Comparison of MAC Techniques for Energy Harvesting Wireless Sensor Networks

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Abstract

In this project we describe the state-of-the-art MAC protocols for Energy Harvesting Wireless Sensor Networks (EH-WSN). Differently from standard WSN, the goal is to efficiently take into account the possibility to recharge the built-in battery in order to improve the overall performance, rather than exploiting just the initial energy available. The protocols we present try to achieve the optimal trade-off between the potentially infinite network lifetime and the uncertain energy availability. Finally, we provide a brief comparison among the solutions described.

I. Overall System Model

Introduction to WSN

Wireless sensor networks consist of a series of linked nodes that are able to cooperatively send and receive data to and from a common base, the sink. The objective is to sense physical conditions (such as temperature, sound, pressure) of a determinated spatial area where many nodes are randomly distributed, or transmit simple commands for a transducer (turn ON/OFF a device).

A common device is equipped with a sensor probe to recover information from the surrounding, a processing unit to elaborate them, a wireless transmission system to communicate message to a gateway (the sink node) and a battery block. In addition to a generic sensor, we assume that some energy harvesting mechanism is also available. The sink, which is a type of base station that collects messages from the sensor nodes, could be connected to other networks or directly to the Internet through a gateway.

Like Internet, this technology was born for military purpose and is now being more and more useful in many industrial, medical and consumer applications.

Multi-hop model

Informations collected by nodes must be sent to the base station and to overcome the limited transmission range, a multi-hop random topology can be considered. A quite common choice

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is to deal with a single-sink network, even if a more general scenario involves multiple sinks. A larger number of them will decrease the probability of isolated clusters of nodes that cannot deliver their data, but it would require much more complexity in protocol design. Data to be transmitted are gathered in packets and are routed in a multi-hop lossy wireless fashion to the base station: it may be possible that one or multiple transmissions are necessary to successfully deliver a message. If there is a sink within transmission range of a node, the message will immediately be transferred. Otherwise if there are other sensor nodes within transmission area, the node transmits the message to them which forward it again by iterating the procedure. The process successfully ends when eventually the message will reach a sink.

The WSN can be represented as a graph $G = (V, E)$ where vertices $v \in V$ represent the nodes and an edge $(u, v) \in E$ represents a wireless link between the two nodes $u, v \in V$.

Types of scavenging

There are many free energy sources in nature [1] [2]: how to harvest and storage these energies efficiently in small devices is still object of research activity.

Solar The basic principle of optical collection is to absorb a large number of photons by the use of photovoltaic materials. The main disadvantage of this energy source is the great dependency on time and on solar environment exposure. Indeed during night and cloudy days it not guaranteed sufficient energy incoming.

Thermal Thermoelectric scavenging exploiting the differences of temperature, is nowadays a very well known technology. Devices of this type can be small, light and are able to work in harsh environments.

Motion If nodes are subject to movements, oscillations and vibrations in the surrounding could be scavenged according to Faraday's law of electromagnetic induction. The main advantage of this source is that, in some particular scenarios, it could provide constant energy.

Electromagnetic When a node is exposed to an electromagnetic field, energy related can be drawned with the use of an inductor. Manos Tentzeris, a professor in the Georgia Tech School of Electrical and Computer Engineering, and his team state: "There is a large amount of electromagnetic energy all around us, but nobody has been able to tap into it. We are using an ultra-wideband antenna that lets us exploit a variety of signals in different frequency ranges, giving us greatly increased power-gathering capability" [3]. It is believed that the technique could provide a promising new way to power wireless sensors networks.

Related issues

Energy management is one of the main issues in EH-WSN because it critically threats the sustainability. Since the nodes are distributed in extensively wide and complex environments, it becomes very difficult to replace the battery: energy efficient policies and harvesting techniques must be jointly developed. Furthermore, the large dimensions of WSN impose a strict bound on production costs, consequently limiting computational power, energy storage capability, memory size, etc. Finally, entrusting the entire energy scavenging to a unique source is not reliable, as it could provide a non uniform energy supply. Of course, each energy harvesting system must be properly designed according to network requirements and nodes parameters.

II. Harvesting sensor node architecture

A. *Overall architecture of a sensor node*

The overall architecture of a sensor node is depicted in Fig.1

Power Supply The power supply unit of the sensor node provides power to all its components. In the majority of cases it consists of a rechargeable DC battery.

Micro controller It is responsible for all processing and decision making.

Sensors These sense the surrounding environment and inform the controller about what is being observed. For example, they can sense light, temperature, humidity, pressure.

Transceiver It deals with transmission and reception of the data to and from the base station. Usually RF based communication is preferred, as Infrared or Laser technologies need a direct sight for the correct communication.

Memory Sensor nodes are equipped with a programmable Flash memory and RAM in most cases. Usually storage capacity is limited, so the protocols that are designed for sensor networks should be simple enough to be loaded into the available memory.

