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Tools for the selection of the transmission probability in the cluster formation phase for Event-Driven Wireless Sensor Networks

Herramientas para la selección de la probabilidad de transmisión en la fase de formación de Clusters en Redes Inalámbricas de Sensores Accionadas por Eventos

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Abstract

In the literature, it is common to find studies on Wireless Sensor Networks (WSNs) that consider the Carrier Sense Multiple Access (CSMA) protocol with a fixed transmission probability for means of the random access strategy. This is especially true for event-driven applications for clustered-based architectures. However, due to the highly variable environment in these networks in terms of the number of nodes attempting a transmission (at the beginning of the cluster formation all nodes in the network contend for the channel, while at the end only a few nodes attempt a transmission), a fixed transmission probability may not entail an adequate performance. Specifically, the energy consumption may be too high by considering a fixed transmission strategy, because the use of a low transmission probability at the beginning of the cluster formation reduces the collision probability, but at the end entails long idle periods. In view of this, the effects of three different transmission probability strategies for event-driven WSNs are studied. Based on the obtained results, it is shown that a careful selection of the transmission probability is required in order to prolong the network lifetime.

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---------- *Keywords:* Transmission probability, clustering, event-driven WSNs, Markovian analysis

Resumen

En la literatura es común encontrar trabajos sobre redes inalámbricas de sensores que consideran al protocolo de acceso aleatorio CSMA (Acceso al Medio por Sensado de Portadora, por sus siglas en inglés) con una probabilidad de transmisión fija. Esto es particularmente usado en aplicaciones de detección de eventos y bajo una arquitectura de formación de grupos de nodos. Sin embargo, en estas aplicaciones, el ambinte es altamente variable en cuanto al número de nodos que intentan transmitir (al inicio de la formación de grupos todos los nodos de la red transmiten mientras que al final de este proceso, solo pocos nodos intentan transmitir) y una probabilidad de transmisión fija no ofrece un buen desempeño del sistema. Específicamente, el consumo de energía puede ser muy alto considerando una estrategia de transmisión fija ya que al inicio de la formación de los grupos una probabilidad de transmisión baja que reduzca la probabilidad de colisión genera mucho tiempo libre al final del mismo. En vista de lo anterior, se propone en este trabajo el estudio del efecto de la probabilidad de transmisión para tres estrategias diferentes en el ámbito de aplicaciones para detección de eventos. A partir de los resultados obtenidos, se puede apreciar que la selección de esta probabilidad es crucial para aumentar el tiempo de vida de la red de sensores.

---------- *Palabras clave*: Probabilidad de transmisión, agrupación de nodos, red inalámbrica de sensores para detección de eventos, Modelo de Markov

Introduction

Event-driven Wireless Sensor Networks (WSNs) are deployed over a target area to supervise certain phenomena of interest. Once an event occurs, it is reported to the sink node by the sensor nodes within the event area, i.e, the area where the event may be detected by the sensor nodes. Each node takes readings from the local environment, processes and transmits a predefined number of packets, containing the sensed data to the sink node. Two common modalities can be used to access the shared medium to communicate the data to the sink node: unscheduled and scheduled-based transmissions [1]. In this work, a clustered based architecture is considered partly based on the encouraging results presented in previous works, such as [2]. In a cluster based architecture, there are two distinct phases: a) Cluster formation phase, where all the active nodes (the nodes that detect the event) transmit a control packet among each other in order to be part of the event cluster and b) Steady state phase, where, once the event cluster is formed, all the nodes in the event cluster transmit their data packets first to the CH and then the CH transmits the aggregated data packet to the sink node. In the cluster formation phase, it is impossible to know beforehand the number of nodes that detected the event. Hence, transmissions cannot be scheduled. As such, the active nodes transmit the control packet using a random access protocol where the channel is shared among all nodes and hence, collisions are possible. On the other hand, in the steady state, the Cluster Head (CH) assigns resources by clarifying which sensor nodes should utilize the channel at any time through a Time Division

Multiple Access (TDMA) protocol, ensuring a collision-free access to the shared data channel. One important advantage in this phase is that only the transmitting node is awake to transmit in the pre-assigned channel, while the rest of the nodes enter in sleep mode to save energy.

