Adaptive Data Transmission Protocols for Energy Harvesting WSNs Used in Agriculture

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https://doi.org/10.26636/jtit.2024.1.1390

Abstract — Energy consumption is a major concern in wireless sensor networks (WSNs) as it affects the lifespan of sensor nodes. Battery-based WSNs have a short operating period, which makes them impractical for real-time applications, for instance in agriculture. Energy harvesting and suitable medium access control (MAC) protocols have been used to extend the lifetime of nodes. Receiver-initiated protocols have been proved to be the best solution for energy harvesting WSNs. However, they suffer from a key disadvantage, i.e. an increase in collision rate. These collisions need to be reduced using a multi-layer protocol structure. In such a context, a new solar-based hybrid MAC (SHMAC) protocol relying on receiver-initiation and characterized by a multi-layer structure is proposed. It is an adaptive protocol capable of adapting to changing weather conditions. The nodes with a high energy harvesting rate have a higher level of residual energy and are active for longer time periods compared with those with low energy harvesting characteristics. The proposed work has shown improvements in two major MAC layer parameters, i.e. collision rate and energy neutrality operation ratio (ENO).

Keywords — green WSN, MAC protocols, solar energy harvesting

1. Introduction

Wireless sensor networks (WSNs) are used in numerous applications, e.g. agriculture, home automation, healthcare, wildlife monitoring etc. The major limitation encountered in outdoor applications is the limited amount of energy stored in the batteries powering the nodes. To solve this problem, solar energy harvesting technologies are considered as a potential candidate to serve as a source of continuous energy for WSN networks and to increase their lifetime. Energy harvesting-based wireless sensor networks (EHWSNs) present, however, new design challenges, since this kind of energy is unpredictable in nature [1], [2]. Therefore, there is a need to store this energy for future use and to use the capacity wisely during the non-availability periods [3].

The block diagram of an energy harvesting system is shown in Fig. 1. First, solar energy is harvested and stored using a Texas Instruments energy harvester (EZ430) and a power manager integrated circuit (BQ25505) [4], [5]. A variety of sensors, a microcontroller, and an RF transceiver are powered.

In energy harvesting applications, some sensor nodes may have more energy available than their counterparts, due to

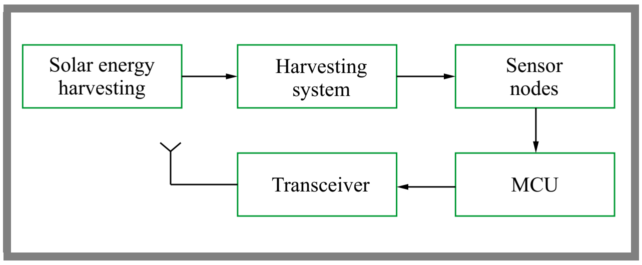

Fig. 1. EHWSN node block diagram.

the uneven distribution that is impacted by node location, as well as shadows from buildings or trees. Such nodes may perform more energy-intensive tasks, while low energy nodes may be in the sleep state, recharging. The MAC protocol used needs to adapt to the changes in energy levels available in the environment [6], [7]. Otherwise, nodes with lower residual energy levels will discharge the battery and will then go into a dead state, creating voids in the sensing area and making the entire network unreliable.

The protocol's adaptivity is expected to balance the load throughout the network. Nodes with good energy levels have a better energy neutrality operation (ENO) rate than other nodes [8], [9]. Hence, the protocol may entrust them with more tasks to utilize this excess energy efficiently. This helps in improving the fairness index of the network [10], [11]. Keeping this in mind, a SHMAC adaptive protocol is proposed in this paper and is then optimized to maximize its performance.

The paper is structured as follows. Section 2 presents the related work. Section 3 shows the process of designing the SHMAC protocol, while Section 4 describes the simulation process. Section 5 evaluates and compares the overall performance of the proposed protocol with the existing solutions. The work is concluded in Section 6.

2. Related Work

The amounts of energy consumed by network nodes is the most important parameter affecting the nodes' lifetime [12]. Therefore, MAC helps improve a crucial network parameter [13], [14]. Sender-based protocols are often utilized by battery-based WSNs. In sender-based communication, the process is initiated by the sender node whenever it wants to transmit the data, whereas in receiver-based communication, it is the sink which commences the process. Receiver-initiated schemes offer many benefits in comparison to their sender-initiated counterparts.

In receiver-based protocols, listening in idle state is insignificant, as in this case, channel utilization time of the nodes is negligible. This results in an increase in network throughput, as more nodes can interact with each other.