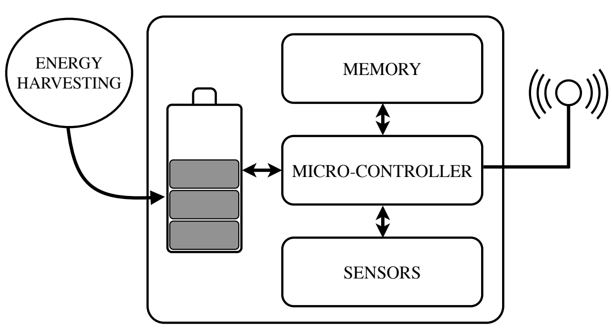


Fig. 1: Sensor node architecture

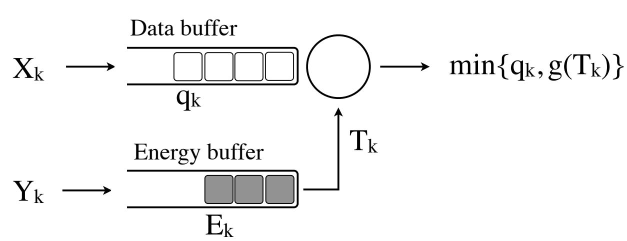


Fig. 2: Energy model

B. *Energy model*

A possible energy model for a WSN [4] can be seen in Fig.2. Assuming slot-divided time, X_k represents the amount of bits received by the node in slot k, that are stored in a buffer. At time

k, q_k bits are present in that buffer of which only $g(T_k)$ can be transmitted in the $(k+1)^{th}$ time slot: T_k represents the quantity of energy available for the transmission in slot k. We assume that Y_k is the energy scavenged from the sensor at time k and E_k is the amount of energy stored in the sensor (of course $T_k < E_k$).

Assuming that transmission consumes most of the energy and ignoring the other possible sources of energy consumption, if $\{X_k\}$ and $\{Y_k\}$ are i.i.d, processes $\{E_k\}$ and $\{q_k\}$ satisfy

$$E_{k+1} = E_k - T_k + Y_k \quad (1)$$

$$q_{k+1} = (q_k - g(T_k))^+ + X_k \quad (2)$$

The function g is assumed monotonically non-decreasing and a relation between the number of bit transmitted and the energy exploited is given by Shannon's capacity formula for Gaussian channels

$$g(T_k) = \frac{1}{2}\log(1 + \beta T_k) \quad (3)$$

where β is a constant such that βT_k is the SNR. Possible generalizations of this simple energy model for a wireless sensor can take into account energy inefficiency in storing energy in the buffer or energy leakage from the energy buffer. In addition to this, fading properties of the channel and energy consumption in sensing and processing can be considered.

C. Set of operational states

The node activity cycle can be divided into three different states:

OFF The node is sleeping and so the transceiver and the microprocessor consume as less energy as possible.

IDLE The device has no data to be transmitted but senses the channel in order to detect incoming transmissions from other nodes.

TX The node has to transmit its own previously generated data.

In general, transmission state is the most energy consuming among the three operating states described.

III. MAC PROTOCOLS IN HARVESTING WSN

The activity of sensing, processing and broadcasting under energy constraint policies implies the necessity of a well designed medium access control schemes.

Most protocols proposed in literature for non harvesting WSN aims at preserving network lifetime by avoiding energy wasting operations like packet collisions, protocol overhead and overhearing. EH-WSNs are required to achieve the trade-off between the potentially infinite network lifetime and the uncertain energy availability.

In EH-WSN an important goal is to reach and maintain an energy neutral operation (ENO) state, where the energy consumed by a node is always less than or equal to the energy harvested from the environment. If achieved and correctly managed, ENO state leads to infinite network lifetime, meaning that lifetime is not constrained by power supply unless hardware failures.

Recently, several solutions to manage power at the MAC layer in EH-WSNs have been proposed; the approaches can be distinguished into two main categories.

A. Synchronous

Sensor nodes are organized in virtual clusters and share a common sleep/wake duty cycle, reducing overheads once scheduling calculation has been accomplished. This approach is not feasible for EH-WSN because ready-to-use energy is required, in contrast to the random behavior of harvesting processes: if a node runs out of energy, it could not wake up when required by the synchronism schedule. Examples of this synchronous-based MAC are S-MAC and T-MAC.

B. Asynchronous

In this type of MAC protocols every node manages its duty cycle independently from the neighbours. Asynchronous protocols can be further distinguished in two sub-categories.

1) Preamble based: before the transmission of every packet over the channel, the node communicate a preamble that lasts as long as the sleeping period of the receiver. Once received, the preamble aware of the imminent transmission. In this approach there are two source of overheads: the preamble transmission and the periodical listening of the channel for incoming packets. An example of preamble-based MAC is X-MAC.

2) Beacon based: this approach is similar to the preamble one but here transmissions are receiver initiated. Availability to receive is announced with a periodically beacon broadcast. Source of overhead are related to those of the preamble-based: beacon transmission and listening of channel for their broadcasts. Examples of this approach are ODMAC, P-MAC, EH-MAC, EA-MAC.

