Efficient Power Utilization Techniques for Wireless Sensor Networks – A Survey

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***Abstract* - Micro-sensor networks are widely deployed sensor network in typical geographical areas where human intervention is almost impossible. A WSN is a collection of several small energy limited sensors. These devices are autonomous devices performs the job of data collection and forwarding it to the central node called sink node. The observed data can travel through multiple paths to reach sink node. Sink node performs the task of data fusion to determine a meaningful output. The micro sensors use battery power supply to achieve this goal. The considerable part here is to utilize that limited power supply for a longer time period. Although latest developments in the area of electronics has enabled the development of low-cost and low power sensor networks, still researchers are developing protocols by different approaches to optimize power utilization for such tiny micro-sensors. This paper studies various approaches used by researchers to enhance power utilization.**

Keywords: sensor network, data acquisition, node mobility, data aggregation, MAC protocol.

I. INTRODUCTION

A wireless sensor network is a collection of micro-sensor nodes distributed over a large geographical region for monitoring physical phenomena like temperature, humidity, vibrations etc. A sensor node here is a small device consisting of three main components: a sensing subsystem to collect the data from the environment, a processing subsystem for local data processing and storage. In addition it contains a wireless communication subsystem for data transmission. A persistent power supply therefore is needed by the device to perform the programmed task. This power source often consists of a battery with a limited energy capacity. The difficult part here is recharging the batteries as the sensors are randomly deployed in a large geographical area. In some cases the power supply should support applications for a long time. An external resource [1] like solar cells can be used as energy in some specific cases. But because of non-continuous behavior of these devices some energy buffer (a battery) is needed as well. Therefore, energy conservation is a key issue in the design of systems based on wireless sensor networks. In this paper we will refer mainly to the sensor network model shown in Figure. 1 and consisting of one sink node (base station) and a (large) number of sensor nodes deployed over a large geographic area (sensing field). Data are transferred from sensor nodes to the sink through a multi-hop communication paradigm [2]. Here two scenario of sensor network are considered, first the case in which both the sink and the sensor nodes are static secondly, for sensor networks with mobile elements. Generally data transmission is very expensive, while data processing consumes significantly less in respect to energy usage [3]. The energy cost of transmitting a single bit of information is approximately the same as that needed for processing a thousand operations in a typical sensor node [4]. The energy consumption of the sensing system depends on the specific sensor type. The energy saving techniques hence focus on two aspects, the design of networking protocols and the techniques, to reduce the amount or frequency of energy-expensive samples. The lifetime of a sensor network can be extended by applying different methods [6]. For example, design of energy efficient protocols to minimize the energy consumption during network activities; switching off node components that are not temporarily needed etc. This paper surveys the main enabling techniques used for energy conservation in wireless sensor networks.

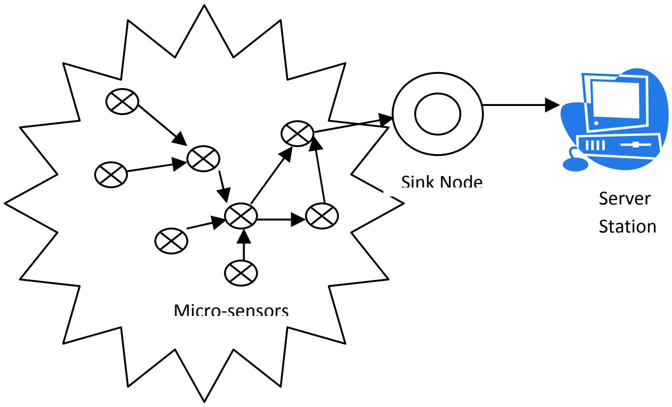

Figure 1: Sensor Network Architecture

II. ENERGY CONSERVATION SCHEMES

The WSN model, depicted in Figure.1 is the most widely used model in the literature. Moreover, Figure. 2 below show the architecture of a sensor node, as usually assumed in the literature. The four essential components of the architecture are: (a) a sensing subsystem having one or more sensors along with analog-to-digital converters for data acquisition; (b) a processing subsystem including a micro-controller and memory for local data processing; (c) a transmitter subsystem for wireless data communication; and (d) a power supply unit. Sensor nodes may also include additional components like a location finding system to find their mount location, a mobilizer to configure or change their location, depending on application need. From the study [3] the following analysis are identified:

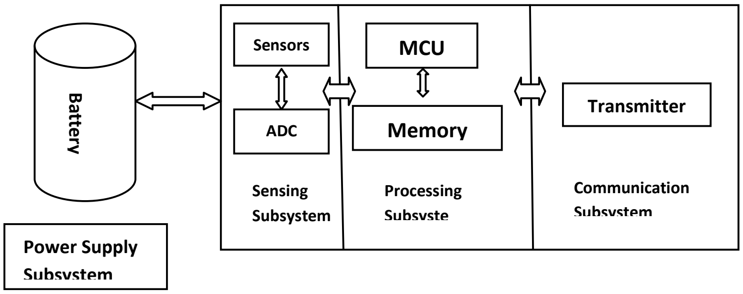

Figure 2: Architecture of typical wireless sensor node

- The communication subsystem consumes more energy than the computation subsystem.
- The energy consumption of radio is same while transmission, reception and idle states, and it drop significantly in the sleep state.
- There is variable energy consumption if there is different type of applications.

Considering above architecture and power breakdown, the various approaches can be categorized among three categories namely cyclic approach, data oriented approaches, and motion based approaches [5]. The various approaches are depicted briefly in Figure 3 and are explained further briefly.

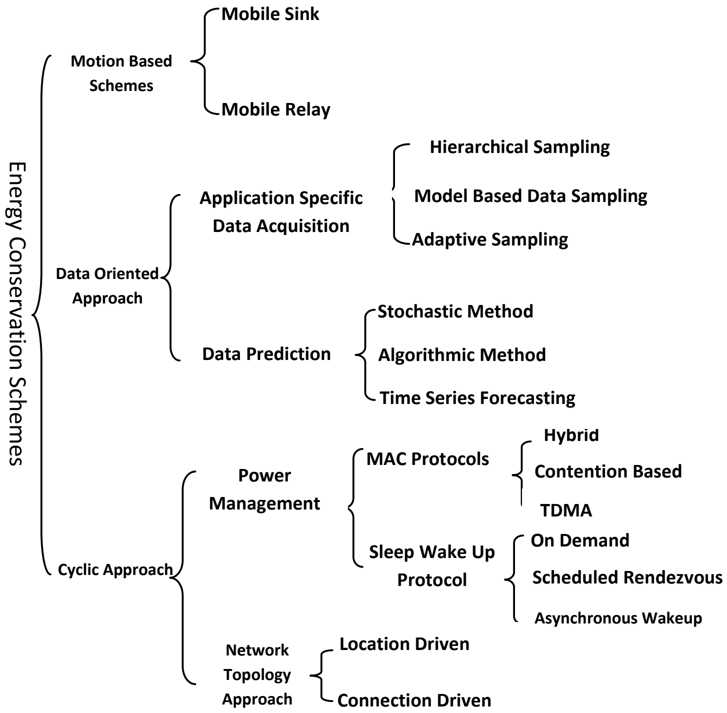

Figure 3: Energy Conservation Schemes in sensor networks

II.I CYCLIC APPROACH

Cyclic approach is focused on the networking subsystem. The approach is to keep radio transceiver in the sleep mode whenever communication is not required. Thus the nodes alternate between active and sleep periods depending on network activity. Cyclic approach can be achieved through two different approaches. First, adaptively select only a minimum subset of nodes to remain active for maintaining connectivity. Nodes that are not needed for keeping connectivity can go to sleep and save energy. The objective here is to identify the minimal subset of nodes to keep connectivity. This approach is termed as network topology. Thus the theme of network topology is to exploit the network redundancy to prolong the network longevity. The active nodes can switch off the radio when there is no network activity, thus alternates between sleep and wakeup periods. Thus, cyclic approach is applied to active nodes and for power management. The network topology and power management are complementary terms. Power management protocols (Figure 3 above) can be implemented either as independent sleep/wakeup protocols or strictly integrated with the MAC protocol itself. The latter scheme permits to optimize medium access functions based on the specific sleep/wakeup pattern used for power management. Contrary to this, independent sleep/wakeup protocols permit a greater flexibility as they can be tailored to the application needs. The various approaches are explained below.

II.I.I Network Topology Protocols

Network topology protocols exploit network redundancy aspects to extend network life time where the network is assumed to be always on [75]. It minimizes the number of active nodes by dynamically adapting the network topology. The application specific network operations take advantages of these active nodes. Several criterions can be used to decide which nodes to activate or deactivate, and when. Network topology protocols can be broadly classified in two categories (Figure 3 above). Location driven protocols define which node to turn on and when, based on the location of sensor nodes. Connectivity driven protocols dynamically activate or deactivate sensor nodes so that complete sensing coverage [7], is fulfilled.

