MAC Protocols for Energy Harvesting Wireless Sensor Networks: Survey

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Energy harvesting (EH) technology in the field of wireless sensor networks (WSNs) is gaining increasing popularity through removing the burden of having to replace/recharge depleted energy sources by energy harvester devices. EH provides an alternative source of energy from the surrounding environment; therefore, by exploiting the EH process, WSNs can achieve a perpetual lifetime. In view of this, emphasis is being placed on the design of new medium access control (MAC) protocols that aim to maximize the lifetime of WSNs by using the maximum possible amount of harvested energy instead of saving any residual energy, given that the rate of energy harvested is greater than that which is consumed. Various MAC protocols with the objective of exploiting ambient energy have been proposed for energy-harvesting WSNs (EH-WSNs). In this paper, first, the fundamental properties of EH-WSN architecture are outlined. Then, several MAC protocols proposed for EH-WSNs are presented, describing their operating principles and underlying features. To give an insight into future research directions, open research issues (key ideas) with respect to design trade-offs are discussed at the end of this paper.

Keywords: Energy harvesting, ambient energy, solar, medium access control.

I. Introduction

Wireless sensor networks (WSNs) typically consist of a set of resource-constrained sensor nodes with a finite capacity of power sources, each of which has the capabilities of sensing, computation, and wireless communication to perform a common task [1]. Over the last two decades, WSNs have been a topic of significant research with a broad range of applications, including environmental, industrial, military, and health applications. An inherent feature of WSNs is their random deployment in inaccessible areas where replenishment (recharging or replacement) of a node's energy source is often impractical. Sensor nodes lose their operation when their power source is depleted. Emphasis has, therefore, been extensively placed on maximizing the lifetime of WSNs based upon the effective utilization of their source of power.

In the search for the ability to prolong the lifetime of WSNs, the design of energy-efficient medium access control (MAC) protocols has emerged as a central research topic; MAC protocols control the operation of radio through efficient and intelligent assignment of channel capacity in a shared medium. It is well-known that *communication* in a WSN is more energy-consuming than computation, which makes the development of energy-efficient MAC protocols vitally important. A large number of MAC protocols have been proposed for conventional energy-constrained WSNs that provide high channel utilization, low delay, and low energy consumption [2]–[3]. Although these MAC schemes do extend the lifetime of WSNs, inevitable battery depletion will ultimately result in a network losing its perpetual operation.

Recent advances in energy harvesting (EH) technology have resulted in the design of new types of sensor nodes (see Fig. 1), which are able to extract energy from the surrounding

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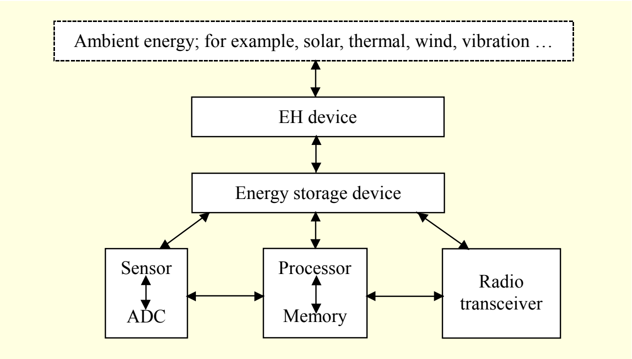

Fig. 1. EH node architecture: charge-store-spend model.

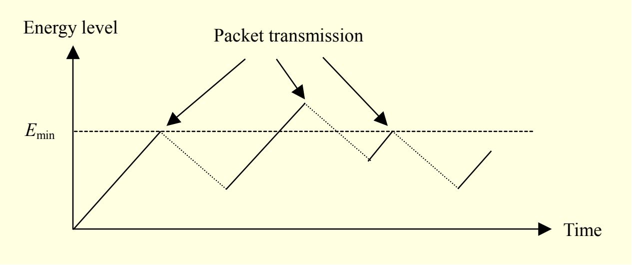

Fig. 2. Energy characteristic of EH-WSN node.

environment [4]. The major sources of EH include solar, wind, sound, vibration, thermal, and electromagnetic power. The concept of extracting ambient energy is to convert harvested energy from existing environmental sources into electricity to power sensor nodes; an energy storage device is used to accumulate such energy.