We now describe the most common EH-WSN MAC protocols, whose performance analysis is presented in Sec. IV

ODMAC

This On Demand MAC protocol has been introduced to operate as close to the ENO-Max state as possible, i.e. the state where a sensor operates at the maximum performance while maintaining an energy neutral condition. The key peculiarities are:

- communication is on demand, i.e. the receiver asks for the transmission

- the protocol provides a tool to adjust the energy consumption in accordance to the application requirements
- end-to-end delay significantly decreases, thanks to an opportunistic forwarding scheme

We now briefly describe the main features of the protocol, more details can be found in [5]. Fig.3 depicts a typical communication between a transmitter and a receiver.

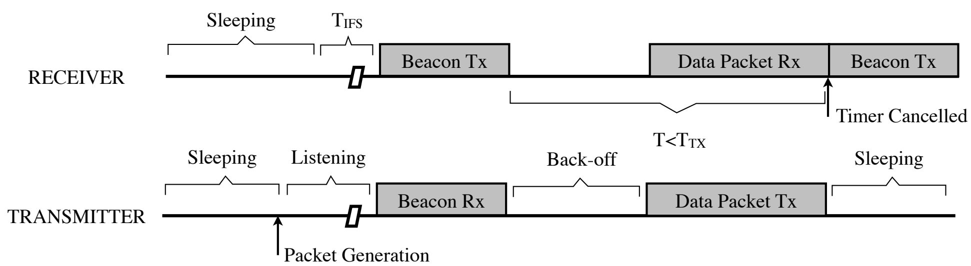


Fig. 3: ODMAC typical communication

ODMAC uses the carrier sensing scheme in order to support individual duty cycles. Each receiver periodically broadcasts a beacon indicating the availability to accept incoming data packet transmissions. All nodes having queued packets that need to be forwarded to the sink are listening to the channel waiting for an appropriate beacon. Upon receiving the beacon, after the expiration of a random back off timer the data packet transmission follows. This approach completely eliminates the idle listening from the receiver node: it just spends energy to periodically broadcast a tiny beacon frame. After each successful transmission, the receiving node immediately retransmits a new beacon. If two transmitters are waiting for the same beacon or two neighboring nodes transmit their beacon at the same time, a collision may occur. However the protocol is able to handle these problems. The trade off between end-to-end delay and energy consumption can be tuned by the network administrator according to the application requirements, by choosing between static and dynamic duty cycle mode. Instead of waiting for a specific beacon, the ODMAC transmitter opportunistically forwards each frame to the owner of the first beacon received as long as this node is included in a list of potential forwarders, as specified by the routing protocol. In this list, all the node that are closer to the sink (in terms of number of hops) are included.

X-MAC

By employing a shortened preamble approach, X-MAC represents a solution to the problems of B-MAC or T-MAC in terms of energy consumption. The first contribution is to embed address information of the target in the preamble so that non-target receivers can quickly go back to sleep and continue their duty cycling, otherwise it sends an early acknowledgment packet back to the sender that stops sending preambles and starts to send the data packet: this addresses the overhearing problem. The second contribution is to transmit a strobed preamble (series of short packets) to allow the target receiver to interrupt the process as soon as it wakes up and determines that it is the target receiver. This short strobed approach reduces time and energy wasted waiting for the entire preamble to complete.

This protocol provides a variable duty cycle, which is an essential requirement in EH-WSNs: in cases of limited environmental energy it can be tuned to consume as less energy as possible. For a more detailed description, we refer the readers to [6].

EA-MAC

Energy Adaptive MAC is a protocol designed for single-hop WSNs scavenging radiofrequency energy, introduced in [7]. Energy is transferred from a RF-emitting sink node (called also master node) to EH nodes located in the surrounding, connected in a star topology. Master node is always awake to receive data packets and distribute RF energy. On the other hand, sensor nodes have two main states, sleep and active, depending on the level of their remaining energy. In sleep state the node turns off processor and radio to save energy, while maintaining harvesting capability. In active state the node contends for the channel and transmits its data, if possible. The transition from the sleep state to the active one is determined by the attainment of a sufficient amount of energy δ, necessary to contend and transmit. After the transmission of a packet or if the node fails to contend the channel, it goes to sleep state. It is assumed that a node can transmit only one fixed-length packet per duty cycle and a node i receives a constant rate of energy, given by

$$P_{in,i} = eP_{tx}G_{tx}G_{rx}\left(\frac{\lambda}{4\pi R_i}\right)^2 \tag{4}$$

where e is the energy harvesting efficiency. Harvested energy decreases proportionally with the second power of the distance R_i from the master node, leading to highly variable and unfair energy rates among nodes: a sensor node that is far away from the sink will have a lower energy harvesting rate and consequently an increased sleep time.

EA-MAC protocol adaptively manages the contention period to compensate the unfairness. This is performed by the Energy Adaptive Contention algorithm (EAC), based on the unslotted CSMA/CA algorithm of IEEE 802.15.4, where the backoff time is controlled by the energy harvesting rate of the node. The resulting algorithm is described in Fig.4: NB_i is the number of clear channel assessment (CCA), BE_i is the backoff exponent and ω_i is the weight factor used to compensate the unfairness and calculated as the ratio between the node harvested energy and the average harvested energy of all nodes in the network.

