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Hybrid MAC Protocols Characteristics in Multi-hops Wireless Sensor Networks

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Abstract—In the current decade, wireless sensor networks are emerging as a peculiar multi-disciplinary research area. By this way, energy efficiency is one of the fundamental research themes in the design of Medium Access Control (MAC) protocols for wireless sensor networks. Thus, in order to optimize the energy consumption in these networks, a variety of MAC protocols are available in the literature. These schemes were commonly evaluated under simple network density and a few results are published on their robustness in realistic network's size. We, in this paper, provide an analytical study aiming to highlight the energy waste sources in wireless sensor networks. Then, we experiment three energy efficient hybrid CSMA/CA based MAC protocols optimized for wireless sensor networks: Sensor-MAC (SMAC), Time-out MAC (TMAC) and Traffic aware Energy Efficient MAC (TEEM). We investigate these protocols with different network densities in order to discuss the end-to-end performances of these schemes (i.e. in terms of energy efficiency, delay and throughput). Through Network Simulator (NS-2) implementations, we explore the behaviors of these protocols with respect to the network density. In fact, this study may help the multi-hops sensor networks designers to design or select the MAC layer which matches better their applications aims.

Keywords—Energy efficiency, medium access control, network density, wireless sensor networks.

I. INTRODUCTION

NOWADAYS, with the enormous technological innovations, the low-cost sensor devices development has become possible. Moreover, it is feasible to deploy wireless sensor networks that are able to sense and report several physical phenomena in a real time manner. A wireless sensor network consists of a sensor nodes group that are miniaturized computers' systems, interconnected by a wireless technology in an ad hoc fashion. In fact, theses networks are practical in various applications such as environmental supervision, medical care and military domain ...

Practically speaking, the recent wireless sensor networks pose many challenges as for as communication protocols are concerned. The communication character in a wireless sensor network has a huge impact in use. However, the proposed protocols for wireless networks aren't suitable for the sensor networks and don't meet their needs. Since wireless sensor nodes have limited battery supply, it becomes clear that, renewing or recharging the battery is not practical taking into consideration the wireless sensor network applications' nature. As a matter of fact, the sensor node shall conserve energy as much as possible to extend its lifetime and so the whole network lifetime. For this reason, it is crucial to design techniques that are able to reduce the node's energy consumption. In fact, many researches have been directed to focus on developing communication protocols taking into account the stated energy constraints. Among others, the MAC layer which specifies how nodes access to the shared channel has a great influence on the energy consumption. This is because it emerges as a major responsible for managing the radio system which presents the most energy consumer component in the sensor node. In this area of research, the wireless sensor network community has proposed, implemented and evaluated several MAC protocols as being energy efficient techniques. Further, these schemes can be subdivided into three classes which are reservation-based, contention-based and hybrid approaches. According to the literature, the latest category is the most promised way to fulfill the wireless sensor networks requirements. However, these approaches are commonly evaluated under simple network density which doesn't present the real sensor application deployment that shall contain various nodes, typically dispersed at high densities. Accordingly, the node's density impacts the network characteristics and more precisely affects many end-to-end network properties such as energy, latency and throughput [1].

Many recent publications on the performance evaluation have pointed out miscellaneous MAC protocols characteristics in context of the wireless sensor networks [2], [3]. To the best of our knowledge, few has addressed the real network deployment impacts. Unlike these studies, we, in this paper, examine the network's density effect on the MAC layer characteristics in the wireless sensor networks. To do this, we adopt the square grid-based pattern which presents an efficient way to guarantee sensing coverage in wireless sensor networks [4], [5]. In addition, this regular deployment allows us to concentrate on the inherent properties of the investigated MAC protocols. Accordingly, through NS-2 implementations, we review three prominent hybrid CSMA/CA based MAC protocols proposed specifically for wireless sensor networks : SMAC [6], TMAC [7] and TEEM [8]. The rest of this paper is structured as follows. The major energy waste sources in wireless sensor networks are analytically investigated in section II. Section III will cover the studied MAC protocols' basic mechanisms. Section IV will present the simulations' results and their interpretations followed by concluding findings in section V which also will explore our future works.

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II. ANALYTICAL ENERGY INVESTIGATION

In this section, we enumerate the energy waste sources in wireless sensor networks, then, we investigate them under the grid-based deployment. Note that one of the MAC protocols designers' substantial goals is to limit these sources without affecting the rest of characteristics (i.e. delay and throughput). The major sources of energy loss are identified as the following:

-Overhearing: it means that a node receives a data packet which is destined to another node.

-Idle listening: it manifests when a node listens to receive a data packet which is not sent.

-Collision: it occurs when two nodes send a data packet at the same time which leads to the packets corruption and then a retransmission should be envisaged.

-Control packets overhead: this refers to the energy wasted through the exchanged control packets.

In paragraph A, we begin by studying how the overhearing impacts the consumed energy in wireless sensor networks. We then, address the idle listening in paragraph B. The collision is studied in paragraph C. Finally, in paragraph D, we explore the impact of the control packets overhead on the wireless sensor network energy consumption.

A. Overhearing analysis

In this section, we address the effect of the overhearing on the overall energy consumption for transmitting a $L-bits$ data packet in a grid topology composed from $n*n$ nodes [9]. Because of the limited transmission range of wireless network interfaces, multiple network hops may be required for one node to exchange data with another across the network. In fact, for investigating the multi-hops network characteristics, we consider a $h-hops$ wireless sensor network with only one source and one sink situated on the two opposite corners of the grid. Hence, the hop's number separating the source and the destination will be adjusted by varying the grid's size.

