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Heterogeneous WSN Modeling: Packet Transmission with Aggregation of Traffic

Canek Portillo
Facultad de Ingeniería
Universidad Autónoma de Sinaloa
Culiacán, México
canekportillo@uas.edu.mx

Jorge Martinez-Bauset
Departamento de Comunicaciones
Universitat Politècnica de València
València, Spain
jmartinez@upv.es

Vicent Pla
Departamento de Comunicaciones
Universitat Politècnica de València
València, Spain
vpla@upv.es

Vicente Casares-Giner
Departamento de Comunicaciones
Universitat Politècnica de València
València, Spain
vcasares@upv.es

***Abstract*—The modeling and the performance analysis of a heterogeneous WSN transmitting in an APT (Aggregated Packet Transmission) mode is presented. With APT is possible to send more than one packet per cycle during the data transmission process. Packets are encapsulated in a unit of information called frame. The study considers the activity and procedures that occur during the data period of the transmission cycle. Results have been obtained and discussed for the following performance parameters: average packet delay, throughput and average power consumption.**

***Keywords*—aggregated packet transmission, heterogeneous WSN, wireless sensor networks, WSN modeling.**

I. INTRODUCTION

One of the ways in which information is usually transmitted in WSN is by transmitting a single packet per cycle (SPT, Single Packet Transmission) [1], [2]; however, Aggregated Packet Transmission (APT) is also possible. Unlike SPT, in APT mode nodes transmit more than one packet (a batch) per cycle. Data aggregation, which is the process of combining multiple data packets into a single data unit called frame, is often used to improve energy efficiency in WSNs. This mechanism can help to reduce the number of transmissions and, consequently, it can help to diminish the consumption of energy [3]. Furthermore, data aggregation also helps to decrease the media access contention as well as the number of packets transmitted and, therefore, it can help to minimize the packet transmission delay [4]. Many data aggregation schemes that contribute to save energy, reduce packet delay and packet collisions have been proposed [3]-[5]. However, there are scarcely any analytical models for evaluating the performance of WSNs with traffic aggregation. There are some proposals related to packet aggregation schemes for WSNs [6]-[8], although these approaches are focused from a routing perspective and without considering any specific MAC layer protocol. Other MAC protocol proposals [9]-[11] integrate data aggregation in WSN, but these studies have been achieved mainly through simulations or based on tests with experimental prototypes. In [12], the authors have developed DTMC models to evaluate the APT scheme for a WSN whose MAC operates with duty-cycled (DC), but the study does not consider heterogeneous scenarios or node classes, nor any prioritization scheme. In [13] and [14], we have carried out a performance analysis of a heterogeneous WSN composed of different classes of nodes, operating with a MAC protocol governed by a synchronized DC, where there is prioritization and where nodes transmit in SPT mode. In the present work, a model with the characteristics mentioned above is developed, but which also expands the capabilities of the nodes to transmit with traffic aggregation.

The rest of the paper is distributed as follows: in section II, the network scenario is presented; in section II, the corresponding modeling of the system is shown; section IV explains how the performance parameters are obtained; section V deals with the numerical results; and finally, the conclusion is in section VI.

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II. NETWORK SCENARIO

A. Network operation and assumptions

The network scenario considers the existence of two classes of nodes (N1 and N2) that send packets to a central cluster node called sink (shown in figure 1). This heterogeneous WSN has two classes of nodes. The nodes of class 1 have priority for accessing the channel, while nodes of class 2 can access the channel after nodes of class 1 have vacated the medium. A reference node (RN) is defined for each class. In general, the same assumptions are made as in [13], [14], except that in this model, the nodes can perform the aggregation of packet according to the packets they have in their queues. It is important to note that the packet aggregation capability applies to each class of nodes regardless of its priority. The sum of packets due to the packet aggregation results in a unit of information called frame. For practical reasons, the model defines a maximum frame size, F, in packets. When the RN, of any class, gains the access to the medium, it transmits this frame, and the number of packets in the queue of the RN is reduced according to the number of packets or the size of the frame sent. For example, if q is the number of packets in the queue, Q, of the node, and if $q \leq F$, when there is a successful transmission the queue of RN will be empty; on the contrary, if $q \geq F$, a frame with F packets will be transmitted, leaving $q - F$ packets in queue.