EH sensor nodes have the potential to perpetuate the lifetime of a battery through continuous EH. This has changed the fundamental design criterion of MAC protocols for EH-WSNs. However, the amount of ambient energy that can be harvested is time-variable and heavily dependent on environment conditions [5]. The main objective of new EH-WSN MAC protocols is to increase the performance of a network in association with the available rate of energy to be harvested [6].

Because of the uncertainty of the availability of ambient energy, appropriate MAC protocols are required to carefully check the level of residual energy to coordinate the transmission of EH-WSN nodes. To realize a successful transmission, a certain amount of energy that is required to transmit a packet should be harvested. On the other hand, any relevant energy storage device has only a limited capacity; therefore, there is the potential for a wastage of excess harvested energy. Therefore, the key principle is to achieve an effective balance between energy usage and energy storage. Consequently, EH-WSN nodes can operate perpetually as long as their energy level exceeds E_{min}, as illustrated in Fig. 2.

This paper provides a detailed survey of recently-proposed MAC protocols for EH-WSNs. With the key benefit of a perpetual lifetime, designing new MAC protocols for EH-WSNs will gain a great deal of attention in the future. Background information on the topic is presented in Section II, covering the components of EH, design issues, and power management. Section III presents the details of the MAC protocols for EH-WSNs, highlighting their main mechanisms. We discuss the open issues and potential research directions for researchers in Section IV. Finally, Section V concludes the paper.

II. Background to EH-WSNs

The potential of EH technologies for WSNs with the capability of extracting energy from the environment has been introduced in [6]–[8]. In this section, we provide background information on EH-WSNs in detail.

1. Main Sources of Ambient Energy for EH-WSNs

A variety of potential energy sources that can be obtained from the environment are available for use in EH-WSNs. Detailed informative studies of ambient energy sources can be found in [8] and [9]. This section only introduces the most promising energy sources for EH-WSNs.

Solar power is perhaps the most promising energy source; it is the conversion of sunlight into electricity using photovoltaic cells. Solar energy conversion is a commercially established technology providing high power outputs and is suitable for large-scale applications. However, the availability of solar power is a significant constraint and strongly depends on environmental conditions, particularly the intensity of sunshine.

Wind EH — converting air-flow energy into electricity — is traditionally used in a wide range of high-power applications with large wind turbine generators (WTGs). The physical size of typical WTGs is a challenge for small-scale applications and the strength of the wind can vary significantly over time due to weather conditions. Therefore, the prediction of the rate of EH is an important task, and effective models have been proposed to accurately estimate future energy availability based on past energy observations [10]–[11]. Designing small-scale wind EH for EH-WSNs is still ongoing research; an example of a wind-driven EH system for EH-WSNs can be found in [12].

Thermal EH is the process of extracting energy from temperature difference/gradients between two junctions of a conducting material, such as that found in devices mounted on the human body. A recent publication has presented the design of a new thermoelectric generator that exploits natural temperature variations (even small changes) to harvest ambient thermal energy [13]. Powering EH-WSN nodes with ambient temperature changes is an efficient way of obtaining power. A combination of light and thermal EH schemes for indoor applications has been proposed to prolong the lifetime of a wireless sensor node, thereby enhancing the performance of EH-WSNs [14].

Mechanical sources, including vibration, kinetic, mechanical pressure, and strain movement, can be used to harvest energy to power EH-WSN nodes, such as environmental vibration–based harvesting [15]. Therefore, harvesting this type of energy offers a great potential for powering EH-WSN nodes. In particular, mechanical vibrations can provide higher energy density for indoor applications.

