so as to corroborate or dismiss the initial suspicion, while the central node remotely transmits information about the possible alert (e.g. damage localization). Finally, the sensor units return to sleep.

2) Multi-scale sensing: A different use of hierarchical sensing consists of identifying areas within the monitoring field that require a more accurate observation. This is obtained by relying on a coarse-grained description of the field with lower accuracy sensors and activating additional high-resolution ones only in areas where their accurate acquisitions are requested. These approaches are referred as multi-scale sensing [25]. An example of such a strategy is suggested in [26] for a multi-scale approach to fire emergency management. The sensor field is instrumented with static sensors which monitor the environment. When a given area presents an anomaly (i.e. the sampled temperature is above a given threshold), static nodes ask the base station for a deeper investigation. As a consequence, the base station sends a mobile sensing unit to visit the potentially critical location which collects data and takes a snapshot of the scene. After having observed the event, the mobile unit goes back to the base station and reports the acquired data.
B. Adaptive sampling

Adaptive sampling techniques are aimed at dynamically adapting the sensor sampling rate by exploiting spatial and/or temporal correlation among acquired data (activity-driven adaptive sampling) and/or the available energy whenever the sensor node is able to harvest energy from the environment (harvesting-aware adaptive sampling).

1) Activity-driven adaptive sampling: Activity-driven adaptive sampling exploits the correlation (both temporal and spatial) among the acquired data. Temporal correlation has been considered in [27], where the authors proposed an adaptive sampling algorithm for minimizing the energy consumption of a snow sensor. A similar approach has been suggested in [28], where the sampling rate is adapted based on the output of a Kalman filter. Unlike the previous case, here authors take a decentralized approach, i.e. the Kalman filter is executed on sensor nodes. A spatial correlation approach has been investigated in [29], where the authors propose the backcasting scheme, in which more nodes should be active in those areas where the variation of the sensed quantity is high. The solution proposed in [30] exploits both spatial and temporal correlation within an environmental monitoring application. Authors use an actuation-enabled robotic sensor which consists of a mobile node carrying meteorological sensors.

2) Harvesting-aware adaptive sampling: The harvesting-aware adaptive sampling techniques (e.g. [31]) exploit knowledge about the residual and the forecasted energy coming from the harvester module to optimize power consumption at the unit level. The approach requires development of models able to characterize the evolution over time of energy availability and the energy consumption of sensor units.

C. Model-based active sampling

Model-based active sampling consists of building a model of the sensed phenomenon on top of an initial set of sampled data. Once the model is available, next data can be predicted by the model instead of sampling the quantity of interest, hence saving the energy consumed for data sensing. Whenever the requested accuracy is not satisfied anymore, the model needs to be updated, or re-estimated, to adhere to the new dynamics of the physical phenomenon under observation.

Model-based active sensing was first proposed in [32] in the framework of the Barbie-Q (BBQ) query system. The query system relies on a probabilistic model and a query planner, both present in the sink. A similar approach has been suggested in [33], where an Adaptive Sampling Approach to Data Collection (ASAP) is proposed. In contrast with BBQ, ASAP splits the network into clusters. The correlation-based sampler selection is performed at each cluster head and aims at determining those sampler nodes that capture at the best the spatial and temporal correlations among the other sensor readings. The values of not sampling nodes are predicted using the probabilistic models.

VI. HETEROGENEOUS WIRELESS SENSOR NETWORKS — APPLICATIONS

Heterogeneous WSNs consist of nodes containing different sensors and sensing modalities, enabling that the low-resolution, low-power, low-cost sensors cover more densely in time and space the monitored area and trigger the high resolution, high-consuming sensor nodes in case of an interesting event. Their advantage over the homogeneous WSNs is the reduction of the amount of collected and transferred data from the monitored environment, thus, reducing the activity and power consumption of the power-consuming nodes. Some energy- and context-aware WSNs for smart video surveillance and smart gas detection, with PM techniques and challenges are presented hereafter.