II.I.I.I Location Driven

Geographical Adaptive Fidelity (GAF) [8] is a location driven protocol that reduces energy consumption while keeping a constant level of routing fidelity. Here the sensing area is divided into small virtual grids. Each virtual grid is defined such that, for any two adjacent grids X and Y, all nodes in X are able to communicate with nodes in Y and vice-versa (Figure. 4). The nodes lying within the same virtual grid have equal rights for routing, but only one node should be active at a time. Therefore, nodes have to coordinate with one another to decide which one can sleep and how long. Initially a node starts in the discovery state (discovery time is T_d) where it exchanges discovery messages with other nodes. After broadcasting the message, the node enters the active state (active state time T_a). While active, it periodically re-broadcasts its discovery message. A node in the discovery or active state can change its state to sleeping (sleeping time T_s) when it detects that some other equivalent node will handle routing (transition state Figure 5). After some specific sleeping time period nodes wake up and again goes to the discovery state. The periodic re-election of the leader is done in GAF for load balancing. This elected leader remains active to manage routing. The routing node is chosen through a rank-based election algorithm. The algorithm considers the nodes' residual energy for election, thus allowing the network lifetime to increase in proportion to node density [8]. GAF does not significantly affect the performance of the routing protocol in terms of packet loss and message latency.

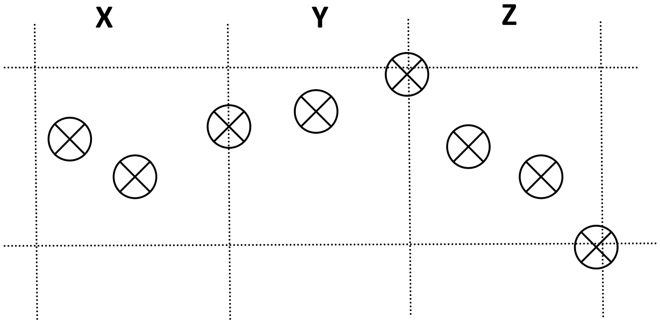

Figure 4: GAF Virtual Grids

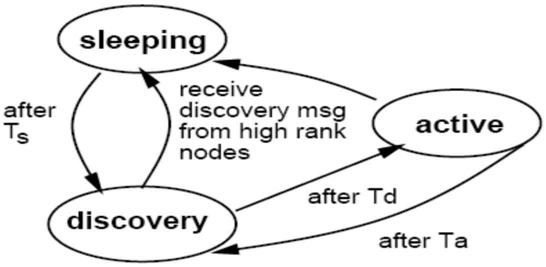

Figure 5: GAF State Transition

Nodes switch between active and inactive states periodically. Active nodes participate in routing process. Data transmission starts as soon as a node has a packet to send. The node becomes active and broadcasts a packet containing its own location and the location of the intended receiver. One of the active neighbors of the sender will be selected to forward the packet towards the destination. The active node has a priority calculated in respect of the distance of it from the destination. Additionally, a distributed randomization scheme is also used, to reduce the probability that many neighboring nodes are simultaneously sleeping. All the active nodes with higher priorities contend for forwarding, any one of them having channel access simply forwards the packet and the process ends. Otherwise, multiple data transmission from several nodes may cause collision that needs a resolution technique to select a single forwarder. There may be the case when no node can forward the packet because all nodes in the region are sleeping. Thus in the next transmission attempt, the forwarder will be chosen among nodes in the second highest priority region and so on.

II.I.I.II. Connection Driven

Span and Modified span [9] is a connectivity-driven protocol that adaptively elects ‘‘coordinators” of all nodes in the network. The coordinators are active nodes and perform multi-hop routing, while the other nodes stay in sleeping mode and periodically check if it is needed to wake up and become a coordinator. To guarantee a sufficient number of coordinators Span uses coordinator eligibility rule. The rule state, if two neighbors of a non-coordinator node cannot reach each other either directly or via one or more coordinators, that node should become a coordinator. However, at some time several nodes may decide to be coordinator due to lack of sufficient coordinators, to handle such situation nodes that are willing to become coordinator must, differ their announcement with some delay. Each node uses a function to identify the number of neighbors that can be connected by a potential coordinator node. The selection of coordinator depends on the nodes with a higher expected lifetime and should be least in number. Also each coordinator periodically checks if it can stop being a coordinator to avoid too many coordinator. The Span election algorithm uses routing protocols to know neighbor and connectivity information to decide whether a node should become a coordinator or not. The modified Span [9] works above link and MAC layer, and interacts with the routing protocol. Routing protocol takes the advantage of power saving techniques of MAC layer. Nodes in modified Span broadcast HELLO packets to tell about its existence. The coordinator announcement procedure is same as existing Span. The difference between both algorithms is in coordinator withdrawal procedure. Adaptive Self-Configuring Sensor Networks Topologies (ASCENT [10]) is a connectivity-driven protocol. It does not depend on the routing protocol. In ASCENT every node measures information about connectivity and packet loss and based on it, decides whether to join network or remain sleep. The basic idea of ASCENT is that initially only some nodes are active, while all other ones are passive, i.e., they listen to packets but do not transmit. If the number of active nodes is not large enough, the sink node may experience a message loss. In that case, the sink sends some wakeup messages to neighboring nodes that are in passive state to join the network by changing their state from passive to active. Passive neighbors have their radio on and listen to all packets transmitted by their active neighbors. Passive nodes do not forward data packets or exchange routing information – they only collect information about the network status without interfering with other nodes. On the contrary, active neighbors forward data and routing messages until they run out of energy. Active nodes can also send wakeup messages when they find the local data loss at an unacceptable level. Once a node is activated it monitors the network condition and signals its presence as an active node through a neighbor announcement message. This process is repeated till the number of active nodes is sufficient enough, that the message loss is below a pre-defined application dependent threshold. The process repeats when there is a node failure or topology change occurs. ASCENT is independent of the routing protocol and it limits the packets loss due to collisions because the node density is explicitly taken into account as a parameter (in the form of a neighbor threshold value). Finally, the protocol has good scalability properties. Here the, energy saving does not increase proportionally with the node density as it depends on passive-sleep cycle rather than the number of active nodes.

II.I.I.III Summary

- Location-driven network topology protocols requires that sensor nodes can somewhat know their position.
- Sensors position is known through GPS which is quite expensive and energy consuming.
- GPS can be installed on limited nodes.
- Commonly available sensor platforms lack the hardware suitable to acquire location information.
- Connectivity-driven protocols are generally preferred as information needed by them can be derived from local measurements.
- Network topology protocols can typically increase the network lifetime by a factor of 2–3 with respect to a network with nodes always on [62, 73]**.** This value may not be acceptable for many practical applications.
- Network topology protocols should be coupled with other kinds of energy conservation techniques, described in the following section for optimization.

II.I.II Power Management

The various power management protocols dealing with MAC and Sleep Wake Up pattern are as described below:-

II.I.II.I. MAC Protocols

Various MAC protocols are available in the literature [71, 74, 78 and 79]. The following discussion focuses mainly on power management issues rather than on channel access methods. The most common MAC protocols are classified as TDMA-based, contention based, and hybrid protocols.

II.I.II.I.I TDMA Based MAC Protocols

TDMA allows fixed time-slots for exclusively assignment to the nodes. Because of this feature it provides the best control over energy consumption and end-to-end delivery delay. Fixed time slots allocation in TDMA allows periodic transmission without contention. In WSNs, TDMA is desirable for saving energy as it minimize idle listening. Moreover, existing distributed algorithms are highly applicable to TDMA and hence for WSNs. A TDMA scheduling algorithm was proposed in [31] for sensor networks to find the smallest length conflict-free assignment of slots. These slots allow collision free receiving of data packets generated at each node. More specifically, they showed that the minimum-delay scheduling can always be found by using a simple algorithm for routing schemes based on TDMA, when the network is loop-free and has only one sink node. The results of their experimental work show that a substantial reduction of energy and delay is possible. Cui et al. [32] propose a simple link scheduling algorithm to find the minimum-delay schedule that provides the slot lengths for all the links. Their next step is to combine the obtained results with their previous work concerning an energy-optimal cross-layer design in order to reduce to the minimum, the delay of transferring a fixed number of bits from the source nodes to the sink in an energy limited manner. Moreover, they study the tradeoff between the total energy consumption and delay. Another approach is the improvement to TDMA approach called LEMMA proposed by the author in [33]. Latency-Energy Minimization Medium Access (LEMMA) is a spatial-reuse

TDMA MAC protocol for WSNs, which was developed aiming to minimize latency in the most energy efficient way, taking into account compatibility with the IEEE 802.15.4 and Zigbee specifications. LEMMA is divided in two parts, each addressing a different phase of WSN operation: time-slot allocation during the initialization phase (transitory state) and interference free data transmission (steady-state). In steady-state LEMMA seeks to minimize latency in the most energy efficient way, assuming a sporadic converge cast traffic pattern and corresponding tree topology. These goals are achieved coupling a near-optimal cascading TDMA slot allocation (low-latency) with a very low duty-cycle (energy-efficiency). The TDMA frame is divided into a number of time-slots. In the case of converge cast, the slot allocation algorithm tries to assign the time-slots with the highest number to the nodes that are directly connected to the sink node, and a similar policy is followed at each level of the tree, resulting in a cascading assignment that minimizes the latency required to transmit one packet from source to sink. The slot allocation algorithm assures that the access to each time-slot is interference-free; assigning each slot to only one node within the interference vicinity, but it takes advantage of spatial slot reuse outside of that vicinity. An illustrative example is presented in Figure 6, where the numbers inside the time-slots represent the node assignment for data transmission. In this example a TDMA frame of duration 1 s is divided in 200 time-slots of 5 ms. To each node only one slot is assigned, which is used to transmit data to its parent in the converge cast tree (with the sink at node 0), but LEMMA supports multi-slot assignments as well. The example considers that nodes 5, 6 and 7 do not interfere with nodes 3 and 4. This allows the same slots to be assigned to 3 and 5 and to 4 and 6. Each time-slot must be long enough to allow at least one DATA/ACK exchange (considering the maximum length of DATA packets).

