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Survey paper

A comprehensive review on energy harvesting MAC protocols in WSNs: Challenges and tradeoffs

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A B S T R A C T

Nowadays, wireless sensor networks (WSNs) are broadly used to set up distributed monitoring infrastructures in self-healing, self-configuring, and self-managing systems. They are composed by many elementary devices (or motes) equipped with basic sensing, computing, and communications capabilities, which interact on a collaborative basis to sense a target environment and report collected data to one or more sinks. WSNs are expected to be operational for very long periods of time, even if each mote cannot bring large energy storage units. Accordingly, Energy Harvesting mechanisms can greatly magnify the expected lifetime of WSNs. Over the years, Energy Harvesting-Wireless Sensor Networks (EH-WSN) have been thoroughly studied by the scientific and industrial communities to bridge the gap from the vision to the reality. A critical facet of EH-WSN lies in the interplay between EH techniques and MAC protocols. In fact, while EH technologies feed motes with energy, the MAC layer is responsible for a significant quota of spent energy because of message transmission/reception and channel sensing operations. In addition, the energy brought by EH technologies is not easily predictable in advance because of time-varying nature: this makes the design of the MAC protocol even more challenging. To draw a comprehensive review of the state of the art on this subject, the present manuscript first provides a detailed analysis on existing energy harvesting systems for WSNs; then it extensively illustrates pros and cons of key MAC protocols for EH-WSNs with a special focus on: fundamental techniques, evaluation approaches, and key performance indicators. Finally, it summarizes lessons learned, provides design guidelines for MAC protocols in EH-WSNs, and outlooks the impact on Internet of Things.

1. Introduction

A collection of tiny nodes capable of sensing the environment, performing simple computations and supporting wireless communications to accomplish a monitoring task can be referred to as Wireless Sensor Network (WSN). After almost a couple decades since their emergence, WSNs have been adopted in almost all possible areas including but not limited to Smart Homes [1], Smart Healthcare Systems [2,3], Intelligent Transportation Systems [4], Disaster Management Systems [5], and Continuous Video Surveillance Systems [6].

Lifetime is the Achilles' heel of WSNs: in fact, network nodes (also known as motes) are usually battery operated and spend a remarkable quota of energy to handle wireless communications primitives [7]. To avoid a frequent replenishment of batteries, it is necessary to optimize all the operations running in each single mote and quite a few approaches have been proposed so far in this

direction [8–10]. Nevertheless, the experimental evidence demonstrates that WSN lifetime is never enough [7].

The bulk of proposed approaches to optimize the living time of conventional battery-powered WSNs include but not limited to energy-aware MAC protocols (SMAC [11], BMAC [12], XMAC [13]), routing and data dissemination protocols [14–16], power aware storage, duty-cycling strategies [17,18], adaptive sensing rate [19], tiered system architectures [20–22] and redundant placement of nodes [23,24].

Energy harvesting (EH) technologies [25–27] can significantly prolong WSN lifetime by converting solar, wind, vibrational, thermal or RF energy into electrical energy. Their disruptive potential has led to the formulation of the so called Energy Harvesting-Wireless Sensor Networks (EH-WSNs). The effectiveness of EH-WSNs mainly depends on the interplay between EH technologies and the protocol stack (as explained in Section 2).

Medium Access Control (MAC) protocol always plays a significant role in the design of WSNs as major energy consumption is due to the sensing, reception, and transmission process. Accordingly, a special attention has been paid to MAC protocol design

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[28–30] and a wide hierarchy of protocols has been proposed for WSNs.

With EH-WSNs, MAC design becomes even more challenging because the pattern of energy harvested from the environment is not easily predictable in advance. Although, it can be predicted up to short or medium time intervals that can be of the order of microseconds to hours (e.g. harvesting solar vs. RF) depending on various factors including but not limited to application, topology, energy harvesting technique and, the environment but, even then, MAC protocol has to seek the best tradeoff between Quality of Service (QoS) and energy efficiency at run time based on the actual status of nodes. The proposals formulated so far (and thoroughly discussed in Section 4) differ to each other with respect to many features and design principles that deserve an in-depth analysis. Unfortunately, most of the surveys [28, 31–37] available in literature describe MAC protocols for plain WSNs but only a couple of them [38,39] approach EH-WSNs by simply overviewing the functionalities of a very limited number of protocols without providing the current challenges and tradeoffs for the performance optimization. They do not either deal with the pros and cons of specialized MAC protocols for EH-WSN that are vital for understanding their limitations. To the best of our knowledge, there is not a single study available in literature to date correlating the characteristics of energy harvesting technologies with the performance of specialized MAC protocols for EH-WSN because each specialized protocol may behave differently when employed against different harvesting technologies.

To bridge this gap, a detailed analysis on the need for special MAC design (Section 2), energy harvesting technologies (Section 3) and, MAC protocols for EH-WSNs (Section 4) is proposed hereby. A list of motivations for a special MAC design instigating the need for special type of protocols is presented in Section 2. Moreover, for each technology described in Section 3, the key implications on EH-WSNs are discussed. The pros and cons of the protocols proposed in [73–85] are thoroughly analyzed in Section 4 along with a general classification taxonomy that highlights their similarities and differences based on number of parameters. Some open issues related to MAC protocols for EH-WSN are discussed in Section 5 highlighting the challenges and future research opportunities. Finally, conclusions and lessons learned are reported in Section 6.

2. Motivation for special MAC protocols targeting EH-WSN

As the plain MAC protocols are not capable to undertake the requirements imposed by EH-WSNs, it is inevitable to consider special MAC protocols customized for EH-WSNs. To gain a thorough understanding of the problems associated with plain protocols, it is significant to understand how plain WSN are different from EH-WSN and why the plain MAC protocols behave inappropriately for EH-WSN. MAC protocols already available in the literature for non-energy harvesting WSN are intended to prolong the network lifetime by avoiding the energy exhaustive operations enlisted in Section 3.2.1. On the other hand, special MAC protocols for EH-WSN aim at achieving the best tradeoff between uncertain energy conditions and longer network life with optimum performance. There are multiple factors that instigate the need for a special type of MAC protocol intended for EH-WSN presented throughout this section.

2.1. Design principle

There exists a fundamental difference in the design principle of EH-WSN with respect to battery-operated WSN as the later were developed with the intention to achieve longer life times. Contrarily, energy harvesting paradigm relaxes the power constraints

faced by battery-operated WSNs and the focus of EH-WSN is rather to improve the network performance (i.e. throughput, delay, inter-arrival time etc.) operating in a sustainable energy state. Hence, the design principle differentiates the need for a special MAC protocol that should be designed keeping in view the performance requirements (i.e. targeting QoS improvement instead of longer lifetime) of EH-WSN.

2.2. Adaptive duty-cycle

The individual nodes in plain WSN usually undergo a common duty cycle because of the obvious energy availability as they are equipped with a battery, gradually goes on decreasing with time. Instead in EH-WSN, the actual amount of energy at hand at any given instance is not straight forward due to certain environmental limitations of harvesting mechanisms. Hence, the MAC protocol design for EH-WSN demands for an adaptive duty-cycle of individual nodes as compared to a system wide common duty-cycle based on their individual energy availability at hand. This special kind of MAC protocol would enable the low energy nodes to manage their operations (switching between sleep and wake-up mode) independent of the global system inducing flexibility of operation.

2.3. Harvesting capabilities

Unlike plain WSN, end-nodes in EH-WSN are equipped with harvesters that enable them to scavenge some amount of energy from the environment. On one hand, it helps these nodes to continue their ongoing operations but, on the other hand, it may be challenging for the nodes because the harvesting capabilities are not the same for all the nodes in an EH-WSN. This variation may be due to several factors including harvesting mechanism, time, environment or the precise position of the harvester. For example, the amount of energy harvested by a node equipped with solar cells positioned in direct sun radiations would be different compared to the node coincidentally placed in a shadowed area. The special MAC protocol should be designed to smartly compensate the lower energy nodes making available the surplus energy harvested by the nodes with higher capabilities.

2.4. ENO-MAX state

Energy Neutral Operation (ENO) mode of a node ensures that consumed energy is always lesser or equal to the amount of harvested energy for a node. A node refers to the ENO-MAX state when it is able to achieve ENO mode yielding the maximum level of performance. Unlike simple MAC protocols, the special protocols for EH-WSN are designed to support a node towards achieving ENO-MAX state. As the level of energy availability varies for different nodes belonging to EH-WSN, it is extremely important to tune the existing MAC protocols with respect to the instant energy level of individual nodes towards achieving performance optimization.

2.5. Energy characteristics

It is important to note that WSN exhibit very different energy characteristics as compared to EH-WSN. The energy level in battery operated-WSN reduces with time and they are continuously operational until zero energy level. Contrarily, nodes belonging to EH-WSN usually consume higher energy (in their routine operations) than they can harvest in certain periods of time. Hence, a certain level of energy accumulation is recommended using the storage before starting with the normal operation of EH-WSN. This characteristic behavior offers (theoretically) unlimited amount of energy to EH-WSN that makes them suitable for many energy intensive applications [5,6] demanding extended battery life-time. It

Table 1
Comparison of maximum power density from energy harvesting technologies.

Harvesting method	Power density	References
Solar energy—outdoors	15 mW/cm ³ - bright sunny day 0.15 mW/cm ³ -cloudy day	[43]
Solar energy—indoors	6 μ W/cm ³	[44]
Vibrations (piezoelectric—shoe inserts)	330 μ W/cm ³ -105 Hz	[45–47]
Vibrations (electrostatic conversion)	184 μ W/cm ³ -10 Hz	
Vibrations (electromagnetic conversion)	0.21 mW/cm ³ -12 Hz	
Thermoelectric (5–20 °C gradient)	40 μ W –10 mW/cm ³	[48]
Magnetic field energy	130 μ W/cm ³ -200 μ T, 60 Hz	[49]
Wind energy	65.2 μ W/cm ³ -5 m/s	[50]
Ambient RF Energy	0.08 nW-1 μ W/cm ³	[51]

is inevitable for the designers to incorporate these dynamics to the special MAC protocols for EH-WSN.