After entering the active state the node will compute ω_i, initialize $NB_i = 0$ and $BE_i = BE_{min}$, waits for a random number in $\lfloor \omega_i 2^{BE_i} - 1 \rfloor$ of backoff slots and performs a CCA. If the channel

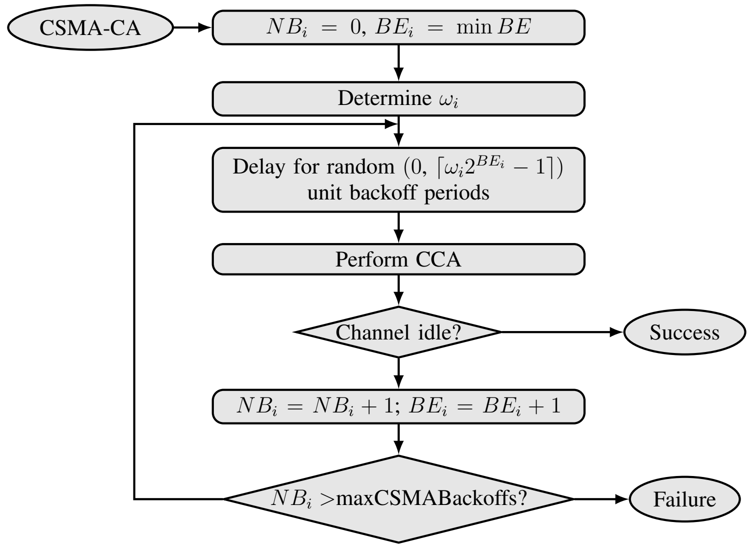


Fig. 4: CSMA-CA algorithm in EA-MAC

is busy, NB_i and BE_i are incremented by one and a new time delay is calculated, until NB_i exceeds $NB_{i,max}$. When this happens the algorithm ends with a transmission failure and the node goes to sleep state. Otherwise if the channel is assessed to be free, the packet is transmitted. An useful model that examine the performance of this protocol is given in [8].

EH-MAC

Energy Harvesting MAC, proposed in [8], is based on asynchronous, receiver-initiated probabilistic polling and is implemented in a multi-hop network. The receiver may not know which nodes are awake at the instant of polling due to the unpredictability in energy harvesting process, so instead of having a sensor's ID in the polling packet, the requesting node sends a contention probability p_c. Upon receiving the polling packet, a node would generate a random number x in [0, 1]. The sensor will transmit its data packet if $x < p_c$, otherwise it will either remain in the receiving state or switch to the charging state if its energy is below that required to transmit one data packet. Ideally, only one out of all the polled sensors in receiving state should transmit a data packet. It can be shown that the optimal contention probability is $1/n_{active}$ where n_{active} is the number of active neighbours of the receiver node. In order to estimate this value, authors of [8] offer two different dynamic contention probability adjustment schemes: the first is Additive Increase Multiplicative Decrease (AIMD) algorithm and the second is Estimated Numbers of Active Neighbors (ENAN) alghorithm.

P-MAC (Pulsed-MAC)

PMAC [9] is an evolution of TMAC and SMAC, which are here briefly described.

S-MAC (Sensor-MAC): In SMAC [10] every node has two possible fixed-length states: sleep and listen. Neighbouring nodes try to synchronize their listen periods and exchange packets exploiting RTS/CTS mechanisms. Energy consumption is also reduced by sleeping after overhearing an RTS or CTS destined for another node. Finally, SMAC makes use of a method called Message Passing, which permits to divide long packets in smaller fragments and send a series of them exchanging just a CTS/RTS pair.

T-MAC (Timeout-MAC): TMAC [11] tries to reduce the time spent in idle listening if no traffic is detected on the wireless channel by the use of a timeout. This timeout is re-initialized only if no particular activation events occur, otherwise a node is able to enter a low power sleep mode, in order to save energy.

The aim of PMAC is to decrease nodes energy consumption by exploiting pulses from the base station to wake up individual nodes. As a result, by PMAC it is not necessary for the nodes to wake up and listen to the base station: nodes can set their radios into a sleep mode and in so doing conserve power. Sensors are provided with a pulse detection circuit and a charge pumping circuitry to scavenge energy from the pulses: in this way the pulse detection does not consume power. Also, a star topology is assumed.

Even if TMAC protocol succeeds in reducing the idle time in which a nodes listens to the channel when no traffic is detected, it is possible for it to remain active although no data is requested from it.

To achieve high power savings, it is necessary for the base station to address a particular node at any time: this is made by means of a Pulsed Interval Encoding (PIE) by which 0s and 1s of an address are encoded with a pulse of a given time T followed by a silence for an additional time 2T and a pulse of length T and a silence of the same length, respectively. A typical pulse consists of 4 bytes of information: the first byte is reserved for the synchronization of tx and rx, the last provides a CRC code and the others are devoted to sensor address.