In [15], Ye *et al.* presented a sensor MAC (SMAC) protocol, introducing the concept of duty cycling in WSNs. Such an approach results in lower energy consumption as it the amount of idle listening is negligible. Dam *et al.* [16] proposed a time-out MAC (TMAC) adaptive protocol, while Lin *et al.* presented, in [17], a receiver initiated cycled receiver (RICER) as an example of a receiver-initiated scheme. It used a random delay between the reception of the beacon and the transmission of data. In [18], Tan introduced an energy harvesting-based probabilistic polling MAC (PPMAC) protocol. Its performance is analyzed for CSMA and polling-based MAC protocols for the single-hop network.

Analytical models of slotted CSMA, ID polling, and PPMAC were presented and simulated with the use of the Qualnet simulator in [19], while Fafoutis and Dragoni proposed an on-demand medium access control (ODMAC) approach in [20], [21], where the load is assigned based on the status of the harvested energy. Selahattin showed another extensive review of the MAC protocols for EHWSN [7], while Ramezani *et al.* [22] researched the advantages and disadvantages of each protocol along with solutions that can be possibly integrated into future work.

Tan *et al.* [23] presented a case study for energy harvesting and energy management, while Jha *et al.* [24] introduced a multi-layer MAC (MLMAC) protocol designed to have a low duty cycle and lower collisions for battery-based WSN networks. It is a contention-based MAC protocol, where the nodes discover their acquaintances based on the strength of the radio signal. Another energy-harvested receiver-initiated MAC protocol (ERIMAC) was introduced by Nguyen *et al.* in [25]. It is based on a receiver-initiated scheme and is as a combination of ODMAC and RIMAC protocols. As far as real time adaptivity is concerned, Kosunalp *et al.* [26] shows a prediction algorithm for solar energy harvesting. It considers the past and the most recent weather conditions to calculate, approximately, the near future availability of harvested energy.

Most of the MAC protocols described in the literature assume that the amounts of available energy to be harvested are uncertain. It needs to be borne in mind that solar energy generally exhibits similar patterns in a given area and season. Therefore, energy predictions may be relied upon to optimize overall performance. This is currently the missing part of the majority of the research projects described. In this work, an adaptive transmission-based SHMAC protocol is introduced, being proposal aiming to optimize solar energy harvesting. Thanks to such an approach, remarkable performance improvements over other similar-related protocols may be achieved.

3. Design of Adaptive Hybrid MAC Protocol

Solar energy is considered to be the preferred source of energy needed to power up sensor nodes in unattended areas, for instance in forest fire monitoring applications. The quantity of energy that can be harvested depends on the season and on the area in which the solar panel is deployed. Solar energy efficiency depends on the weather, installation angle, location coordinates and time.

Shadows created by trees and buildings impact energy harvesting conditions even in the same specific area. Various sunlight incidence angles need to be taken into consideration as well. Therefore, it is difficult to predict which node should be in the power saving mode and which should exit this power limited state. In the proposed solution, this variable is monitored by the MAC layer and the protocol should be capable of adapting to changing harvesting conditions. Figure 2 shows an example of hourly solar curves for two cities. Depending on the season, the amount of solar energy available varies a lot. Hence, when implementing a WSN, the MAC protocol has to be aware of those conditions. To achieve this, two approaches (predictive and reactive) may be relied upon. The predictive approach predicts the available amount of energy and adjusts the operation of the node to the expected conditions. In the reactive approach, the node's energy level is continuously monitored and its operation is adjusted based on the harvested energy level. A hybrid approach is used in the proposed work, in which the first reactive approach is used to decrease energy consumption, with a prediction being incorporated at a later stage to make the protocol more reliable. Dedicated hardware is used to compute the amount of energy harvested from the environment.

The nodes operate in two modes, i.e. active and sleep modes. In the active mode, there are three different layers, as shown in Fig. 3. Depending on the environmental conditions, the low energy harvesting layer (L1) is used at night or during winter, the medium energy harvesting layer (L2) is relied upon when shadows are created by trees and buildings, and the high energy harvesting mode (L3) is used at noon. The better the harvesting conditions, the higher the level active. The most important feature for checking the reliability of any energy harvesting-based protocol is its ability to adjust the

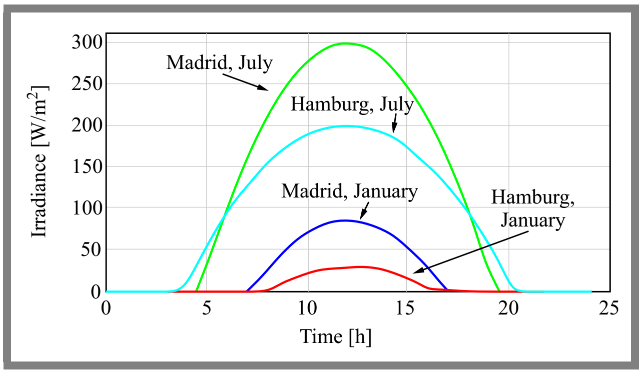

Fig. 2. Solar energy profile example [10].