In our energy model, we only consider the dissipation caused by the radio electronics and the power amplifier. Thus, for transmitting a $L-bits$ packet, the sensor node dissipates $L(e+ud^k)$. Where e is the amount of energy required by the radio circuitry. The ud^k term presents the energy used by the power amplifier to generate a signal able to resist face to the propagation loss over distance d. We measure the energy E_{Grid} as,

$$E(withNoOverhearing) = E_R + E_E + E_{Rt} \qquad (1)$$

$$E(withOverhearing) = E_R + E_E + E_{Rt} + \mathbf{E_O} \qquad (2)$$

Taking into account the hypothesis stated above, the consumed energies are as follows:

$$E_R = E_{Reception} = Le \qquad (3)$$

$$E_E = E_{Emission} = L(e+ud^k) \qquad (4)$$

$$E_{Forwording} = L(2e+ud^k) \qquad (5)$$

$$E_{Rt} = E_{Routing} = N_{Router} * E_{Forwording} \qquad (6)$$

Where L is the packet length, e is the amount of energy spent in the radio circuitry, ud^k is the amount of energy required by the radio amplifier, and d the distance separating the source to the destination.

The routing protocol considered in our investigation is the Greedy Perimeter Stateless Routing (GPSR: will be described in section IV). In fact, the number of router nodes N_{Router} which is required to perform the data gathering cycle (i.e. the path from the source to the destination) is equal to $(2n-3)$. It follows that,

$$E_{Routing} = L(2n-3)(2e+ud^k) \qquad (7)$$

The expected energy without considering the overhearing effect is given by:

$$E(withNoOverhearing) = 2L[(n-1)(2e+ud^k)] \qquad (8)$$

Many routes can be chosen by the GPSR routing protocol. Routes which cut through the grid or follow the grid boundary. In our analysis, we consider the routing path which realizes the minimal overhearing: the boundary alternative. In this way, each node belonging to this path has at maximum three neighbors when using GPSR in the square grid topology. For this path, $E_{Overhearing}$ should be:

$$E_{Overhearing} = [2(n-1)]E_{Reception} \qquad (9)$$

By combining (2) and (9), we derive that the total energy with overhearing is expressed as (10).

$$E(withOverhearing) = 2L[(n-1)(3e+ud^k)] \qquad (10)$$

It is evident, that the energy consumption with overhearing is the highest as it is compared to the energy without taking into account the overhearing effects. We plot in figure 1 the consumed energy amount with and without considering the overhearing effects by using equations (8) and (10). We assume that $e = 0.5mJ/bit/m^2$, $u = 10pJ/bit/m^2$, $L = 300bits$ and $k = 2$ as we consider that the sensor nodes will be deployed in free space [10].

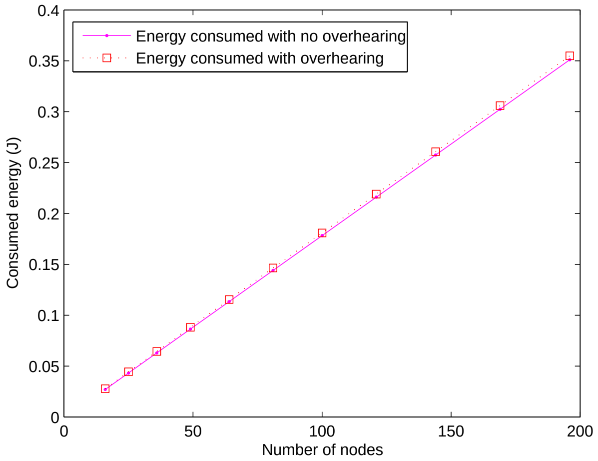

Fig. 1. The overhearing effect in the energy consumption

Figure 1 shows that the overall system energy cost will be larger when the grid size becomes numerous. From this plot, it is clear that the overhearing consumes a small energy amount.

B. Idle listening analysis

Table I demonstrates the power consumption values for the well known Mica Mote [11] sensors in the different communication modes. As it is indicated in table I, the sensor node power consumption is strongly dependent on the operating mode. Note that in the idle mode, the radio consumes almost as much power as in Rx mode. For this reason, when designing MAC protocols, the radio needs to be shut off as much as possible in order to save power, taking into account that in sensor networks idle time is the dominator. In the grid's context, only the source, the sink and the intermediate nodes will participate to the data communication. The immediate neighbors will overhear the exchanged data packets. Whereas, the grid's remaining nodes will be in the idle state during all the data transmission. The total energy consumed through idle listening is expressed as follows:

Mode	Tx Power	Rx Power	Sleep Power
Power	25mW	22mW	0.02mW

TABLE I
SENSOR NODES POWER CONSUMPTION

$$E_{Idle} = E_{idlePath} + E_{idleNoPath} \qquad (11)$$

Where $E_{idlePath}$ and $E_{idleNoPath}$ are respectively, the energy lost in the nodes which belong to the routing path and the energy which is lost in the remaining nodes, by means of idle listening.