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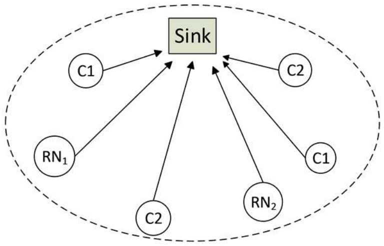

Fig. 1. Wireless sensor network in a heterogeneous scenario formed with different types of nodes.

B. Prioritization of access to the medium

The process considered here, in general, is the same as that described in [13], [14]. The main difference is that the transmissions made by the nodes, whatever their class, includes frames with packet aggregation, instead of a single packet. Nodes belonging to class 1 has priority to the transmission channel. In figure 2, the scheme of the transmission of a frame during the data period of a cycle can be observed. Note that the synchronization period has been omitted for any class of nodes. Also note that, as part of the MAC protocol, the CSMA/CA contention mechanism with the RTS/CTS/FRAME/ACK packet exchange is used. When cycle begins, just nodes of class 1 compete for access to the medium. Nodes of class 2 must wait until the contention window (W_1) of nodes of class 1 have finished. When the nodes of class 2 detect an available medium, because there is not any transmission in progress, the nodes of class 2 will attempt to access to the medium through the activation of the contention mechanism. But, if a node of class 2 detects a busy channel, they will return to a sleep mode to save energy and will wake up once anew in the next cycle. For cycles in which nodes of class 1 collide, nodes of class 2 are considered to detect the activity and will not contend.

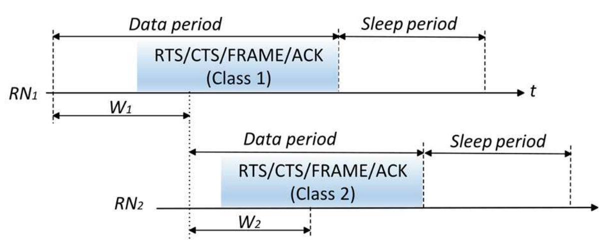

Fig. 2. Frame transmission scheme and the MAC protocol procedure.

III. System Modeling

For facility in the explanation, in the following sections and particularly in expressions from (1) to (6), the notation is presented in a generic format, although it could represent both classes of nodes.

A. Access to the medium

Although explained in detail in [13], [14], it is convenient to expose some of the main model assumptions related to the access to the medium. Only the nodes that have at least a packet in its queue are capable of generate a backoff time. The time value is randomly selected from [0, W-1]. A successful transmission of a packet by the RN occurs when the other nodes that contend for the medium select greater backoff time values, compared with that selected by the RN. A collision or a failed transmission will take place when the backoff value obtained by the RN and the same value of at least one of the other nodes are coincident. Besides it must be the smallest value generated in the cycle. There are two possibilities if the resulting backoff time is not the smallest of all: (i) another node transmits with success; (ii) other nodes will collide their packets. All other nodes that could not transmit their packets go to an energy saving mode until the next cycle. Considering a cluster of nodes with packets in its queues, the variable k defines the nodes different from the RN, where: $0 \leq k \leq N-1$. According to the generic notation, N means the nodes of any class. Now, three probabilities can be established: $P_{s,k}$, $P_{sf,k}$ and $P_{f,k}$, which are defined as the probabilities when a packet is successfully transmitted, a packet is transmitted successfully or with collision, and a packet is transmitted with failure, respectively, when the RN and other k nodes contend for the access to the channel.