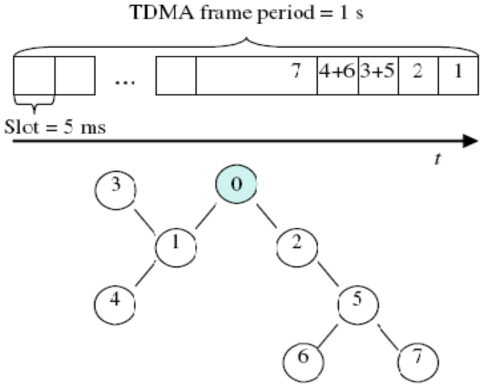

Figure 6: TDMA slot assignment for low-latency low duty-cycle operation

Although LEMMA – just like other TDMA protocols – assures interference-free transmission during the steady-state, carrier sense is still employed for medium access within each slot in order to detect and counter any interference resulting. LEMMA is also able to support very low duty-cycles, since each node must listen in the beginning as many slots as the number of children. It can be easily concluded that in the absence of physical layer errors the maximum end-to-end delay for a single packet is bounded by the length of one frame, plus the total duration of the slots that were allocated in that frame (note that data can be generated at any point in time during the TDMA frame).

II.I.II.I.II Contention Based MAC Protocols

In contention based MAC protocol [34] nodes contends for a single shared channel. Therefore collision happens during the contention procedure in such systems. Classical examples of contention based MAC protocols include ALOHA and carrier sense multiple access (CSMA) [35]. In ALOHA, a node simply transmits a packet whenever it is generated or at the next available slot. The collided packets are discarded and re-transmitted later. In CSMA, a node listens to the channel before transmitting. If it detects a busy channel, it delays access and retransmit later. Contention based protocols are influenced by a number of constraints like *Collision avoidance* is the principal task of all such MAC protocols that determines when and how a node can access the medium and transmit its data. *Scalability and adaptability* are another attributes of MAC protocol that accommodate changes in network size, node density, and topology. *Mobility* in wireless sensor networks poses a challenge as it should adapt itself to changes in mobility patterns, making it suitable for sensor environments. *Latency* is the time required to send a packet by the sender until the packet is successfully received by the receiver. *Channel utilization* refers to how the entire bandwidth of the channel is utilized in communications. *Throughput* refers to the amount of data successfully transferred from a sender to a receiver in a given time. *Reliability* for reliable delivery of data is a classical design goal for all network infrastructures. PAMAS (Power aware multi-access with signaling) protocol [36] attempts to conserve battery power by switching off nodes that are not transmitting or receiving. PAMAS is using two transceivers: one for data messages and the other for control messages. Using this separation can prevent collisions of the larger data messages and hence save power. Control channel exchanges use RTS, CTS messages, and a busy tone. The busy tone is used to indicate that the data channel is in use by the receiving device. Message transfer in PAMAS starts by the source sending an RTS message to the destination on the control channel. The destination then decides if it should transmit CTS by examining the data and control channels. A source that does not receive CTS in time will back off using a binary exponential algorithm. Once the source receives a CTS message it transmits the data message over the data channel. The destination starts transmitting a busy tone over the control channel once it starts receiving the data message. The main drawback of PAMAS is the inclusion of multiple radios which will greatly increases the energy consumption and the device cost of the sensor network. Additionally, controlling access to two wireless mediums increases the MAC protocol complexity. Collaborative MAC (CC-MAC) CC-MAC protocol attempts to conserve energy [38], while fulfilling application requirements, by utilizing the fact that sensor nodes located near each other generate correlated measurements. To achieve energy savings, CC-MAC filters measurements from highly correlated sensor nodes in an effort to reduce the number of messages the sensor network must handle. CC-MAC consists of two components: the event MAC (E-MAC), which filters sensor node measurements to reduce traffic and network MAC (N-MAC), which forwards the filtered measurement to the sensor network sink. E-MAC reduces the traffic generated in an area by having only sensor nodes separated by at least the correlation distance generate measurements. Other nodes periodically sleep to save energy and awake to forward messages. The main disadvantage of CC-MAC is that it requires sensor nodes posses or obtains ranging information about their neighbors in order for N-MAC to filter data from correlated sensor nodes. Furthermore the complexity of the CC-MAC protocol may limit the application of the protocol. SIFT is a MAC protocol proposed for event-driven sensor network environments. In SIFT when an event is sensed, the first R of N potential reports is the most crucial part of messaging and has to be relayed with low latency. Authors of the protocols use a non-uniform probability distribution function of picking a slot within the slotted contention window. If no node starts to transmit in the first slot of the window, then each node increases its transmission probability exponentially for the next slot assuming that the number of competing nodes is small. Another protocol Is “Alert” MAC protocol for collecting event-triggered urgent messages from a group of sensor nodes with minimum latency and no cooperation or pre-scheduling among the senders or between senders and receivers during protocol execution. Alert minimizes contention among nodes by using a combination of time and frequency multiplexing. Multiple frequency channels are used within time slots and contention is minimized by controlling the selection probability of each channel by the nodes. The Alert protocol divides the time into slots which are called Alert slots. Each alert slot can be used to exchange one data packet and its acknowledgment between a sender–receiver pair. In each alert slot, multiple frequency channels can be used by the senders and receivers.

II.I.II.I.III. Hybrid MAC Protocol

Hybrid MAC is a concept of switching the protocol behavior between TDMA and CSMA, depending on the level of contention. The Probabilistic TDMA (PTDMA) approach had already been proposed in [39] for wireless network. In PTDMA time is slotted, and nodes are distinguished in owners and non-owners. The protocol adjusts the access probability of owners and non-owners depending on the number of senders. By doing so it adapts the MAC protocol to a TDMA or a CSMA scheme depending on the level of contention in the network. Since PTDMA was proposed for a one-hop wireless scenario, it does not take into account issues such as topology changes, synchronization errors, interference irregularities which are quite common in wireless sensor networks. Another hybrid protocol in wireless sensor networks is Z-MAC [40]. Z-MAC starts with a preliminary setup phase; by means of the neighbor-discovery process each node builds a list of two hop neighbors. Then a distributed slot assignment algorithm is applied to ensure that any two nodes in the two-hop neighborhood are not assigned to the same slot. As a result, it is guaranteed that no transmission from a node to any of its one-hop neighbor interferes with any transmission from its two-hop neighbors. Z-MAC does not use a global frame equal for all nodes in the network. It would be very difficult and expensive to adapt when a topology change occurs. Instead, Z-MAC allows each node to maintain its own local time frame that depends on the number of neighbors and avoids any conflict with its contending neighbors. The local slot assignment and time frame of each node are then forwarded to its two-hop neighbors. Thus any node has slot and frame information about any two-hop neighbors and all synchronize to a common reference slot. After this setup phase nodes can be in one of the following modes: Low Contention Level (LCL) and High Contention Level (HCL). A node is in the LCL unless it has received an Explicit Contention Notification (ECN) within the last TECN period. ECNs are sent by nodes when they experience high contention. In HCL only the owners of the current slot and their one-hop neighbors are allowed to compete for accessing the channel. In LCL any node (both owners and non-owners) can compete to transmit in any slot. However, the owners have priority over non owners. This way Z-MAC can achieve high channel utilization even under low contention because a node can transmit as soon as the channel is available.

II.I.II.I.IV. Summary

TDMA-based protocols are inherently energy efficient, as nodes turn on their radio only during their own slots and sleep for the rest of the time. A good design of slot assignment algorithm and a correct sizing of the protocol parameters can minimize energy consumption. In addition, TDMA-based MAC protocols can solve problems associated with interference among nodes, as it is possible to schedule transmissions of neighboring nodes to occur at different times. However, in practice, TDMA-based protocols have several drawbacks that compensate the benefits in terms of energy saving [40]. First, they have limited flexibility and scalability, because of frequent topology changes due to many factors (e.g. channel conditions, node failures etc.) Second, they need tight synchronization and they are very sensitive to interference [41]. Moreover, TDMA-based protocols perform worse than contention based protocols in low traffic conditions. For all the above reasons, TDMA MAC protocols are not very frequently used in practical wireless sensor networks. Contrarily, contention-based MAC protocols are robust and scalable. In addition, they generally introduce a lower delay than TDMA-based ones and can easily adapt to traffic conditions. Unfortunately, their energy expenditure is higher than TDMA MACs because of contention and collisions. Duty-cycle mechanisms can help reducing the energy wastage, but they need to be designed carefully to be adaptive and to be low latency. Finally, hybrid protocols try to combine the strengths of TDMA-based and contention-based MAC protocols while offsetting their weaknesses. However, these techniques seem to be too complex to be feasible in deployments with a high number of nodes.

II.I.II.I.II Sleep/Wakeup Protocols

Sleep/wakeup schemes are applicable to the radio subsystem of the sensor node, without relying on topology or connectivity aspects. The sleep/wakeup protocols, depending on their characteristics, can be subdivided into three main categories [11]: on-demand, scheduled rendezvous, and asynchronous schemes (Figure. 3 above). In on-demand protocols a node should wakeup only when another node wants to communicate with it. The main problem associated with on-demand schemes is how to inform the sleeping node that some other node is willing to communicate with it. Hence such schemes typically use multiple radios with different energy/performance tradeoffs i.e. a low power radio for signaling, and a high power hungry radio for data communication. In scheduled rendezvous schemes, every node with all its neighbors should activate at the same time. Typically, nodes wake up according to a wakeup schedule, and remain active for a short time interval to communicate with their neighbors. Then, they go to sleep until the next rendezvous time. Finally, an asynchronous sleep/wakeup protocol uses an asynchronous protocol that means a node can wake up when it wants and can communicate with its neighbors. This goal is achieved by properties implied in the sleep/wakeup scheme and hence no explicit information is needed among nodes for sharing. The three schemes are briefly described as below.