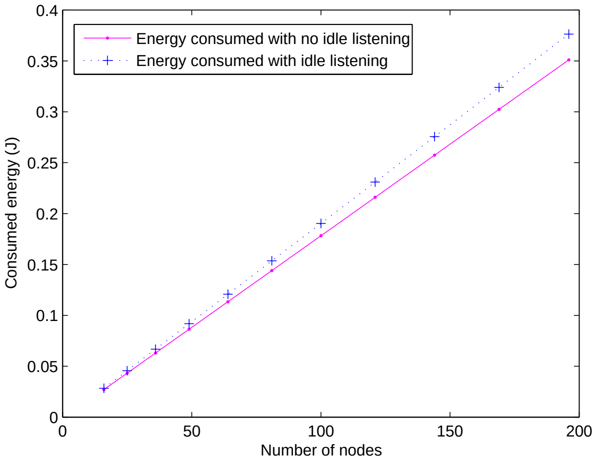

Fig. 2. The idle listening effect in the energy consumption

To simplify our discussion about the energy consumed through idle listening, we don't compute the $E_{idlePath}$ as it is negligible comparing it to $E_{idleNoPath}$. Besides, we consider that the idle mode and the receive one consume the same energy amount. Hence, the number of nodes that will be in idle state during all the data's transmission should be:

$$N_{Idle} = n^2 - N_{Router} - 2 \qquad (12)$$

It follows that,

$$N_{Idle} = n^2 - 2n + 1 \qquad (13)$$

And,

$$E_{Idle} = [n^2 - 2n + 1]Le \qquad (14)$$

In figure 2, we show the amount of energy lost by the idle mode as a function of the network's size. As it is demonstrated in figure 2, the idle listening phenomenon limits the network energy efficiency characteristic. To reduce the idle state, many proposed MAC protocols adopt periodic listen/sleep mechanisms like in SMAC, TMAC and TEEM which are CSMA/CA based protocols postulated for wireless sensor networks.In figure 3, we compare the amount of energy wasted by idle listening versus the energy wasted by overhearing. From the obtained curves it is clear that the idle listening phenomenon is the most energy consumer than overhearing.

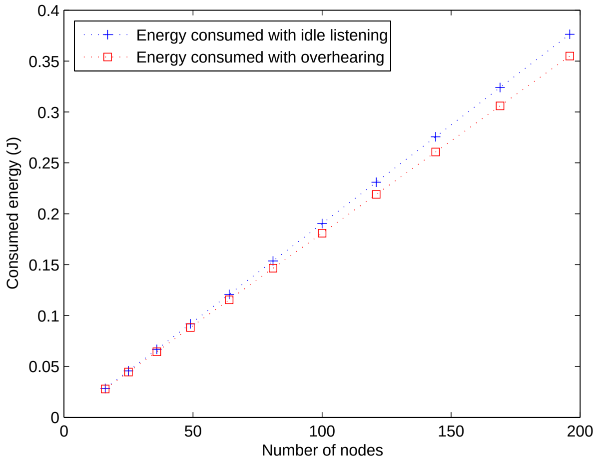

Fig. 3. The overhearing and the idle listening energy consumption

C. The collisions

In a wireless shared medium, not all nodes using the channel can be sensed by anyone node. As a matter of fact, a collision may be occurred at any receivers from two nodes that can't sense each other when adopting a hybrid or a contention based MAC protocol. In the literature, this phenomenon is called: hidden terminal. Collisions cause retransmissions and increase latency, both resulting in wasted energy due to the radio use. Since we focus on wireless sensor networks with a regular topology, nodes others than the ones placed in the grid's boundary will have four neighbors. Accordingly, the collision's number may be multiplied as the network's size increases. As we show later, the increase in packets collision degrades the MAC protocol energy efficiency. For this reason, the energy efficient MAC designers try to avoid at most the collision phenomenon.

D. The control packets

The most hybrid MAC protocols proposed for wireless sensor networks are based on the famous Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) access method [6], [7], [15] (e.g. SMAC, TMAC and TEEM). Note that, CSMA/CA uses control packets such us Request-To-Send (RTS), Confirm-To-Send (CTS) and Acknowledgment (ACK) that will be exchanged without transmitting any useful data. These packets are required to schedule the medium reservation then limit the collisions probability. However, the energy consumed for exchanging the above mentioned control packets can represent a significant energy amount, especially when the network is lightly loaded. Further, under a multi-hops topology, each exchanged control packet will be overheard which provokes additional energy consumption added to the useful amount. In fact, the number of control packets used by the MAC protocol should be kept as low as possible to preserve energy then improve the MAC performances.

III. PROTOCOLS UNDER STUDY

The MAC hybrid schemes are based on specifying the periods of time when nodes must be in the active state (i.e. awake) to communicate. This leads to minimize the delay as well as the energy wasted in idle listening [13]. Various hybrid MAC protocols have been designed explicitly to reduce overhearing, idle listening, collisions and the exchanged control packets.
Over the recent past, several MAC protocols [12] have attempted to minimize the energy consumption but failed to consider the protocol implementation's complexity. Three pertinent protocols which satisfy the need of the sensor networks applications (i.e. simple in terms of implementation and meet the sensor nodes' resources constraints) are selected to be investigated through the experimental part of this paper, namely, SMAC, TMAC and TEEM. In fact, SMAC presents the most known and used MAC protocol in the sensor networks' literature. For this reason, TMAC as well as TEEM are proposed to limit the SMAC's shortcomings. Hence, the evaluation of these protocols may offer concrete guidelines for sensor networks practitioners as how they can be adopted in dense sensor networks deployment for optimal performances. In what follows, we will respectively describe the main mechanisms of SMAC, TMAC and TEEM.