When a pulse is received by a sensor, it is interpreted by the onboard microcontroller to determine if the main radio has to be turned on or not. In this way radio can be set active only when it is needed to receive a request for data and retransmit the appropriate packets.

Nodes can not give origin to a transmission, so the base station has to take on the responsibilities of managing the requests for transmissions to the nodes according to the necessary frequencies. As nodes only have to reply to the pulses, if the base station, after the transmission of a request for data, does not receive an answer, it has to transmit another pulse followed by a data request up to 5 times, and then it moves on to the next node. Finally, once the base station has communicated with every node in the network, it will go to sleep until a new frame starts (Fig.5).

As regards a particular node, when a pulse addressed to it is detected, radio is set to receive

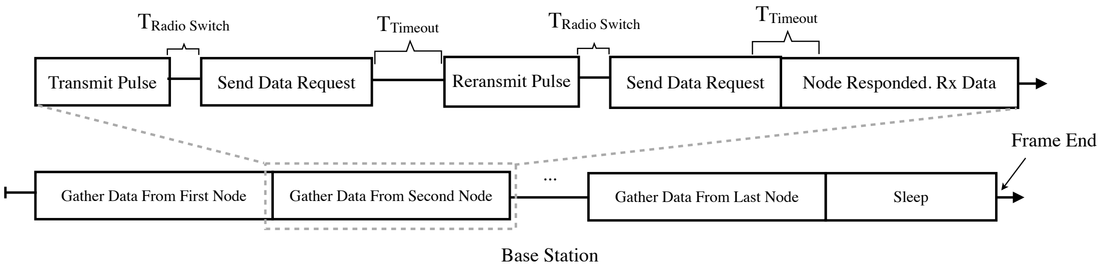


Fig. 5: Base Station Single Frame Timeline

mode. Once the request for a specific packet has been received the node transmits it and then sets its radio back to sleep mode, in order to save as much energy as possible. Finally, in the special case where a node receives a pulse, switches on its radio, but does not receive the request for data (for example due to interference), it will automatically set the radio back to sleep mode when a data request addressed to another node is overheard. This prevents any node from staying in idle listening for too long (Fig.6).

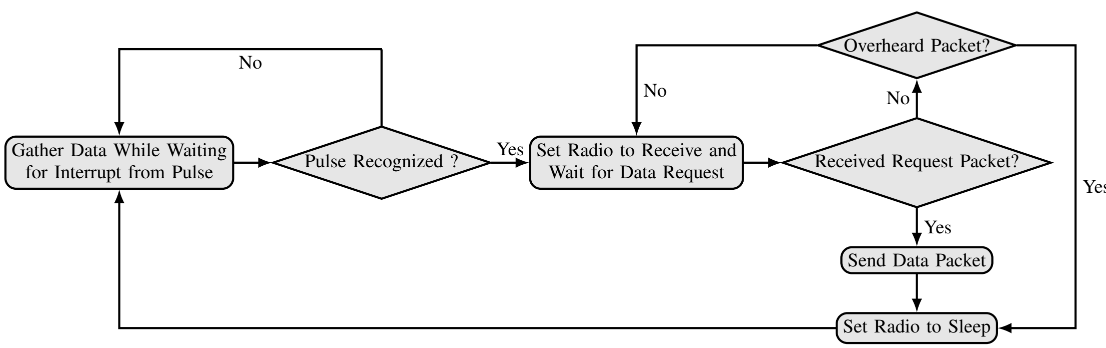


Fig. 6: PMAC sensor node MAC processing flowchart

IV. MAC PROTOCOLS COMPARISONS

Since synchronous-based protocols are not suitable for energy aware devices, we decided not to take into account their analysis. In literature many solutions have been presented, e.g. [12] introduced different TDMA enhancements, [13] addressed the analysis by focusing on TDMA, Framed-ALOHA (FA) and Dynamic-FA (DFA) by introducing a novel metric, referred to as delivery probability.

As regards asynchronous-based approach, we now discuss the following comparisons.

A. *ODMAC and X-MAC*

In this section ODMAC and X-MAC are compared according to different performance metrics [5]. The two MAC approaches are now compared in terms of energy consumption overhead and channel utilization overhead for different values of duty cycle period.

Power consumption overhead Only the power consumption overhead on the coordination process is addressed, as the rest of consumption sources are equal for both protocols. In ODMAC, the total power consumption overhead is given by the sum of the power consumed while waiting for an appropriate beacon, and the power consumed for beaconing. In addition, in X-MAC the power needed to transmit pre-ack packets and to periodically listen the channel for short preambles are considered.

Channel utilization overhead This is the percentage of time a node transmits overhead data, namely beacons or short preambles. The higher this metric is, the more probable is for a node to find the channel occupied while attempting to transmit.

For a fair comparison, both protocols are supposed to use the same opportunistic forwarding scheme: instead of waiting for a specific receiver, nodes forward frames to the node that wakes up first. Fig.7 well depicts the main differences between ODMAC and X-MAC, indeed from the analysis it turns out that the trends of all the performance metrics behaves similarly.