$$P_{s,k} = \sum_{i=0}^{W-1} {}^{1}\!/_{W} \left(W-1-{}^{i}\!/_{W}\right)^{k}, \tag{1}$$

$$P_{sf,k} = \sum_{i=0}^{W-1} {}^{1}\!/_{W} \left(W-{}^{i}\!/_{W}\right)^{k}, \tag{2}$$

$$P_{f,k} = P_{sf,k} - P_{s,k} = {}^{1}\!/_{W} \, . \tag{3}$$

For class 1, these probabilities are calculated considering the reference node RN_1 and the corresponding contention window W_1. For class 2, RN_2 and W_2 are considered.

B. Classes and priorities

For the modeling of each class of nodes we use a two-dimension discrete-time Markov chain (2D-DTMC). These classes are represented by the reference nodes RN_1 and RN_2. Each chain models how the number of packets in the queue of the respective RN evolves over the time, as well as the number of nodes with packets in its queue of each class. The state of each 2D-DTMC is represented by (i,m) . The probability of transition from state (i,m) to state (j,n) is represented by: $P_{(i,m)(j,n)}$. Where $i \leq Q$ represents the number of packets in the queue of the RN, and m is the number of nodes that have at least a packet to transmit, besides de RN, and $m \leq K$. For a better explanation and due to space limitations, the transition probabilities of both 2D-DTMC are shown in [15]. A fundamental part of the model is the implementation of the coupling between the two 2D Markov chains. For that reason, in the construction of the expressions for the transition probabilities that are developed for the 2D-DTMC of class 2, the parameter $R_{1,0}$ has been properly defined and incorporated. This parameter refers to the fraction of cycles in which nodes of class 1 have no need to use the channel, and its inclusion is important for the adequate coupling between both Markov chains. Another way to view this parameter is as the probability that there are not active nodes of class 1 in the WSN. At this point, is important to remark that due to the incorporation of the packet aggregation scheme, the expressions of the transition probabilities of each Markov chain are significantly modified. These changes are made through the F and α parameters. The first one was already mentioned in a past section and refers to the maximum number of packets that can be aggregated in a frame; the second one is the number of packets that have been aggregated to the frame. The new expressions of the transition probabilities that we have obtained are presented in [16].

C. Solution of both coupled Markov chains

The set of linear equations shown in (4) have been used to solve each 2D-DTMC.

$$\boldsymbol{\pi P} = \boldsymbol{\pi}, \ \ \boldsymbol{\pi e} = 1 \ . \tag{4}$$

Where $\boldsymbol{\pi} = [\pi(i,n)]$is the stationary probability distribution, $\boldsymbol{P}$ denotes the matrix composed of the transition probabilities, and its different expressions are established in [15] and [16]. The parameter $\boldsymbol{e}$ refers to a column vector of ones. On the other hand, the average probability, P_s, of that the corresponding RN successfully transmits a packet in a random cycle, conditioned on the RN being active, is given by:

$$P_s = \frac{1}{G}\sum_{i=1}^{Q}\sum_{k=0}^{K}\pi(i,k)\cdot P_{s,k}, \tag{5}$$

$$G = \sum_{i=1}^{Q}\sum_{k=0}^{K}\pi(i,k) = 1 - \sum_{k=0}^{K}\pi(0,k). \tag{6}$$

