Power Management in Wireless Sensor Networks:
Challenges and Solutions

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Abstract—This paper provides a novel taxonomy of various energy conservation techniques applied to sensor networks applications in recent times. Moreover, we present our novel approaches in the same context including utilizing software sensors and local adaptive data compression based on Fuzzy Transform.

Keywords—Wireless Sensor Networks; Power Management; Data Compression; Taxonomy; Fuzzy Transform

I. INTRODUCTION

In the last decades, interactive environments transformed our life styles. Sensing has a significant role in renovating our daily life towards more comfort. For instance, networked sensors in our homes with some sorts of deduction capabilities turn them into smart homes. Such an application involves family security, family medical treatment, family data processing, family entertainment and family business [1]. Accordingly, the world is covered by millions of sensing systems that extract information about the surrounding environment. However, it is essential to achieve cooperation among these sensors. This led to a new technology called wireless sensor networks (WSNs). Wireless sensor nodes have the ability to observe a phenomenon, perform various kinds of signal processing, and broadcast their event detections. In 1999, scientists mentioned that WSNs are one of the most important technologies for the 21st century [2]. WSNs are cheap, tiny, smart, and densely deployed sensing devices whose event detections are transmitted via multi-hop communication through wireless links and the Internet. These features open the doors for unprecedented opportunities for instrumenting and controlling homes, cities, and the environment [3]. Below, the general architecture of such networks will be discussed in more details.

In most cases, the network is composed of measurement nodes (MNs), gateways and software. The spatially distributed MNs contain different sensors in order to collect environmental data and transmit them wirelessly. A central gateway, that can work independently or connected to a host system, aggregates, processes, and analyzes the measured data. A special type of MNs may have additional functionality such as routing for improving the scalability and the dependability of WSNs. The software manages the allocation of node resources in a controlled manner. Operating systems must subsume the special requirements of WSN applications and the resource constraints in WSN hardware platforms. As shown in Fig. 1, MNs are mostly composed of four subsystems including power supply, sensing, processing, and radio communication subsystems.

The analog signal detected by the sensors is digitized by an analog-to-digital converter (ADC) and is then sent to the processor for further processing. Memory types in a sensor node consist of in-chip flash memory and RAM of the microcontroller as well as of external flash memory. The processing subsystem is responsible for scheduling tasks, processing data and controlling the functionality of other hardware components. A transceiver is responsible for the wireless communication of a MN with its neighbors or with the gateway. Finally, power supply can be stored in batteries or capacitors. However, today, batteries are the main source of power supply for MNs. More details about the architecture of WSNs can be found in [3], [4].

Fig. 1: General architecture of a wireless sensor node

The ideal characteristics of a typical WSN are low power consumption, scalability, dependability, remote configuration of MNs, programmability, fast data acquisition, security, and fidelity of data flow over the long term and with little or no maintenance [5]. For instance, it is essential to ensure that service and information can be accessed at the time they are required and WSNs should have the capability to maintain the functionality even if some MNs fail. Many research studies are exerted to achieve these challenges [6]–[8]. However, minimizing the overall network power consumption is more significant due to the complexity of the given problem; it still a fertile research area. Therefore, this paper covers the main techniques developed for minimizing the energy consumption. Then, it provides answers to some research questions such as: 1) What are the actual power consumption of each subsystem inside the MN? 2) Which power saving technique is the supreme? 3) Are there novel ideas for extending the life

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expectancy of a MN or a WSN as a whole?

The remainder of this paper is organized as follows. Section 2 defines the problem of energy consumption in more detail. Section 3 presents a novel taxonomy for power management approaches in WSNs. Finally, in Section 4, a conclusion is drawn and future work is addressed.

II. PROBLEM FORMULATION

Economically, WSNs are superior to wired sensing systems provided that the latter require a separate twisted shielded-pair wire connection. Thus, implementation costs for the latter are high. However, a WSN has to function for an extensive period of time in order to achieve cost minimization and to successfully complete its particular mission. Notably, there is a trade-off between the life expectancy of a WSN and the power consumed in the various network operations. Furthermore, minimizing the energy consumption is a key concern due to many factors. First, capacity of batteries is limited when MNs are getting smaller in size. Second, continuous operation drains batteries and makes the MNs inoperable. Third, replacing batteries is an impractical option since a network might have several hundred MNs spread over a large geographical area. As a result, conserving the allocated energy is very important and represents a major challenge that stands against the wide-spreading of this technology. Under those circumstances, utilizing a holistic approach to the issue of energy management in WSNs is crucial. However, investigating the sources of energy consumption is essential to diagnose the problem properly. Therefore, these sources will be elaborated in the following.