2.6. Variable charging profiles

MAC protocol plays its part in achieving optimal, fair and, timely monitoring achieved by the coordination of sensor nodes that requires the nodes to stay awake as maximum as possible. As discussed above, the charging time for all the nodes varies depending on the environment, time and type of the harvester. The nodes go asleep while they charge enough battery to accomplish their ongoing operations. It puts another constraint towards traditional MAC design that directly influence the performance metrics. Hence, this new set of MAC design considerations for EH-WSN sets them apart from the plain WSN and special MAC protocols for EH-WSN (described throughout the next Section) are based on the new design constraints imposed by energy harvesting architectures.

3. Research on energy harvesting

This section discusses about different type of energy scavenging mechanisms specifically used for WSNs along with system architecture and design alternatives for EH-WSNs.

3.1. Energy harvesting mechanisms

The concept of renewable energy dates back to centuries and it has been the most widely used way of energy transformation before the invention of coal. Many natural energy sources have been known till date [40,41] but the mechanisms of energy scavenging and storing are still a challenge in some cases. These days, the most common sources of ambient energy harvesting are solar, thermal, wind and, water that transform different forms of energies to electrical energy. Unfortunately, energy harvesting for low power devices (like in WSNs) is challenging because of the size compatibility of harvesting devices with the small motes. Designing the circuits for energy harvesting devices is fairly complex task because of being highly dependent on the type of energy source, energy storage devices, power management capabilities, protocols used, and underlying application's requirements. Solar, vibrational, electromagnetic, thermal, wind and, RF energy sources are the few known ways of ambient harvesting from the environment for WSNs where the research efforts [42] have been extended with special emphasis as shown in Fig. 1.

Table 1 presents a clear comparison of maximum power density possible from each kind of energy harvesting technologies.

3.1.1. Solar

The solar power sources are the most widely used ambient energy sources [42] due to their readily available and consistent en-

ergy scavenging capabilities in the light hours with a mere disadvantage of non-availability of their operation in night times or bad weather conditions. This kind of harvesting mechanisms usually employ a single or double level storage capacity (e.g. battery or super-capacitor) for ongoing operations even in the absence of harvesting hours. The circuit designed for this kind of source converts light energy into an electric current. Research efforts have been spent [52] for supporting WSNs because the classic solar systems were not designed to cope with modern challenges of WSNs. To prevent the energy wastage during the transfer from harvester to sensor, Maximum Power Point Tracker (MPPT), a tracker circuit [53] has been proposed to effectively transform the newly harvested energy with minimal power loss.

3.1.2. Vibrational

Vibrational or mechanical source [42] of ambient energy harvesting is due to the motion of certain objects according to Faraday's law of electromagnetic induction that may sometimes be referred to as kinetic energy. This source of scavenging the energy is being deployed growingly by many advanced WSNs applications ranging from button press [54] to the shoe sensor [55]. The latter is fed by harvested energy due to the force exerted by human walk which serves various types of WSN applications fulfilling the energy needs of a certain sized information packet. Similarly, a traffic sensor [56] becomes operational for a reading due to the amount of energy produced when a vehicle passes through that sensor. The results show that the amount of energy acquired from these sources is sufficient enough keeping in view the needs of applications requiring seldom operation.

3.1.3. Electromagnetic

This is another type of harvested energy by different frequency radio signals when a node is exposed to electromagnetic field. A sufficient amount of energy can be obtained by the use of inductors to feed various types of WSN applications [42]. According to Tentzeris *et al.* [57], there are various electromagnetic energy scavenging sources around us in this universe but humans are unable to get into them. Furthermore, such kind of sources have been explored using ultra-wideband antenna to achieve higher power gains. It is believed that this technique may open up new horizon for the researchers working in this particular area [57].

3.1.4. Thermoelectric

Due to the potential difference or gradients of temperature between two poles of the same material, thermoelectric harvesting is made possible that is pretty common in a variety of prospective applications these days [42]. For example, the temperature reading of a human body and the environment around it because the kind of devices having direct contact with body may harvest an amount of energy using Thermogenerators [58]. The design of such micro-structured devices has been proposed [59] to cater the energy demand of communication and embedded applications. These



Fig. 1. Few known sources of harvesting energy available in the environment from [42].

devices may be able to last for relatively longer than vibrational devices because of lesser movements of objects.

3.1.5. Wind

This form of energy harvesting has always been challenging in WSNs due to the size incompatibility of wind turbines with regard to sensor applications [42] that adds yet another constraint in the deployment of this technology in WSNs. The focus of the work in this area has been on the large-scale energy harvesting and only few research articles consider it for small scale harvesting applications [60–63]. The major flaw associated with wind energy is unreliability due to the non-constant and unpredictable behavior of wind hence it is unable to harvest the equal amount of energy all the times. Moreover, it might suffer electrical noise due to the movement in the mechanical part of turbines.

3.1.6. Ambient RF energy

Although, this kind of energy scavenging exhibits very low power density but it can be harvested with full potential employing high gain antennas. Ambient RF sources keep on increasing with the great expansion of broadcasting infrastructure hence, it has become a valuable source of energy available almost every hour throughout the day. The higher power densities can be achieved especially in the urban areas and within the closed proximity of radio sources (e.g. Base Stations or Broadcasting Towers) [51]. It provides the most appropriate way to recharge the sensor nodes deployed at a location (e.g. Home Automation or Structural Health Monitoring applications) where it is difficult to substitute the batteries frequently. The distance between the power source and the harvester can significantly affect the efficiency of the total power output. Similarly, non-line of sight sources, power output from RF source, path loss, shadowing, fading and, RF-DC con-

version efficiency are also some major downsides of this kind of techniques [51].

3.2. Energy harvesting architecture

Energy harvesting architecture can be referred as the combination through which various components in an energy harvesting system may combine and interact together to achieve an optimal performance level. Before going into the details of possible combinations and their corresponding interactions, it is important to have a look at the entities involved in an EH-WSN system. Fig. 2 shows the overall architecture depicting various components of the energy harvesting system and their interactions. Energy harvesting architecture can be seen as the combination of three fundamental components; Load, harvesting source and, harvesting system. The brief details on each of the components is presented in this subsection covering basic operations and how these components interact with each other to achieve optimum performance level.

3.2.1. Load

It can be seen as an energy consuming process in the system such as a sensor node in the WSN. A node generally consumes energy in the following activities [64]:

- ✓ Sensing (when a shared medium is used, the sender senses the channel before transmitting to reduce the probability of generating a collision)
- ✓ Contention (when multiple nodes simultaneously have data to transmit on the shared medium, a contention stage is entered to limit the impact of collisions)
- ✓ Transmission (Similarly, after the successful contention, nodes undergo actual transmission of data to their intended nodes)
- ✓ Collision (e.g., Hidden or Exposed Terminal Problem)
- ✓ Idle Listening (Listening the channel with no packet)

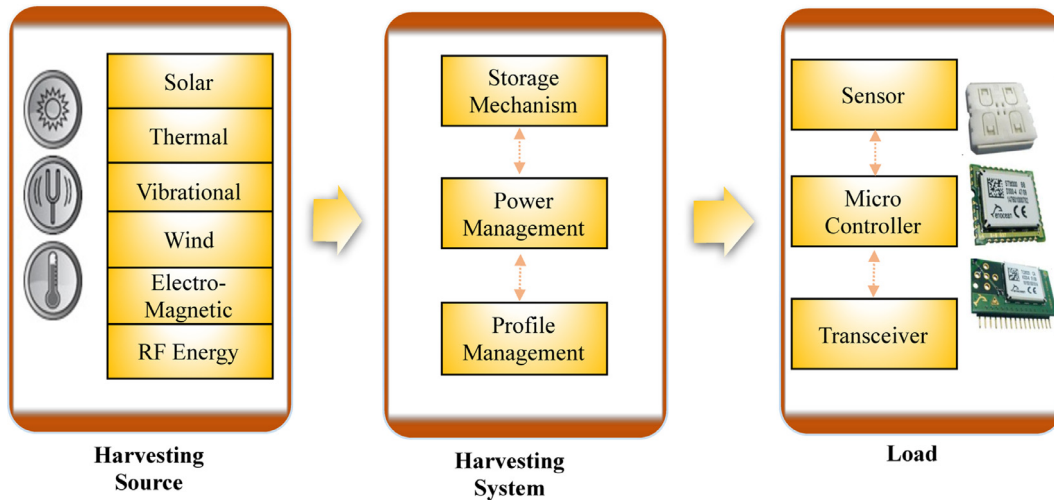


Fig. 2. Energy harvesting architecture.

- ✓ Overhearing (Receiving unintended messages)
- ✓ Control Packet Overhead (Control message or extra payload fields)
- ✓ Over Emitting (Sending while receiver is not ready)

We may significantly reduce the amount of energy consumed by the load by adopting especially tuned MAC protocols (as thoroughly discussed in Section 4).

3.2.2. Source

Source can be seen as any harvesting technology being used such as solar, wind, vibrational or thermal or other alike technologies capable of extracting ambient energy from the natural sources. The amount of harvested energy at the source side plays a vital part in the overall system design because it can exhibit unpredictable and time-varying dynamics that strongly affect the lifetime of a WSN. The literature [40,41,65,66] clearly emphasizes that no single source can be sufficiently enough for all kinds of applications in WSNs. Accordingly, the characteristics of WSN applications need to be in the exact accordance with the type of harvesting technology being used.