2. EH Node Architecture

A good survey of the characteristics of EH sensor systems has been recently published in [4]. A typical EH-WSN node employs an EH device to harvest an ambient source of energy. Most of the nodes use the *Harvest-Store-Spend* policy in which the architecture has a storage component to store the harvested energy. This strategy performs well when the level of ambient energy to be harvested is greater than the current energy consumption. Alternatively, the *Harvest-Spend* strategy allows EH only when needed, and a node becomes operational as long as the power output of the EH device provides sufficient energy. Because of the uncertainty surrounding the future availability of energy, the *Harvest-Store-Spend* policy is more suitable for EH-WSN applications, because it can prevent energy shortages at particular scheduled operation times.

The choice of storage component is of paramount significance in EH systems. Two popular storage solutions for EH-WSN nodes are rechargeable batteries and super-capacitors. Rechargeable batteries offer limited recharge cycles and high charge times [16]. The charging characteristics of super-capacitors, theoretically an unlimited number of times, make them suitable for long-term use in EH-WSNs. Another benefit of super-capacitors is their capability of storing higher power density. The circuit complexity of super-capacitors is simple and there is no need for extra circuitry to protect the system from full-charge or deep-discharge. The key characteristics of these energy storage devices are summarized in Table 1.

Table 1. Key characteristics of super-capacitors and rechargeable batteries.

Parameter	Super-capacitor	Li-ion battery	NiMH battery	SLA battery
Recharge cycles	Unlimited	1,200	1,000	500–800
Charge time	Low	Medium	High	High
Energy density	2 to 6 Wh/kg	156 Wh/kg	100 Wh/kg	26 Wh/kg
Power density	1 to 10 kWh/kg	0.1 to 1 kWh/kg	0.25 to 1 kWh/kg	0.18 Wh/kg

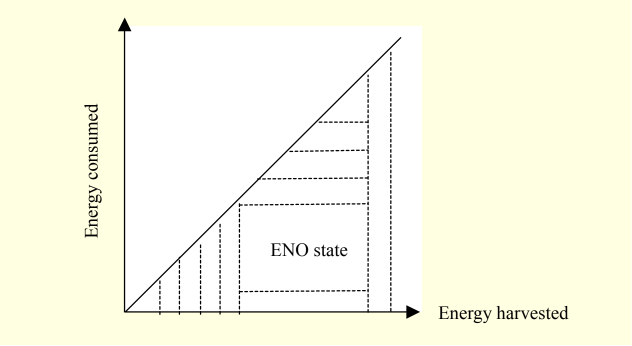

Fig. 3. Energy-neutral operation (ENO) condition.

3. Power Management

In traditional MAC protocols, the main goal of the power management scheme is to minimize energy consumption. However, the objective of the power management scheme in MAC protocols for EH-WSNs is to maximize the lifetime of WSNs by balancing energy usage with the rate at which it can be harvested. Therefore, a new power management approach is essentially required to provide perennial operation considering the variable behavior of the relevant energy sources. To achieve a perpetual lifetime (subject to hardware failure), the amount of energy harvested should always be greater than or equal to the amount of energy consumed (see Fig. 3). This is called an ENO state [17]; networks in ENO states are able to continue to operate perennially.

III. MAC Protocols

In this section, the MAC protocols proposed for EH-WSNs are described briefly along with their fundamental design properties. Additionally, several approaches to evaluating the performance of traditional MAC protocols with EH are presented.

1. Probabilistic Polling MAC (PP-MAC)

The performance analysis of various existing MAC protocols, CSMA and polling-based schemes, has been studied for EH-WSNs on a single-hop scenario [18]. Two variants of the CSMA protocol, slotted and unslotted, have been modified for use in EH-WSNs. An ID polling scheme is considered in which a sink broadcasts a polling packet including the ID of a

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sensor to be polled, which is then followed by the immediate response of a packet transmission from the polled node. Due to the changing energy charging times, the sink selects the polling ID at random. It is assumed that the polled node will then be registered as being in a “charging” state so as not to be polled again in the next round. Polling-based protocols have a number of drawbacks, such as long delays waiting for the associated polling packets or the adaptation of new nodes to be added or failed nodes to be removed.