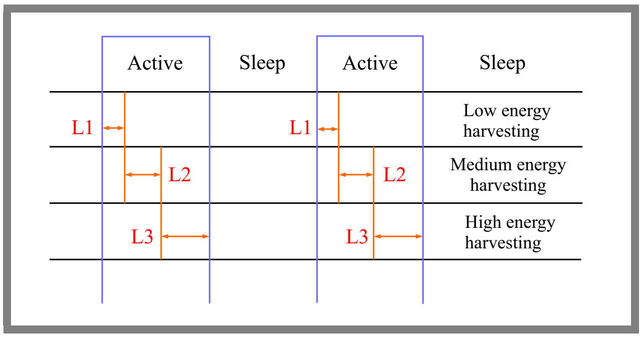

Fig. 3. Multi-layer structure for varying energy harvesting conditions.

operation of sensor nodes to the prevalent energy harvesting conditions. For such a verification, the ENO ratio denoted by R should be greater than one for the nodes to prevent network outages.

$$R = \frac{E_h}{E_c} , \quad (1)$$

where E_h is the energy harvesting rate and E_c is energy consumption. To keep $R > 1$, energy consumption E_c needs to be kept as low as possible. Therefore, each node's duty cycle needs to adapt to the harvesting conditions. A common schedule for all the nodes cannot be implemented, as each node has a different initial energy level and if affected by varying harvesting conditions which depend on its position within the WSN.

To reduce energy consumption E_c, the number of transmissions for each node should be decreased to keep ratio R within a safe limit. Depending on the time of the day and environmental conditions, E_h varies as well. Hence, in the proposed protocol, with both factors in mind, E_c is decreased by an adaptive duty cycle factor d and Eq. (1) takes the form of:

$$R = \frac{E_h}{d\, E_c} , \quad (2)$$

where d is the adaptive duty cycle responsible for the changing environmental conditions.

The initial deployment scenario for the SHMAC protocol is shown in Fig. 4. Total N nodes are taken into consideration, sending the collected information to the sink node positioned in the center. Depending on the conditions, those nodes are divided into three layers. Layer 1 nodes have the minimum energy, L2 nodes are in the shadow of buildings or trees, and L3 nodes operate in a goof energy harvesting environment as they are exposed to direct sunlight.

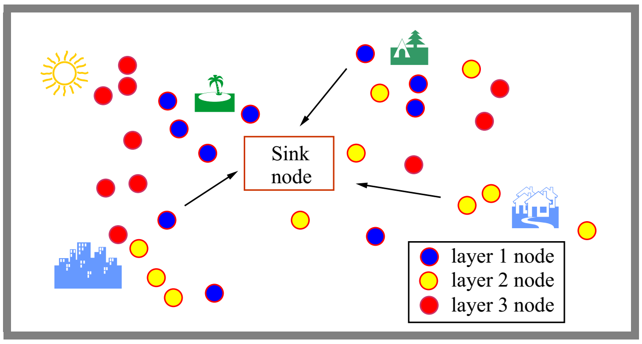

Fig. 4. Deployment scenario for N nodes and 3 layers.

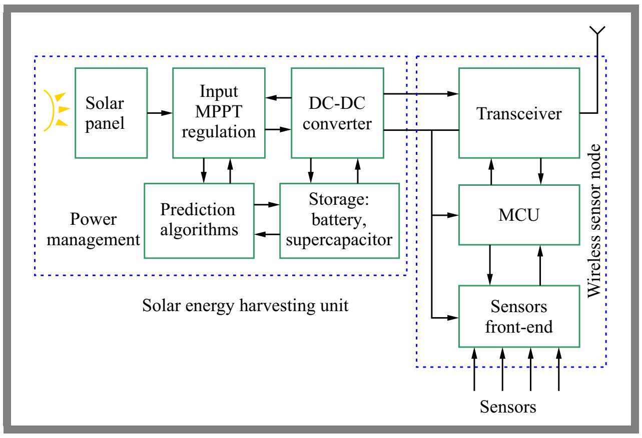

Fig. 5. Block diagram of solar energy harvester [26].