Equation 1 describes the power consumption $P_d$ in terms of the supply power $P_s$ and the available power $P_{av}$. In addition, the main sources of energy consumption in WSNs can be classified into effective $P_{e}$ and ineffective power dissipation $P_i$.

$$P_d = P_s - P_{av} = P_e + P_i$$

Equation 1

$P_i$ is considered wasted energy since it does not contribute to the functionality of the network. It comprises the power consumed by control packet overhead, idle listening, over-emitting, collisions, and state transitions. In the first type, power is wasted in handling the networking operations such as routing and topology control. Idle listening occurs when a receiver switches to the active state frequently waiting for incoming packets. In over-emitting, packets are transmitted to a neighbor which is not ready for packets reception. Overhearing occurs when MN receives packets intended to other MNs. Collision occurs when multiple transmissions are initiated simultaneously. Finally, switching between modes of operation results in increased power consumption due to leakage currents.

$P_e$, on the contrary, incorporates the power consumed during sensing phenomena, processing query requests as well as transmitting and receiving packets. First, the sensing subsystem converts the surrounding phenomenon into an electrical signal. The energy consumption of the sensing subsystem strongly depends on the specific application. Equation 2 indicates the energy consumed in measuring mode $P_{mes}$ and sleep mode $P_{sl}$ of operation. $T_{mes}$ and $T_{sl}$ are the time durations spent in each mode. Fig. 2 shows the power dissipated by different sensors. Note, that sensing gases demands much more energy than any other sensing application [9].

$$E_{sensor} = (P_{mes} \times T_{mes}) + (P_{sl} \times T_{sl})$$

Equation 2

Second, the processors embedded in many MNs have the ability to function in different low power modes. For instance, the MSP430 processor can switch among an active mode and five low power modes through disabling the CPU and some clock signals [10]. An interrupt event can 1) wake up the device from any of the five low-power modes, 2) service the request, and 3) switch back to the same low-power mode. Similarly, Eq. 3 defines the energy dissipated by the embedded processor in the active mode $P_{act}$ and $N$ low power modes $lpm1$, $lpm2$, ..., $lpmN$. Equation 4 delineates the power consumed in each state which is proportional to the operational frequency $f$ and the square of the supply voltage $v$ where $C$ is the total capacitance [11].

$$E_{processor} = (P_{act} \times T_{act}) + \sum_{x=0}^{N} (P_{lpmx} \times T_{lpmx})$$

Equation 3

Finally, radio communication is an “energy-hungry” task compared to other tasks. Studies showed that the energy cost of transmitting a single bit of information is approximately the same as the energy consumed in processing a thousand operations in a typical sensor node [12]. Fig. 3, which indicates a comparison among the power consumption per time unit by each subsystem of the sensor nodes (CM5000MSP) [13], supports these findings. Equation 5 models the energy required for broadcasting $k$ bits of information within a distance of $d$, where $E_{elec}$ is 50 nJ/bit and $e_{amp}$ is 100 pJ/bit/m$^2$. Equation 6 computes the energy consumed while listening for data during $T_{on}$ seconds [14]. Eventually, the overall energy dissipated in radio communication $P_{rc}$ can be determined as in Eq. 7 through multiplying the power consumed in each state (transmit, receive, idle, sleep) by the time spent in this state.

$$E_{tx}(k,d) = (E_{elec} \times k) + (e_{amp} \times k \times d^2)$$

Equation 5

$$E_{rx} = P_{rc} \times T_{on}$$

Equation 6

$$E_{radio} = \sum (P_{state} \times T_{state}) = (P_{tx} \times T_{tx}) + (P_{receive} \times T_{receive}) + (P_{sleep} \times T_{sleep}) + (P_{id} \times T_{id}) + (P_{sl} \times T_{sl})$$

Equation 7
important criteria: energy consumption of a WSN consisting of given by Eqs. 9-11. Specifically, Eq. 9 minimizes the total can be formulated as an integer linear programming problem must satisfy the user’s specifications Sys represented by the MNs and operating in the environment Env of allocating a certain amount of energy for the system respectively. However, in some applications, the sampling period may be larger than the storing time. Therefore, Pps and Psf must be exchanged in the previous inequality.