3.2.3. Harvesting system

This is the most crucial and significant part of the architecture. It serves as a mediator between the source and load, keeping in view energy consumption/generation profiles and application requirements. As inbound and outbound energy flows cannot be deterministically known in advance, the harvesting system should be designed based on worst case conditions. It can also be seen as an energy management module that stores excessive energy when the inbound flow is larger than the outbound one to face under-provisioning periods. It is also capable of tuning the load profiles (e.g., altering the data rate) to achieve optimal performance level. In distributed system paradigms, it plays a crucial role where all the individual nodes may have different sources of energy and locally oversee their needs. Here, energy saved at one node may play an important role to make the other nodes operational when they are out of their local energy hence to make the overall architecture as robust as possible.

Power management aspect is as important in EH-WSNs as the harvesting process itself because the ultimate goal is to come up with a best tradeoff between performance and life time. In conventional power control mechanisms, the primary design consideration was to extend the battery lifetime as maximum as possible. In EH-WSNs, instead, the key design goal has turned out to be performance as a whole rather than battery conservation only. In this

context, the prediction policy for future energy availability is the key to optimum decision making process and it is required at various stages of the operational system [67].

A similar predictive approach has also been proposed in [68] emphasizing that quick learning of the adoptive energy environment and energy sources can be exploited efficiently using the already collected information. Further contributions in [69,70] also argue the adoption of power management with an ultimate goal of achieving optimal performance of WSNs without the consideration of only battery life.

Power management module in harvesting system widely plays its part in achieving Energy Neutral Operation (ENO). It refers to a situation of an EH-WSN where the rate of energy scavenging is always greater or equal to the amount of energy being consumed or it satisfies the underlying consumption profile [69]. It can also be regarded as when the amount of harvested energy on source is always greater than the amount of consumed energy by a load then the system is said to be in ENO. ENO is the foremost objective to be achieved by today's WSNs that lets the designers to further move onto the performance maximization in the next stage. This kind of systems may have various distributed components bearing their own set of harvesting sources where the entire performance does not depend on the local profiles of available energy but it is always regarded as how this energy is used to ensure an optimal network wide performance.

3.3. Harvesting design alternatives

We argue that harvesting system design is equally important as MAC Protocol design because it is nearly impossible to come up with a desired performance level considering only one of them. Fig. 3 classifies different design alternatives that will be further explored within this sub-section. A comparison of different features related to the energy harvesting systems for these design alternatives are presented above in Table 2.

3.3.1. Store-consume alternative

This is the conventional architectural style existed in WSNs as shown in Fig. 3(a) where small sensor nodes are equipped with a compatible sized battery storage containing a sufficient amount of energy required to keep the node operational for as long as possible keeping in view the type and energy demand of underlying application. The focus in this kind of scenarios is prolonging the lifetime by optimizing the protocol stack: clearly delays and throughput can be impaired in order to save energy and prolong

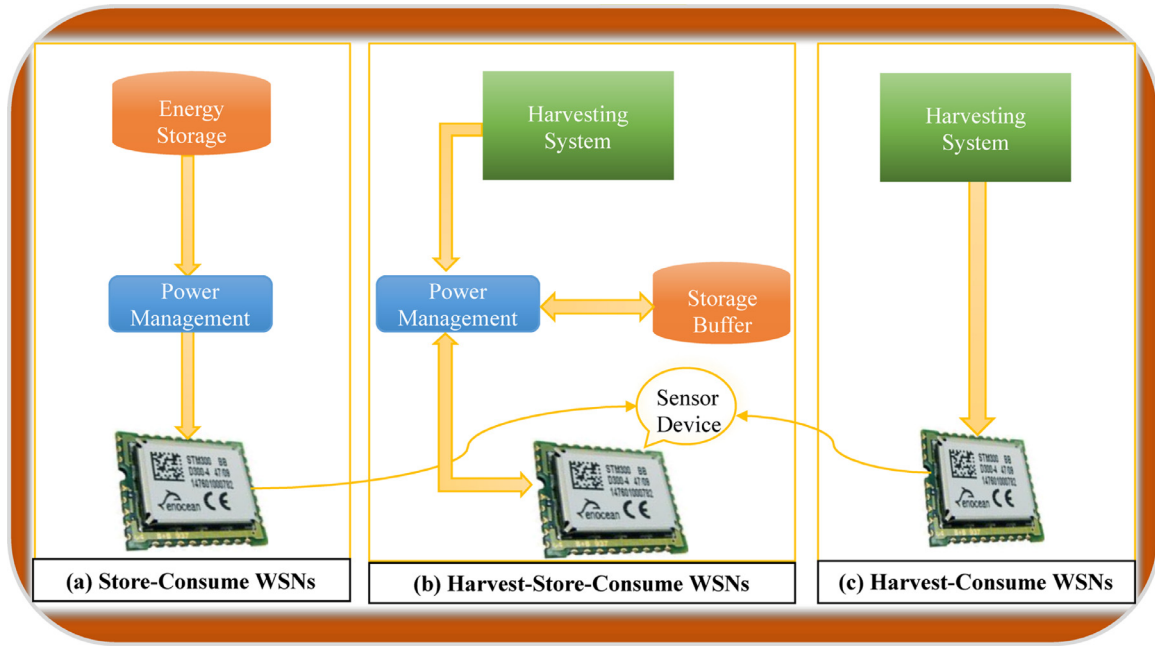


Fig. 3. Energy supply alternatives for wireless sensor networks.

Table 2
Comparison of features for possible design alternatives of WSN.

Sr. no. Main candidates/ Characteristics	Alternative 1 Store-consume WSNs [17-30]	Alternative 2 Harvest-store-consume WSNs [31-37]	Alternative 3 Harvest-consume WSNs [54-56]
Design flexibility	A tradeoff between Latency and Throughput for longer network lifetime	Achievable long lifetime by backing up the battery power with energy harvesting and energy management techniques	Due to the availability of renewable energy, no threat to lifetime and it is possible to achieve optimal throughput with suitable delays by applying some techniques
Energy prediction	Sleep and wakeup schedules can precisely be predicted	Sleep and wakeup schedules are predictable depending upon the future energy availability prediction	Sleep and wakeup schedules are not easier to predict because of uncertainty of future energy availability
Energy model	Energy Model is well understood	Energy model can be predicted to accuracy controlling some aspects	Energy model highly depends upon the EH rate across time, space as well as type of harvesting source.
Protocol design challenge	Protocol may perform well within the lifetime constraints	Protocols can exhibit adequate performance being parameter specific, not in general	Protocol can be environment specific because of high variations and unpredictability in the context

the WSN lifetime. For example, sensors belonging to a fire detection system deployed in a forest are usually equipped with a small storage buffer aimed at prolonging the life time as best as possible.

3.3.2. Harvest-store-consume alternative

Adding up the harvesting system leads to a set of complexities and tradeoffs in addition to the major advantage of energy scavenging mechanism as shown in Fig. 3(b). Energy harvesting sensor nodes with a storage technology exploit the advantage of potentially unlimited amount of energy availability where the focus can fearlessly be turned towards the performance parameters of the system instead of energy hence the tradeoff between energy and performance is a bit relaxed in these WSNs. Although harvesting system imposes the challenge of energy uncertainty at a particular time T due to the random energy arrivals but a range of protocols has been proposed [66,68] to achieve predictable sleep and wake-up schedules of communicating nodes to cope with this problem up to some extent.

The interplay of power management and topology control strategies seems relevant in EH-WSNs. In fact, if a sufficient amount of energy is not available to a particular mote to be operational, it would eventually turn to sleep mode to harvest some amount of energy for future operations. Generally speaking, several

nodes may at a time be switched between sleep and active (wake-up) modes simultaneously that would cause a frequent topological variation. This alteration may impair the performance of the WSN. Different strategies for sleep and wake-up schedules have been analyzed in [71] based on various aspects (such as channel or battery state, queue-based and solar radiation-based) keeping in view the context and, a game-theoretical approach to find out optimum parameters for sleeps and wake-up schedules is also presented [71].

The added advantage can be achieved by inducing a global distributed energy management module that employs more than one type of energy harvesting systems and keeps track of the exact amount of energy utilization on any node at time T and saves the extra amount of energy harvested for future needs of the same node or to compensate the need for another node when it is energy deficient. A range of today's IoT applications (such as smart cities, smart agriculture as well as smart industries) employ this kind of alternative where a lot of efforts have been made towards prolonging the life time of end nodes [31-37].

3.3.3. Harvest-consume alternative

Another widely used approach is to have the harvesting system on the node but newly harvested energy is directly provided to node for its operations without an intermediary energy stor-

age buffer as depicted in Fig. 3(c). Since energy is directly provided through renewable sources and there is no storage limitation hence no threat to the lifetime of the system. It lets the designers to focus on achieving the optimal throughput and delays (i.e. performance parameters) relaxing the overhead of energy storage and management module present in Fig. 3(b). The main challenge towards this approach is the energy wastage. When the harvested energy is greater than the consumed energy, the extra energy is simply wasted. Contrarily, in case of lesser harvested energy than the energy required for a node to perform certain action, the amount of newly harvested energy goes to the wastage due to the absence of storage. Here, it becomes difficult to schedule the sleep and wake-up intervals for communicating nodes because of unpredictable nature and amount of energy being harvested.

Energy availability in this kind of scenarios is highly dependent upon the time, environment and the type of harvesting technologies. Several use-cases in wellbeing monitoring applications [54,55] follow this kind of architecture. For example, the energy harvested from the pair of shoes during the walk/running can be utilized to transmit some important readings taken by the temperature, heart beat or blood pressure sensors to the application server. Similarly, Energy harvesting from a button press can be fed to a sensor belonging to smart home applications.