II.I.II.II.I. Asynchronous Wakeup Schemes

Asynchronous schemes allow each node to wake up independently and there is a guaranteed overlapped active periods within a specified number of cycles. Quorum Based asynchronous wakeup protocol was introduced in [27] with reference to IEEE 802.11 ad hoc networks. In [27] author has focused on MANET that consists of a set of mobile hosts and can communicate in multi hop manner. The Quorum technique considers two aspects, first is *wakeup prediction*: where host need to know when it will turn its radio on so as to correctly deliver packets to it at the right time. Secondly, *neighbor discovery*: as the hosts' transmission/reception activities are reduced under the power saving mode, a host may take longer time, or maybe even unable, to detect the arrival and departure of other hosts in its radio covered range. More recently, Zheng et al. [28] took a systematic approach to design asynchronous wakeup mechanisms for ad hoc networks. Their scheme applies to wireless sensor networks, as well. They formulate the problem of generating wakeup schedules that rely upon asynchronous wakeup mechanisms [29]. According to optimal results from the analysis, they design an Asynchronous Wakeup Protocol (AWP). AWP can detect neighboring nodes in a finite time without requiring slot alignment. AWP can also handle packet collisions and variations in the network topology. In AWP each node is associated with a Wakeup Schedule Function that is used to generate a wakeup schedule. If two neighboring nodes want to communicate, their wakeup schedules must overlap, irrespective of their clock differences. The idea is illustrated in Figure. 9 by means of an example of asynchronous wakeup schedule for a set of 7 neighboring nodes. This example is based on a symmetric (7, 3, 1)-design of the wakeup schedule function. Symmetric means that all nodes have the same duty cycle, while (7, 3, 1)-design indicates that: (i).each schedule repeats every seven slots; (ii).each schedule has three active slots out of seven (dark slots); and (iii).any two schedules overlap for at most one slot. As shown in Figure 7 below, by following its own schedule, each node is guaranteed to communicate with any other neighboring node. Asynchronous scheme ensures that, each node can contact any of its neighbors in a finite time length. In this scheme it never happens that all neighbors are simultaneously active. Therefore, it is not possible to broadcast a message to all neighbors [11]. Random Asynchronous Wakeup (RAW) [30] takes a different approach for it. It considers the fact that sensor networks are densely deployed networks, that cause existence of several paths between a source and a destination, and thus, a packet can be forwarded to any of such available paths.

Schedule	1	2	3	4	5	6	7
124	**	**					
235		**	**				
346			**	**			
547				**	**		
561					**	**	
672						**	**
713							**

Slot Number

Figure 7: Asymmetric schedule based on (7, 3, 1) function

Actually, the RAW protocol consists of random wakeup scheme. The basic idea of the random wakeup scheme is that each node wakes up randomly once in every time interval of fixed duration T remains active for a predefined time Ta, and then sleeps again. Once awake, a node looks for active neighbors by running a neighbor discovery procedure. The random wakeup scheme is extremely simple and relies only on local decisions. This makes it well suited for networks with frequent topology changes. With RAW, it is not guaranteed that a node can find another active neighbor upon wakeup. Hence, RAW does not guarantee the packet forwarding within one time frame (T), while AWP does. An alternative approach to ensure that an asynchronous node finds its communication counterpart active when it wakes up, is forcing the receiver to listen periodically. The receiver wakes up periodically and listens for a short time to discover any potential asynchronous sender. If it does not detect any activity on the channel it returns to sleep, otherwise remains active to send/receive packets.

II.I.II.II.II. Scheduled Rendezvous Schemes

Scheduled rendezvous schemes require that all neighboring nodes wake up at the same time. Here the nodes wake up periodically to check for potential communications and then they return to sleep until the next rendezvous time. The major advantage of such schemes is that when a node is awakened it is guaranteed that all its neighbors are awakening as well. This allows sending broadcast messages to all neighbors [11]. In scheduled rendezvous schemes nodes are synchronized in order to wake up at the same time. This concept needs a clock synchronization scenario in wireless sensor networks. Different scheduled rendezvous protocols differ in the way network nodes sleep and wake up during their lifetime. The simplest way is using a Fully Synchronized Pattern [17]. In this case all nodes in the network wake up at the same time according to a periodic pattern. More precisely, all nodes wake up periodically every T_{wakeup}, and remain active for a fixed time T_{active}. Then, they return to sleep until the next wakeup instant. Due to its simplicity this scheme is used in several practical implementations including TinyDB [19] and TASK [18]. A fully synchronized wakeup scheme is also used in MAC protocols such as S-MAC [20] and T-MAC [21]. Even if simple, this scheme allows a low duty cycle provided that the active time (Tactive) is significantly smaller than the wakeup period (Twakeup). A further improvement can be achieved by allowing nodes to switch off their radio when no activity is detected for at least a timeout value [21]. In addition, due to the large size of the active and sleeping part, it does not require very precise time synchronization [19]. The main drawback is that all nodes become active at the same time after a long sleep period. Therefore, nodes try to transmit simultaneously, thus causing a large number of collisions. In addition, the scheme is not very flexible since the size of wakeup and active periods is fixed and does not adapt to variations in the traffic pattern and/or network topology. Some sleep/wakeup schemes take advantage of the internal network organization by sizing active times of different nodes according to their position. The network topology changes as the nodes joins or leave the network hence node balancing need to be done periodically. However, under the assumption that nodes are static, the data-gathering tree is supposed to remain stable for a reasonable amount of time [22]. In the Staggered Wakeup Pattern [17] (Figure. 7), nodes at different levels of the data-gathering tree wake up at different times. Obviously, the active parts of nodes belonging to adjacent levels must be partially overlapped to allow nodes to communicate with their children.

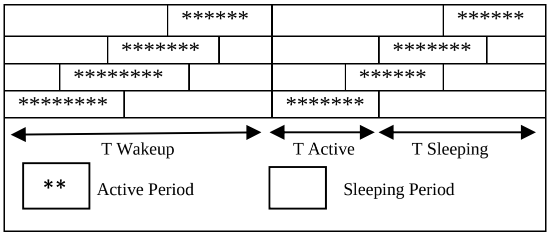

Figure 8: Staggered Sleep/Wakeup Pattern

The active parts of different levels are arranged in such a way that the portion of the active period a node uses to receive packets from its children is adjacent to the portion it uses to send packets to its parent (Figure. 8). This minimizes the energy dissipation for transitioning from sleep to active mode. The staggered wakeup pattern shown in Figure 8 is also called backward staggered pattern [17] as it optimizes packet latency in the backward direction i.e., from leaf nodes to the root. It is also possible to arrange nodes' active periods in such a way to optimize the forward packet latency (i.e., from the root to leaves). The resulting scheme, called forward staggered pattern [17] is however not very used in practice, because in real networks most of data flows from sensor nodes to the sink. A combination of the backward and forward staggered pattern is also possible. The (backward) staggered scheme was first proposed in the framework of TinyDB [19] and TAG [23]. A staggered wakeup pattern is also used in D-MAC [22]. The advantages of staggered approach are; since nodes at different levels of the data-gathering tree wake up at different times, at a given time only a (small) subset of nodes in the network will be active, hence reduction in the number of collisions. The active period of each node is thus significantly shortened with respect to the fully synchronized scheme and resulting in energy saving. This scheme is also suitable for data aggregation as parent nodes receive data from all their children before they forward such data to their own parent at the higher level. This allows parent nodes to filter data received from children, or to aggregate them. The drawback of this approach is that, since nodes located at the same level in the data gathering tree wake up at the same time, collisions can potentially still occur. In addition, this scheme has limited flexibility due to the fixed duration of the active (T_{active}) and wakeup (T_{wakeup}) periods. Ideally, the active period should be as low as possible, not only for energy saving but also for minimizing the latency experienced by packets to reach the root node (see Figure. 7). Still the changes in traffic pattern are possible because of change of topology by nodes movements. An adaptive and low latency staggered scheme is proposed in [24]. This adaptive scheme not only minimizes the energy consumption but also provides lower average packet latency with respect to a fixed staggered scheme. It also reduces collisions by allowing different lengths of the active period for nodes belonging to the same level, but associated with different parents [24].

Another approach derived from the on demand TDMA scheme, is taken in Flexible Power Scheduling (FPS) [25]. FPS takes a slotted approach, i.e. time is assumed to be divided in slots of duration Ts. Slots are arranged to form periodic cycles, where each cycle is made up of m slots and has a duration of T_c =m T_s. Each node maintains a power schedule of what operations it performs during a cycle. A node must keep its own radio on only when it has to receive/transmit from/to other nodes. The two common problems with this scheme are: they are not flexible and require a strict synchronization among nodes and to achieve flexibility, FPS includes an on-demand reservation mechanism that allows nodes to reserve slots in advance. Twinkle that supports broadcast is an improved version of FPS, presented in [26]. In [17] the authors also propose a multi-parent scheme that can be combined with any of the above sleep/wakeup patterns. The multi-parent scheme assigns multiple parents to each node in the network. This results in significant performance improvements in comparison with single-parent schemes.