From (4) and (5), the stationary probability distribution is a function of P_s , $\boldsymbol{\pi}(P_s)$. There is a dependency relationship between P_s and $\boldsymbol{\pi}$, which enables the resolution of the set of (4), following an iterative fixed-point procedure that allows its solution to be determined, in this case: $\boldsymbol{\pi}$. To solve the second chain, it is necessary to have solved the first one, since that information is needed. However, in the process of coupling the Markov chains for both classes of nodes, the first chain is first solved with the iterative procedure to obtain the stationary distribution of the nodes of class 1 ($\boldsymbol{\pi_1}$). From $\boldsymbol{\pi_1}$, it is obtained the fraction of cycles in which the nodes of class 1 are inactive or the probability that the nodes of class 1 are inactive: $R_{1,0} = \pi_1(0{,}0)$. This parameter $R_{1,0}$ is fundamental in the formation of the transition probability matrix $\boldsymbol{P_2}$ of class 2, therefore, it can be established that the stationary distribution of the nodes of class 2 is also a function of $R_{1,0}$, that is: $\boldsymbol{\pi_2}(P_{s2}, R_{1,0})$. Finally, $\boldsymbol{\pi_2}$ is obtained with the mentioned iterative procedure. In the same way, $R_{1,0}$ must be considered for the determination of the performance parameters of nodes of class 2. This parameter allows the model to indicate that during the transmission of nodes of class 2, there are no active nodes of class 1 trying to transmit. Therefore, it is important for the correct operation of the protocol, especially in relation to the inclusion of the priorities of access to the medium.

IV. PERFORMANCE PARAMETERS

A. Throughput

For the determination of throughput, a conceptually significant incorporation is made; the accumulated number of packets by traffic aggregation and their transmission in a single frame is considered in the calculation. The throughput per node, η, is defined as the average number of packets that a node has successfully delivered in a cycle. The total throughput or system throughput, whose measurement unit is packets per cycle, is the addition of all individual throughputs due to each node, whatever the class it belongs. For class 1 nodes, the throughput per node is obtained with (7), while the total system throughput is determined with (8).

$$\eta_1 = \sum_{i=1}^{Q_1}\sum_{k=0}^{M_1}\alpha_1\pi_1(i_1,k_1)P_{s1,k1} \ , \tag{7}$$

$$Th_1 = N_1\eta_1 \ , \tag{8}$$

$$\alpha_1 = \min(i_1, F_1) \ . \tag{9}$$

Where α_1 represents the aggregated packets, i_1 refers to the packets in the queue of RN_1, and F_1 is the maximum number of packets that can be added according to the configuration set. For nodes of class 2, the throughput per node and the total throughput of the system are given by (10) and (11), respectively.

$$\eta_2 = \sum_{i=1}^{Q_2}\sum_{k=0}^{M_2}\alpha_2\pi_2(i_2,k_2)P_{s2,k2}\cdot R_{1,0} \ , \tag{10}$$

$$Th_2 = N_2\eta_2 \ , \tag{11}$$

$$\alpha_2 = \min(i_2, F_2) \ . \tag{12}$$

Where α_2 represents the aggregated packets, i_2 refers to the packets in the queue of RN_2, and F_2 is the maximum number of packets that can be added according to the configuration set. Note that for the calculation of the throughput for class 2, it is necessary to consider the inactivity of the nodes of class 1, through the parameter $R_{1,0}$, which is the stationary probability distribution of not finding active nodes of the class 1 (fraction of cycles where nodes of class 1 are idle).

B. Average paket delay

D is defined as the average delay experienced by a packet from its arrival at the queue of the node until it is successfully transmitted, and it is measured in cycles. For the determination of D, Little's law is applied. For class 1 nodes, the delay is calculated with the following expressions:

$$D_1 = N_{av1}/\gamma_{a1} \ , \quad N_{av1} = \sum_{i=0}^{Q_1} i\pi_{i1}, \tag{13}$$

$$\gamma_{a1} = \eta_1, \quad \pi_{i1} = \sum_{k=0}^{M_1}\pi_1(i_1,k_1) \ . \tag{14}$$

Where π_{i1} is the class 1 stationary probability of finding i_1 packets in the queue of the corresponding reference node of class 1, RN_1. $N_{av1}$is the average number of packets in queue of RN_1, and $\gamma_{a1}$is the average number of packets accepted by the queue of RN_1, which is equal to η_1. For class 2 nodes, the delay is calculated with the following expressions:

$$D_2 = N_{av2}/\gamma_{a2} \ , \quad N_{av2} = \sum_{i=0}^{Q_2} i\pi_{i2}, \tag{15}$$

$$\gamma_{a2} = \eta_2, \quad \pi_{i2} = \sum_{k=0}^{M_2}\pi_2(i_2,k_2) \ . \tag{16}$$

Note that the previous terms can be defined in a similar way as for those of class 1, only that class 2 must be considered in all parameters.