Solar energy efficiency σ is given as:

$$\sigma = \frac{S_{max}}{D\, S} , \quad (3)$$

where S_{max} is solar power in watts, D is solar density and s is the surface area. The efficiency of popular solar harvesters equals up to 30%, meaning that only part of the captured solar energy can be used for operating a node. Therefore, residual energy E_r of any node at time t is calculated as follows:

$$E_r = (E_i + E_h) - E_c , \quad (4)$$

where E_i is the initial energy level of the node, E_h is the energy harvested by the node, and E_c is the energy consumed by the node for performing its assigned tasks.

3.1. Solar Energy Harvester

The energy harvesting model used in the proposed work relies on the "accumulate and spend" scheme, meaning that energy will be accumulated until a particular threshold level, referred to as E_{ct}, is reached. This threshold value will depend on the type of a specific application and on the deployment area. A high energy threshold is used in critical applications, where information delivery is crucial. In contrast, in such applications as hourly weather forecasts, if the level of energy harvested is a little lower that required, the node may wait with the transmission until the energy level reaches a sufficient value. This means that the data transmission will start only after this threshold value is achieved.

Figure 5 shows a block diagram of a solar energy harvester (SEH) node. The main components include the following: photovoltaic cells, supercapacitor, MPPT tracker, energy prediction circuit, and DC-DC converter.

Prediction algorithms are used to make the operation of the transceiver energy-aware. Three main types of algorithms are reported in the literature, i.e. exponentially weighted moving average (EWMA), weather conditioned moving average (WCMA), and weather conditioned selective moving average (WCSMA), as shown in Tab. 1.

EWMA is the most popular prediction algorithm used in SEH due to its low complexity and simple hardware implementation. It calculates the current energy requirement based on energy available at similar time periods during the last

Tab. 1. Comparison of solar energy prediction algorithms [26].

Prediction algorithm	Authors	Formula	No. of multiplications	Memory requirements	Computational time
EWMA	Bergoenzini *et al.*	$E_p(y+1) = \alpha E_r(y) + (1-\alpha)\alpha E_p(y)$	4300/45 days	96 bytes	9 µs
WCMA	Piorno *et al.*	$E(x,y+1) = \alpha E(x,y) + G_k(1-\alpha)\lambda_D(x,y+1)$	19000/45 days	384 bytes	51 µs
WCSMA	Jiang *et al.*	$E(x,y+1) = \alpha E(x,y) + (1-\alpha)H(x,y+1)$	–	–	–

few days. WCMA takes into account short-lasting climate variations by taking considering a given day's sunrise time and other conditions. It makes fewer prediction errors compared with EWMA, whereas WCSMA relies on an advanced processing technique to predict the weather conditions more accurately. The harvested energy is then stored in rechargeable batteries with low self-discharging values and offering thousands of recharging cycles over their entire lifetime.

4. Simulation Parameters

In Tab. 2, Matlab simulation parameters used for evaluating the SHMAC protocol are presented. T_{ta}, $T_{standby}$, T_{proc}, $T_{sensing}$, T_{pm} values are taken from Texas Instruments' EZ430-RF2500-SHE datasheet for better estimation of the real world deployment scenario. T_{rx}, T_{tx}, T_{sleep} are calculated from simulations.

Algorithm 1 Adaptive SHMAC protocol code

Energy_pred_proc

{
$E_p(y+1) = aE_r(y) + (1-a)E_p(y)$ ▷ EWMA
▷ prediction algorithm where:
▷ E_p is the new predicted value
▷ E_r is the last real value and
▷ a is the weighting factor
}
Calculate $R = \dfrac{E_p}{E_c}$ ▷ nodes distribution in different
▷ layers
traffic_generation_proc ▷ Weibull
nodes_distri_proc
{
for $i = 1$ to n **do**
  if $R > 1$ **then** ▷ check the ENO ratio value
    L←3 node is in layer 1
  end if
  if $R = 1$ **then**
    L←2 node in layer 2
  end if
  if $R < 1$ **then**
    L←1 node in layer 3
    $R' = \dfrac{R}{d}$ ▷ reduce the duty cycle of nodes
  end if
end for
}