In the following, we introduce the energy efficiency problem in a deterministic way.

Symbolically, the dilemma of energy consumption can be expressed as shown in Eq. 8. Under the assumption Asm of allocating a certain amount of energy for the system Sys represented by the MNs and operating in the environment Env, Sys must satisfy the user’s specifications Spec. These demands can be formulated as an integer linear programming problem as given by Eqs. 9-11. Specifically, Eq. 9 minimizes the total energy consumption of a WSN consisting of k nodes with two important criteria:

1) The lifetime L of each MN s must be greater than (or equal to) the expected lifetime δ as expressed in Eq. 10.
2) The accuracy A of measurements m at each MN s is an indication for the convergence between the collected data at the sink node and the sensors readings. This Quality-of-Service (QoS) parameter must be greater than or equal to a user predefined value ψ as expressed in Eq. 11. However, A might not be optimum but still tolerable by the application [15].

\[
Asm \vdash (Env \parallel Sys) sat Spec
\]  

\[
\text{minimize } \left( \sum_{s=1}^{k} (P_{sf}(s)) + P_{ed}(s) \right)
\]  

provided that

\[
L(s) \geq \delta \quad \forall s \in WSN
\]  

\[
100\% \geq A(s,m) \geq \psi \quad \forall s,m
\]

Generally speaking, the mentioned sources of energy consumption have – in most cases – to be optimized to achieve a substantial lifetime extension. Therefore, in the next section, a novel taxonomy for power management techniques is presented. It is intended to serve as a potential basis from which researchers can refer to in order to systematically develop more advanced and dedicated approaches.

III. POWER MANAGEMENTS

Many research studies discuss the dilemma expressed in Eqs. 8-11 [17], [18], [20]–[34]. In this section, a novel taxonomy for the most significant approaches for maximizing the life expectancy of WSNs is discussed. Moreover, a brief explanation of these techniques is presented. As it can be seen in Fig. 4, energy management in WSNs can be classified into energy harvesting and energy conservation. The former includes exploiting the surrounding environment by scavenging energy to fully (or partially) energize an MN. However, the amount of power that can be harvested is very limited. Furthermore, external power supply sources, in many cases, exhibit a non-continuous behavior which can cause system malfunctioning. Therefore, this paper focuses on the latter techniques in which reducing the power dissipated in the various operations can be accomplished from two different scopes: device-level, and network-level.

A. Device-level Approaches

This section presents approaches for reducing the power consumed in MNs excluding networking operations. It comprises hardware component selection and their configuration to achieve minimum energy consumption. Based on this concept, many techniques have been proposed. Below, each technique will be discussed briefly.

1) Scaling: According to Eq. 11, peak accuracy is not always required. Therefore, the processors operating voltage and frequency can be dynamically adapted based on instantaneous computational load requirements. As a result, significant processing power can be saved through this method, called dynamic voltage scaling (DVS) [16]. Additionally, dynamic modulation scaling (DMS) can be used to optimize broadcasting energy with respect to the number of packets that need to be transmitted at that particular time intervals [17]. However, DMS may increase system latency.
2) **Data Compression:** As expressed in Eq. 5, radio power consumption strongly depends on the packet size. Therefore, removing redundancy existing in the data is essential to find a more compact representation. Compression (sometimes called encoding) may be *lossy* or *lossless* according to the compression algorithm. There are different algorithms for data compression in WSNs such as wavelet transform and low-complexity video compression [18]. In this context, we propose the utilization of the Fuzzy transform (F-transform) for compressing measurements [19]. The core idea of the F-transform is dividing the data being processed into fuzzy partitions of interval \([a, b]\). Thereafter, a weighted average of the original function is determined by the direct F-transform. An approximated version of the original function is determined by the inverse F-transform. The adaptive compression algorithm we propose, is as follows. First, the sensor readings extracted in time period \(t\) are MN-locally stored for processing. Second, if these readings reflect a real danger category, then an alarm must be broadcasted to the neighboring nodes. Third, if the readings are not dangerous, then the processor checks whether these readings are *normal* or *above-normal*. Afterwards, the F-transform is applied using a particular basic function with a certain compression ratio. However, a predefined threshold for the residual energy must be checked in the second category. If the available energy is below this threshold, the F-transform is forced to use a basic function with the largest compression ratio (among the predefined basic functions available) to maximize the battery lifetime.