A. The SMAC protocol

The most widely used MAC protocol for wireless sensor networks is SMAC [6]. This protocol is based on virtual clusters in which nodes share sleep and wake up schedules. SMAC is mainly inspired by the power save mode proposed in the IEEE 802.11 standard. In fact, SMAC lets the nodes alter their state (i.e. inactive/active) in order to keep the energy that would be wasted by idle listening. To face the hidden terminal problem SMAC proposes the same RTS/CTS sequence used in IEEE 802.11. SMAC adopts also an adaptive listening mechanism to reduce the sleep delay which may occur by a node sleeping. In fact, using this technique, the duty-cycle is dynamically adjusted to avoid data latency at each hop. But, this mechanism is only applicable for the next hop neighbor taking into account that only, the sender and the receiver neighbors will overhear the exchanged RTS/CTS packets.

B. The TMAC protocol

Paper on TMAC [7] showed that the SMAC protocol doesn't perform well with variable traffic loads. To perform better, TMAC improves the SMAC's energy usage by employing a very short listening window at the beginning of each active period. In fact, after the SYNC part of this latter, there is a short time reserved to exchange RTS and CTS packets. If no activity occurs during that period, the node returns to the inactive state. In contrast, in the SMAC scheme, the nodes will remain awake during each active period even if they are neither sending nor receiving data [13]. However, in case of no data reception in the active period, the node joins the inactive state. But, if the node receives data, it remains awake until no further packet is received. By its adaptive duty-cycle, TMAC saves power at a cost of reduced throughput. Also, this protocol suffers from the same SMAC scaling problem.

C. The TEEM protocol

Another MAC protocol postulated for wireless sensor networks is TEEM [8] which is also inspired from SMAC. In order to reduce the energy consumption, TEEM makes two major modifications over the basic SMAC. First, nodes will not be active during the complete sleep period. Indeed, it goes to sleep directly when no data packets are buffered to be transmitted. Second, TEEM divides the listen period into two parts: $SYNC_{data}$ and $SYNC_{nodata}$. For this reason, a new packet called SYNCRTS is used instead of a separated SYNC and RTS packets. Thanks to the SYNCRTS packet, nodes will be able to identify the data destination node as well as to perform synchronization at the same time. Accordingly, each node expects the destination should be inactive without listening during the second part of the listen period (i.e. the time reserved to send or receive a CTS packet). As a result, this node saves energy. It is worth to note that no attempt has previously been made to address the TEEM's robustness in a large scale sensor network deployed in an application trend. To the best of our knowledge, this protocol has been only evaluated in reference to [8] where the considered topologies are very light and can't be met in our real life.

D. MAC protocols implementations

To evaluate the above mentioned MAC protocols, we performed simulations using the network simulator NS-2 with the CMU Monarch extension [14]. We have experimented these protocols under NS-2 while adopting the NS-2.29 Energy Model [14]. We have found and fixed several bugs in the released SMAC implementation which are robustness related. We implemented TMAC and TEEM as part of these sources to have a configurable protocol. In this manner, we select the running mode (SMAC, TMAC or TEEM) before starting the simulation.

IV. SIMULATIONS

A. Simulation configuration

In this section, we provide some experimentations' details. As we realized simulations with respect to the grid density, we constructed static networks with $n * n$ grid topologies where n is varied between 4 and 14. In our grids, the radio propagation is limited to the node immediate neighbors along vertical and horizontal axes. Regarding the traffic nature, we used a Constant Bit Rate (CBR) generator which is able to produce packets periodically with a configurable message inter-arrival which is set to 12s. Each simulation experiment lasts 500 seconds of simulated time. In fact, the source node generates its data packets each 12s during the total simulation time.

Table II summarizes the implementation details of the simulation.

Parameter	Value
Routing protocol	GPSR
Message inter-arrival	12s
Transmission range	55m
Inter-node distance	40m
Packets length	100bytes
Channel bandwidth	20kbps
SYNCPERIOD	10
Duty cycle	10%
SYNCCW	31
DATACW	63

TABLE II
SIMULATION SETTINGS

As a routing layer, we perform our simulations across GPSR [15]. It is the common protocol used by the authors of the SMAC and the TEEM protocols for the performance evaluation matter. In GPSR, the forward decisions will be based on the routers positions and the packet destination. Accordingly, this protocol makes its greedy forward decision based only on the immediate neighbor router in the topology. In order to provide significant statistical results, we run each experiment five times with different seeds. Hence, we compute the average characteristics with 95% confidence intervals.

B. Simulation Results

We have carried extensive simulations for comparing the performance of SMAC, TMAC and TEEM. Indeed, we have studied the MAC end-to-end characteristics with respect to the grid's size. In order to understand the density impact, we have varied the node number using respectively the MAC layers under study. We have written several bash scripts in order to extract and process the useful data from the NS-2 traces. We will present the simulation results in the following subsections.

1) Energy analysis: Similar to the RFM TR3000 [16] radio system, the used radio power values in transmitting, receiving, idle and sleeping states are respectively as follows: 36 mW, 14.4 mW, 14.4 mW and 15 microW. In figure 4, we consider the total energy consumed (i.e. energy wasted by the entire network) as the measure for energy consumption.

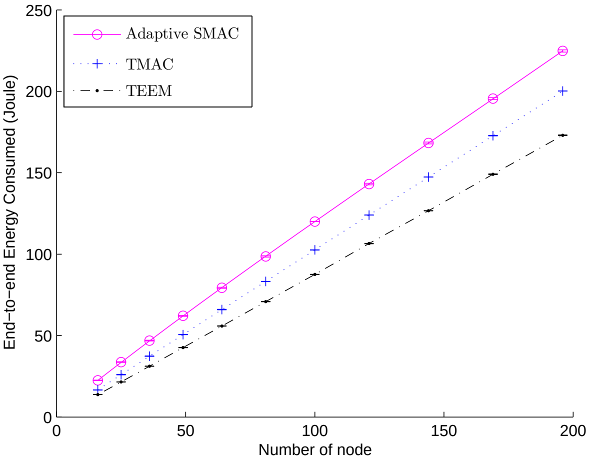

Fig. 4. Total energy consumed on all nodes: 95% confidence intervals are shown.