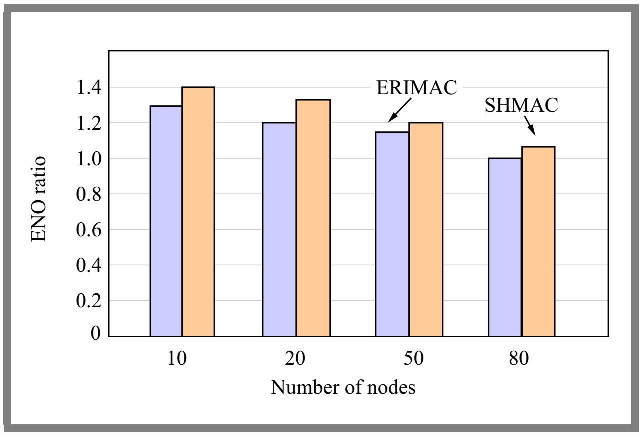

Fig. 6. Energy neutrality ratio versus number of nodes.

To calculate the total consumed energy, different states of the nodes of the SHMAC protocol need to be considered. SHMAC calculates the time every node spends in each mode, such as E_C is the total power consumed, and P_{rx}, P_{tx}, P_{sleep} are power values consumed by nodes in receiving, transmitting and sleep states, respectively. Respective time periods spent in each state are T_{rx}, T_{tx}, and T_{sleep}, while P_{ta} and $P_{standby}$ are values of power consumed in turn-around and standby states. $P_{sensing}$, P_{proc} and P_{pm} are values of power consumed in data sensing, data processing, and power management states, respectively. $T_{standby}$, T_{proc}, $T_{sensing}$, and T_{PM} are corresponding times spent by nodes in standby, data processing, and data sensing, respectively.

5. Results and Discussion

The most important parameter for the reliable operation of energy harvesting-based systems is to maintain the ENO ratio (i.e. energy harvested to energy consumed) above 1.

In the source code for the adaptive SHMAC protocol (Algorithm 1), the energy prediction is realized by using the EWMA scheme. It has the lowest prediction time and complexity compared with other prediction methods. Since the size of sensor nodes is limited, as is their memory capacity, complex algorithms cannot be used in such SEM type devices. Hence, EWMA is well suited for this purpose. Once energy prediction has been done and E_H value has been obtained,

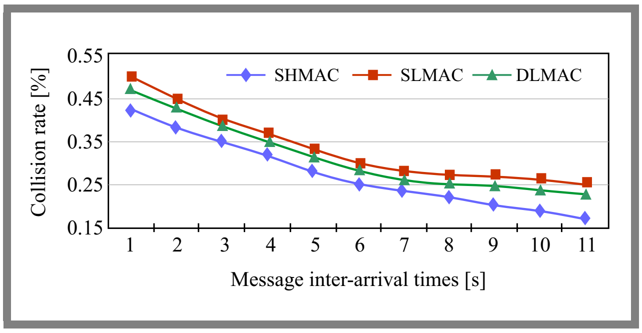

Fig. 7. Collisions rate as a function of message inter-arrival time.

the ENO ratio R is calculated. If $R > 1$, there is no need to compromise the quality of the network, hence a transceiver is used that offers the longest active time, i.e. L3.

If $R = 1$, then the network is in the equilibrium stage, but its performance remains satisfactory. The active time spent by the nodes in L2 is shorter than in L3. If $R < 1$, then an adaptive measure needs to be taken to save the nodes from a power outage, i.e. the duty cycle needs to be decreased and the transceiver's on-time needs to be kept at the minimum, i.e. at L1 state as shown in Fig. 3. To maintain the ENO ratio over 1, an adaptive factor d is used to prevent the nodes from switching to a dead state – Eq. (2). It is used to reduce energy consumption by controlling the duty cycle of the nodes, i.e. to lower the number of transmissions.

Tab. 2. Simulation parameters.

Parameter	Value
Number of nodes n	10–200
Number of layers L	3
Frame duration T_f	1 s
Layer duration	Adaptive (T_a/L) ms
Receiving power P_rx	68.58 mW
Sleeping power P_{sleep}	4.118 µW
Transmitting power P_{tx}	80.23 mW
Data sensing power $P_{sensing}$	4.899 mW
Data processing power P_{proc}	68 mW
The average data rate λ	250 Kbps
The average packet length l	51 bytes
Data sensing time $T_{sensing}$	19.76 ms
Data processing time T_{proc}	61.4 µs/byte
T_{pm}	2.5 ms
$P_{standby}$	29.22 mW
P_{ta}	71 mW
P_{pm}	3.124 mW
T_{ta}	196 µs
Standby time $T_{standby}$	0.77 ms
Traffic model	Weibull

Tab. 3. Impact of variable d parameter on ENO ratio ($E_c = 13$ mJ, $N = 50$ nodes).