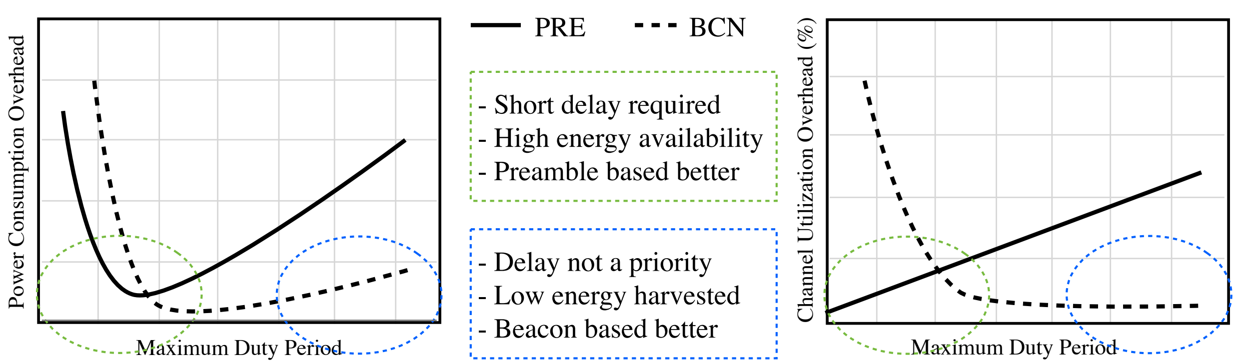


Fig. 7: Comparison between ODMAC and X-MAC performance

Generally, the beaconing scheme (BCN) performs better at large duty cycle periods, namely in cases of limited environmental energy, while the preamble scheme (PRE) performs better at low periods, that is for delay-sensitive applications in environments that allow to consume more energy. For what concern the utilization overhead, preamble scheme performs better because of the frequent beacon transmissions.

Increasing the sensing period, as it is intuitive, improves the channel utilization overhead of the preamble scheme, and the power consumption of both. Similar improvements are obtained decreasing the beacon/preamble size or increasing the transmission rate, although at higher duty cycle periods the influence is less significant. Lastly it is worth to state that for high duty cycle periods, as the network density grows, perfomance gets better.

B. EA-MAC

In [6] EA-MAC with and without EAC are compared over different metrics. The scenario consists in one master node that feeds, with different powers, nine sensor nodes located from two to ten meters away from the former, with interval of one meter. For both versions of the protocol and for each sensor node, throughput, contention time and fairness are observed.

Details of throughput analysis are provided in [8], where it is assumed that:

- Each sensor node has a deterministic power harvesting rate determined by its distance to the master node
- No hidden terminal problem is considered
- The data packet size is constant, and thus also the transmission time of a data packet
- Each node can transmit only one packet per round

Under these hypothesis, the throughput of a generic sensor node i, over h rounds, is

$$S_i = \frac{\eta \sum_{t=1}^{h} T_{p,i}(t)}{\sum_{t=1}^{h} T_{c,i}(t) + \sum_{t=1}^{h} T_{tx,i}(t) + \sum_{t=1}^{h} T_{s,i}(t)} \tag{5}$$

where η is the data rate, $T_{p,i}$ is the time necessary to successfully transmit data at round t, $T_{tx,i}(t)$ is the duration of the transmit state, $T_{c,i}$ is the duration of the contention period and $T_{s,i}$ is the duration of the sleeping period. Introducing the two parameters α_i and β_i, taking into account the ratio between sensor node power consumption and harvesting rate, (5) becomes

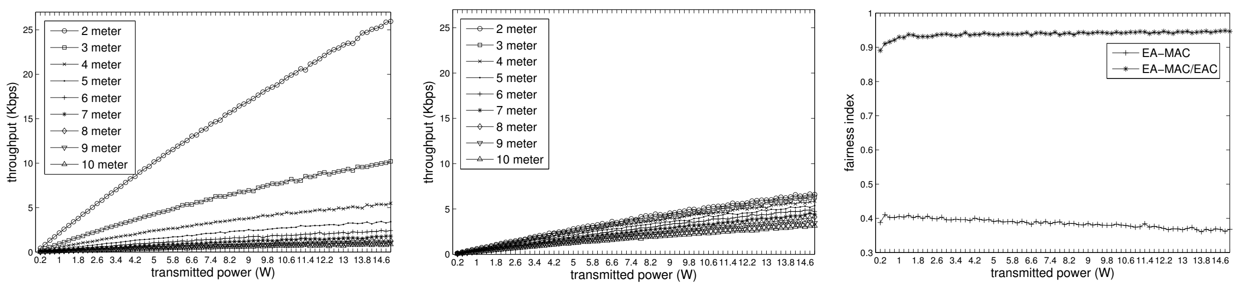
$$S_i = \frac{\eta \bar{T}_{p,i}}{(1+\alpha_i)\bar{T}_{c,i} + (1+\beta_i)\bar{T}_{tx,i}(t)} \tag{6}$$

where $\bar{T}_{p,i}$, $\bar{T}_{c,i}$ and $\bar{T}_{tx,i}$ are the time averages of $T_{p,i}(t)$, $T_{c,i}(t)$ and $T_{tx,i}(t)$. The average time $\bar{T}_{c,i}$ spent in contention state is obtained by modeling EA-MAC backoff behaviour by a Markov chain. States are defined as pairs of two integers $\{s_i(u), c_i(u)\}$, where $c_i(u)$ and $s_i(u)$ are stochastic processes representing the backoff time counter and the backoff stage for node i at time slot u. From this chain, stationary probabilities of each state as well as $\bar{T}_{p,i}$, $\bar{T}_{c,i}$ and $\bar{T}_{tx,i}$ can be calculated.