C. Average power consumption

For the determination of the average energy consumption, the accumulated number of packets by traffic aggregation and their transmission in a single frame is considered, as well. This consideration is a conceptually significant incorporation. The energy is calculated during the data period, and just the energy consumption due to the transmitter and receiver is considered in the study. The average energy that the RN consumes in a cycle during the data period can be determined by the following expression:

$$E_d = E_s^{tx} + E_f^{tx} + E^{oh} . \quad (17)$$

Where, E_s^{tx}, E_f^{tx} and E^{oh} represent the terms of the energy consumed when the RN transmits with success, with failure and when it listens to the transmission of other nodes (overhearing), respectively. The E_s^{tx} consumption value is obtained with the following expressions:

$$E_s^{tx} = \sum_{i=1}^{Q} \sum_{k=0}^{M} \pi(i,k) P_{s,k} \left(P_{s,1}^{tx} + \alpha P_{s,2}^{tx} + P_{s,1}^{rx} + P_{s,2}^{rx}\right) \quad (18)$$

$$P_{s,1}^{tx} = t_{RTS} P_{tx} \ , \ \ P_{s,2}^{tx} = t_{DATA} P_{tx} \ , \quad (19)$$

$$P_{s,1}^{rx} = \left[t_{CTS} + t_{ACK} + 4D_p\right] P_{rx} \ , \ \ P_{s,2}^{rx} = BT_{s,k} P_{rx} \ . \quad (20)$$

Where t_{RTS} , t_{DATA} , t_{CTS} and t_{ACK} are the transmission times for the control packets used during the transmission process. P_{tx} and P_{rx} are the transmission and reception power levels, D_p is the one-way propagation delay, and $\alpha = \min(i, F)$ is the number of aggregated packets. $BT_{s,k}$ is the average backoff conditioned to a successful transmission of packets from the RN, when competing with k other nodes [14]. The factor α determines the number of packets that are added to the frame that is transmitted, in such a way that the greater the number of packets added, the greater the energy consumption when they are successfully transmitted. To determine E_f^{tx} and E^{oh}, the same procedure is carried out as that developed in [14]. To determine the average energy consumption per cycle for nodes of class 1, E_1, and for nodes of class 2, E_2, the following is expressions are used:

$$E_1 = E_{d1}, \quad (21)$$

$$E_2 = \left(1 - R_{1,0}\right) E_0 + R_{1,0} . E_{d2} \ . \quad (22)$$

Where E_{d1} is the energy consumption during the data period for the nodes of class 1, and E_{d2} is energy that is consumed during the data period due to the nodes of class 2. $R_{1,0}$ refers to the stationary probability distribution of not finding active nodes of class 1. E_0 is the energy consumed by nodes of class 2 to wake up and detect if that medium is occupied.

V. Numerical results

A. Parameter configuration and scenarios

From the developed models that are explained in section III, we have obtained analytical results which have been validated by simulation. To obtain simulation results, a discrete event simulator has been developed in C language, which simulates the WSN according to the network scenario explained in section II. It should be noted that the simulator previously developed for other related studies has been modified so that it can transmit with traffic aggregation, considering different possibilities of maximum queue size for any of the classes. It is important to note that the results that have been obtained analytically with the model, are totally independent of the results obtained with the simulator. In the following sections, the performance parameters results are presented. In the different figures, the simulation results are represented with markers only, while the results obtained analytically are represented with lines and markers. The analytical and simulation results perfectly match, confirming that the analytical model is highly accurate. We have obtained confidence intervals with a confidence level of 95%, however, as they are very small, they have been omitted from the figures for clarity. The parameter configuration is summarized in table I.