E_h [mJ]	d	R	R'
15	1	1.154	1.154
14	0.9	1.077	1.197
13	0.8	1	1.25
12	0.8	0.923	1.154
11	0.7	0.846	1.209
10	0.7	0.769	1.099
9	0.6	0.692	1.154
8	0.6	0.615	1.026
7	0.5	0.538	1.077
6	0.4	0.462	1.154
5	0.3	0.385	1.282
4	0.3	0.308	1.026

As shown in Tab. 3, as the energy harvesting values decrease and the energy consumption rate remains unchanged, the value of R is decreasing, so the nodes are going into the dead state. Contrary in R' parameter due to incorporated adaptive factor, this value is always maintained above 1, so the network operates continuously. This adaptive factor decreases the number of transmissions by varying the duty cycle of the nodes. As a node is in the active state for a shorter period of time, its energy consumption is reduced.

Next, the ENO ratio for the ERIMAC and SHMAC protocols is compared, for a varying number of nodes (Fig. 6). One may notice that the energy neutrality ratio is greater than one for all network sizes tested, varying from 10 to 80. As the number of nodes is increased from 10 to 20, a decrease in ENO ratio is observed in SHMAC, but its value still remains greater than 1 at all times and it performs better than the ERIMAC protocol.

Throughput is another important parameter for WSN networks. It is the number of data packets received per unit of time. It can be determined by:

$$S = \frac{N_{rx}}{T_{rx}} , \tag{5}$$

where S is the throughput, N_{rx} is the number of packets received and T_{rx} is the receiving time.

Receiver initialization helps in the reduction of energy waste due to idle listening, while the multi-layer nature helps lower the number of collisions. Both features offer better throughput versus the ERIMAC protocol and the optimal polling technique. As the energy harvesting rate increases, an additional amount of energy is available for the nodes to communicate. Therefore, throughput is higher. The adaptive duty cycle also makes the particular node's operation more efficient. The prediction algorithm used improves performance even further in comparison with the other two protocols, i.e. ERIMAC and optimal polling, where such a mechanism is not used.

Tab. 4. Comparison of the proposed SHMAC protocol with other protocols.

Parameter	ERIMAC protocol	SHMAC protocol	Percentage improvement
Collision rate	0.33%	0.27%	22.8%
ENO ratio	1.16	1.25	7.2%

The collision rate is another major cause of energy losses. In such a context, a reduction in the parameter defining the probability of collisions offers another advantage in terms of energy efficiency. The collision rate is the number of collisions encountered for a given transmission attempt and is calculated for varying message inter-arrival times, as shown in Fig. 7. The higher the traffic, the shorter the message inter-arrival time and the higher the probability of a collision. As the traffic becomes lighter, collision probability decreases as well. The MAC protocol is simulated with different numbers of layers taken into consideration. SHMAC has three layers, SLMAC is a single layer solution, and the proposed protocol, as well as DLMAC, are of the dual-layer type. The collision rate is found to be lowest in the proposed SHMAC protocol.

Comparison of the collision rate for SHMAC and ERIMAC protocols is presented in Fig. 8. The collision rate remains low for dense traffic in SHMAC, as its multilayer structure helps reduce the number of collisions. However, as the packet inter-arrival time increases, i.e. traffic becomes light, both protocols are showing almost the same performance. This means that traffic profiling is important for achieving a low collision rate.

The final performance comparison between the proposed protocol and other solutions is shown in Tab. 4. As one may notice, the proposed SHMAC protocol offers a considerable performance enhancement by reducing the collision rate, thus helping reduce energy consumption. A 7.2% improvement in the ENO ratio is achieved thanks to the introduction of the adaptive factor d.

6. Conclusion

The primary goal of solar-based nodes used in WSNs is to maintain continuous operation as energy availability varies. This requires that an adaptive protocol be deployed to manage energy harvesting applications. Our adaptive SHMAC protocol combines a multilayer structure with adaptive timing to control various energy harvesting states in agricultural applications. Nodes with a high energy harvesting rate and significant residual energy levels are active for longer periods of time compared with their counterparts experiencing low energy harvesting conditions. The protocol ensures energy neutrality and offers higher throughput values compared with the ERIMAC protocol. The lower collision rate saves significant amounts of energy, boosting the solution's efficiency even further.