4. Special MAC protocols for energy harvesting-wireless sensor networks

This section aims at covering the current state of the art of various MAC protocols present in the literature for energy harvesting-wireless sensor networks. It focuses on the fundamental design, several evaluation methodologies and key performance indicators considered by this set of protocols. Various pros and cons of these protocols keeping in view the future design considerations are also highlighted. Finally, a comprehensive comparison is drawn among all these protocols towards a clear vision of what we have in literature at the moment and what should be the orientation of possible future research in this area. As we have already discussed in previous sections, there is a rich variety of categories for MAC protocols in general based on various parameters to differentiate one type by another, Fig. 4 presents a clear overview of the hierarchy of MAC protocols specifically customized for EH-WSNs based on the duty-cycling techniques and the initiation process.

It is worth mentioning that synchronous MAC protocols are not deemed appropriate for EH-WSN because of different duty cycle requirement for individual sensor nodes caused by variable energy availability. For example, a sensor node running out of energy could not be woken back as promised by synchronous schedule. Hence, only the asynchronous MAC protocols are considered in this study for EH-WSN. These MAC protocols for EH-WSN can be classified into three main categories with respect to duty-cycling techniques and the initiation process as in Fig. 4.

Moreover, MAC operation becomes critical in EH-WSNs and the protocols proposed in this area behave differently in the presence of each energy harvesting mechanism (discussed in Section 3.1) with respect to different application requirements. For example, as a constituent of smart home application, a carbon dioxide sensor to estimate the crowdedness of space has been developed [72] where the appropriate ventilatory measures (e.g. opening up the window) are taken in case of suffocation. The prototype is based on RTX4100 powered by artificial indoor light bulbs. The MAC operation in this scenario follows a basic duty cycle. Initially, the process starts by assessing the energy availability based on the voltage comparison of storage buffer with the preset threshold. In case of sufficient energy at hand, it polls out for the reading. If the reading is significantly different than the previous one and it is above a particular threshold measurement, it consequently

transmits that reading to take appropriate actions and goes back to sleep until next cycle. The study investigates the performance of prototype in presence of both; a non-energy harvesting (IEEE 802.11) and energy harvesting protocols (On-Demand Medium Access Control (ODMAC), discussed later in this section). The study concludes that the sustainable energy-efficient operation, with different input power levels, is only possible with energy harvesting MAC protocol.

Most of the protocols presented in Fig. 4 can be seen in the category of receiver initiated protocols because of the following reasons. First, receiver-initiated protocols successfully reduce the major overhead incurred by collision between two senders in a sender-initiated protocol that causes a significant delay to slower down the protocol initiation process. Second, receiver-initiated protocols make the new data exchange possible just after completing the previous exchange without going into sleep which, on the other hand, speeds up the ongoing communication yielding better performance. The special MAC protocols for EH-WSN are analyzed throughout this Section under the same taxonomy presented in Fig. 4.

Although, majority of protocols discussed throughout the Section 4, do not seem to be built on each other but they share common design principles highlighted in classification taxonomy presented in Fig. 4. They further aim at achieving the common characteristics shown in Table 4. As per the brief chronological evolution, energy harvesting protocols were initially proposed in all three categories shown in Fig. 4 including single-hop probabilistic polling [73], MTTP [74], ODMAC [80] and SEHEE-MAC [90]. Then, Multi-hop probabilistic polling [79] was built on Single-hop probabilistic polling [73] extending the same concept for multi-hop communication. Then, QAEE-MAC [83] was proposed being the first ever EH-MAC protocol targeting QoS. A huge bunch of protocols was customized in the middle era exploiting two right most techniques in Fig. 4 (e.g. LEB-MAC [81], ERI-MAC [82] ED-MAC [84], DeepSleep [87], EL-MAC and, RF-MAC [91]). RF-MAC [91] targeted the same QoS parameters in addition to achieve energy optimal operation as compared to QAEE-MAC [83]. Here, ED-MAC [84] employs similar dual filtered scheme like DeepSleep [87] and EL-MAC [89]. Similarly, some protocols have been proposed lately in recent couple of years in two most right categories shown in Fig. 4 including RF-AASP [75], AH-MAC [76] and, SyWiM [86] where last two also support multi-hop communication.

4.1. Sink-initiated asynchronous MAC protocols

4.1.1. Probabilistic polling for single-hop WSNs

A *probabilistic polling* approach for single hop WSNs is presented in [73] where several experiments are set up to emphasize that the rate of harvested energy is directly related to many aspects such as time of the day, location of harvester, and the source of harvested energy. As discussed in the previous sections, the abrupt variation in energy arrival rates needs some kind of adaptation in every MAC protocol design for EH-WSNs to handle the harvesting dynamics. A sink initiated paradigm is presented in [73] where sink node incorporates harvesting dynamics by announcing the contention probability i.e., P_c based on the current energy levels of nodes while the nodes below this probability will automatically be out from the pool of contending nodes and they will have to wait for the next polling. Whenever a node is out of residual energy, it would not take part in contention switching to the charging state to harvest enough energy for future operations.

Pros:

The contention probability follows Additive Increase Multiplicative Decrease (AIMD) policy for the number of nodes that are currently in active state. If the sink does not receive any data packet from any node in response to polling, it would increase the polling

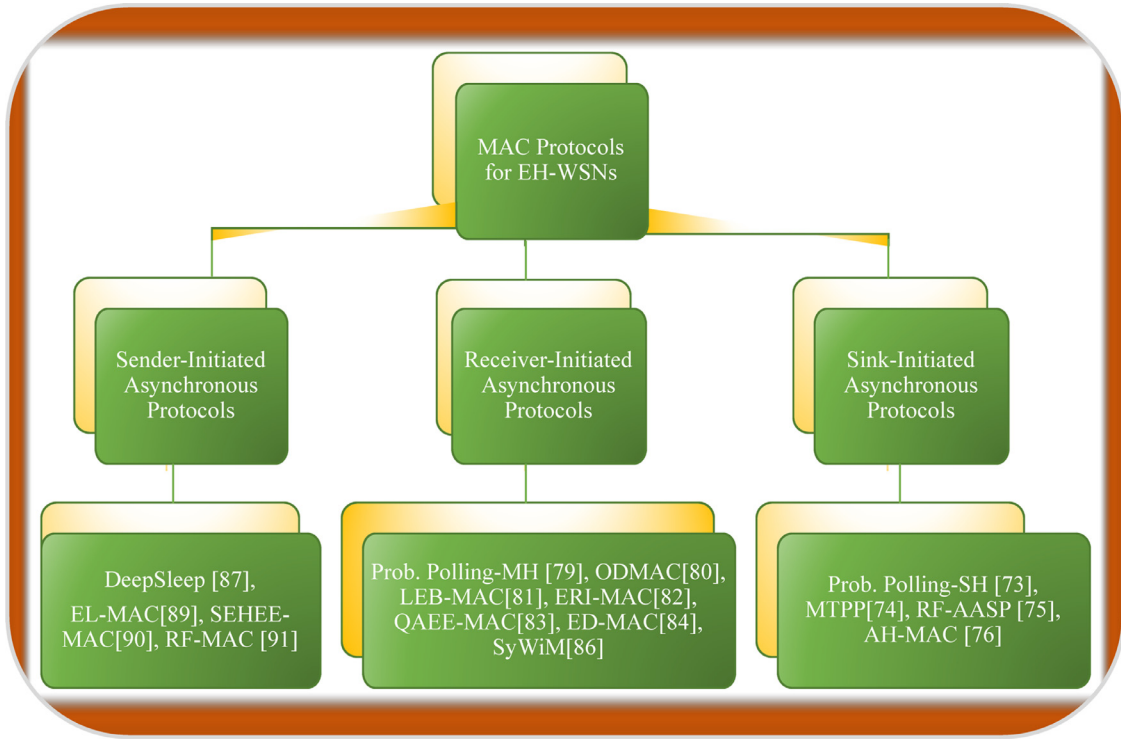


Fig. 4. Categorization of MAC protocols for EH-WSNs.

probability of next cycle considering that there are not enough nodes in contention. Conversely, polling probability would be decreased if there are collisions within the system. This yields higher throughput, scalability and fairness and it well handles the collision situations by probability adjustment leading to the fair source allocation.

Cons:

Although probabilistic polling approach responds appropriately to dynamic energy harvesting conditions, it may take too long to converge in a frequently changing environment. In fact, if a bulk of nodes joining and leaving the system abruptly causes frequent changes in increasing or decreasing the contention probability then nodes may either face collisions or may not get the opportunity of transmitting data due to that probability fluctuation. This causes latencies and leads to wastage of energy and bandwidth in the long run. Additionally, this protocol only supports single-hop communication scenarios assuming that next receiving node would be the intended destination while that is not always the case in EH-WSNs as there may be several relay nodes involved responsible for onward transmission of the data packet towards intended destination.

4.1.2. Multi-Tier probabilistic polling (MTPP)

Building on the probabilistic polling approach discussed in [73], MTPP [74] is another protocol with the extension towards achieving multi-hop data delivery that employs a tiered hierarchy model with a cluster of sensor nodes formed based on the distance from the sink. Tiers are represented by natural numbers (Tier 1, Tier 2, Tier 3...) comprising a group of nodes ($n_1, n_2, n_3...$) in each tier. Sink is responsible for broadcasting a polling packet to Tier 1 nodes (the closest ones). One of the nodes from Tier 1 would be chosen to broadcast this packet to the next tier nodes above it and it would start waiting for the data packet to be received and so on for the next tiers in hierarchy. An 8-bit tier number is incorporated within the polling packet. Initially, all the immediate neighbors of the sink are associated with the Tier 1 and rest of the nodes are

assigned tier 255 that can be the maximum possible tier number. The nodes then gradually identify their corresponding tier looking at the polling packet.