The main contribution of this work is to provide general guidelines on the selection of the transmission probability in the cluster formation phase on clustered WSNs. This issue has been largely neglected in the literature since most previous works consider a fixed value of the transmission probability, which is selected independent of the network density [3-5]. This entails a considerable energy wastage, as it is shown in the following sections. Additionally, most papers (even if no clustering is considered) do not consider the energy wastage or the delay for transmission due to the inherent use of the random access protocol, such as [6-8]. As such, the results obtained in this work can be applied for the selection of an appropriate probability transmission and/or transmission strategy independently of the network's architecture or application. Also, in terms of the performance evaluation of random access protocols, previous works such as [9-11] have studied the CSMA/CA protocol. However, it has been shown that this access strategy is not well suited in WSNs due to the extra energy consumed in the sensing procedure. Previous works on event-driven WSNs attempt to reduce the collision probability by reducing the number of active nodes. For example, [12] proposes a CC-MAC that takes advantage of the spatial correlation inherent in such applications, in order to reduce the number of messages that have to be transmitted. Another approach proposed in [13] is to use multiple paths to reduce the collision probability. However, none of these works proposed a suitable value of the transmission probability of the messages.

Three different strategies for selecting the transmission probability in the cluster formation phase are studied: Maximum success (MAXS) transmission probability, fixed transmission probability and, adaptive transmission probability. For the first strategy, the transmission probability that maximizes the success transmission probability is used. As it will be explained in further detail, this transmission probability strategy is difficult to implement in a practical network. The fixed transmission probability scheme selects a suitable value for the transmission probability and remains unchanged during the operation of the system. Finally, in the adaptive strategy, the transmission probability is adjusted according to the outcome of the previous slot. Specifically, the transmission probability is increased in case of finding the channel idle; it is decremented in case of collision, and it remains without change in case of a successful transmission.

The rest of the paper is organized as follows. First, it describes the network model as well as the suppositions considered in the paper, including the random access protocol and energy consumption models, mathematical analisis and numerical results. Following this, the paper presents a summary of conclusions and contributions.

Development

Network Model

Two different models are presented: Analytical and Simulation models. The interest of the analytical model is to study the basic operation of the transmission probability strategies on the random access protocol using a simplified network, while the simulation model is used to study the complete network operation, including both the cluster formation phase and the steady state phase. In order to simplify the mathematical analysis, only the cluster formation phase is considered in the analytical model. Without loss of generality, it is assumed that whenever a node performs any transmission, it consumes 1.0 unit of energy while for any reception, it consumes 0.5 units of energy, i.e, the energy consumption for the transmission of a control packet is normalized. As such, the presented analysis can be easily applied to any type of commercial node. The case where the sensors run out of energy is not considered.

Under these conditions, the pair $W(t)$ = ($N(t)$, $M(t)$) is a transitory homogeneous Markov chain for the MAXS and fixed transmission strategies, while it is a transitory non-homogeneous Markov chain for the adaptive case. $N(t)$ is the number of sensor nodes remaining to transmit their control packet and $M(t)$ is the number of actual transmissions at time t. The chain goes from state (n,m) to state (k,l) with probability $\Pi_{nm\rightarrow k}$ (called Π below). Specifically, the initial state is $W(t)$=(N,0) which means that the cluster formation begins with the N nodes that sensed the event and at the beginning of the first time slot there are no transmissions. For any state (n,1), n>0, the system goes to state (n–1,m) in case that only one transmission occured in the time slot. Hence, one node experiences a successful transmission. For the case where the system is in state (n,m), $m\neq 1$ the system remains with n nodes either because there were no transmissions, or because there were multiple transmissions leading to a collision in the slot. For the state (0,0), the system has finished the cluster formation phase and the steady stat phase can initiate. Note that state (0,0) corresponds to a trapped state and corresponds to the case where all nodes have succesfully transmitted their control packet and the cluster formation phase is finished. Hence, as a main contribution of this paper, we have developed the possible transitions and their respective probabilities and are described in (1):

$$\Pi=\begin{cases} 0 & k=m-1, n\neq 1; k>m, k<(m-1) \\ \dfrac{k!}{l!(k-l!)}\tau^{l}(1-\tau)^{(k-l)} & k=m, n\neq 1; k=m-1, n=1 \\ 1 & m,n,l=0, k=0 \end{cases} \tag{1}$$