Clearly, as it is accumulated, this energy keeps increasing over running time. As it is expected, TEEM always performs better than TMAC and SMAC from this view. This result remains true for the low and high network densities. From the plot, it is clear that SMAC and TMAC in the same manner vary for all the studied grids. This observation can be explained by the traffic homogeneity. Still in the energy analysis, we investigate the consumption in the different network levels, namely, in the source node, in an intermediate node and in the sink node. Thus, we plot three figures showing the behaviors of the energy consumption in view of the three cited levels. To study the energy consumption in the source node, we measure the consumed energy over the simulated time. This makes sense since our traffic generator is a constant bit rate. We plot the obtained results in figure 5. Note that, the y-axis shows the remaining energy in the source node over the simulation time. Also, the same experimental

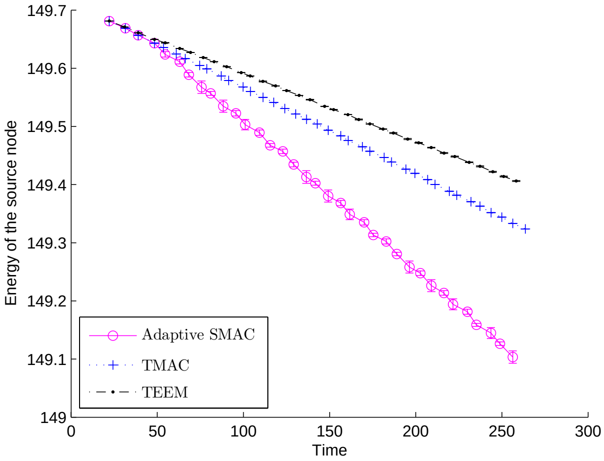

Fig. 5. The remaining energy of the source node as a function of the simulation time: 95% confidence intervals are shown.

methodology is used as for the rest of the paper. Regarding the network density, we present these simulations for the $4*4$ grid topology.

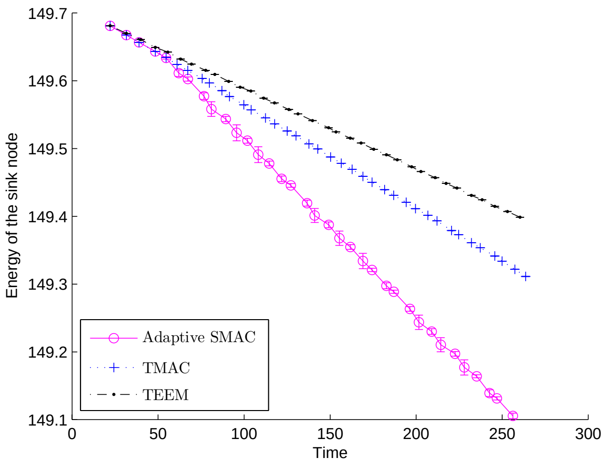

Fig. 6. The remaining energy of the sink node as a function of the simulation time: 95% confidence intervals are shown.

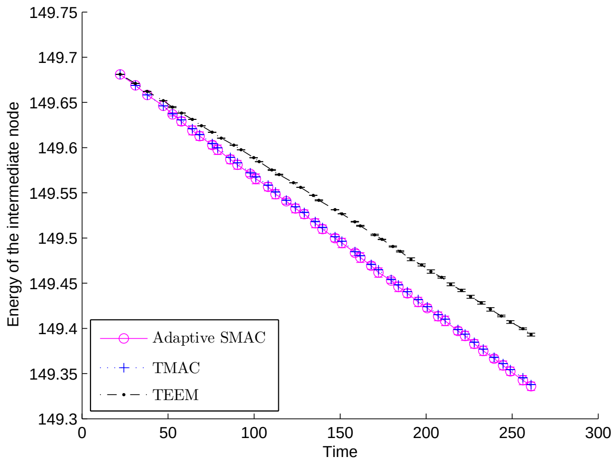

Fig. 7. The remaining energy of the intermediate node as a function of the simulation time: 95% confidence intervals are shown.

All the results shown in figures 5 and 6 are similar to the three protocols. Further, the consumed energy remains almost the same for the source as for the sink node. This is because these nodes are undergoing to the same overhearing intensity as it is illustrated in paragraph II.A. And, as indicates table I, the consumed energies for receiving or transmitting a data packet are comparable. For the intermediate node, it is clear that the energy decreases quickly compared to the source and the sink nodes. These results confirm that the intermediate node drains energy for both receiving and transmitting the received data packets; This is obvious in figure 7. In figure 8, we consider the consumed energy as the overall energy loss in the network divided by the number of packets that are received by the sink node. This plot shows the trade-off made in terms of throughput by the studied protocol in order to improve the energy consumption. The mean energy consumption per byte is calculated as follows:

$$EnergyByte = Energy/BytesRecvSink \tag{15}$$

What is interesting about these results is that figure 8 clearly shows that TEEM consumes more energy in transmitting data packets than do SMAC and TMAC. This energy increases with the growth of the grid density. We notice that this result is a product of the traded throughput for improving energy efficiency as it is observed in figure 4. According to the preceded figure, SMAC and TMAC keep their realizations. But, SMAC consumes slightly more energy than TMAC. This observation shows that this latter doesn't affect the SMAC throughput.