A. WSNs for smart video surveillance

One of the most challenging tasks for a WSN is collecting the multimedia-based data, as opposed to the scalar data collected by classical WSNs [34, 35]. Multimedia data can be defined as image, video or sound. These types of data are relatively large and are likely to be represented in an array or a stream. Due to the greater amount of data, processing operations are more calculation-intensive than on scalar data. Thus, a new class of WSNs has been developed to sense multimedia data. These Wireless Multimedia Sensor Networks (WMSNs) form a special group of WSNs and need new designs to master their challenges. Fig. 6 shows standard WMSN architectures — from a single-tier homogeneous sensor network to a multi-tier heterogeneous sensor network.

Technology advancements are bringing ultra-low-cost cameras to the market, encouraging research in distributed multicamera surveillance systems. Table I lists several most popular wireless video sensor nodes, with the camera resolution and the MCU board type as the main characteristics.

Deploying multiple cameras is beneficial in Wireless Video Sensor Networks (WVSNs), as it enables wider area coverage, occlusion avoidance, tracking etc. Unfortunately, CMOS
TABLE I
WIRELESS VIDEO SENSOR NODES

<table>
<thead>
<tr>
<th>WVS node</th>
<th>Camera resolution</th>
<th>MCU board</th>
</tr>
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<tbody>
<tr>
<td>Panoptes</td>
<td>QVGA</td>
<td>Stargate ARM</td>
</tr>
<tr>
<td>Cyclops</td>
<td>CIF</td>
<td>IMCA 2</td>
</tr>
<tr>
<td>CMUCam 3</td>
<td>CIF</td>
<td>Tmote Sky</td>
</tr>
<tr>
<td>MeshEye</td>
<td>VGA</td>
<td>ARM7-based</td>
</tr>
<tr>
<td>WCa</td>
<td>256x256</td>
<td>8051-based</td>
</tr>
<tr>
<td>Fleck</td>
<td>VGA</td>
<td>Fleck</td>
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<tr>
<td>CITRIC</td>
<td>1.3 MPix</td>
<td>Tmote Sky</td>
</tr>
<tr>
<td>FER Cvorak</td>
<td>2 MPix</td>
<td>ZigBit</td>
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</table>

Imagers are power-hungry, thus constant video surveillance presents serious shortcomings in terms of energy autonomy. Privacy is another barrier to continuous video surveillance, and we need to mitigate privacy violation concerns by narrowing down the range of situations where full video traces are acquired. Since interesting events for many surveillance applications occur quite rarely, there have been efforts to restrict a camera’s activity to interesting events in the monitored area by adding a low-cost, low-power sensor to the video node. For instance, a multimodal wireless video sensor node with a low-power Pyroelectric InfraRed (PIR) sensor mounted onboard is presented in [36, 37], that enables the camera to be inactive while the scene is idle. When the PIR sensor detects a person’s presence, it activates the camera to capture the image. Moreover, the node can dynamically change the PIRs sensing range, depending on the available energy, directly affecting the number of detected events, thus prolonging the nodes lifetime [38]. The PIR is mounted in a way that it has almost the same Field Of View (FOV) as the camera, meaning that the camera is triggered whenever something enters its FOV.

A Pyroelectric InfraRed (PIR) sensor is a low-power, low-cost sensor that detects person presence by detecting variations of incident infrared radiation of a body that is not in thermal equilibrium with the environment. Being passive and very low-power, but still reliable, it is very convenient for usage in battery-powered systems. From the analog output we can recognize the direction of the movement of the person (Fig. 7(a)). For one direction the first peak is positive, for the other direction the first peak is negative. That capability is very useful for implementation of hierarchical event-driven sensing in WVSNs. Deploying a heterogeneous network of PIRs and cameras instead of homogeneous network where a PIR is mounted on each video node enables definition of more complex triggering conditions such as the distance from the sensor, direction and speed of movement, as described in [39]. By gathering these data, a more specific area of interest (i.e. active area, smaller than the whole cameras FOV) can be formed, further reducing cameras ON-time compared to the case when the presence of a person in the entire FOV generates the trigger. Deploying a network of PIR nodes that can communicate with a network of cameras provides system flexibility, at the same time providing energy efficiency and minimizing the privacy impact [40, 41].