Pros:

A fixed polling interval of 33 ms has been used [74] to ensure the end devices receive the polling packet within an interval when their radio is on because it is not feasible for the end devices to turn on its radio all the times due to a limited amount of energy at hand hence radio control is another significant feature of this protocol. Moreover, dynamic tier assignment is also one of the novelties of MTPP as end devices sometimes suffer interference offered by other devices (e.g. based on WiFi) which causes some nodes to push them from Tier 1 to Tier 2 due to their inability to listen to the polling packet remaining in Tier 1.

Cons:

The evaluation of MTPP is done on a 2-Tier scale considering the simplest case but the authors are unsure about the performance exhibition on large scale only hoping the effectiveness of the protocol for dynamic network scenarios. It can be an obvious fact to limit the scenario with as minimum number of tiers as possible because large number of tiers would eventually affect by incurring an overhead of polling packets that may lead to increasing collisions within the system causing wastage of significant amount of energy.

4.1.3. Radio frequency based adaptive, active sleeping period (RF-AASP) MAC

RF-AASP [75] presents a technique to dynamically adapt the active sleeping period to switch the sensor nodes harvesting more energy from the ambient RF energy sources in the environment. This scheme adapts the active sleeping period depending on multiple factors such as varying traffic loads, residual energy of individual sensor nodes and, the estimation of RF energy available from surrounding. This approach intends to minimize the contention level and maximizes the probability of energy harvesting which results not only improving the energy efficiency but also

the network throughput. The sink node is responsible to estimate the current traffic conditions by counting the number of incoming packets from an IoT application in current Beacon Interval (BI) and compares it with the number of packets in the previous BI to estimate the actual variation for tuning the QoS parameters. This kind of schemes usually employ two different antennas at the sensor nodes; one for harvesting the required RF energy while the other for the actual communication. Power management unit on each sensor node is the decision-making entity that finalizes either the node has to activate antenna 1 to recharge itself through RF energy in the harvesting interval or it has to use antenna 2 to transmit the data in the transmission period.

Pros:

The foremost concern of RF-AASP protocol is to consider two important aspects of energy efficiency and QoS achievement and it seeks the best trade-off between them as compared to other protocols (e.g. QAEE-MAC [83]) striving to optimize only one of them. RF-AASP presents a comprehensive analytical model for RF energy harvesting process, energy consumption model and, incoming harvesting RF energy estimation. This protocol assumes variable traffic conditions for tuning the sleeping period which eventually provides flexibility to the MAC design targeting QoS achievement.

Cons:

RF-AASP assumes only a 25m radius for deploying RF energy harvesting source (eNodeB) and harvester in their simulation study [75] which does not seem to be a realistic assumption for the evaluation of this approach through simulation. The best way to evaluate the RF energy harvesting could be to deploy the real test beds towards a precise estimation. The evaluation comparison of this protocol was drawn with another MAC protocol (i.e. ABSD) proposed for non-energy harvesting WSN that may not be justifiable in this respect.

4.1.4. AH-MAC: adaptive hierarchical MAC protocol for low-rate wireless sensor network applications

Adaptive Hierarchical MAC Protocol [76] is another sink initiated protocol suitable targeting low data rate applications for large scale wireless sensor networks. AH-MAC is built on Low-Energy Adaptive Clustering Hierarchy (LEACH) [77] and IEEE 802.15.4 [78] and does its job by exploiting the advantages of each of them. AH-MAC considers only a fraction of end nodes (only cluster heads) equipped with energy harvesting circuit while rest of the nodes in the network are kept battery operated. Consequently, AH-MAC shifts most of the network activities to cluster heads leaving the rest of the nodes with minimal job aiming to prolong the lifetime of nodes in the presence of battery-supported operations. AH-MAC follows hierarchical routing with sink being the grandparent and all other nodes are further divided into cluster heads and followers. Initially, the sink starts sending its beacon at the start of its frame and stays alive until the active period has elapsed. It then goes back to sleep until the start of the next slot and the first child cluster head starts sending its beacon in the second slot. Similarly, the second child cluster head sends its beacon in the third slot and so on. Thanks to this mechanism, only one cluster is active at a time and all other are sleeping that prevents cluster interference. Every cluster head has to wake twice during a frame; first during the slot of its parent to stay synched with parent and upload its data and, second in its own slot to send the beacon and let its followers upload their data.

Pros:

As AH-MAC well exploits the many of the advantages of 802.15.4 [78], it is capable to outperforms conventional LEACH protocol in terms of energy efficiency and delivery ratio when considering low data rate use-cases. Unlike LEACH where the node is active throughout the whole frame, the active time in AH-MAC is

limited to only one slot as compared to conventional LEACH which results in saving a reasonable amount of energy.

Cons:

This approach successfully reduces the energy consumption of nodes on the cost of increased energy consumption of cluster heads which are assumed to be connected with unlimited energy harvesting source while this assumption seems to be unrealistic because each energy harvesting source may have its own limitation and cannot be seen as source of unlimited energy at any given time. Secondly, in case of a cluster head failure in this kind of approaches, the election for a new cluster head can appear to be a bottleneck because the followers would not be able to upload their data even if they have enough energy unless a new cluster head has been chosen that would lead to wastage of useful resources along with incurring delays within clusters.

4.2. Receiver-initiated asynchronous MAC protocols

4.2.1. EH-MAC probabilistic polling for multi-hop WSNs

An enhanced version [79] of the *probabilistic polling* technique discussed above [73] was also proposed from the same authors for multi-hop communication scenarios common in EH-WSNs. Another solution formulated for the same problem has been presented in this protocol emphasizing on the idea of the number of neighbors currently active for contention probability adjustment. All the nodes taking part in the contention wait for a random time between 0 and $t_{\max}$ and try sending the polling packets only if they sense an idle channel. The polling probability P_c is included in the packets that plays its role in deciding which nodes are eligible for transmission in that specific cycle. A new probability adjustment technique Estimated Number of Active Neighbors (ENAN) is employed in addition to AIMD in this protocol. Contention probability in this protocol can also be seen as inversely proportional to the number of active neighbors. Moreover, the receiver decreases contention probability where a collision occurs assuming that there are more estimated number of active neighbors than the system is expecting. Similarly, the value of contention probability tends to increase where nodes encounter an empty slot and no one takes part in contention for transmission.

Pros:

This protocol exhibits improved throughput and latency just like its first version for single hop WSNs and is pretty scalable for traffic loads, energy scavenging rates and various density levels of network. On the top of it, EH-MAC enjoys an added advantage of employing ENAN approach for contention probability adjustment in addition to AIMD that offers more control as compared to other duty-cycle tuning schemes.

Cons:

Due to the lower contention probabilities, it is more likely for the nodes to wait for longer period of time before getting their first opportunity to transmit in higher network densities. It is even worse in multi-hop scenarios where nodes have to wait for longer because of each intermediary relaying node towards destination which causes a greater end-to-end delay within network. In addition to the problem of inefficient convergence with frequently changing topologies, it also suffers in terms of energy, bandwidth and time wastage in case of no or corrupted response.

4.2.2. On-demand medium access control (ODMAC)

ODMAC [80] is a prominent MAC protocol for EH-WSNs initiated by the receiver with periodic beacons towards the intended senders. These beacons inform the senders about readiness of receiver to receive their responded packets. As soon as the senders receive these beacons, the transmission would instantly be started. This protocol is based on the duty cycle adjustment and *opportunistic forwarding* techniques to reach the ENO-MAX state (energy

neutral state when harvesting energy fully compensate the consumed energy keeping in view the performance) after which the protocol claims to achieve an optimum performance level. Duty-cycle can further be adjusted by two different methodologies; beacon period adjustment and sensing period adjustment. A node with extra harvested energy can decrease either the beacon or sensing interval (time between consecutive beacons or sensing operations) and the deficient energy nodes can contrarily increase either of these parameters based on the type of application and its requirements. The node can further tune either of the intervals in case of extreme energy shortage. Each node maintains a list of relay nodes in opportunistic forwarding and sends the packet instantly whenever it receives a beacon by the list members avoiding the need of keep waiting for a particular receiver.

Pros:

ODMAC makes best use of the energy harvesting by duty-cycle adjustment to achieve improved end-to-end delay and sensing reliability. Minimal energy is wasted on idle listening by employing opportunistic forwarding mechanism which helps the node forwarding their packets as soon as possible. They define a new approach named binding mode where extreme low power nodes are hard bound with the duty cycle of a particular node to further prevent it going in dead state.

Cons:

The technique in ODMAC is based on the current information in hand regarding system state and does not support smart decision making based on future predictions for the adjustment of duty-cycles. On the other hand, the newly introduced binding mode in ODMAC requires having a complete information regarding the duty-cycle of intended binding receiver that is not easily feasible in EH-WSNs.

4.2.3. Load & energy balancing MAC (LEB-MAC)

LEB-MAC [81] is another receiver initiated protocol that informs the senders by broadcasting a receiver beacon carrying the wake-up schedule of receiving node. Keeping in view the information just received by beacons, senders schedule their wake-ups a bit prior to the wake-up schedule of their intended receiver. In the beginning, senders do not have any concrete information about their receivers but they have the ability to learn the schedules by subsequent transmissions. However, the maximum possible waiting time (SL_{max}) for a sender to learn this information is application dependent and the duty cycle adjustment always functions keeping in view the residual energy level of the node. Fuzzy logic has been proposed to formulate appropriate sleep intervals keeping in view the energy level of the nodes. The collision scenarios have been divided into two types; occurrence of a collision when none of colliding nodes have prior communication history with receiver and collision where some senders have already communicated with the receiver in past cycles.