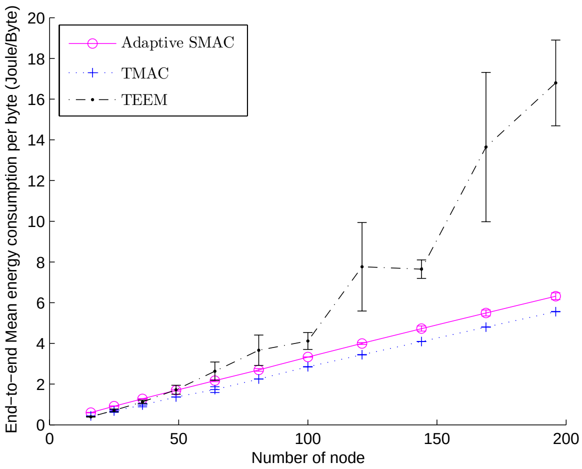

Fig. 8. Mean energy consumption per byte: 95% confidence intervals are shown.

2) End-to-end delay analysis: We define the end-to-end delay as the mean value of the differences in time when one data packet is generated at the source node to the time when this packet is received by the sink node [3], [17]. So, the mean end-to-end delay is expressed as (16).

$$MeanDelay = SumDelays/NumPcktRecv \tag{16}$$

Noting that, in the TEEM paper, the designed protocol is not compared to SMAC in respect to the introduced end-to-end delay. From figure 9, we remark that the end-to-end delay results show that the TEEM consistently achieves lower delay than SMAC and TMAC under all the networks sizes. This is because TEEM eliminates the communication of a separate RTS control packet; thus, its listen period is minimized (i.e. listen to exchange 2 packets: SYNCrts and CTS instead of 3 packets which are SYNC, RTS and CTS). Therefore, the data packets will reach the sink node too early. The delay characteristics for SMAC and TMAC shown in figure 9 are statistically the same for all the studied networks. This result is expected since the TMAC mechanism focused on reducing the idle listening. Henceforth, it minimizes the energy consumption without affecting the end-to-end delay property.

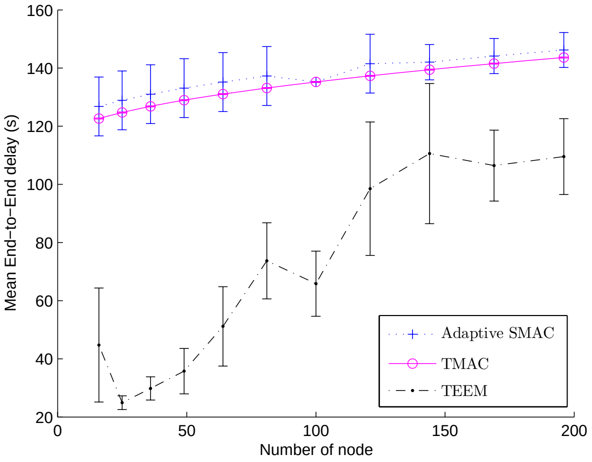

Fig. 9. Measured end-to-end delay: 95% confidence intervals are shown.

3) Throughput analysis: In order to evaluate the throughput property, we measure and compare the studied protocols' channel utilization. From this respect, we make the following observations.

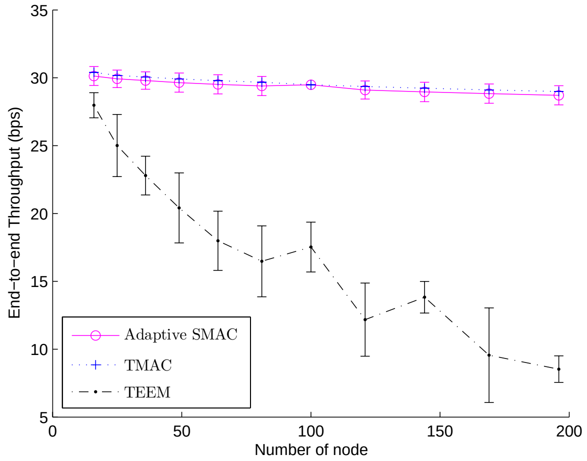

Fig. 10. Measured throughput: 95% confidence intervals are shown.

First we notice that the throughput achieved by SMAC and TMAC are very close. Further, TMAC improves on the overall energy consumption (see paragraph III.A) while maintaining a reasonable throughput. This characteristic is going down slightly with the grid size increase. In fact, SMAC and TMAC present a good characteristic under the grid deployment in respect to throughput. From figure 10, it is also clear that the TEEM throughput decreases as the grid size increases. In viewing that, we argue that the TEEM protocol is not suitable for the applications where a higher throughput is required while keeping an energy efficiency characteristic.

4) Measured collisions and control packets: In this paragraph, we quantify the impact of collisions and control packets on the studied MAC's characteristics. The study of collisions will allow us to figure out an explanation to the end-to-end delay and throughput collapse when the number of node increases. Figure 11 plots the amount of packet collisions over the simulation time according to various grid densities. The presented results show the collisions when arbitrating the medium respectively by SMAC, TMAC and TEEM. To make sense, the same contention window size is selected for the three protocols. The first thing to notice is that, the collisions increases statistically linearly with the network density for all the protocols. Also, for the low densities networks, the studied protocols engender an average similar collisions rate.