To address the drawbacks of the ID polling scheme, the PP-MAC protocol has been proposed to enhance channel performance in terms of network throughput, fairness, and inter-arrival time, which benefits from EH rate, node density, and packet collisions. In PP-MAC, nodes first harvest sufficient energy in only a charging state and then stay in a “receive” state to receive a polling packet. If the level of energy in a node is not adequate to transmit a packet, then the node goes back to a charging state (the *Harvest-Spend* policy). The distinctive feature of PP-MAC is that a sink transmits a contention probability, p_c, in a polling packet instead of broadcasting the ID of a sensor. This is to set a probability in each node to decide whether to transmit. When a polling packet is received, the contention probability is compared with a number that is uniformly generated in the range from zero to one. If p_c is greater than the generated number, then the sensor node sends its packet. Upon the reception of the polling packet, it is ideally expected that only one node will be able to transmit a data packet. The p_c is dynamically updated based upon the nodes’ responses. If the sink hears nothing after sending the polling packet, then it increases the value of p_c. If a packet transmission is either successful or fails due to a weak signal, then p_c remains at its current value. The value of p_c is reduced when a collision occurs at the sink. Additionally, the value of p_c decreases if new nodes are added to the network, and increases when nodes fail or are removed from the network. Analytical models for the slotted CSMA, ID polling, and PP-MAC have been presented and validated by simulations developed on the Qualnet [19] simulator. The simulation results show that PP-MAC achieves high throughput and fairness, as well as providing flexibility on scalability to support a high number of nodes in a dense EH-WSN. The EH rate is obtained from empirical characterization of commercial harvesting devices [20]. However, the PP-MAC does not support multi-hop networking.

2. Energy Harvesting MAC (EH-MAC)

EH-MAC is proposed to extend a PP-MAC that supports multi-hop scenarios by considering the following three key issues:

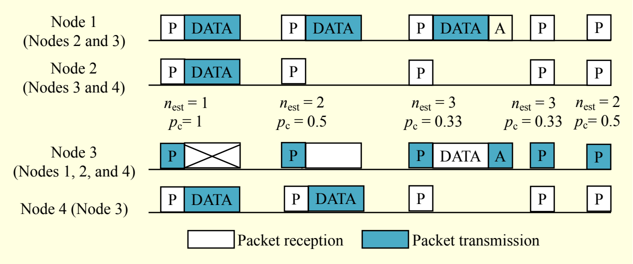

Fig. 4. Example process of EH-MAC.

- the coordination of multiple polling packet transmissions
- a distributed way of adjusting the contention probability at each node
- the traditional hidden terminal problem [21]

A node, after some random time, senses a channel before transmitting a polling packet to see whether the channel is idle. A random time is selected between 0 and t_p (t_p is the packet transmission time) to lower the probability of polling packets colliding. If the node does not sense a clear channel, then it waits until a channel is free. Also, the buffer of nodes is assumed to be limited (to ten data packets in this paper), and a polling packet is not sent if the buffer is full.

In PP-MAC, it has been theoretically estimated that the optimum contention probability value is $1/n_{active}$, where n_{active} is the number of active neighbors that are not in a charging state and are available to receive a polling packet.

Additive-increase/multiplicative-decrease (AIMD) and estimated number of active nodes (ENAN) schemes are used to achieve an optimum value for the contention probability. AIMD has been studied in PP-MAC and achieves high throughput when appropriate parameters are set. In ENAN, the optimum contention probability is adjusted using $1/n_{est}$, $n_{est} \geq 1$, where n_{est} is the estimated number of active nodes. The value of n_{est} depends only on the outcome of the previous polling packet. The objective is to get only one response, but if there is more than one response, then n_{est} is increased by one, and it is decreased by one if no response is received.