Pros:

Each receiver maintains a list of its prospective senders including those who have previously communicated with this receiver and it sends a dedicated beacon to the sender list if it involves a second type of collision. If more than one colliding sources are present in its senders list, the receiver would send a beacon to schedule the next transmission based on the information obtained from last cycles hence introducing a priority mechanism. Energy consumption is intelligent in LEB-MAC because of the known wake-up scheduling of receivers. As the receivers serve as senders for some other nodes so it smartly plays with the duty cycle of other nodes keeping in view the energy level that would end up towards achieving fairness and load balancing in a system.

Cons:

As the first time senders do not have any scheduling information about their intended receivers so the amount of waiting time

in this case is non deterministic and they would have to wait for all the previous communicating senders to finish their communication before getting a transmission opportunity for them hence they may experience much longer delays in their first communication cycles leading towards slowing down the system. The issue might be even more serious to be faced in dynamic networks where the new senders are more probable without even having an energy prediction mechanism.

4.2.4. An energy-harvested receiver-initiated MAC (ERI-MAC)

ERI-MAC [82] is another recently proposed receiver-initiated MAC protocol for EH-WSNs that basically uses CSMA/CA as a channel access mechanism. It is quite similar to probabilistic polling and ODMAC schemes discussed above [73,80] in this section in terms of fundamental operation in addition to its readily available support for large scale network conditions having realistic traffic patterns. It comes up with a new dimension of super packet resulted in merging various smaller packets together to reduce the overhead incurred by separate headers for individual packets. This protocol makes use of the packet queuing technique to achieve Energy Neutral Operation (ENO) state by delaying a packet for a safe duration. *Safe duration* can be seen as the amount of time spent by a packet in a (FIFO) data queue to ensure the residual energy is always greater or equal to the consumed energy required during packet transmission.

Pros:

The protocol offers a value feature of packet concatenation presenting a concept of super packet where the primary purpose of this long packet is to successfully reduce the header overhead in case of smaller packets. The novelty of ERI-MAC is its retransmission support (reasonably significant for EH-WSNs) in addition to conventional contention handling that differentiates this protocol from the counterparts leading it to a step ahead towards achieving QoS in data critical applications.

Cons:

While attempting to reduce the header overhead by a super packet, protocol may compromise the usefulness of this feature due to maximum size bound limitations by some radio platforms (such as IEEE 802.15.4 CC2420 [78] can maximum support 127 bytes of data packet). The protocol was evaluated on a real testbed of 49 node grid in ERI-MAC and the performance can be compromised in the situations where the size of the network is non-deterministic in the start of some applications due to higher dynamics of a network.

4.2.5. In QoS-aware energy-efficient MAC (QAEE-MAC)

QAEE-MAC [83] is another sender-initiated protocol with the aim of achieving QoS improvement that employs data priority mechanism where the packets with differentiated importance may be transmitted faster than the normal data packets ensuring urgent communication for critical applications. In this protocol, sender indicates the importance of its data through broadcasting a beacon just after waking up from sleep and waits for the receiver's response. Consequently, the receiver wakes up a bit earlier to collect all beacons of this nature just to know the importance level of each sender keeping in view the communication urgency. The receiver then prioritizes the list of senders and responds by broadcasting a beacon containing the ID of the currently selected sender letting him to transmit while all other nodes tune themselves to go for sleep for the duration of this transmission to avoid interference.

Pros:

The protocol offers a precise priority assignment mechanism and the receivers beacon in response not only broadcasts the new priority assignment decision but also acknowledges the previously accomplished communication similar to the functionality of

ERI-MAC that is perhaps a desperately needed feature for toady's WSNs. Moreover, nodes keep track of their energy level while scheduling their duty cycles in QAEE-MAC.

Cons:

The evaluation studies show that the protocol suffers in terms of performance because it is experimented with only one receiver and few senders in a single-hop way and may experience long delays in case of large scale network scenarios. Secondly, the priority assignment mechanism also causes significant energy consumption in terms of idle listening at all the senders that may eventually prove to be a bottleneck for such energy critical nodes who are already in a low energy situation and require to be handled with great caution.

4.2.6. Exponential decision based medium access control (ED-MAC)

ED-MAC [84] is fundamentally based on residual energy of each individual sensor node and tunes the adaptive duty-cycles for all the sensor nodes individually. Just like DeepSleep [87] and EL-MAC [87], it also employs two different kind of filters. In the first phase, exponential MAC is solely based on the current state of residual energy of an individual node. The node is assumed sleeping in the initial stage. It wakes back and calculates its residual energy. This scheme evaluates the slope of the decision graph to know the status of energy availability on each node by comparing it to different preset energy levels (i.e. maximum residual energy (E_{max}), threshold residual energy (E_{th})). Then, it calculates the maximum off time (T_{dc}) for each individual node that dynamically increased or decreased depending on the residual energy. In the second phase, this protocol takes in account the prospective residual energy that a node is expected to harvest in a course of time. The off time (T_{dc}) of an individual node can be squeezed based on its estimate of future energy availability.

Pros:

This protocol not only considers the current residual energy but also employs mechanism to estimate the future energy availability at individual nodes. This prediction capability makes possible to tune the duty-cycles of individual sensor nodes dynamically. Consequently, it enables sensor nodes to maximize their performance keeping in view not only the current residual energy but also the energy availability in future. It compares the various performance metrics (e.g. end-to-end delay, average energy consumption and, packet delivery ratio) with another static receiver-initiated MAC protocol supporting linear dynamic duty-cycle approach. Results show that ED-MAC exhibits better energy utilization and management as compared to its counterpart.

Cons:

The evaluation procedure shows that the protocol suffers in terms of performance in multi-hop scenarios because it is experimented on very small scale with a single-hop fashion and may experience long end-to-end delays in case of large scale network scenarios. Secondly, every time a node wakes up, it compares its residual energy to different preset energy levels. If the residual energy remains lesser than a particular threshold, the node would again go to sleep. It causes the wastage of bandwidth, energy and duty-cycle of individual nodes that may yield delays in the overall system. Third, this kind of schemes are application dependent and behave differently for each topological structure. They do not fit well in the applications experiencing frequently changing network topologies.

4.2.7. Synchronized wake-up interval MAC protocol (SyWiM)

SyWiM [85] is another receiver initiated protocol proposed targeting on two significant aspects; timing offset and clock drift to improve the overall QoS. Timing offset may occurs if the nodes are deployed at different times during initialization or resynchronization phases while clock drift refers to the frequency deviation

of local oscillator. SyWiM employs solar panels as the source of renewable energy assuming sun light during the sunny day and light bulbs in the indoor environment at night times or during cloudy days with 24h periodic pattern. In SyWiM, whenever a node has data, it waits for the wake-up beacon from the associated receiver. As soon as the beacon is received, it transmits the data after clear channel assessment and calculation before transmission operations. The receiver may confirm the receipt of this packet by sending an acknowledgement back to the sender before going to sleep. Due to the difference in timing offset, the first communication between nodes incurs long idle listening intervals that are reduced to normal interval from the next communication after the first communication has successfully been taken place. During the second time, the transmitter is able to find out the exact timing offset and accordingly updates the next wake-up interval. Similarly, the next wake-up deals with the clock drift after resolving timing offset. For this purpose, the transmitter wakes up an interval p prior to the wake-up schedule of its receiver to maintain synchronization where p is equal to the maximum possible clock drift between the nodes.

Pros:

SyWiM successfully improves many QoS parameters (like data rate, latency, energy consumption). The experimental setup of SyWiM not only involves simulation platforms but the authors also validate their proposal with real WSN hardware platforms considering PowWow [86] as the potential candidate. Moreover, SyWiM adopts super capacitors as storage mechanism that exhibit increased number of recharge cycles up to 500,000 as compared to conventional battery powered solutions [85] which also contributes towards prolonging the battery life of sensor nodes.

Cons:

Although, SyWiM improves many QoS metrics but the authors [85] exhibit the usefulness of their proposal considering a network size of up to 50 nodes only. In case of large deployments, the performance may severely be affected. Moreover, three different energy harvesting profiles are considered that are randomly selected among the pool without any mechanism that may not be suitable in some scenarios where the amount of energy in hand may not be equal to or less than the amount of harvesting energy (selected harvesting profile) assumed for supporting the continuous operation.

4.3. Sender-initiated asynchronous protocols

4.3.1. DeepSleep; an 802.11 extension for EH-M2M

DeepSleep [87] can be seen as an extension to IEEE 802.11 Power Saving Mode (PSM) [88] specifically designed for Energy Harvesting Machine-to-Machine (EH-M2M) communication with the mere provision to support large scale EH sensor networks compared to other variety of protocols present in this area. The MAC protocol design considerations for M2M communication are quite similar to WSNs hence, many proposed schemes for M2M are stimulated by WSNs. In 802.11 PSM [88], time can be seen in terms of beacon intervals that are further divided into Ad-hoc Traffic Indication Map (ATIM) window and transmission intervals. If a node has some data destined for another intended destination, it first exchanges a pair of ATIM packets (request and acknowledgement) with corresponding next hop and all other devices switch to sleep mode except this pair of nodes woken-up for rest of the beacon interval. The devices going below a particular energy threshold will observe DeepSleep to save energy at hand and to harvest sufficient amount of energy for future operations. This protocol further introduces another filter approach named *Controlled Access* in which newly woken-up devices from DeepSleep would further compete with peer nodes to reduce the number participating in the contention process. It

further enhances the chance of participating devices to fairly get a transmission opportunity.

Pros:

The primary advantage brought by these techniques may be the reduction of number of active nodes participating in the contention leaving the rest of nodes in better (lower) contention situation. The devices woken back from sleep in result of applying both of these mechanisms are assigned a shorter contention window for the sole purpose of prioritization of nodes to get the channel sooner. Consequently, it may lead to a reduction in collisions, overhearing and idle listening.