TABLE I. PARAMETER CONFIGURATION

Parameter	**value**	**Parameter**	**Value**
Cycle duration (T)	60 ms	Propagation delay (Dp)	0.1 us
t_{SYNC}, t_{RTS}, t_{CTS} and t_{ACK}	0.18 ms	Slot time (ts)	0.1 ms
t_{DATA}	1.716 ms	Contention window (W)	128 slots
Data packet size (S)	50 bytes	Queue size (Q)	5 packets
Transmission power (Ptx)	52 mW	Reception power (Prx)	59 mW
Node number and scenarios	N1 = 5 (SC1 and SC2)	Number of packets per frame (F)	F1=F2= {2,5,10}
	N2=4N1=20 (SC2)	Packet arrival rate (packets/s)	λ_1 = {0.5, 1.0}
			λ_2 = [0.5, 4.5]

B. Average packet delay

In figure 3, the average packet delay is shown, which is measured in cycles. The scenario considers both classes of nodes, both transmission schemes (SPT, APT) and a packet arrival rate λ_1=0.5. D_1 and D_2 refer to the average delay of packets that each class has successfully transmitted, respectively.

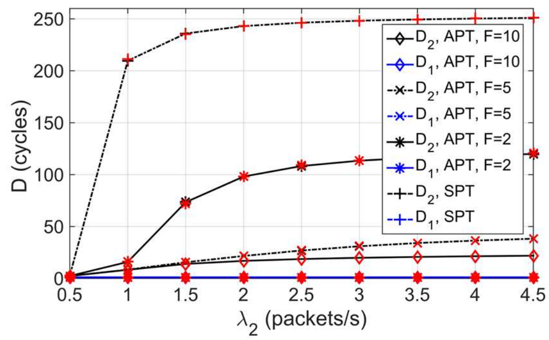

Fig. 3. Average packet delay for both classes and both transmission schemes.

As expected, class 1, being the priority class, experiences very low delay for both schemes (SPT, APT) and for the different sizes of F used in APT (F= 2, 5, 10). Consider that nodes of class 1 work with low load and have their queues empty most of the time. Therefore, when a packet arrives at its queues, it is transmitted almost immediately and with a very low probability of collision. It is also clear that for nodes of class 2 (the non-priority class), the impact of increased traffic and collisions is significant. Note that D_2 increases with λ_2, since the fraction of colliding packets increases with λ_2, and more retransmissions are required to successfully transmit their packets. It is also observed that for APT scheme, lower values of D_2 are reached, when the value of F increases. This effect is very significant for the values of F= {5, 10}. The queue of the node empties faster when multiple packets are transmitted together, reducing contention for media access and, in consequence, also reducing the packet collisions.

C. Throughput

Figure 4 shows the throughput per node for both classes of nodes (class 1 and class 2). It also shows how class 2 (non-priority) benefits from the use of the APT scheme, obtaining higher throughput values.

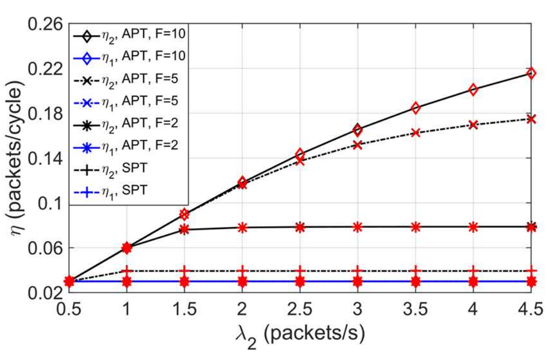

Fig. 4. Throuhgput per node for both classes and for both transmission schemes.