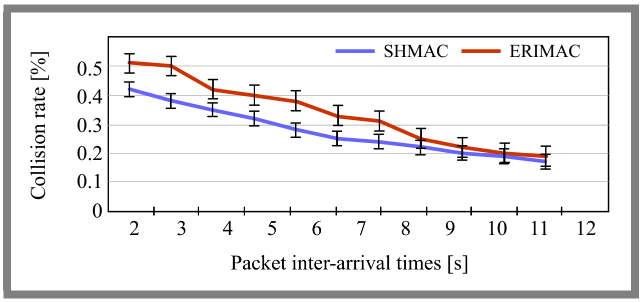

Fig. 8. Comparison of collision rate.

References

[1] X. Fafoutis, A. Di Mauro, M.D. Vithanage, and N. Dragoni, "Receiver-initiated Medium Access Control Protocols for Wireless Sensor Networks", *Computer Networks*, vol. 76, pp. 55–74, 2015 (https://doi.org/10.1016/j.comnet.2014.11.002).

[2] D. De Donno, L. Catarinucci, and L. Tarricone, "Enabling Self-powered Autonomous Wireless Sensors with New-generation I2C-RFID Chips", *2013 IEEE MTT-S International Microwave Symposium Digest (MTT)*, Seattle, USA, 2013 (https://doi.org/10.1109/MWSYM.2013.6697449).

[3] A.S.M.Z. Kausar, A.W. Reza, M.U. Saleh, and H. Ramiah, "Energizing Wireless Sensor Networks by Energy Harvesting Systems: Scopes, Challenges and Approaches", *Renewable and Sustainable Energy Reviews*, vol. 38, pp. 973–989, 2014 (https://doi.org/10.1016/j.rser.2014.07.035).

[4] X. Fafoutis, *Medium Access Control in Energy Harvesting: Wireless Sensor Networks*, Ph.D. Thesis, Technical University of Denmark, Applied Mathematics and Computer Science, 2014 (https://core.ac.uk/download/pdf/19504479.pdf).

[5] P. Kaur, P. Singh, and B.S. Sohi. „Hybrid Multilayer Receiver Based MAC Protocol for Green Wireless Sensor Networks", *2019 IEEE International Conference on Electrical, Computer and Communication Technologies (ICECCT)*, Coimbatore, India, 2019 (https://doi.org/10.1109/ICECCT.2019.8869167).

[6] S. Kosunalp, "A performance Evaluation of Solar Energy Prediction Approaches for Energy-harvesting Wireless Sensor Networks", *International Journal of Applied Mathematics Electronics and Computers,* (*Special Issue*), pp. 424–427, 2016 (https://dergipark.org.tr/en/pub/ijamec/issue/25619/266963).

[7] S. Kosunalp, "MAC Protocols for Energy Harvesting Wireless Sensor Networks: Survey", *ETRI Journal*, vol. 37, no. 4, pp. 804–812, 2015 (https://doi.org/10.4218/etrij.15.0115.0017).

[8] R. Margolies *et al.*, "Energy-harvesting Active Networked Tags (EnHANTs) Prototyping and Experimentation", *ACM Transactions on Sensor Networks*, vol. 11, no. 4, pp. 1–7, 2015 (https://doi.org/10.1145/2831236).

[9] P. Kaur, P. Singh, and B.S. Sohi, "Adaptive MAC Protocol for Solar Energy Harvesting Based Wireless Sensor Networks in Agriculture", *Wireless Personal Communications*, vol. 111, no. 4, pp. 2263–2285, 2020 (https://doi.org/10.1007/s11277-019-06985-9).

[10] H. Sharma, A. Haque, and Z.A. Jaffery, "Solar Energy Harvesting Wireless Sensor Network Nodes: A Survey", *Journal of Renewable and Sustainable Energy*, vol. 10, no. 2, 2018 (https://doi.org/10.1063/1.5006619).

[11] P. Schaumont, B. Yuce, K. Pabbuleti, and D. Mane, "Secure Authentication with Energy-harvesting: A Multi-dimensional Balancing Act", *Sustainable Computing: Informatics and Systems*, vol. 12, pp. 83–95, 2016 (https://doi.org/10.1016/j.suscom.2015.10.002).

[12] P. Kaur, P. Singh, and B.S. Sohi, "Traffic Models for Energy Harvesting Based Wireless Sensor Networks", *Recent Advances in Electrical & Electronic Engineering*, vol. 13, no. 2, pp. 219–226, 2020 (https://doi.org/10.2174/1872212113666190306145721).