II.I.II.II.III. On-Demand Schemes

On-demand schemes are based on the idea that a node should be awaken just when it has to receive a packet from a neighboring node. This minimizes the energy consumption and this feature makes it suitable for sensor applications having very low duty cycle e.g., fire detection, surveillance of machine failures etc. In such scenarios sensor nodes spend their most of the time in monitoring environmental-state. As soon as an event is detected, nodes transit to the transfer state. On-demand sleep/wakeup schemes therefore reduce energy consumption by remaining in monitoring state and show a limited latency for transitioning in the transfer state. The two different channels are used for on-demand scheme implementation: a data channel for normal data communication, and a wakeup channel for awaking nodes when needed. It has two major draw backs: first, is the additional cost for the second radio which is limited as the radio system typically accounts for a small percent of the entire cost of a sensor node, secondly, is the possible mismatch of coverage area of the two radios. Sparse Topology and Energy Management (STEM) [12] uses two different radios for wakeup signal and data packet transmissions, respectively. The wakeup radio is not a low power radio (to avoid problems associated with different transmission ranges). Therefore, an asynchronous duty cycle scheme is used on the wakeup radio as well. Each node periodically turns on its wakeup radio for some duration. When a source node has to communicate with a neighboring node, it sends a stream of periodic beacons on the wakeup channel. As soon as the target node receives a beacon it sends back a wakeup acknowledgement, and turns on its data radio. If a collision occurs on the wakeup channel, any node that senses the collision activates its data radio ‘‘up”. The wakeup beacon transmission is repeated to a maximum time unless a wakeup acknowledgement is received from the target node. This approach is known as STEM-B. In [13] the authors propose a variant of it as STEM-T that uses a wakeup tone instead of a beacon. The main difference is that in STEM-T all nodes in the neighborhood of the initiator are awakened. Both STEM-T and STEM-B can be used together with network topology protocols. In STEM the inter-beacon period is such that there is enough time to send the wakeup beacon and receive the related acknowledgement. Let T_{wakeup} and T_{wack} denote the time required to transmit a wakeup beacon and the related acknowledgement, respectively. Since nodes are not synchronized, the receiver must listen on the wakeup radio for a time T_{active} at least equal to 2 T_{wakeup} + T_{wack} to ensure the correct reception of the beacon. Clearly T_{active} depends on the bit rate of network nodes. In low bit-rate networks the time between successive active periods (T) must be very large to allow a low duty cycle on the wakeup channel. This results in large wakeup latency, especially in multi-hop networks with a large hop-count. To identify relationship between energy saving and wakeup latency, [14] proposes a Pipelined Tone Wakeup (PTW) scheme. PTW also relies on two different channels for transmitting wakeup signals and data packet. A wakeup tone is used here to awake neighboring nodes. Hence, any node in the neighborhood of the source node will be awakened. In PTW the tone detection is done by sender rather than receiver. The duration of the wakeup tone is therefore long enough to be detected by the receiver that turns on its wakeup radio periodically. The theme of this solution is that the sender sends a wakeup tone only when an event is detected, while receivers wake up periodically. In addition, the wakeup procedure is pipelined with the packet transmission so as to reduce the wakeup latency. The idea is illustrated in Figure 10 with reference to the string topology network depicted in Figure 9**.**

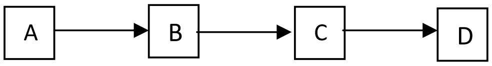

Figure 9: String Topology

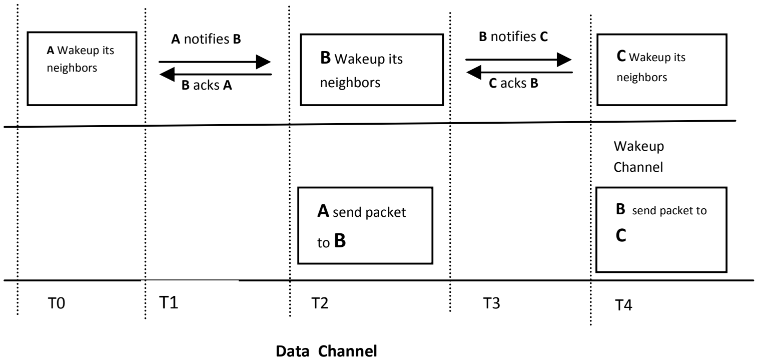

Figure 10: PTW Pipelined Wakeup Procedure

Let’s suppose that node A has to transmit a message to node D through nodes B and C. At time t0 A starts the procedure by sending a tone on the wakeup channel. This tone awakens all A’s neighbors. At time t1 A sends a notification packet to B on the data channel to inform that the next data packet will be destined to B. Upon receiving the notification message B learn that the following message is not intended for them. Therefore, they turn off their data radio. Instead, B realizes to be the destination of next data message, and replies with a wakeup acknowledgment on the data channel. Then A starts transmitting the data packet on the data channel. At the same time, B starts sending a tone on the wakeup channel to awake all its neighbors. As shown in Figure. 6 the packet transmission from A to B on the data channel and the B’s tone transmission on the wakeup channel are done concurrently. A different approach is to use two different powered radios. A low power radio for the wakeup channel which remains continuously in stand-by mode, and whenever receives a signal it wakes up the data radio [76, 77]. The wakeup latency is thus minimized. The high power radio is used in data transmission. The main drawback of this approach is that the transmission range of the wakeup radio is significantly smaller than that of the data radio. This may limit the applicability of such a technique as a node may not be able to wake up a neighboring node even if it is within its data transmission range. A side effect of using a second radio for the wakeup channel is the additional power consumption, which may not be negligible even when using a low-power radio. To overcome problems associated with the extra-energy consumed by the wakeup radio, a

Radio-Triggered Power Management scheme is investigated in [15]. The basic idea is to use the energy contained in wakeup messages (e.g. STEMB beacon) or signals (e.g., STEM-T and PTW tones) to trigger the activation of the sensor node. This approach is similar to the one used in active Radio Frequency Identification (RFID) systems [16]. In radio triggered power management method, a special hardware component and a radio-triggered circuit is used to capture the energy contained in the wakeup signal, and uses such energy to trigger an interrupt for waking up the node. The radio-triggered approach is significantly different than using a stand-by radio to listen to possible wakeup messages from neighboring nodes. The stand-by radio consumes energy from the node while listening, while the radio-triggered circuit is powered by the wakeup message. The main drawback of the radio-triggered approach is the limitation on the maximum distance from which the wakeup message can be sent. With the basic radio-triggered circuit proposed in [15], the maximum achievable distance is 3 m. However this distance may be increased up to certain extent with additional cost.

II.I.II.II.IV. Summary

On-demand protocols concept is the ideal one, as it maximizes energy saving as nodes remain active only for the minimum time required for communication. In addition, there is only a very limited impact on latency, because the target node wakes up immediately as soon as it realizes that there is a pending message. The radio triggered wakeup scheme is almost always impractical, because it can be only applied when the distance between nodes is very short indeed. An additional wakeup radio is a more promising but costly and generally it is not shipped with commonly used sensor platforms. So, when a second radio is not available or convenient, other solutions – such as the scheduled rendezvous and the asynchronous wakeup schemes – can be used. The scheduled rendezvous approach is convenient, because it is suitable to data aggregation and supports broadcast traffic but it requires nodes to be synchronized, which in some cases can be difficult to achieve or expensive. On the other side, asynchronous wakeup protocols do not need a tight synchronization among network nodes. Asynchronous schemes are generally easier to implement and can ensure network connectivity even in highly dynamic scenarios. In the asynchronous schemes nodes need to wake up more frequently than in scheduled rendezvous protocols. Therefore, asynchronous protocols usually result in a higher duty cycle for network nodes than their synchronous counterparts.

II.II. DATA ORIENTED APPROACH

Data Oriented approaches works on data sensing impacts on sensor nodes. It has two aspects:

- Avoid redundant information communication to the sink node.
- Power consumption of the sensing subsystem i.e. reducing communication is not enough when the sensor itself is power hungry.

The first case highlights the unneeded samples that result in useless energy consumption. The second statement depicts that the consumption of the sensing subsystem is not negligible. Data Oriented approaches (Figure.3) can be divided in to two cases. Case 1 of data reduction; address the case of unneeded samples. Case 2 of energy-efficient data acquisition schemes are mainly aimed at reducing the energy spent by the sensing subsystem. By following these methods, the amount of data is reduced while traversing the network towards the sink. In network, processing technique depends on the specific application and must be tailored to it. Data compression scheme involves encoding information at nodes which generate data, and decoding it at the sink. There are different methods to compress data**.** Since compression techniques are not generally related to WSNs, the topic is not discussed here. Data prediction consists in building an abstraction of a sensed phenomenon, i.e. a model describing data evolution. The model can predict the value sensed by sensor nodes within certain error bounds, and resides both at the sensors and at the sink. The various approaches studied are given below.