The aforementioned Markov chain has been simulated for 1000000 events. Remember that each event corresponds to the case where the N sensors become active until all the involved sensors have successfully transmitted their control packet. For the case of the more detailed model, a network simulator was developed in C++. In this model, a total number of N_T sensor nodes are uniformly distributed in an area between the coordinate points (0,0) and (100,100) meters. The sink node is situated outside of the supervised area at the coordinate (50,175) as in [3]. All sensor nodes have the same amount of initial energy (2 J). Each sensor node remains in sleep mode until it senses an event. In this case, it wakes up and takes part in the formation of the cluster with the rest of nodes that sense the event. After the cluster is formed, each node senses its area and transmits T_{dur} packets containing the produced data information to the sink node using a TDMA protocol. The event can be sensed by all the sensors that are in the sensing range, which corresponds to a circle with a radius of C=20 meters that will be referred as *event area*. Whenever an event occurs, all sensor nodes within the event area attempt a control packet transmission with probability τ. The first sensor that successfully transmits this control packet is selected as the CH, and the rest of the nodes become Cluster Members (CMs). The nodes can use power control to vary the amount of transmit power. The data packet size l (280 bits) comprises the data (256 bits), the length of the identification field, *Id* (16 bits), and the *Len* field (8 bits) to specify the length of the payload data. The control packet size only comprises the *Id* field. The energy consumed to transmit a packet depends on both the length of the packet, l, and the distance between the transmitter and receiver nodes, d. Namely, $E_{tx}(l,d)=lE_{elec}+l\varepsilon d^{\alpha}$ as it is considered in [3], where E_{elec} is the electronics energy, α=2 and $\varepsilon=\varepsilon_{fs}$ when $d<d_0$, and α=4, $\varepsilon=\varepsilon_{mp}$ when $d\geq d_0$, d0=20 meters. The energy consumed at the reception of the packet is calculated according to $E_{\gamma x}(l)=lE_{elec}$. For both the simulation model and the analytical model, the network starts with N active nodes. Note that for the simulation model N depends on the network density, N_T and the event sensing area, C. Hence, the initial number of active nodes is not constant as in the analytical model. Additionally, for the simulations, whenever the number of nodes that have consumed all the energy of their battery is over 60 percent of N_T, the network is automatically refilled with new sensor nodes in order to have N_T sensors in the network again. This procedure is repeated 1000 times and then the simulation is finished. The rests of the parameters are listed in table 1.

Table 1 Parameters setting

Parameter	*Value*
ε_{fs}	10 pJ/bit/m^2
ε_{mp}	0.0013 pJ/bit/m^4
E_{elec}	50 nJ/bit
Idle power	13.5 mW
Sleep power	15 μW
Initial energy per node	2 J
Transmission bit rate	40 kbs
T_{dur}	10 packets

The Slotted Non Persistent Carrier Sense Medium Access (NP-CSMA) protocol is selected by random access protocol, mainly because its intrinsic capacity of continuously listening to the channel. Therefore, sensors can infer if there was a successful transmission, a collision or an empty slot. Other protocols, such as the ALOHA based protocols do not have this capacity. As such, a fixed retransmission probability has to be used in such protocols which entails higher energy consumption. On the other hand, CSMA/CA (Carrier Sense Medium Access with Collission Avoidance) entails a higher energy consumption due to the additional listening procedure as proved in [2]. Under the NP-CSMA protocol, a sensor node listens to the medium before transmission. If the medium is sensed idle, the node starts transmission. Otherwise, the node draws a random waiting time (backoff period) before attempting to transmit again. Whenever a collision occurs, sensor nodes must retransmit their packet according to the Geometric Backoff (GB) policy, i.e., the backoff delay at a node experiencing collisions is geometrically distributed with probability τ.

Transmission Probability Strategies

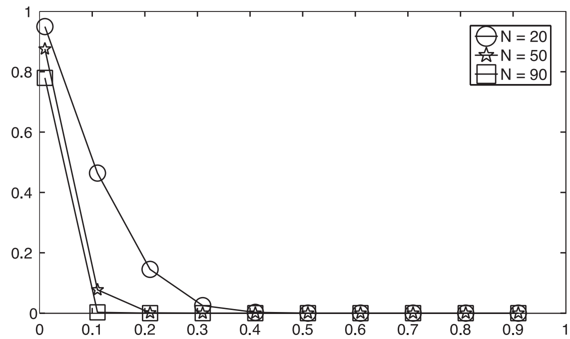
The success transmission probability, energy consumptions per event and event reporting latency are considered for the system performance metrics. Let us first focus on the MAXS scheme. The success transmission probability when there are i nodes remaining to transmit their control packet can be calculated as $P_{succ}(i)=i\tau(1-\tau)^{i-1}$, i.e., only one node transmits while the rest of the nodes remains silent. From this, it is straightforward to find the value of τ that maximizes this probability as $\tau = 1/i$. The main problem of using this strategy is that in a practical system, it is very difficult to know the exact number of nodes that sensed the event, which is the number of nodes that contend for the use of the channel in the following time slot. In other words, it is difficult to know the value of i in order to adjust the value of τ.