A special type of heterogeneous networks networks is called Multi-tier Multimodal Wireless Sensor Networks (M2WSNs). They are based on a hierarchical layout and are usually used in surveillance. Kulkarni et al. [42] present SensEye, a four-tier two-modal sensor network for intruder detection and surveillance. The first tier comprises vibration sensors, the second tier low-power, low-fidelity cameras (Cyclops or CMU-cams), the third tier high-fidelity web-cams and the fourth tier a sparse network of pan-tilt-zoom cameras. In [43] VigilNet is presented, a distributed network of nodes equipped with acoustic and magnetic sensors deployed in order to achieve longevity, adjustable sensitivity, stealthiness and effectiveness in a military surveillance application. On the detection of a moving vehicle, the 2 cameras are triggered. A M2WSN with two modalities and three tiers for environmental monitoring is presented in [44]. The first tier contains PIR sensors, the second tier visual nodes able to identify objects (CMUcam2) and the third tier a webcam connected to a PC that runs tracking algorithms. In [45] a preliminary study of an energy efficient multimodal WVSN is presented, with a main node that decides which camera to trigger based on the information from a distributed PIR network and available energy of each camera (Fig. 7(b)). The advantage over the previous work described in [36] is the restricted area of camera’s interest, thus reduced camera node’s activity and energy consumption. On the other hand, there is a trade-off introduced with the communication energy overhead.

B. WSNs for smart gas detection

Air quality monitoring in indoor environments is of great significance for comfort and health especially nowadays that people spend more than 80% of the day indoor. Most convenient gas sensors for WSN applications are those fabricated in Metal Oxide Semiconductor (MOX) technology, due to the small form factor, fast response time and power efficiency. A substantal study of the pulse mode for three different fabricated MOX gas sensors and the sensitivity, selectivity and response time dependance on the sensing layer temperature is presented in [46] and [47], respectively. It is important to emphasize the power savings of an order of a magnitude compared with...
typical commercial off-the-shelf (COTS) MOX gas sensors (the fabricated sensors consume only about 9 mW).

There are several examples in literature of sensor systems for monitoring Indoor Air Quality (IAQ). In [48], an automated decentralized indoor climate control system is presented, including stationary wired multi-gas sensor modules and wearable wireless devices. Energy consumption of the system is not mentioned. Postolache et al. [49] present a WiFi network for indoor and outdoor air quality monitoring with MOX sensor arrays. They are focused on the advanced onboard processing and data publishing on the Web. Power consumption of the nodes is quite high (8 W). Choi et al. [50] present design and implementation of a sensor board for air pollutant monitoring applications. They developed an automated sensor-specific power management system and use pulse mode of the gas sensors, but the current consumption of their solution is still quite high (about 100 mA).

VII. CONCLUSION

This overview presents various PM techniques that comprise reduction on both communication and sensing energy in WSNs. Traditionally, communication energy has been a major part of a node’s energy consumption. But, with the necessity of implementing high-consuming sensors in WSNs, sensing unit has to also be driven carefully. Real-life implementations of these WSNs require autonomy of several years, with battery power supply. Thus, energy resources should be managed judiciously — with energy consumption reduction on the sensor level, node level and network level. Further research interests will be focused on designing energy-efficient, heterogeneous WSNs for ambient intelligent areas, with high-consuming CMOS cameras for smart video surveillance and MOX gas sensors for smart gas monitoring. Combining radio PM and sensing PM methods (e.g. radio duty-cycling or wake-up radio and event-driven hierarchical data dissemination, respectively) would enable design of flexible, context- and energy-aware pervasive systems.

REFERENCES