The performance of an EH-MAC is evaluated on a random topology with a varying number of nodes, from 50 to 500 in two scenarios — one with a constant EH rate and the other with a varying EH rate. An illustrative example of the process of receiving data packets and updating n_{est} is presented in Fig. 4; the neighbors of the nodes are shown in brackets.

3. Multi-tier Probabilistic Polling (MTTP)

An MTTP protocol is another approach to extending PP-MAC to multi-hop data delivery [22]. MTTP uses a tier-based hierarchy model in which a group of nodes is formed in each tier corresponding to the distance from the sink. Each tier is

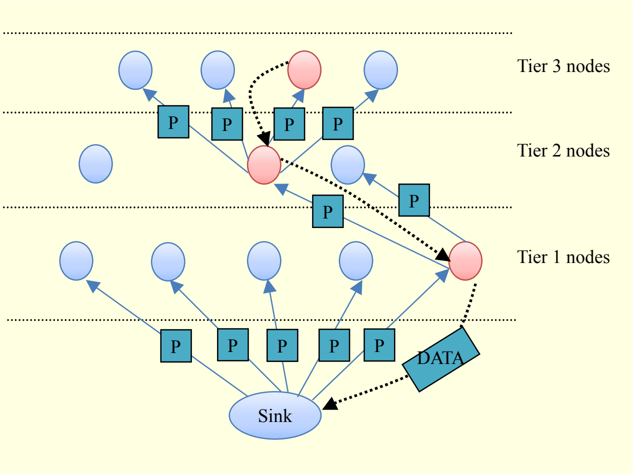

Fig. 5. MTTP concept with three-tier scale.

represented by a number (for example, tier 1, tier 2, tier 3, and so on). The sink broadcasts a polling packet with a probabilistic value to the tier 1 nodes. One of the nodes in tier 1 is then polled to broadcast the same probabilistic value to the upper tier; it then waits to receive a data packet. This process with a three-tier scenario is illustrated in Fig. 5.

The tier number is an 8-bit long number and is sent in the polling packet. Prior to deciding to join a tier, the immediate neighbors of the sink are assigned to tier 1. Initially, other nodes are given a tier number of 255, which is the highest possible tier number. Then, each node determines its tier number by looking at the tier number of the received polling packets. If the tier number of a received polling packet is lower than the tier number of the receiving node, then the tier number of the receiving node is assigned to the received tier number plus one. This scheme considers the case where a node receives polling packets from the upper tier more frequently than from the lower tier. Each node sets a counter that counts the number of polling packets that are not sent from the lower tier. If ten consecutive polling packets from the upper tier arrive, then the tier number is set to the upper tier. Whenever a polling packet comes from the lower tier, the counter value is reset. The purpose of this is to deal with dynamic environments and changing channel conditions, such as a highly variable communication range.

The performance of the MTTP protocol has been evaluated on commercially available devices with only a 2-tier scale. Therefore, performance evaluations on larger scales have significant potential to demonstrate the effectiveness of the protocol. It is clear that a high number of tiers would potentially produce a considerable overhead of polling packets, leading to increasing packet collisions. Another drawback of the protocol is that the coverage of a polled node should be within the sensing area of the upper tier to deliver polling packets to all nodes.

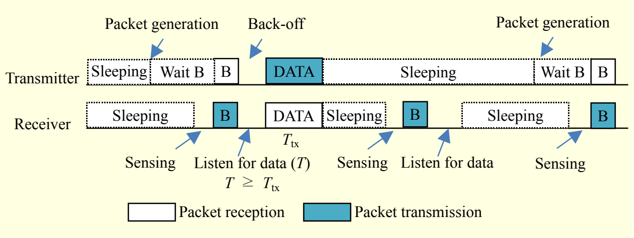

Fig. 6. Basic operation of OD-MAC protocol.