The second observation is that, TEEM has more packet collisions than both SMAC and TMAC. This explains why the end-to-end delay realized by TEEM increases exponentially when the node density increases (as already stated in figure 9). Moreover, it states that the throughput is decreasing when the network becomes larger (as it is illustrated in figure 10).

The third observation is that, the collision's number vary in the same way as the energy consumption (see figure 4). This confirms that the occurred collisions impact the energy consumption characteristic. In what follows, we now assess the effects of the control packets on the MAC protocols' performances. The exchanged control packets comparison between SMAC, TMAC and TEEM is shown in figure 12. We can observe from this plot that, the control packets number becomes larger as the grid size increases. Also, it is clear that TEEM significantly outperforms SMAC and TMAC. These results confirm that one of the throughput degradation causes is the control packets overhead. In the same manner, the control packets overhead impacts the energy consumption as well as the realized end-to-end delay as it is already illustrated in the previous paragraphs.

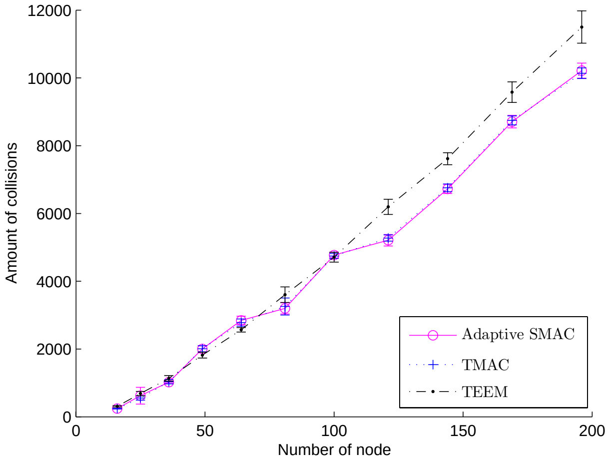

Fig. 11. Number of collisions: 95% confidence intervals are shown.

5) Network life-time: We, now, examine the network life-time where we assume that our source, which is a periodically data generator, will continuously deliver data packets while the network is permitting this. Also, we assume that all nodes consume energy uniformly (i.e. all nodes will be lost at the same time). Taking into account these assumptions, the network life-time can be determined while using the energy

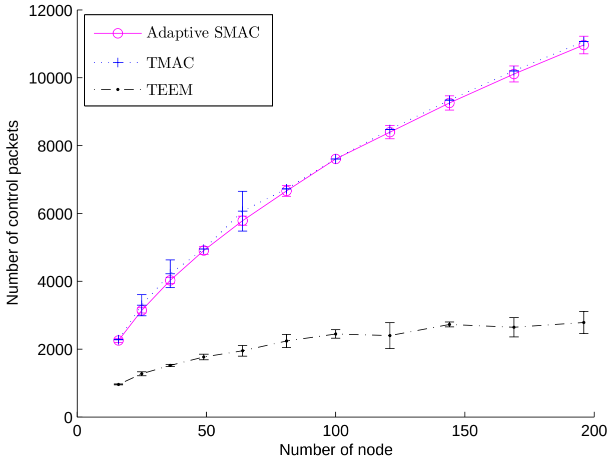

Fig. 12. Number of the exchanged control packets: 95% confidence intervals are shown.

measurements results. Note that in our experimentations, we initialize the energy node to 150 Joules.
As it is illustrated in figure 13, the life-time decreases exponentially as the grid size increases for the three investigated protocols. But, it is clear that the TEEM protocol outperforms SMAC and TMAC in respect to the determined network life-time. This also translates the reduction of the energy wasted by idle listening in this protocol. Note that the 95% confidence intervals are too small to be indiscernible in this plot.

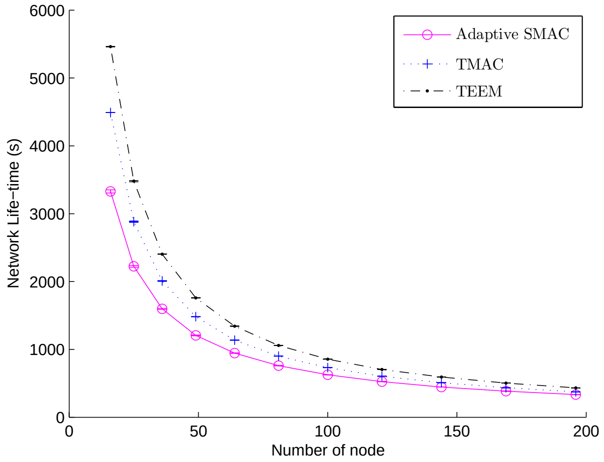

Fig. 13. The calculated network life-time over running time: 95% confidence intervals are shown.