3) **Software Sensors:** As shown in Fig. 2, sensors may dissipate a huge amount of energy depending on the application. Therefore, based on the fact given in Eq. 11, implementing sensors using software algorithms may be an effective technique for reducing the overall power consumption. For instance, a GPS sensor is very expensive in terms of energy. Thus, determining the location relative to other nodes may save a considerable amount of energy. The novel concept of software sensors will be implemented and evaluated in our future work.

4) **Energy-efficient Cognitive Subsystem:** Cognition can be defined as the process of learning through observation, reasoning, knowledge and intuition [20]. In the WSN context, the protocol stack of WSNs was modified by adding a Knowledge Plan (KP) to build a network that has the ability to adapt itself to changes [21]. For instance, KP can learn the radio component’s characteristics. Based on this information, the radio parameters and component characteristics can be adapted to minimize the radio power consumption. Obviously, the same approach can be applied to other subsystems in MNs. On the other hand, data acquisition controls the sensing power especially in cases of “energy-hungry” sensors such as gas and GPS sensors. For instance, adaptive sampling techniques reduce the number of samples by exploiting spatio-temporal correlations between sensed data [22].

5) **Memory Leakage Control:** The leakage current can be optimized to save energy [23]. Different approaches were proposed such as 1) ones which make their leakage management decisions based on performance feedback, 2) techniques that manage cache leakage in an application-intensive manner (e.g. by periodically turning off cache lines), and 3) techniques that utilize feedback from the program behavior.

6) **Software Optimization:** Micro-operating systems (µOSs) in WSNs are classified into *event-driven* µOS and *multi-threaded* µOS. The former are efficient in terms of resources utilization. Whereas, the latter ones have superior event processing capabilities [24]. Recent µOSs, such as Contiki and SOS, comprise generic abstractions to manage the power consumed by peripherals of the sensor devices. Generally, µOSs can accomplish significant energy reduction by performing energy-aware task scheduling and resource management. On the other hand, compilers have been studied to generate efficient code in terms of power consumption [23]. For instance, *spill code reduction* techniques managed to save energy and improve the overall system performance. *Power-aware instruction scheduling* is also a known technique for decreasing energy consumption.

### B. Network-level Approaches

In this section, a collection of power saving techniques which involve optimization of communication techniques and networking protocols is presented.

1) **Mobility:** The techniques are based on either employing mobile sinks or mobile relay nodes in order to reduce the number of multi-hops and thereby minimizing the transmission cost [25]. These mobile nodes are often attached to mobile entities in the environment such as vehicles, animals, or dedicated robots.

2) **Data-driven:** In this approach, distributed processing is made through the entire network in order to prolong the WSN lifetime. For instance, *compressive sensing* (CS) is a distributed compression technique in which the data is processed to remove redundancy by exploiting spatial correlation. CS depends on reconstructing the sparse WSN’s data from a small number of random-linear readings [26]. *Coding by ordering* and *pipelined in-network* are other distributed compression
techniques which can be applied in the context of WSNs [18]. Data prediction is another technique in which identical predictors, implemented in the source and sink nodes, are utilized in order to minimize the number of transmitted packets [27]. Many prediction algorithms are utilized in WSNs including time series forecasting, stochastic and algorithmic approaches.

3) Duty Cycling: As can be seen in Fig. 3, transceivers consume the majority of the energy available. Therefore, switching the transceiver into sleep mode helps to greatly prolong the network lifetime. Selecting which node (or set of nodes) must go to sleep can be based either on aggregation techniques, redundancy control, or on MAC protocols. In the first approach, data is aggregated either through event-driven, periodic sampling, or store and forward strategies. They have already been described in Section 2.