II.II.I. Data Prediction

Data prediction techniques are based on model of sensing, so that queries can be answered using the model instead of the actually sensed data. The two instances of model are possible, one residing at the sink and the other at source nodes. The sink model can be used to answer queries without requiring any communication, thus reducing the energy consumption. The sensor nodes sample data as usual and compare the actual data against the prediction. If the sensed value falls within an application dependent tolerance, then the model is considered valid. Otherwise, the source node may transmit the sampled data and/or start a model update procedure involving the sink as well. Data prediction technique models are data specific. The three main classes are: a stochastic characterization, i.e. in terms of probabilities and/or statistical properties. Here data is either mapped to a random process given by probability density function or by a state space representation phenomenon can be used. The second class of data prediction techniques is time series forecasting, where a set of historical values obtained by periodical samplings are used to predict a future value in the same series. This technique differs from other in respect of explicitly considering the internal data structure. The last class of data prediction techniques relies on a heuristic or a state-transition model describing the sensed phenomenon. Such algorithmic methods derive methods or procedures to build and update the model on the basis of the chosen characterization.

II.II.I.I. Time Series Forecasting

Moving Average (MA), Auto-Regressive (AR) or an Auto Regressive Moving Average (ARMA) models best describes time series methods. These models are quite simple, and can be used in many practical with accuracy. PAQ [43] is based on a low-order AR model, with the aim of reducing the amount of computation to be performed by sensors. A set of sampled value are taken by this model for computation. The sample is stored in queue, when the queue is full they are send to sink. The communication between nodes and the sink is limited to the parameters of the model and does not include sensor readings. Each model is associated to a user-specified error bound. When a predicted value falls within the error bound, the model is considered valid for the given sensed quantity. Otherwise one of the following cases can occur. (i) Sampled data are marked as outliers, for example because of a wrong reading. Outliers can be ignored at the source. (ii) The model is marked as invalid, so that it has to be recomputed and re-sent to the sink.

SAF [44] made an improvement to the earlier work by refining the AR model to include a trend component in the forecast as well. This leads to a better prediction of phenomena with sharp variations in their values. Moreover, SAF can detect not only outliers, but also inconsistent data. Nodes here can improve model stability in two steps: (i) they can filter the data to smooth outliers; (ii) they can enlarge the size of used data to decrease the impact of the outliers. Also the authors present a centralized clustering scheme which is optimal in the number of clusters and has a complexity of O (n **log** n). The work in [15] extends the time series forecasting scheme with an adaptive multi-model selection mechanism. In multi model selection method system itself choose the appropriate model for that every system must have a set of models. Here the complex models can give better prediction at the expense of a higher update cost. All models are updated instantly but only the current one is used for prediction. If the error between sensed data and the current model is higher than the allowed threshold, then the current model is switched to the one satisfying the requested accuracy and minimizing the cost of the update. Then an update procedure is performed to ensure that both source and sink nodes are synchronized to the newly selected model. To save nodes' resources, poorly performing models are discarded over time by using a racing mechanism.

II.II.I.II Algorithmic Method

The algorithmic approach is based on predictions computed on heuristic or behavioral characterization of the sensed phenomena. In [37] prediction approach is applied to sensor networks in analogy with video compression. Here, at a given instant, a sensor network can be thought as an image where each ‘‘pixel” is represented by the data sensed at a given node. Therefore it is possible to exploit the spatial correlation between samples. In addition, as sensed data generally vary over time, the evolution of readings can be seen as a ‘‘sensor movie”. Hence the authors present a data prediction technique, called PREMON, which is inspired by the concepts of MPEG encoding. When the monitoring starts sensor nodes send their initial readings to the sink. Then the sink computes the model by evaluating the correlations between macro-blocks and deriving a motion vector relative to each block. After the model has been obtained, it is sent back to the sensors. From this time on, sensors compare each sample with the prediction derived from the model. When sensed data are close to the prediction within a user-specified error, sensors do not transmit the data to the sink. The model is periodically invalidated, and not representing sensed data any more. After the expiration, the process of data collection and model computation starts again from the beginning.

Initially PREMON uses a centralized solution that was extended by buddy protocol [38] for distributed systems. In detail, each node attempts to establish a buddy relationship with its neighbors. As a consequence, a number of buddy-groups (i.e. clusters) are formed so that only a single node is representative for all its buddies. This representative node (cluster-head) is responsible for monitoring and query processing, while the others can go to sleep. Within the buddy-group, the cluster-head is rotated so that the energy consumption is spread over all nodes in the group. Communication between ordinary nodes and the cluster-head can be one of default and PREMON. In the default mode, nodes simply send sampled data to the cluster-head. In the PREMON mode, nodes just send a model to the cluster-head, and data which do not fit the predictions. Based on cost estimation every node decides whether to use default or PREMON. For stable sampled phenomenon PREMON mode is more convenient, so as to reduce exchanged packets. However for fast, data change the overheads of PREMON mode is so high that the default mode can be more energy efficient in this case.

Another approach introduced is Energy Efficient Data Collection (EEDC) [45], where each node associates an upper and a lower bound, difference of which represents the accuracy of readings, to the actual value of the sensed data. These bounds are sent to the sink, which stores them for each sensor in the network. While acquiring the data, the sensors check the samples against the current bounds. If they fall outside the expected accuracy, the nodes send an update to the sink. This kind of interaction is called source-initiated update. On the other side, the sink receives queries from users with an associated requested accuracy. When the requested accuracy is lower than the actual accuracy provided by the value bounds, the sink can respond using the cached range. Otherwise the sink may request the real value and its new approximation to be used for subsequent queries directly to the sensor. This kind of interaction is called consumer-initiated request and update. Clearly the updates described above impact on the power consumption of nodes. Here the cost is related to the method to select ranges and the way sensor manages their state. The authors hence present a method to compute the optimal ranges to represent data.

II.II.I.III Stochastic Method

Stochastic methods use a probabilistic model to predict sensed value. In [42] (ken model) this concept is well defined. After a training phase a probability density function referred to a set of attributes is obtained. When the model is not considered valid any more, the source node updates it and transmits a number of samples to the sink, so that the corresponding instance can be updated. Ken is flexible enough to use models tailored to a specific phenomenon and exploiting spatial or temporal correlations. For example, temporal correlations can be modeled as Markov processes. Spatial correlations are somewhat more difficult as they require bringing correlated data together at one node, and manage the model representing the evolution of the phenomenon in a certain area. Indeed nodes have to coordinate such that the communication cost is minimized. The authors of [37] exploit a similar approach, but use a Kalman filter as the core model for predictions. An extension of [42] is given in [37], where a Dynamic Probabilistic Model (DPM) is exploited to implement a probabilistic database view. The concept of bringing to the user such a hidden state of the sensor database can be actually implemented through model-based views [35]. The solution proposed in [37] obtains these views by means of a DPM. An interesting application of DPMs consists in deriving the internal (hidden) state of the sensed phenomenon through the available sampled data. For example, it is possible to get the operational state of a node on the basis of its readings, even though a specific variable is not available in the system. In detail, the authors use a particle filter approach to store the output of a DPM as a set of weighted samples. The querying system converts queries referring to the DPM view into queries suitable to the particle-based representation. The resulting queries can also be optimized and can perform aggregates over requested data. Particles are updated to match the incoming data stream by performing particle Filtering.

II.II.I.IV. Summary

The stochastic techniques are general and sound and provide high level operations such as aggregation. The main drawback of this class of techniques is high computational cost, which may be too heavy for current off-the shelf sensor devices. Stochastic approaches seem to be more convenient when a number of powerful sensors are available. The time series forecasting techniques can provide satisfactory accuracy even when simple models (i.e. low order AR/MA) are used. To this end, their implementation in sensor devices is simple and lightweight. In addition, most advanced techniques like [43] do not require the exchange of all sensed data until a model is available. Moreover, they provide the ability to detect outliers and model inconsistencies. An interesting motivation involves the adoption of a multi-model approach as the one taken in [15]. Finally the algorithmic techniques are more application specific and need to be used specifically.

II.II.II. Application Specific Data Acquisition

Sensors are randomly distributed devices in a geographical environment and most of them are application specific. It state that the energy consumption of the sensing subsystem is not only relevant, but it can also be greater than the energy consumption of the radio [46]. There could be several factors affecting it [47].

Power hungry transducers: Some sensors intrinsically require high power resources to perform their sampling task. For example, sensing arrays such as CCDs or CMOS image sensors or even multimedia sensors [48] generally require a lot of power.

Power hungry A/D converters. Sensors like acoustic [49] and seismic transducers [50] generally require high rate and high-resolution A/D converters. The power consumption of the converters can account for the most significant power consumption of the sensing subsystem, as in [51].

Active sensors: Another class of sensors can get data about the sensed phenomenon by using active transducers (e.g. sonar, radar or laser rangers). In this case sensors have to send out a probing signal in order to acquire information about the observed quantity, as in [52].

Micro sensor design: In [82] different system design approaches used in micro sensor (Figure: 11) systems are presented. It shows modular, scalable, power-aware micro sensor architecture intended to deal with dynamic range required of sensor network systems.

Long acquisition time: The acquisition time may be in the order of hundreds of milliseconds or even seconds; hence the energy consumed by the sensing subsystem may be high, even if the sensor power consumption is moderate.

Under application specific data acquisition the conservation schemes have to reduce actual acquisitions instead of communications. These techniques are aimed to reduce energy consumption of the sensing subsystem as well as number of communications.