Cons:

The probability to go back to sleep for all the nodes in controlled access is equal including those that have just woken back after DeepSleep. Although the protocol favors the newly awoken devices by assigning a shorter contention window to enable them avoiding a longer contention before transmission but it is equally likely that a node would be forced to go DeepSleep even if it has just woken back. These forced slept nodes would again harvest more energy even if they already had sufficient amount of energy for their prospective transmissions. This phenomenon would starve the nodes with higher energy level for fair channel access in comparison to other contending nodes within the system.

4.3.2. Energy level based MAC (EL-MAC)

EL-MAC [89] is another sender initiated MAC protocol presented for Energy Harvesting Secondary Users (EH-SUs) in Cognitive Radio Sensor Networks (CRSN). The operation in CRSN is performed based on the exploitation of spectrum holes during the utilization period of Primary Users (PUs) without interfering the ongoing process initiated by PUs. EL-MAC takes a whole super frame as a combination of sensing, contention and transmission periods. If an SU finds the channel busy during sensing period, it immediately goes to sleep, otherwise, it further proceeds to take part in the contention period. If the contention is successful based on the Differentiated Access Probability (DAP), it enters in transmission period to go ahead with the transmission leaving behind other contenting nodes. This protocol uses CSMA/CA as a channel access method in addition to *Differentiated Access Probability (DAP)* and *Differentiated Contention Window (DCW)*; two newly introduced filters. SUs compute their DAP which is supposed to be inversely proportional to their current energy levels turning some users to sleep mode. The second filter (DCW) is applied to existing nodes to further enhance the probability of medium access for low energy nodes switching few more nodes on sleep.

Pros:

As EL-MAC forces some nodes going to sleep based on their residual energy so it successfully enhances the contention level for the rest of the nodes leaving them fewer in numbers. EL-MAC provides special provision to low energy nodes to best utilize their residual energy and ensures the minimum amount of energy is wasted during contention and idle listening if a low energy node has packets for transmission. It further offers the energy saving for high energy nodes turning them to sleep even if they have sufficient energy level, they may harvest a bit more energy instead of wasting their own.

Cons:

The mechanisms employed by EL-MAC always pushes the high-energy nodes out of contention hence they are switched on sleep mode not only to save some energy but to harvest an additional amount of energy. Consequently, these nodes always remain high energy nodes that may eliminate their chances for accessing the medium for their own transmissions and they may never get the transmission opportunity being in high energy level. Moreover, as mentioned in ODMAC [80] and DeepSleep [87], this protocol is also intended for single-hop WSNs where the destination is one

hop away. But in multi-hop WSNs, one may not be sure about the transmission success because of not having the current state of the intended receiver.

4.3.3. Solar energy harvesting energy efficient MAC (SEHEE-MAC)

SEHEE-MAC [90] assumes solar energy as the renewable source and introduces the notion of slotted preamble technique to control the radio over a sensor node. It can save the significant amount of energy by reducing the duty-cycle of individual sensor nodes based on their energy status and switching the low energy nodes on sleep mode. A sender initiates the process by sensing the channel employing CSMA type basic mechanism. If the channel is idle, it keeps on sending the slotted preamble unless all the neighboring nodes turn on and receive the preamble for at least once. The intended receiver would acknowledge back with a request to send the full packet back to the sender. As soon as the sender receive the full packet request, all the other nodes turn off their radio switching themselves to sleep mode while sender successfully transmits full packet. After each successful transmission, the residual energy of sending node is compared to minimum energy threshold. It increases the slotted preamble interval if the threshold is reached or keeps on sending the full packets otherwise. The node would calculate its back-off interval if it senses a busy channel unless it reaches the maximum back-off limit.

Pros:

Unlike conventional preamble techniques, SEHEE-MAC employs slotted preamble technique to control the radio activities of a sensor node which helps to save an adequate amount of energy. A solar based energy harvesting system is also studied along with this MAC approach conforming to the energy requirement imposed by habitat monitoring applications. An analytical energy model is also proposed to evaluate the precise energy requirement in case of both energy harvesting and battery-operated WSN for different traffic conditions.

Cons:

In an attempt to reduce the energy consumption, SEHEE-MAC undergoes some serious limitations. The neighboring nodes turn their radios on just after the reception of preamble and keep on listening until they receive acknowledgment by a receiver with full packet request which causes idle listening. Moreover, SEHEE-MAC is also topology specific and does not fit well in the applications with frequently changing topologies. The evaluation procedure shows that this protocol was compared with other non-energy harvesting protocols instead of a logical comparison with the similar counterparts.

4.3.4. A radio frequency based MAC for wireless energy harvesting in WSN (RF-MAC)

RF-MAC [91] strives to identify how different factors (such as placement, selected frequency range and, the number of RF energy transmitters) impact the charging time through ambient RF energy. These factors are considered while designing RF-MAC which not only minimizes data transmission disruption but also optimizes the energy delivery to the nodes. The sending node undergoes channel sensing employing fundamental CSMA access technique and waits for DIFS amount of time. Here, it is important to note that DIFS is defined separately in RF-MAC for both data and energy transfer. Sensor nodes with higher energy harvesting rates have shorter charging durations. Sensors with greater residual energy are assigned a higher priority for the data transmission yielding optimal network lifetime. Similarly, RF-MAC introduces the notion of adaptive back-off period where the nodes with greater residual energy experience the shorter back-off time as compared to low energy nodes. The contention window is randomly selected for the data exchange between a range of minimum and current window values. This selection of contention window is independent of the

residual energy of the sensor nodes which helps to prevent *Convoy Effect* (preventing nodes with higher residual energy to always occupy the channel that puts all the lower energy nodes on wait).

Pros:

RF-MAC not only deals with the energy harvesting and MAC design but also emphasizes on wireless energy transfer employing the idea of collaborative beam forming of distributed transmitters on the top of IEEE 802.15.4 mechanism [78]. It also attempts to optimize the power output employing high-frequency signals with different phases in order to improve the energy efficiency. Furthermore, this scheme is not only evaluated employing real testbeds (i.e. MoCA2) but it also justifies the performance comparison through simulations [91].

Cons:

In an attempt to optimize the power output using high-frequency signals with different phases, time synchronization for high-frequency signals may always be a challenge in this kind of protocols. Moreover, the scheme is evaluated in comparison with two different approaches. One of them is modified CSMA which is actually a non-energy harvesting approach hence inappropriate for the evaluation.

5. Open issues, challenges, lessons learned and future research directions

Each protocol discussed so far was aimed at catering to one or two specific aspects bearing a clear set of advantages and disadvantages. Different application requirements and design considerations were also taken into account. Summary of the techniques used by these protocols to make them compatible for EH-WSNs is presented in Table 3. The hop count and validation method for each energy harvesting MAC protocol have also been indicated after a detailed study on the protocols. Nevertheless, all the protocols (discussed in the Section 4) experience several critical issues of general nature in addition to their individual pros and cons. This immediately translates to a new set of challenges and opportunities that will be explored in this section.

To draw a general comparison, the most relevant key performance indicators (KPIs) have been identified in Table 4 for all the protocols analyzed in Section 4. Here, it is pertinent to note that the significance of each individual KPI depends on the type of WSN application. For example, some applications like fire detection may rate latency as the most critical KPI as compared to energy utilization. Similarly, fairness may be the first choice to consider in some applications with bandwidth constrained wireless links. Hence, the choice of optimization for certain KPIs is challenging and is a matter of tradeoff between most critical KPIs based on the underlying application.

According to the literature review presented so far, fairness is one of the primary KPI (mentioned in Table 4) in EH-WSNs. In fact, it is still challenging in WSNs to ensure a fair share of the total bandwidth of the system to the different nodes in order to pursue load balancing and extend network lifetime. Secondly, certain applications in WSNs may be required to achieve guaranteed data delivery due to application critical data frames and it may not always be possible for EH-WSNs because of the non-availability of an active sending node due to its duty-cycle expiry hence it would impose a new design goal. A well-designed transport protocol is also one of the challenging design consideration to regulate the data flow irrespective of the location of the node within the network.

Most of the protocols analyzed in Section 4 were proposed to optimize QoS while exploiting the presence of renewable energy. Hence, the mere focus of these protocols was to target the KPIs like throughput and delay optimization instead of energy saving operations and they have been quite successful to improve throughput of the system except [84]. Similarly, most of them are suitable

for the delay critical applications except [79,83,90] that incur relatively higher delays as compared to their counterparts as shown in Table 4.

Energy and data buffers on individual nodes are assumed to be of infinite capacity for the sake of simplicity while designing energy harvesting systems. Similarly, the initial channel conditions are assumed to be of perfect synchronization for simpler experimental set-ups. Furthermore, the only energy consumption source in most of the harvesting models discussed in [92] is assumed to be data transmission, ignoring all other energy consuming processes. This kind of assumptions are unrealistic while modeling energy harvesting systems and future works should consider these shortcomings while modeling the energy harvesting environments.

Despite being most significant and desperately needed design consideration, only MAC protocol is not enough for a desired performance level in EH-WSNs. Routing protocols are also consideration candidate as in multi-hop WSNs, it is difficult to predict the waking time of the next possible hop for a communication. It may prove to be an even worse scenario if the next hop has depleted the whole energy during the last cycle. Consequently, it would lose the time stamp for the next wake-up and only SyWiM [86] employs mechanism to resynchronize the time stamp. Hence, it would no more be a good choice to wait an unlimited amount of time for that neighbor to be woken back for all other protocols mentioned in Table 4. Broadcasting and opportunistic forwarding may then be useful approaches to be adopted with a mechanism to cope the problem of receiving duplicate frames if multiple neighbors are active and ready for reception so that the harvested energy is not wasted. On the other hand, when there are not enough nodes woken-up to serve as a next hop, then delay-tolerant network (DTN) techniques [93] may prove to be useful to play their parts effectively to forward the data to the best possible hop towards destination.