V. CONCLUSION

To ensure the wireless sensor networks success, the researcher community has to gain a lot of challenges. In this paper, we address the major and common sensor networks characteristics, namely, energy efficiency, end-to-end delay and throughput. Our researches focus on the MAC layer which presents one of the higher energy consumers in the sensor networks communication stack. First, we investigated the energy waste sources in wireless sensor networks. Second, we performed a comparative study of SMAC with TMAC and TEEM which are serious and suitable hybrid MAC schemes postulated specifically for wireless sensor networks. In short, in addition to explore the energy waste sources which are to avoid when designing new MAC protocols, our results would be important to determine the investigated protocols' performances in terms of cost for different network sizes. Further, one distinctive characteristic that differentiate our work from previous researches is the network size that is chosen in realistic ways. Also, to the best of our knowledge, the TEEM protocol has been only investigated in [8] in which the TEEM authors study it only under a five nodes simple topology and with varying traffic loads. In one hand, the analytical study of this paper highlights the major energy waste sources as a function of the network size. According to the obtained results, we argue that the idle listening phenomenon is more energy consumer than the overhearing one. This observation should be take into consideration when designing new MAC protocols. On the other hand, there are several concrete findings from our experimental study that offer useful insights. To be brief, we conclude that the network density has a large impact on the expected TEEM's performances. Hence, it increases the consumed energy as well as the introduced end-to-end delay and minimizes the performed throughput. Also, we observe that the network density slightly affects the end-to-end delay and the throughput realizations for SMAC and TMAC. Thus, these two protocols are suitable for the applications where the network's performances need to be density independent. Regarding the energy characteristic, it increases linearly with the network size for the three protocols under study. This is not a surprising conclusion seeing that the consumed energy will be accumulated when the network's size becomes large. Several points remain opened in this area of research. In addition to conducting investigation on other proposed MAC protocols, such as the scheduled based approaches, we will tackle the following issues as part of our future work:
-Based on the implementations of the protocols studied in this paper, we will design a new MAC protocol that outperforms SMAC, TMAC and TEEM while being suitable for the wireless sensor networks resources constraints.
-In this study we perform simulations which can be enhanced with real test-bed measurements.

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REFERENCES

[1] K. Romer and, F. Mattern, "The Design Space of Wireless Sensor Networks", *IEEE Wireless Communications*, December 2004; 11: pp. 54–61.

[2] G. P. Halkes, T. V. Dam and, K. G. Langendoen, ”Comparing Energy-Saving MAC Protocols for Wireless Sensor Networks”, *Mobile Networks and Applications*, October 2005, pp.783–791.

[3] F. Chen, F. Dressler and, A. Heindl, ”End-to-End Performance Characteristics in Energy-Aware Wireless Sensor Networks”, *Proc. ACM Int. Workshop on Performance Evaluation of Wireless Ad Hoc, Sensor, and Ubiquitous Networks (PE-WASUN’06)*, October 2006, pp. 41–47.

[4] K. Xu, G. Takahara and, H. Hassanein, ”On the Robustness of Grid-based Deployment in Wireless Sensor Networks”, *Proc. ACM Int. Conf. on Wireless Communications and Mobile Computing Conference (IWCMC’06)*, July 2006, pp. 1183–1188.

[5] X. Bai, S. Kumar, D. Xuan, Z. Yun and, T. H. Laiy, ”Deploying Wireless Sensors to Achieve Both Coverage and Connectivity”, *Proc. ACM Int. Symposium on Mobile Ad Hoc Networking and Computing (MOBIHOC’06)*, May 2006, pp. 131–142.

[6] W. Ye, J. Heidemann and, D. Estrin, ”Medium Access Control With Coordinated Adaptive Sleeping for Wireless Sensor Networks”, *IEEE transactions on Networking*, April 2004; 12: pp. 493–506.

[7] T. V. Dam and, V. Langendoen, ”An Adaptive Energy-Efficient MAC Protocol for Wireless Sensor Networks”, *Proc. ACM 1st Int. Conf. on Embedded Networked Sensor Systems (SENSYS’03)*, Novomber 2003, pp. 171–180.

[8] C. Suh and, Y. B. Ko, ”A Traffic Aware, Energy Efficient MAC Protocol for Wireless Sensor Networks”, *Proc. IEEE Int. Symposium on Circuit and Systems (IEEE/ISCS’05)*, May 2005, pp. 2975–2978.

[9] S. B. Raghuvel, L. L. Jacir, C. Jiangtao and, N. Koji, ”Fundamental Protocols for Wireless Sensor Networks”, *Proc. the International Parallel and Distributed Processing Symposium (IPDPS’01)*, April 2001.

[10] J. F. Shi, X. X. Zhong and, S. Chen, ”Study on Communication Mode of Wireless Sensor Networks Based on Effective Result”, Journal of Physics, 2006, pp. 1317–1321.

[11] http:Crossbow ”Mica Mote”, http//www.xbow.com/, last visit November 2008.

[12] H. Li and, P. D. Mitchell, ”Medium Access Control Protocols in Wireless Sensor Networks”, *Proc. Int. Conf. on Communications (ICON’07)*, November 2007, pp. 455–460.

[13] M. Buettner, G. Yee, E. Anderson and, R. Han, ”X-MAC: A Short Preamble MAC Protocol For Duty-Cycled Wireless Sensor Networks”, *Proc. 4th ACM Int. Conf. on Embedded Networked Sensor Systems, (SENSYS’06)*, Novomber 2006, pp. 307–320.

[14] The CMU Monarch Project. ”The CMU Monarch Project’s Wireless and Mobility extensions to NS”, http://www.isi.edu/nsnam/ns/, last visit November 2008.

[15] B. Karp and, H. T. Kung, ”GPSR: Greedy Perimeter Routing for Wireless Networks”, *Proc. Int. Conf. on Mobile Computing and Networking (MOBICOM’00)*, August 2000, pp. 243–254.

[16] ASH Designer guide, RF Monolithics, Inc, ”RFM TR3000”, http://www.rfm.com, last visit November 2008.

[17] L. Stabellini and, A. Proutiere, ”Evaluating Delay and Energy in Sensor Networks with Sporadic and Correlated Traffic”, *Proc. the 7th Scandinavian Workshop on Wireless Ad-hoc Networks (ADHOC’07)*, May 2007.