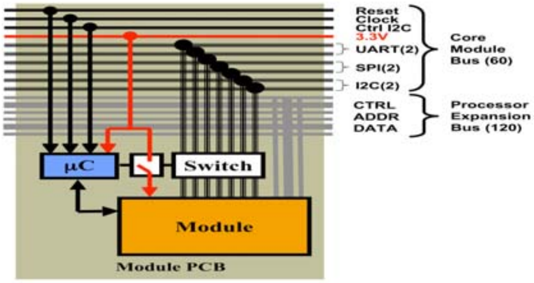

Figure 11: Power-Aware Micro-Sensor Module

The adaptive sampling techniques exploit similarities of correlated sample to reduce the amount of data to be acquired from the transducer. The hierarchical sampling approach assumes that nodes are equipped with different types of sensors. As each sensor is characterized by a given resolution and its associated energy consumption, this technique dynamically selects which class to activate, in order to get a tradeoff between accuracy and energy conservation. The active sampling model takes an approach similar to data prediction. A model of the sensed phenomenon is built upon sampled data, so that future values can be forecasted with certain accuracy. Model-based data sampling exploits the obtained model to reduce the number of data samples, and also the amount of data to be transmitted to the sink.

II.II.III.I. Adaptive Sampling

Adaptive sampling can reduce the number of samples by exploiting temporal correlations between data. Here a periodically sampled data is used to derive the actual signal. From the Nyquist theorem it is known that the sampling frequency needed for the correct reconstruction of the original signal should be FsP2 _ F_{max} where F_{max} is the maximum frequency in the power spectrum of the considered signal. Unfortunately, choosing F_{max} is not trivial because (i) it cannot be known a priori, thus leading to choose an unnecessary high sampling frequency, (ii) it may vary over time To overcome this problem the authors propose an adaptive algorithm that dynamically estimates the current maximum frequency F_{max}, according to the trend of measured data. The algorithm relies on a modified CUSUM test [53] to set the sampling rate. The algorithm is executed at the sink for each sensor node. The estimated sampling rates obtained by the sink are then notified to sensor nodes. A similar approach is proposed in [54], where the sampling rate is derived based on a Kalman filter. This method uses a centralized approach where the sink establishes the sampling rate of nodes. Further the adaptive sampling mechanism is coupled with bandwidth reservation mechanism which guarantees that the overall traffic does not exceed the network capacity. The other scheme is back casting [74] where the nodes deployed with sufficient density do not have to sample the sensed field in a uniform way. It implies that more nodes can be activated if sensed quantity is very high. This can be achieved by initially activating a subset of node for sensing. This set of nodes can get a coarse-grained spatial distribution of the sensed phenomenon through a hierarchical estimation of the field. The estimation takes several steps:-

- The active sensors are deployed, to recursively partition the sensing field in a number of segments with non-uniform pattern.
- Second phase is to group sensors in clusters, managed by a cluster-head.
- Next step is refinement where the fusion center can activate additional sensors in the locations whre the spatial correlation is low. Here the fusion center ‘‘backcasts” an activation message to the cluster heads present in the smallest segment of the initial network.
- These cluster-heads forward the received message to activate additional nodes in the cluster.

Spatial correlation is also exploited in [55] to selectively reduce the number of nodes which have to report data to the sink. The authors define a spatial Correlation based Collaborative MAC protocol (CC-MAC) that regulates sensor node transmissions so as to minimize the number of reporting nodes while achieving the desired level of distortion. To this end, the Iterative Node Selection (INS) algorithm, which resides at the sink, derives the correlation radius Rcorr, given the maximum distortion that can be tolerated by the application. This information is then broadcast to sensor nodes during the network setup and it is used during the operational phase. Since a sensor node can be both a data source and a data forwarder, the CC-MAC protocol includes two different CSMA/CA-based components, Event MAC (E-MAC) and Network MAC (NMAC). E-MAC prevents the transmission of redundant information during the channel access phase; N-MAC manages the transmission of route through packets by giving them a higher priority than newly generated packets. Although this proposal has been conceived for reducing the radio energy consumption, it can reduce the sensor consumption as well, as sensor nodes may switch off their sensing subsystem when they are not reporting data.

II.II.II.II. Model-Based Data Sampling

Model-based data sampling takes an approach similar to data prediction. The data prediction keeps the sampling frequency fixed, and uses the periodical acquisition to tune the model. Although this approach reduces the number of communications, it does not impact on the power consumption due to data acquisition. The model-based data sampling reduces the number of data samples by using a computing model. As an example, the Barbie-Q (BBQ) query system [38] s is a probabilistic model and a planner, both residing at the sink. It is probabilistic, as starting from a given number of samples; a probability density function (pdf) over a set of attributes is derived. The pdf can get both spatial and temporal correlations. From the obtained pdfs it is possible to derive the accuracy that a value is included within a user-specified interval. Moreover the model is updated by combining the pdfs with the observed samples, so that future values can be effectively forecasted. The model is built by the sink after an initial learning phase in which nodes transmit sampled data to get a first instance of the pdfs. The stored model is then updated along with received answers to queries. It's up to the planner to decide in which way to collect data. To this end, the planner builds a query plan including a list of sensors to be queried and the most relevant quantities to get. Upon receiving a query, the planner computes the associated observation cost by considering both sampling and communication costs. A similar approach is used in [58], where an Adaptive Sampling Approach to Data Collection (ASAP) is proposed. In contrast with BBQ, ASAP splits the network into clusters. To this end, a cluster formation phase is performed to elect cluster heads and select which nodes belong to a given cluster. The metrics used to group nodes within the same cluster include the similarity of sensor readings and the hop count. Therefore, clusters are further divided into sub clusters. Within a sub cluster, only a single node (sampler) can acquire data from the environment and send them to the sink. Through an initial set of samples provided by all nodes in the cluster, the cluster head constructs the sub clusters and elect samplers. The probabilistic models – which exploit both spatial and temporal correlations – are built in-network for each sub cluster and are sent to the sink. Then the sink can derive sensed data by using the actual data received from samplers or predict them through the model for the other nodes. Both clusters and sub clusters are periodically recomputed. Note that the model update requires only exchanging data within a sub cluster, so that the communication overhead is reduced as well. A different approach is taken by [59], where a Utility based Sensing and Communication (USAC) protocol is presented in the context of glacial environment monitoring. In this case, a limited-window linear regression model is used to forecast samples. The algorithm for updating the sampling frequency is fully distributed, i.e. it is evaluated at each sensor node, and works as follows. If the predicted value falls outside the confidence interval, then the sampling frequency is increased to a pre-defined maximum value f_{max}. This improves the accuracy during the model update, which follows sudden changes in the observed data. On the other side – i.e., if the prediction lies within the confidence interval – then the sampling frequency is decreased by a factor a 2 [0, 1], unless a minimum pre-defined frequency f_{min} is reached.

II.II.II.III. Hierarchical Sampling

Hierarchical sampling approach contains sensor nodes equipped with different types of sensors. Each of them is characterized by specific performance features, like accuracy and power consumption. As simple sensors is energy efficient but have a very limited functionality while complex sensors have greater functionality but consumes more power. The low-power sensors can be used to get coarse-grained information about the sensing field. If an event is detected, the power hungry sensors can be activated to collect the data. This technique is referred to as triggered sampling scheme. For instance, [44] presents a triggered sampling application for structure health monitoring and damage detection. The structure is split into zones containing sensors with different capabilities: m-nodes and l-nodes. M - Nodes are equipped with accelerometers and sample the environment periodically. On the other hand, l-nodes are provided with strain gauges and they sleep for most of the time. When no problem is detected, m-nodes can sleep until the subsequent activation. Otherwise, first they contact their neighbors to cross-check readings. If the check leads to a suspicious problem, the surrounding densely deployed l-nodes are activated to get fine-grained information and eventually report the damage. For example, in [56] a multi-scale approach is applied to a fire emergency scenario. 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 over a given threshold – static nodes ask the sink for a deeper investigation. Then the sink dispatches a mobile sensor to visit the emergency location, collect data from the static sensors and take a snapshot of the event scene. After observing the event, the mobile sensor gets back to the sink and reports collected data. A similar solution, applied to environmental monitoring, is proposed in [57].

II.II.II.IV. Summary

Adaptive sampling techniques are general and efficient hence are very effective. They require high computations hence are suitable for centralized implementation. Most of the proposed solutions are limited to space or time characterization. The hierarchical sampling techniques are actually feasible for quantitative data measurement, sensed by different transceivers. This approach is very energy-efficient, but limited to specific applications. In fact, it may not always applicable, depending on the specific requirements. Model-based data sampling solutions share almost the same strengths and weaknesses, however in this case the goal of the prediction is to save energy due to data acquisition.

III. MOTION BASED ENERGY CONSERVATION SCHEMES

The earlier approaches described before are using the concept of Figure 1 (above) where nodes are assumed to be static and with high density to allow communication between any two nodes. Recently, the mobility has been considered as an alternative solution for energy-efficient data collection in wireless sensor networks. Motion based approaches considers the movements of either sink nodes or relay node (Figure. 3). The important issue in mobility is the type of control the sensor-network designer has on the mobility of nodes. A detailed discussion on this point is presented in [70, 73]. Mobility of sensor nodes is actually feasible, and it can be accomplished in different ways [60]. However, mobilizers can be used with sensor nodes for changing their location but they are generally quite expensive from the energy consumption point of view, adding mobility to sensor nodes may be not convenient. Here, instead of making each sensor node mobile, mobility can be limited to special nodes which are less energy constrained than the ordinary ones. Moreover the mobility can be achieve by placing sensors on elements which are mobile of their own like car, bus and animals etc. Therefore the two possibilities exist either all sensors are mobile elements or only a limited number of special nodes can be placed on mobile elements, while the other sensors are stationary. In both cases there is no additional energy consumption overhead due to mobility, but the mobility pattern of mobile elements has to be taken into account. Mobility in wireless sensor networks generates several issues regarding connectivity. Because the sensor network design will be a sparse architecture it is not required to deploy a large number of nodes at the same time, as the need increases mobile elements can reach eventual isolated nodes in the network. Moreover a dense network can be converted to sparse after deployment of sensor nodes. Mobility is also useful for reducing energy consumption. Packets coming from sensor nodes traverse the network towards the sink by following a multi-hop path. When the sink is static, a few loaded paths can exist, depending on the network topology and packet generation rates. Alternatively a deputed mobile device can collect data. The nodes other than mobile node have to wait for the passage of the mobile device, so that they can route messages towards it. Hence the ordinary nodes can save energy in terms of reduced link errors, contention overhead and forwarding. The motion based energy conservation schemes can be classified in to two categories mobile sink (MS) or a mobile relay (MR).