4. On-Demand MAC (OD-MAC)

An OD-MAC protocol for EH-WSNs is proposed to support individual duty cycles in which nodes are allowed to maximize their energy consumption [23]. The purpose of this is to achieve an ENO state. To maximize performance, it is ideally desired that the amount of energy harvested be equal to the amount of energy consumed so that all of the harvested energy may be exploited. In an OD-MAC protocol, when a node is available for reception, it broadcasts a small beacon packet to indicate its availability for possible incoming packet transmissions. Nodes wishing to transmit wait for an appropriate beacon before they start transmission. To reduce the energy wastage caused by a long beacon waiting time incurring high end-to-end delay of packets, the concept of the opportunistic forwarding scheme is introduced. The owners of the previous beacons are listed, and instead of waiting for a specific beacon, each packet is opportunistically forwarded to the sender of the first beacon received, assuming that it is included in the list of potential forwarders.

Unlike PP-MAC, nodes have an independent EH operation in which the available energy can be harvested in any state. To dynamically adjust the duty cycle duration, the current EH rate determines the duration of the sensing period with a periodic comparison between the current battery level and a predefined threshold. In the performance evaluations, constant EH rates based on Crossbow MicaZ with a specific harvesting material in [6] are used, resulting in the periodic increasing of the battery level by a certain amount. A drawback of OD-MAC is the lack of retransmissions, as it does not acknowledge the successful reception of packets, which renders it unsuitable in lossy environments. Also, OD-MAC has no mechanism to handle the hidden terminal problem; thus, energy can be wasted through hidden nodes. The performance of OD-MAC is evaluated on a simple grid-based topology. A basic operational implementation of OD-MAC using eZ430-rf2500 sensor nodes [20] has been presented in [24] that allows a single transmitter to adjust its duty cycle to explore a sustainable operation. Also, the principle behind OD-MAC is

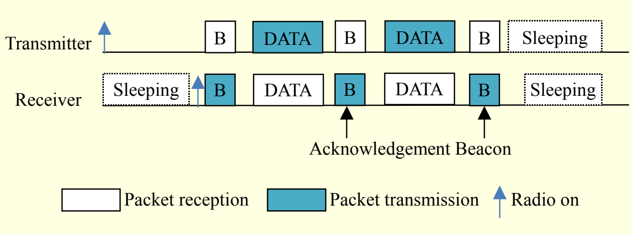

Fig. 7. Basic communication scheme in ERI-MAC.

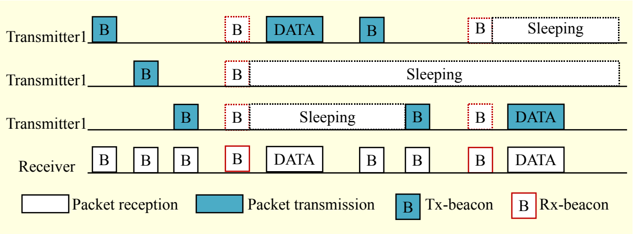

Fig. 8. Example of packet priority mechanism in QAEE-MAC.

very similar to that for MTTP. Figure 6 presents the basic operation of the OD-MAC protocol.

5. ERI-MAC

A receiver-initiated MAC protocol for EH-WSNs (ERI-MAC) is a CSMA-based scheme that employs a queueing framework to adjust the duty cycles of nodes, thereby achieving an ENO state [25]. The packet transmission strategy is similar to that of PP-MAC and OD-MAC. When a node wakes up and if no packet is scheduled to be transmitted, the node broadcasts a beacon packet containing its own ID. After a sender receives an expected beacon, a packet transmission starts with the packet at the head of the first-in-first-out queue being transmitted. As in EH-MAC, an acknowledgement packet is sent to confirm that the packet has been received successfully, which is also used as a new beacon. Figure 7 shows an example operation of communication between a sender and a receiver.

ERI-MAC proposes a packet concatenation scheme to merge several small packets into a single bigger packet, called a superpacket. In a typical MAC layer packet, a header is added to the packet, which may incur a relatively high overhead depending on its length. The advantage of concatenating packets is to efficiently reduce the number of headers by only having one header in a superpacket. However, the length of the packet depends on the specific radio platforms used; for instance, the IEEE 802.15.4-compliant CC2420 radio has a maximum packet size of 127 bytes. Therefore, a superpacket can comprise a limited number of small packets.