While in SPT scheme, class 2 reaches a maximum throughput limit (saturation) at λ_2 =1, when APT is used, these saturation limit values increase with F. Thus, for F=2 the throughput is doubled, and for F=5 and F=10 they do not reach any saturation point for the considered scenario. When there is saturation, all nodes have packets in their queues ready to be sent in almost every cycle. The throughput increases, not only because more packets per cycle are transmitted in APT, but also because the probability of a node successfully transmitting a packet also increases. In APT, the queue empties faster, therefore, the number of contending nodes per cycle decreases.

D. Average power consumption

In figure 5, the average energy consumption per cycle is shown. The scenario considers both classes of nodes as well as the two transmission schemes. The measurement unit used is the millijoule (mJ). The figure 5 also shows that for nodes of class 1, the energy consumed remains constant as λ_2 increases. This is due to the packet arrival rate λ_1 and the number of nodes N_1 are both constant values. For class 2 nodes, the packet arrival rate varies according to the values shown in table I, where the parameter configuration has been set: ($\lambda_2 \in [0,4.5]$ packets/s). However, the nodes eventually reach an activity limit, which has an associated power consumption limit. In addition, when the correspondences of figure 3 and figure 5 are analyzed, some relationships between the energy consumed and throughput can be inferred. For example, higher throughput values imply more transmissions, and, in consequence, more packet deliveries. The above, in terms of energy, also implies a greater activity by the nodes, and therefore, a grater energy consumption.

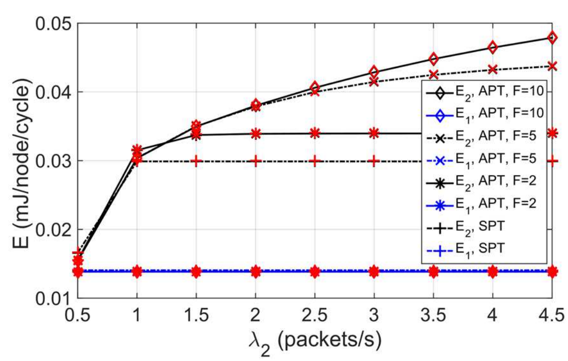

Fig. 5. Average energy consumption for both classes of nodes and both transmission schemes.

However, an important part of this power consumption is due to the node frequently incurring in overhearing (listening to other nodes). This occurs when the node loses the contention for accessing to the channel, but it had to listen to the channel during the backoff period to notice. The node knows if the channel is busy when it detects activity on the channel. With APT there is a higher power consumption per node per cycle compared to SPT. As the value of F increases, the power consumption reaches higher levels.

VI. CONCLUSION

We have carried out a study of the performance of a wireless sensor network composed of different types of nodes. For nodes, it also considers the assignment of priorities to access to the medium. Moreover, the single packet transmission (SPT) and the aggregated packet transmission (APT) schemes are included in the study, although the analysis is focused on APT. To achieve the previous mentioned, an analytical model has been developed for a MAC protocol of a WSN that operates with a synchronized duty cycled and that considers the heterogeneity of the nodes that make up the WSN. Furthermore, the access priorities, and the SPT and APT operation schemes are also considered in the model. Moreover, the analytical model has been proven for different scenarios, obtaining results for the following performance parameters: throughput, average packet delay and average energy consumption. The validation of the analytical model has been done through discrete events simulations, which show accurate results. The analysis shows how, both types or classes of nodes, can be impacted when APT scheme is used, and especially how class 2, the non-priority class benefits from the APT transmission scheme. The above is particularly true when the nodes increase its traffic, allowing them to achieve a better performance than with SPT scheme.

REFERENCES

[1] W. Ye, Heidemann, and D. Estrin, "An energy-efficient MAC protocol for wireless sensor networks," Proceedings. Twenty-First Annual Joint Conference of the IEEE Computer and Communictions Societies, vol. 3, 2002, pp. 1567-1576.