III.I. Mobile-Relay Based Technology

In this method the most well-known approaches is given by the message ferrying scheme [80]. Message ferries are special mobile nodes which are introduced into a sparse mobile ad hoc network to offer the service of message relaying. Message ferries move around in the network area and collect data from source nodes. They carry stored data and forward them towards the destination node. Thus, message ferries are moving communication infrastructure which accommodates data transfer in wireless networks. Data-MULE is similar type of technique [71, 81]. It consists of three-tier architecture (Figure. 12**).** (i) The lower level is occupied by the sensor nodes to perform data sampling periodically from the environment. (ii) The middle level consists of mobile agents named Mobile Ubiquitous LAN Extensions, or MULEs for short. MULEs are free to move anywhere in the area covered by sensors to collect data and temporarily stored in local buffers. Data MULEs can be e.g. people, animals, or vehicles etc. Generally, they move independently from each other by following unpredictable routes.

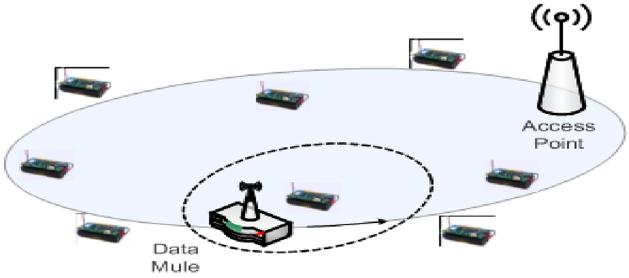

Figure: 12 Data Mule Architecture

(iii) The upper level consists of a set of Access Points (APs) which receive information from the MULEs. They are connected to a sink node where the data received is synchronized and stored, multiple copies are identified, and acknowledgments are managed. The static sensor nodes wait for a MULE to pass by and send data to it. Sensor-to-MULE transmissions make use of short-range radio signals and hence energy consumption is low. While moving around, the MULE eventually passes by any AP and transmits the data collected from sensors to it. Sensor nodes which are located in proximity of the MR path send their data directly to the MR when passing by. Nodes which are far apart from the path followed by the MR send their data over a multi-hop path towards the MR when it passes by or alternatively to one of the nodes which are positioned near to the path of the MR. These nodes act as data caches until the MR passes and finally collects all stored data. Energy saving is addressed in that a large number of nodes is visited by the MR and can thus transmit data over a single hop connection using short range radio. The other nodes which are not in proximity of the path followed by the MR send their data over a multi-hop path which is however shorter, and thus cheaper, with respect to the path established towards a fixed sink node in a classical dense wireless sensor network. As the trajectory of the MR is assumed to be fixed, it can be controlled only in time. MR can be designed in such a way that it can move fast where no or only a few sensors are available and can stop where sensor deployment is dense. The short-range radio communication makes the Data MULEs architecture an energy-efficient solution for data gathering in sparse sensor networks. It also guarantees scalability and flexibility against the network size. This solution has limitations as the latency for data arrival at the sink may be considerable, because (possibly) long time intervals elapse from the sampling instant to the moment the MULE takes the data, and then till the time the MULE actually reaches the AP and delivers the data to it. Moreover sensors have to continuously wait for any MULE to pass and cannot sleep. This leads to energy wastage. Therefore energy efficient approaches based on a single data mule have limited scalability.

III.II. Mobile-Sink Based Technology

Most of the approaches related to mobile sink use Linear Programming techniques to optimize network lifetime. In [61] the authors propose a model consisting of a MS which can move to a limited number of locations (sink sites) to visit a given sensor and communicate with it. During visits to nodes, the sink stays at the node location for a period of time. Nodes not in the coverage area of the sink can send messages along multi-hop paths ending at the MS and obtained using shortest path routing. The authors derive a LP formulation in order to obtain the optimal sojourn times at each sink site. The provided solution maximizes the network lifetime while enforcing balanced energy expenditure, but do not consider the costs due to sink relocation. A similar approach, exploiting multiple MSs, is proposed in [62]. Simulation results show that the multiple sink approach of [72] can achieve a network lifetime which is five/ten times longer than with the static sink approach. The model of [63] is a centralized approach that considers the residual energy at sensors and the routing policy, so that it obtains a longer network lifetime. In [64] a distributed protocol approach is used to approximate the optimal scheme. To this end, the Greedy Maximum Residual Energy (GMRE) scheme is introduced. According to GRME, the MS selects as the new location the one which is surrounded by nodes with the higher residual energy. A special node called sentinel is selected around each site to get the energy information from the surrounding nodes and reply the query coming from the MS. The MS uses this information to decide whether or not it should move. Another heuristic-based relocation scheme is considered in [65], where the MS selects its new location in proximity to the nodes with the higher traffic generation rates. A different class of solutions jointly considers mobility and routing. Some researchers have focused on the definition of a data collection/dissemination scheme suitable to sensor networks with MSs. For instance, in [66] the authors evaluate by simulations the joint impact of MS mobility and data-collection strategy. Several scenarios are analyzed by varying the mobility pattern and the different data collection paradigm. In addition to this study, a number of data dissemination schemes targeted to MSs derives from the well known Directed Diffusion [67]. For example, Two-Tier Data Dissemination (TTDD) [68] is a low-power protocol for efficient data delivery to multiple MSs. Instead of passively waiting for queries coming from sinks, sensor nodes can proactively build a structure to set up forwarding. To this end, the sensing field is represented as a set of grid points. The nodes closest to the grid points (dissemination nodes) are in charge of acquiring forwarding information. The lower tier is composed by sensor nodes within the local grid square of the MS current location (cell). As soon as a node has data available, it builds the grid structure by recursive propagation of data announcement messages. As a result of this grid construction phase, dissemination nodes are elected. Then, the MS sends a query by flooding a message within its current cell. The dissemination node closest to the MS will propagate the query along the grid towards the data source. As a result of the query forwarding process, the path from the data source to the sink is obtained so that the requested data can traverse the network in the opposite direction. TTDD assumes that nodes locations are known and a geographic routing protocol is used. Another approach is Scalable Energy-efficient Asynchronous Dissemination protocol (SEAD). SEAD builds and maintains a dissemination tree (d-tree for short) in which stationary nodes are used as end-points on behalf of the MS. The adopted scheme caches sensed data in the d-tree in such a way to reduce the energy consumption due to data collection.

III.III. Summary

The recent wireless sensor networks with mobile data collectors has well described the behavior of the network and has outlined possible solutions to efficient data collection and energy efficient sink movements. The main challenge here for the ordinary node is the discovery of mobile node. Here energy consumption can be minimizing probability of missing contacts with the mobile elements as low as possible. For it most of the schemes uses a simple periodic wakeup scheme with an active period. However, the discovery scheme can be targeted to the mobility pattern of sinks/relays by identifying its distinctive characterization. Another area of investigation is to define an efficient data transfer protocol specifically targeted to communications between a node and a mobile element. To this end, an Adaptive Data Transfer (ADT) protocol is proposed to tune the communication parameters so as to reduce data transfer times. Further the transmission scheduling issue has been deeply analyzed from the mobile data collector point of view, i.e. the amount of time it has to stay in a given area to collect data coming from static nodes. The other sides of communication i.e. when sensor nodes should transmit gathered data to the mobile element need to be considered. As the data transfer efficiency strictly depends on the detection of the mobile elements, there is a need to jointly characterize protocols for discovery and data transfer, as in [69]. Moreover there is need to design protocols which can adapt to different scenarios (e.g. the mobility pattern of the mobile elements) by automatically tuning the operating parameters to fit actual operating conditions.

IV. CONCLUSION

In this paper we have reviewed the main approaches to energy conservation in wireless sensor networks. A systematic and comprehensive classification of the solutions is presented in this paper. The considered approaches are not the alternatives they should rather be exploited together. An important approach that can be considered for energy saving is integration of the outcome of traditional approaches for energy saving. This involves characterizing the interactions between different protocols and exploiting cross-layer interactions. Most of the solutions are based on the assumption that energy consumption of radio is much higher than the consumption in data sampling or processing, while many real applications shows greater power consumption In data sampling/processing instead of radio transmission. Further it is observed that the field of data acquisition has not been fully explored for energy conservation. Finally, we observe an increasing interest towards MAC protocols used for time synchronization and energy conservation. The mobility of nodes is also a challenging task in energy optimization. In many practical applications Micro-sensor network can be very efficient and robust if communication MAC protocols can appropriately exploit the mobility of collector nodes.

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