To achieve an ENO state, ERI-MAC makes use of queueing packets, where each queued packet is delayed for a safe duration to make sure that the consumed energy is less than the harvested energy. The ratio between the energy consumed and the energy harvested is checked after the safe duration. By this comparison, a node determines whether it exceeds the sufficient energy level. Nodes operating under an ERI-MAC protocol are assumed to know the EH rate. It has been shown that these nodes are prone to consuming more energy with a small EH rate (0.3 mW). An EH rate of 0.6 mW has ensured that such nodes do not exceed the aforementioned safe duration. The ERI-MAC protocol is evaluated on a 49-node grid topology with a fixed distance between two neighbors.

6. QAEE-MAC

A QoS-aware energy-efficient MAC (QAEE-MAC) protocol benefits from a data priority mechanism that allows urgent data packets to be transmitted faster than normal packets [26]. Upon waking up, each sender broadcasts a beacon, a Tx-beacon, to show the priority of its data packets; each then waits for a receiver beacon. The *receiver* is required to wake up earlier and collect all of the Tx-beacon packets. It essentially makes the decision as to which sender has the highest priority to transmit first, broadcasting a beacon packet (an Rx-beacon) to all senders with the ID of the node that can transmit. The sender with the highest priority starts transmitting its packet while others go into a "sleep" state. As in ERI-MAX, the Rx-beacon indicates the successful reception of a previously received data packet. An example process of a priority data transmission is presented in Fig. 8. In QAEE-MAC, nodes arrange their wake-up periods in accordance with their energy level.

The performance evaluation of the QAEE-MAC protocol is limited to only one receiver and a small number of sender nodes in a single-hop manner. Also, the packet priority mechanism incurs a high idle listening time that of all the senders.

7. Other Work

The performances of conventional time-division multiple-access and dynamic framed-ALOHA schemes have been analyzed in [27] by accounting for the impact of unpredictable energy availability in a single-hop WSN. The capability to successfully deliver a packet to a destination (referred to as *delivery probability*) and *time efficiency* (which relates to the rate of channel utilization at a data collection center) has been introduced to measure the network performance. Numerical results demonstrate that the delivery probability and time efficiency are strongly dependent on the EH rate. The EH rate is modelled as a discrete random variable.

The throughput performance of the S-MAC protocol has been investigated in a solar-based WSN [28]. In particular, the achievable throughput in association with a varying duty cycle is presented with an analytical model of an energy harvester. To meet both the quality of service (QoS) requirements and the desired network lifetime requirements, a suitable range for the duty cycle can be chosen based on the minimum duty cycle thresholds obtained.

Two dynamic duty-cycle scheduling schemes for EH-WSNs have been proposed to reduce the duty cycle of sensor nodes and create a balance of energy consumption between sensor nodes [29]. The first scheme adjusts the duty cycle based only upon the current residual energy level. Due to the increase in residual energy over time from EH, the second scheme takes the prospective increase in residual energy with time into consideration to reduce the duty cycle more aggressively if needed. This is done by calculating the difference between the energy consumption and EH rates at the beginning of each duty cycle.

A slotted-preamble technique has been introduced for sleep-wake-up scheduling in a solar-based EH-WSN [30]. Instead of sending long preamble packets, tiny preamble packets are sent in a burst from a transmitting node to reserve the channel, and this lets nearby nodes turn their radio off quickly. A small gap is left between the preamble packets transmission to permit the intended receiver to send an acknowledgement packet. The sender attempts to transmit its packets as long as the receiver is awake and its energy level is greater than a predefined threshold.