Jain's fairness index I, is a widely used parameter that analyzes the degree of fairness in many resource allocation schemes in communication networks:

$$I = \frac{(\sum_{i=1}^{n} S_i)^2}{n \sum_{i=1}^{n} S_i^2} \tag{7}$$

In Fig.8, results reveal the efficiency of the Energy Adaptive Contention algorithm: when applied, the throughput of the nodes having relatively lower energy harvesting rate (i.e. the furthest to the sink) is increased, while that of the nodes having relatively higher energy harvesting rate (i.e. the nearest ones) is decreased. As a consequence, by using EAC the degree of fairness among nodes can be improved.



(a) The throughput of EA-MAC (b) The throughput of EA-MAC/EAC (c) Comparison of Fairness indices

Fig. 8: EA-MAC vs EA-MAC/EAC simulation results

C. EH-MAC

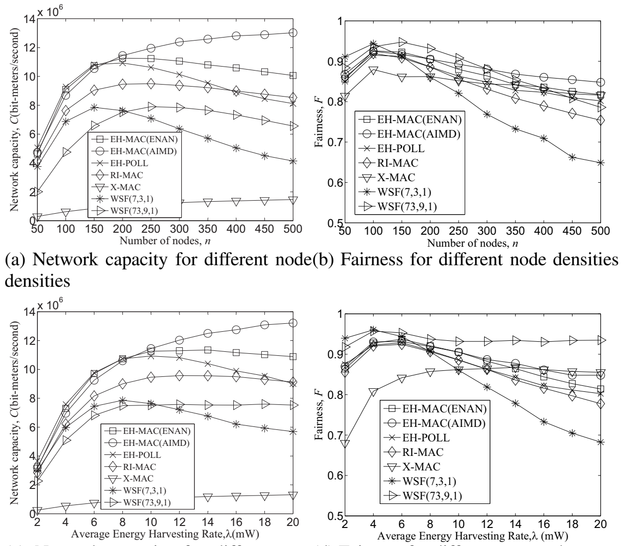
In this section EH-MAC (AIMD and ENAN versions) is compared with WSF-MAC, X-MAC, RI-MAC and EH-POLL, a version of EH-MAC without any contention resolution scheme ($p_c = 1$).

The WSF-MAC, mentioned in [5], is a random access protocol defined using a (u, v, w) block design: each node is awake over a block of u slots, is active over v, such that any pair of nodes has at least w overlapping active slots in common. The RI-MAC falls into the beacon based MAC family, and it is presented in [14].

Performance metrics observed are network capacity, fairness and throughput. The first is simulated within a network in which each sensor node has always packets to transmit, the others are evaluated in an event-driven network: data is sent to a sink whenever a node detects an event or anomaly.

Network capacity, measured in bit-meter/second, is defined as $C = (\sum_{i=1}^{n} \sum_{j=1}^{K_i} d_{i,j})/t$, where K_i is the number of packets successfully sent by node i, $d_{i,j}$ refers to the sender-receiver geographical distance for the j^{th} packet sent by node i and finally t is the simulation time. Fairness is calculated with the Jain's fairness index, already given in EA-MAC section. The throughput is calculated as $S = \sum_{i=1}^{n_s} H_i/t$, where H_i is the number of data packets received from sensor node i, n_s is the number of source nodes and t is the simulation time.

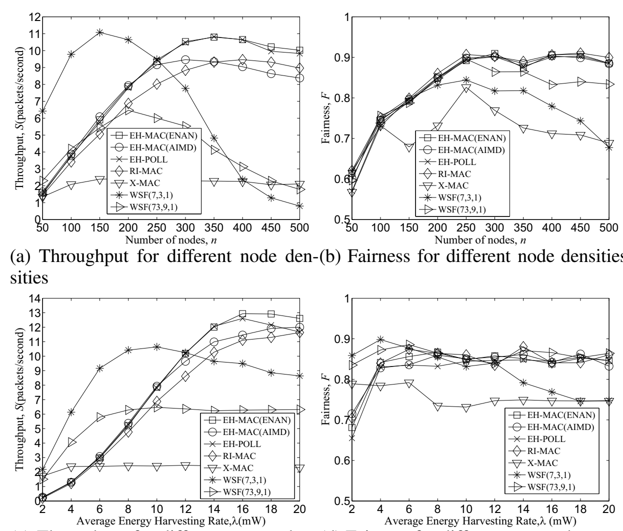
These different metrics are evaluated by varying the node density or the energy harvesting rate.