In a typical MAC protocol, bulk of proposals have already been formulated [11–24] for conventional WSNs to achieve longer battery life. It is inevitable for EH-WSN based MAC design to first highlight the possible source of energy wastage (including different energy leaks depending on harvesting technology) and then deduce new mechanisms to efficiently utilize the energy at hand (e.g. seamless synchrony of sleep and wake-up schedules). It is to note that contention-based CSMA/CA has been prominently chosen as basic approach for many MAC protocols customized for EH-WSNs in [73–76,79–91] because of its simple, yet comprehensive mechanism for traditional WSNs with the addition to one or multiple techniques presented in Table 3. Moreover, another important study is presented in [88,94] depicting the effectiveness of unslotted CSMA/CA against the slotted one where most of the energy is consumed in slot synchronization.

Almost all the protocols customized for EH-WSNs (discussed thoroughly in Section 4) refer to a single harvesting technology (e.g. solar, wind or vibrational) because of the unique complexities and trade-offs involved in each technology. Therefore, energy model for each harvesting technology is protocol specific and is different because of different time and environment. Hence, there is not even a single protocol available to perform well with multiple (or even more than one) harvesting technologies.

Validation method is another important aspect that clearly advocates the superiority of one type of protocol over another. Table 4 highlights the validation method used for each of the protocols discussed in [73–76,79–91] and all of them have been compared against a single or multiple traditional (non-energy harvesting) MAC protocol which does not clearly argue the legitimacy of the evaluation procedure. For an accurate simulation setup to evaluate MAC protocols in EH-WSNs, it is significant to establish a common simulation framework and compare each special MAC protocol against similar other protocols for EH-WSN employing

Table 3

Summary of the MAC protocol techniques customized for EH-WSNs.

Technique	Description	Protocols
Contention probability adjustment	Adjusting the Probability of Packet Transmission based on the energy harvesting rates and/or the number of active nodes.	✓ Prob. Polling SH [73] ✓ MTPP [74] ✓ Prob. Polling MH [79]
Duty-cycle adjustment	Adjusting the duty cycle of the nodes based on their energy levels	✓ RF-AASP [75] ✓ AH-MAC [76] ✓ ODMAC [80] ✓ LEB-MAC [81] ✓ ERI-MAC [82] ✓ QAEE-MAC [83] ✓ SyWiM [86] ✓ SEHEE-MAC [90] ✓ RF-MAC [91]
Load balancing	Distributing the load among nodes based on their energy levels	✓ AH-MAC [76] ✓ ODMAC [80] ✓ LEB-MAC [81]
Energy-aware deep sleeping	Letting the low-energy devices go to deep sleep so they can harvest enough energy for future transmission	✓ ED-MAC [84] ✓ DeepSleep [87] ✓ SEHEE-MAC [90]
Contention Reduction	Forcing some devices going to sleep and leave the contention	✓ RF-AASP [75] ✓ ERI-MAC [82] ✓ ED-MAC [84] ✓ DeepSleep [87] ✓ EL-MAC [89]
Differentiated contention window	Assigning different contention windows to different nodes to prioritize some of them over the others	✓ RF-AASP [75] ✓ ERI-MAC [82] ✓ QAEE-MAC [83] ✓ DeepSleep [87] ✓ EL-MAC [89] ✓ RF-MAC [91]
Wake-up time awareness	Incorporating the next wake-up schedule in the beacon to inform potential senders about when the beacon transmission will take place	✓ LEB-MAC [81] ✓ QAEE-MAC [83] ✓ SyWiM [86]

Table 4

Comparison of performance level of protocols based on important performance indicators.

Protocol	Throughput	Latency	Scalability	Fairness	Energy utilization	Single/Multihop	Validation method
Prob. polling-SH [73]	High	Moderate	Moderate	High	High	SH	Analytical Model
MTPP [74]	High	Low	Moderate	Moderate	High	MH	Real Testbeds
RF-AASP [75]	High	Moderate	Low	High	Moderate	SH	Analytical Model + Simulation
AH-MAC [76]	High	Moderate	Moderate	High	Low	MH	NS-2 Simulation
Prob. polling-MH [79]	High	High	High	High	Low	MH	QualNet Simulation
ODMAC [80]	Moderate	Low	Low	Moderate	Moderate	MH	OPNET Simulation
LEB-MAC [81]	Moderate	Low	Low	Moderate	Moderate	MH	Qualnet Simulation
ERI-MAC [82]	High	Low	High	Moderate	Moderate	MH	NS-2 Simulation
QAEE-MAC [83]	High	High	Moderate	High	High	SH	Analytical Model + Simulation
ED-MAC [84]	Low	Low	Low	High	Moderate	SH	NS-2 Simulation
SyWiM [86]	High	Low	Moderate	High	Low	MH	Real Testbeds + Simulation
DeepSleep [87]	High	Moderate	High	High	Low	SH	NS-2 Simulation
EL-MAC [89]	High	Moderate	Moderate	Low	Low	SH	Analytical Model
SEHEE-MAC [90]	Moderate	High	Moderate	High	Low	SH	Analytical Model + Testbeds
RF-MAC [91]	High	Low	Moderate	High	Moderate	SH	Real Testbeds + Simulation

this framework. For example, precise energy model can be implemented and incorporated to a network simulator to evaluate these special protocols for EH-WSN that may exhibit more logical evaluation characteristics for this class of protocols.

Moreover, most of energy harvesting MAC protocols are evaluated based on simulation setups. There may be a possibility to compromise on several unrealistic assumptions in simulation methods that can be avoided by employing real test-beds. Devising a mechanism for practical implementation of these protocols on the real test-beds can be a challenging task. There may be sev-

eral open issues (e.g. resource allocation and management) while practically implementing the set of protocols on the actual sensor hardware. Therefore, practical implementation and testing of more energy harvesting MAC protocols would significantly influence the performance metrics.

There are separate MAC protocols for special types of energy harvesting sensor network applications (e.g. Body Area Networks [95], Multimedia Sensor Networks [96], Underwater Sensor Networks [97] and, Cognitive Radio Sensor Networks [98]) deserving special attention. MAC protocols for all these applications intend to

achieve different design goals. Therefore, no single energy harvesting MAC protocol can serve more than one type of special applications because of diverse nature of application scenarios. It evolves the need for a special MAC protocol intended to serve each of the applications of sensor networks with respect to energy harvesting constraints. There exists an opportunity to study MAC protocols targeting special applications of wireless sensor networks keeping in view the design implications of harvesting systems.

Majority of the protocols proposed for EH-WSNs employ duty-cycle adjustment and differentiated contention window schemes with some of them focusing on contention reduction method. These techniques are effective for a MAC protocol aiming to achieve low energy consumption but, on the other hand, more shrinking the duty-cycle and frequent switching between active and sleep modes may also severely influence the performance level of individual nodes. Hence, there exists a thin line between low energy utilization and optimum performance level that should be taken care while designing MAC for EH-WSNs.

The present can be seen as the era of transition from 'Internet of People' to 'Internet of Things'(IoT) and this evolution is supposed to be on its peak until 2020 when there may be 50 billion objects connected to the internet according to a report published by CISCO [99]. In addition to their significance as popular standalone networks, WSNs are supposed to be an integral part of ongoing wave of IoT to make them suitable for a range of M2M applications [100]. Compatibility of these MAC protocols for IoT deployments is another challenge. Among the analyzed protocols customized for EH-WSNs, some of them (e.g. [82,87]) can also be considered for a bulk of future IoT use-cases unless they offer scalability for large scale deployments along with low energy utilization. They can be studied further for their deployments towards energy harvesting-IoT networks.

6. Conclusion

Preserving couple of decades of rich history, Wireless Sensor Networks (WSNs) do still exist among the top niche of most widely deployed wireless technologies of the age because of their unmatched characteristics in comparison to other counterparts. The emergence of energy scavenging mechanisms gave birth to a variety of new horizons of WSNs enabling them to be deployed for a huge number of energy critical scenarios and applications. This promising combination led the research towards a new set of challenges and tradeoffs to be compromised for achieving each design goal (e.g. either longer life time or better performance). This paper presents a comprehensive review on the current state-of-the-art of this incredible combination keeping in view a set of limitations towards general design considerations. We first discuss the latest research trends towards energy harvesting area covering various energy scavenging technologies widely used for this combination, energy harvesting architecture, and possible design alternatives significant to this combination. We then elaborate the need for special MAC protocols for EH-WSN. Eventually, we analyze a range of special MAC protocols presented in the literature for EH-WSN along with their pros and cons of this combination towards achieving an optimal design.

Optimum energy utilization is still one of the fundamental goals of EH-WSN because of the difference between harvesting and consumption rate. It is worth mentioning that only few of the proposed MAC protocols for EH-WSN exhibit efficient energy utilization in true sense as shown in Table 4. Furthermore, most of the protocols proposed in this area do not seem to be focusing on minimizing the energy utilization when striving to achieve other performance metrics (e.g. throughput). Most of them do not even evaluate their performance in terms of energy utilization. Furthermore, QoS achievement has also been challenging for this class of

protocols. Most of the protocols targeting QoS parameters still suffer with respect to other criteria (such as end-to-end delay and energy utilization). Moreover, performance evaluation of these protocols through the widespread implementation on real hardware is seriously lacking and there exists a need to evolve more energy harvesting WSN systems employing MAC protocols on top of them for the real-time performance evaluation.

We argue that there are several strongly-coupled factors to be considered while talking about an optimal MAC design for the EH-WSNs and considering only a single set of limitations for each side (e.g. either WSNs or Energy Harvesting) is never enough towards achieving a satisfactory performance level. This study was aimed at providing a clear roadmap for new researchers to step ahead in design considerations and challenges of this area.

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