[2] W. Ye, J. Heidenmann, and D. Estrin, "Medium access control with coordinated daptative sleeping for wirless sensor networks," in IEEE/ACM Transactions on networking, vol. 12, no. 3, pp. 493-506, June 2004.

[3] K. Akkaya, M. Demirbas, and R.S Aygun, "The impact of data aggregation on the performace of wireless sensor networks," in Wireless Comunications and Mobile Computing, vol. 8, no.2, pp. 171-193, 2008.

[4] M. Bagaa, Y. Challal, A. Ksentini, A. Derhab, and N. Badache,"Data aggregation scheduling algorithms in wireless sensor networks: sonlutions and challenges," in IEEE Communications Surveys Tutorials, vol. 16, no. 3, pp. 1339-1368, Third Quarter 2014.

[5] R. Rajagopalan and P.K. Varshney, "Data-aggregation techniques in sensor networks: a survey," in IEEE Comnunications Surveys Tutorials, vol. 8, no. 4, pp. 48-63, Fourth Quarter 2006.

[6] L. Galluccio and S. Palazzo, "End-to-end delay and network liftime analysis in a wireless sensor network performing data aggregation," GLOBECOME 2009 - 2009 IEEE Global Telecommunications Conference, 2009, pp. 1-6.

[7] M. Kamarei, M. Hajimohammaadi, A. Patooghy, and M. Fazeli, "OLDA: an efficient on-line data aggregation method for wireless sensor networks," in 2013 Eighth International Conference on Broadband and Wireless Computing, Communication and Applications, 2013, pp. 49-53.

[8] B. Alinia, M.H. Hajiesmaili, A. Khonsari, and N. Crespi, "Maximum-Quality Tree Construction for Deadline-Constrained Aggregation in WSNs," in IEEE Sensor Journal, vol.17, no. 12, pp. 3930-3943, June 2017.

[9] Z. Li. Y. Peng, D. Qiao, and W. Zhang, "Joint aggregation and MAC design to prolong sensor network lifetime," IEEE International Conference on Network Protocols (ICNP), 2013, pp. 1-10.

[10] Z. Li, Y. Peng, D. Qiao, and W. Zhang, "LBA: Lifetime balanced data aggregation in low duty cycle sensor networks". In 2012 Proceedings IEEE INFOCOM, pages 1844-1852, March 2012.

[11] K. Nguyen, U. Meis, and Y. Ji, "An energy efficient, high throughput MAC protocol using packet aggregation," 2011 IEEE GLOBECOM Workshops (GCWkshps), 2011, pp. 1236-1240.

[12] L. Guntupalli, J. Martinez-Bauset, F. Y. Li, and M.A. Weitnauer, "Aggregated packet transmission in duty-cycled WSNs: modeling and performance evaluation," In IEEE Trans. on Vehicular Technology, vol. 66, no. 1, pp. 563-579, Jan 2017.

[13] C. Portillo, J. Martinez-Bauset, V. Pla, and V. Casares-Giner, "Modelling of S-MAC for Heterogeneous WSN," 2018 9th IFIP International Conference on New Technologies, Mobility and Security (NTMS), 2018, pp.1-6.

[14] C. Portillo, J. Martinez-Bauset, V. Pla, and V. Casares-Giner, "Modeling of duty-cycled MAC protocols for heterogeneous WSN with priorities," in Electronics, vol. 9, no. 3, pp. 1-16, March 2020.

[15] C. Portillo, J. Martinez-Bauset, V. Pla , and V. Casares-Giner, "The state transition probabilities of the two 2D-DTMC," Technical note. [Online], Available:http://personales.upv.es/jmartine/public/2DDTMC.pdf

[16] C. Portillo, J. Martinez-Bauset, V. Pla , and V. Casares-Giner, "The State Transition Probabilities of the Two 2D-DTMC with traffic aggregation," Technical Note: [Online], Available: https://drive.google.com/drive/folders/1ezmxQxjrt410T_GglqUo6YWKgOEJKd1M?usp=sharing