(a) Network capacity for different node densities (b) Fairness for different node densities

(c) Network capacity for different energy harvesting rates (d) Fairness for different energy harvesting rates

Fig. 9: Network capacity and fairness in non event-drived WSN



(a) Throughput for different node densities (b) Fairness for different node densities

(c) Throughput for different energy harvesting rates (d) Fairness for different energy harvesting rates

Fig. 10: Throughput and fairness in event-drived WSN

In Fig.9 it can be seen that EH-MAC gives the highest network capacity: this because it balances energy consumption accordingly to the amount of harvested energy and it uses a probabilistic polling scheme to reduce packet collisions (not supported in WSF-MAC and X-MAC). EH-MAC outperforms RI-MAC because it is more efficient in collisions recovery: while a backoff window is required in RI-MAC, in EH-MAC nodes can transmit packets just after receiving a polling packet.

In second scenario (Fig.10) WSF-MAC outperforms EH-MAC at lower node densities or energy harvesting rates: this because WSF-MAC achieves energy savings from time slots synchronization, leading to a lower collision probability. X-MAC throughput is low because of its inability to adapt to different energy harvesting rates.

Fairness of EH-MAC is almost always the highest, as probabilistic polling ensures to all sensor nodes equal opportunities to access the channel.

D. P-MAC

As depicted in Fig.11, where SMAC, TMAC an PMAC are compared, simulations show that with longer frame times the nodes have greater lifetimes, accordingly to the fact that transmissions are less frequent. As most of the complex operations are transferred to the base station, overheads and clock synchronization are no longer significant sources of energy consumption for the nodes;

moreover the pulse wakeup mechanism eliminates the bottleneck present in SMAC and TMAC due to synchronization overheads and idle listening.

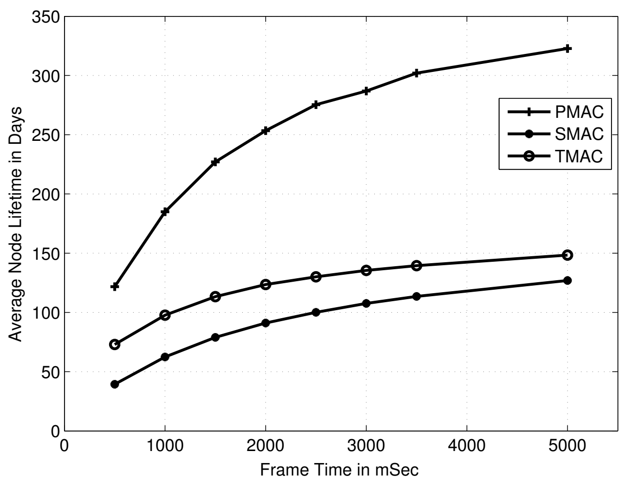


Fig. 11: Frame Times vs Average Node Life Time

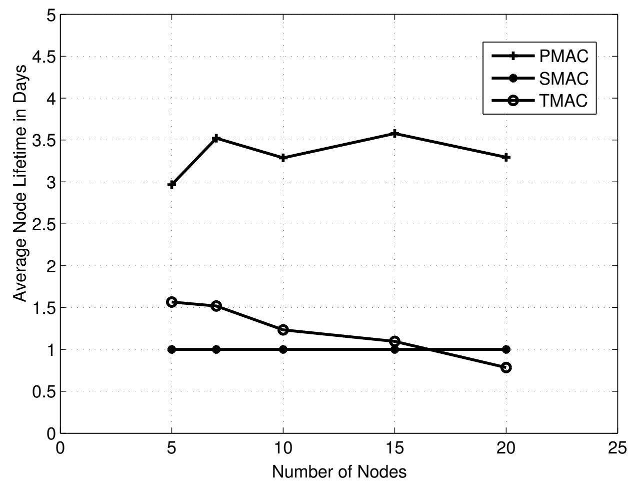


Fig. 12: Average Node Life Time vs Number of Nodes Relative to S-MAC

Finally, Fig.12 shows the effect of adding more nodes to the network, relative to SMAC. TMAC has a non-increasing behaviour as the more nodes are added, the more collisions occur, and it can be seen that eventually it performs worse than SMAC due to this fact. Consequently it will increase the idle listening time, basically wasting more energy.

In conclusion, PMAC efficiently handles the communications allowing networks to last up to three times longer than popular MAC protocols such as SMAC and TMAC.

V. Summary

In this project, we presented and compared different EH-WSN MAC protocols available in literature. Synchronization approaches are unsuitable in energy aware scenarios, as they require synchronized duty cycles. The analytical results discussed suggest that the beaconing paradigm can be tuned to consume less energy, so it is more suitable in cases of limited environmental energy. On the other hand, the preamble paradigm can provide better performance for delay-sensitive applications in environments where the energy is sufficiently available.

We noticed that not all the articles take into account the fairness metric: considering only the overall throughput and network lifetime can be limiting in particular applications where distinct nodes acquire data with different priority. As a result, for a more complete analysis, this metric should be included.

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