The second approach exploits network redundancy to extend the network longevity by switching a number of redundant MNs into sleep mode. In the meantime, active MNs can also be switched into sleep mode according to the workload to further save energy. Choosing the active MNs can be accomplished in two ways: a location-based approach or a connectivity-based approach. In the former procedure, the sensing field is divided into cells as shown in Fig. 5. In each cell, only one MN is activated while others are switched to sleep mode [28]. Consequently, power consumption and collisions are reduced. The latter procedure determines the minimum number of nodes that still guarantee network connectivity. Redundant MNs are deactivated [29].

MAC protocols are responsible for the coordination between neighbors. Optimizing MAC protocols leads to significant reduction in power consumption. For instance, time division multiple access (TDMA) is a well-known MAC protocol. Data collision is avoided by dividing the time frame into slots. As shown in Fig. 6, time frames are divided into slots where each node is assigned two fixed time slots for transmitting and receiving packets. As a result, MNs are active during their assigned slots and inactive during other slots. Advantages of the TDMA protocol comprise eliminating data collision and conserving significant amount of energy. However, this technique requires a precise synchronization among the various nodes which may be difficult in many situations [30].

On the other hand, contention-based MAC protocols allow nodes to independently access the shared wireless medium [31]. These protocols propose minimizing collisions rather than avoiding them completely. Contention-based protocols depend on a carrier sensing mechanism called carrier sense multiple access (CSMA). In this mechanism, transceivers are switched on only for listening to the traffic before broadcasting in order to check the availability of free channels.

4) Energy-efficient Networking: Routing is the process of delivering information to the destination through a – hopefully – short path. Many optimization techniques have been proposed to improve the performance of this task in terms of energy consumption [32]. A classification of routing protocols for WSNs focuses on the following categories [33]:

- **Hierarchical clustering**: These protocols are suitable in case of continuous transmission due to the presence of redundant data. Specifically, this approach is based on splitting the network into groups called clusters. In each cluster, one node is elected as a cluster head which aggregates the packets from its cluster members. Optimizing the collected information might be accomplished by the cluster head in order to decrease energy and traffic. Examples of hierarchical clustering include low-energy adaptive clustering hierarchy (LEACH), power-efficient gathering in sensor information systems (PEGASIS), and adaptive periodic threshold sensitive energy efficient sensor network protocol (APTEEN). Additional information about clustering can be found in [34].
- **Multipath-based protocols**: Here, MNs determine the k-shortest paths to the sink node. Thereafter, MNs divide their load evenly among these paths. Sensor-disjoint multipath and braided multipath protocols are based on this concept.
- **Data-centric protocols**: In this category, MNs send their information to the sink node via neighboring nodes. These intermediate nodes aggregate the readings and perform various processing in order to reduce the traffic. Examples of this approach comprise sensor protocols for information via negotiation (SPIN) and energy-aware data-centric routing (EAD).
- **Heterogeneity-based protocols**: The core idea of this category is to utilize special nodes with unlimited energy sources for assisting the battery-powered sensors in aggregating information. Examples of protocols include information-driven sensor query (IDSQ) and cluster-head relay routing (CHR).
- **QoS-based protocols**: Here, many paths are formed between the sink and the sensor nodes. Afterwards, one path is selected which optimizes the energy consumption and other QoS parameters such as availability, reliability or latency. Examples are sequential assignment routing (SAR) and energy-aware QoS routing.
Generally, the proposed taxonomy draws a map for the possible investigation areas in WSNs to maximize their lifetime. However, designing a holistic approach might require more advanced and dedicated solutions. Therefore, novel ideas such as F-transform-based compression and software sensors have to be addressed in more depth. Unfortunately, due to a lack of space, they could only be briefly sketched here.

IV. CONCLUSION

Due to the importance of the energy management problem in WSNs, a holistic approach for energy conservation in WSNs is essential. However, such an approach is still difficult to find due to the diversity in the WSNs applications and their requirements. This paper briefly indicated the sources of energy consumption in WSNs. Additionally, we presented a novel taxonomy of energy management techniques. It could serve as a potential starting point for a systematic and holistic approach to the solving or softening of the energy efficiency problem in WSNs. Moreover, in this paper, we presented, in brief, two novel approaches: the concept of software sensors and adaptive data encoding using the F-transform. We hope to report on the effectiveness and efficiency of these concepts in the near future.

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