IV. Open Issues and Future Research Directions

Table 2 summarizes the basic properties of the MAC protocols surveyed in this paper. EH-MAC has the same features as PP-MAC as it is an extended version of PP-MAC designed for multi-hop applications. The key properties of the protocols and modifications integrated with the protocols have been tested sufficiently on single-hop and multi-hop networks. However, the scale of the experiments so far is rather small, so it would be better if the performance evaluations of the protocols could be observed on larger scales. None of the protocols have been tested on a random topology. Therefore, implementation of existing and new protocols on large-scale multi-hop networks is an open topic.

Table 2. Comparison of MAC protocols for EH-WSNs.

Protocol	PP-MAC/ EH-MAC	MTTP	OD-MAC	ERI-MAC	QAEE-MAC
Harvesting policy	Harvest-spend	Harvest-spend	Store	Store	Store
Channel access	Polling	Polling	CSMA	CSMA	CSMA
Adaptivity to changes	Good	Fair	Good	Fair	Fair
Topology	Single/ multi-hop	Multi-hop	Multi-hop	Multi-hop	Single-hop
Implementation type	Simulation	Real test-bed	Simulation	Simulation	Simulation

All of the protocols, except MTTP, introduced in this paper have only been evaluated through simulations, where practical considerations of unrealistic assumptions can be avoided. The feasibility of the schemes for practical implementation on a real test-bed is an open issue, because the practical implementation on real sensor hardware can face various challenges, such as the resource limitations (power and memory) of the sensor nodes. It is, therefore, believed that the practicality of new protocols must be considered, since this can have a significant impact on performance.

The receiver-initiated strategy is employed by all protocols and relies on the intended receiver's polling/beacon message to schedule data transmission. To start data transmission, transmitting nodes have to wait until they receive the correct beacon from the target receivers. Therefore, the sender has to turn the radio on until it has delivered the data packets successfully. To avoid idle listening in the waiting beacon, new approaches are required to efficiently and effectively coordinate the transmission between sender and receiver; and particular emphasis can be placed on prediction of the receiver's wake-up time, as in [31]. To understand the architecture of the receiver-initiated technique more deeply, a recent detailed survey of MAC protocols in the receiver-initiated category can be found in [32].

As has been briefly mentioned above, the rate of EH depends highly on the environment conditions. However, constant EH rates are assumed in the performance evaluations of the protocols. This is, however, not a realistic assumption as practical environments are inherently dynamic. If the average rate of EH can be analytically expressed in such a way so that it is dependent upon the properties of the environment, then the effect of a time-variable EH rate can be simply determined and incorporated into the overall system performance. It is therefore believed that future MAC protocol design should take into consideration more practical scenarios and define the dynamics of the environment. It can be concluded that an intelligent method is required to carefully adapt the unpredictability of the EH process to maintain the performance of a protocol at an acceptable level.

Another approach emerging to replenish the batteries of sensor nodes is that of wireless energy transfer through directed radio frequency waves [33]. Here, RF-MAC is proposed to efficiently manage the transfer of data and energy in the same band. After deployment, sensors are allowed to recharge their batteries by broadcasting their request for energy to energy transmitters deployed in the neighborhood. RF-MAC has shown an improvement in network throughput over the classical modified unslotted CSMA–based MAC scheme. It is believed that a combination strategy of environmentally friendly EH and wireless energy transfer would strongly enrich the design of a MAC protocol. In particular, when the ambient energy is not sufficient, the wireless energy transfer can be applied for perpetual operation of sensor networks.

V. Conclusion

This paper has covered the recent studies in the development of EH wireless sensor network (EH-WSN) MAC protocols. A brief background to EH-WSNs has been presented to enable the reader to understand the fundamentals of EH-WSNs. Many proposed MAC schemes for EH-WSNs have been described along with their salient features. The design of these protocols is inspired by the receiver-initiated architecture. The characteristics and operating principles of the MAC protocols have been discussed. The open research issues considering the design trade-offs have been discussed to contribute to further possible research investigations. With the benefit of eliminating the need for replacing/recharging depleted batteries, designing new MAC protocols for EH-WSNs will open a new perspective in the field of WSNs and gain significant attention in the future. This paper will hopefully guide researchers to investigate possible future protocol designs.

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