[13] P. Kaur, B.S. Sohi, and P. Singh, "Recent Advances in MAC Protocols for the Energy Harvesting Based WSN: A Comprehensive Review", *Wireless Personal Communications*, vol. 104, pp. 423–440, 2019 (https://doi.org/10.1007/s11277-018-6028-3).

[14] A. Kochhar, P. Kaur, S. Sharma, and P. Singh. „Protocols for Wireless Sensor Networks: A Survey", *Journal of Telecommunications and Information Technology*, no. 1, pp. 77–87, 2018 (https://doi.org/10.26636/jtit.2018.117417).

[15] W. Ye, J. Heidemann, and D. Estrin, "An Energy-efficient MAC Protocol for Wireless Sensor Networks", *Twenty-first Annual Joint Conference of the IEEE Computer and Communications Societies*, New York, USA, 2002 (https://doi.org/10.1109/INFCOM.2002.1019408).

[16] T. van Dam and K. Langendoen, "An Adaptive Energy-efficient MAC Protocol for Wireless Sensor Networks", *Proceedings of the 1st International Conference on Embedded Networked Sensor Systems*, pp. 171–180, 2003 (https://doi.org/10.1145/958491.958512).

[17] E.-Y.A. Lin, J.M. Rabaey, and A. Wolisz, "Power-efficient Rendezvous Schemes for Dense Wireless Sensor Networks", *2004 IEEE International Conference on Communications*, Paris, France, 2004 (https://doi.org/10.1109/ICC.2004.1313259).

[18] Z.A. Eu, H.-P. Tan, and W.K.G. Seah, "Design and Performance Analysis of MAC Schemes for Wireless Sensor Networks Powered by Ambient Energy Harvesting", *Ad Hoc Networks*, vol. 9, no. 3, pp. 300–323, 2011 (https://doi.org/10.1016/j.adhoc.2010.07.014).

[19] S. Lohier, A. Rachedi, E. Livolant, and I. Salhi, "Wireless Sensor Network Simulators Relevance Compared to a Real IEEE 802.15.4 Testbed", *2011 7th International Wireless Communications and Mobile Computing Conference*, Istanbul, Turkey, 2011 (https://doi.org/10.1109/IWCMC.2011.5982734).

[20] X. Fafoutis and N. Dragoni, "ODMAC: An on-demand MAC Protocol for Energy Harvesting – Wireless Sensor Networks", *Proceedings of the 8th ACM Symposium on Performance Evaluation of Wireless ad Hoc, Sensor, and Ubiquitous Networks*, pp. 49–56, 2011 (https://doi.org/10.1145/2069063.2069072).

[21] X. Fafoutis and N. Dragoni, "Analytical Comparison of MAC Schemes for Energy Harvesting – Wireless Sensor Networks", *2012 Ninth International Conference on Networked Sensing (INSS)*, Antwerp, Belgium, 2012 (https://doi.org/10.1109/INSS.2012.6240580).

[22] P. Ramezani and M.R. Pakravan, "Overview of MAC Protocols for Energy Harvesting Wireless Sensor Networks", *2015 IEEE 26th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, Hong Kong, China, 2015 (https://doi.org/10.1109/PIMRC.2015.7343632).

[23] Z.G. Wan, Y.K. Tan, and C. Yuen, "Review on Energy Harvesting and Energy Management for Sustainable Wireless Sensor Networks", *2011 IEEE 13th International Conference on Communication Technology*, Jinan, China, 2011 (https://doi.org/10.1109/ICCT.2011.6157897).

[24] M. Khurana, R. Thalore, V. Raina, and M.K. Jha, "Improved Time Synchronization in ML-MAC for WSN Using Relay Nodes", *AEU-International Journal of Electronics and Communications*, vol. 69, no. 11, pp. 1622–1626, 2016 (https://doi.org/10.1016/j.aeue.2015.07.011).

[25] K. Nguyen *et al.*, "ERI-MAC: An Energy-harvested Receiver-initiated MAC Protocol for Wireless Sensor Networks", *International Journal of Distributed Sensor Networks*, vol. 10, art. no. 5514169, 2014 (https://doi.org/10.1155/2014/514169).

[26] S. Kosunalp, "A New Energy Prediction Algorithm for Energy-harvesting Wireless Sensor Networks with Q-learning", *IEEE Access*, vol. 4, pp. 5755–5763, 2016 (https://doi.org/10.1109/ACCESS.2016.2606541).

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