In consequence, a fixed transmission value of τ is proposed. In the fixed transmission strategy, all sensor nodes transmit with a constant invariant value of τ. As such, the practical implementation of this strategy is straightforward. However, the use of a constant value does not render the best system performance beacuse, in the cluster formation phase, the number of nodes competing for the shared channel varies in time.

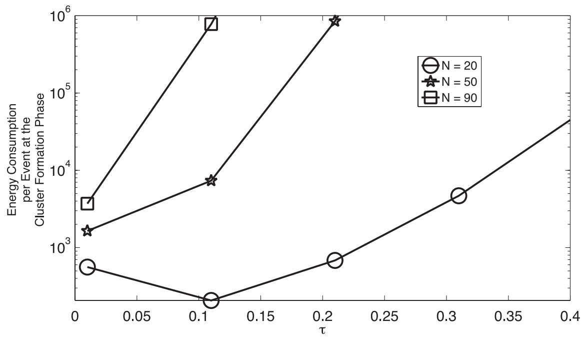
In view of the poor performance of the fixed transmission strategy, a third strategy is proposed. The adaptive transmission strategy constantly changes the value of τ according to the outcome of the last time slot. In case that a collission is detected, the transmission probability is decreased by a factor of γ. In case that an empty slot is detected in the last time slot, the transmission probability is increased by the same factor. Finally, in case of a succesful transmission, the value of τ is unchanged. As it can be seen in the numerical results, this strategy provides high performance but at a higher complexity cost. Note that the parameter γ is a multiplicative factor only that must be carefully selected according to the system conditions. This value establishes how fast or slow the adaptive strategy modifies the value of the transmission porbability, according to the outcome of the previous slot. For high values of γ, the value of τ, is greatly increased or decreased in case of an idle or collisioned slot respectively. This could be well suited in a WSN with a small number of nodes. However, if the number of nodes in the system is high, such abrupt changes in the transmission probability may cause performance degradation in the system. More on the adequate value of γ is discussed later in the paper.

Numerical results

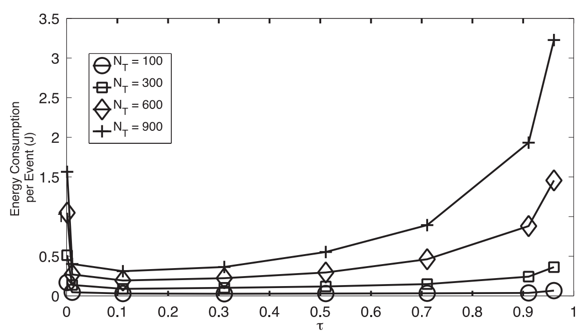
For the simplified analytical model, it can be seen in fig. 1 (a)-(b) that the performance of the system is very sensitive to the number of active nodes. Recall that the normalized energy consumption in the analytical model corresponds to the energy required to transmit a control packet. As such, energy consumption is measured in energy units.



(a) Success Probability, Markov Model



(b) Normalized Energy Consumption (Energy Units), Markov Model



(c) Energy consumption (J), Simulation

Figure 1 Fixed transmission probability performance: a) Success Probability (analysis), b) Energy Consumption (analysis), and c) Energy Consumption (simulation)

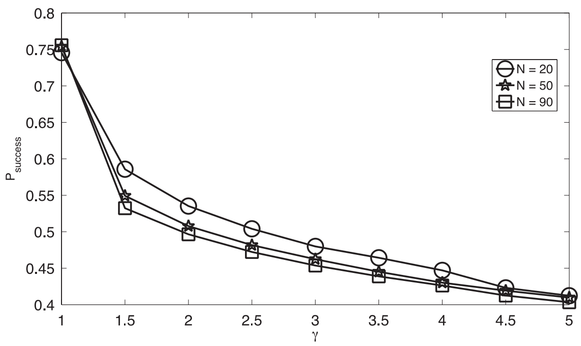
In order to achieve a high success probability, the value of τ should be small. However, this does not guarantee a low energy consumption. For instance, by observing the case where the number of active nodes is relatively small (N=20), a low value of τ causes higher energy consumption. The rationale behind this is that the nodes spend a lot of time in the reception mode consuming unnecessary energy. For the case of high network densities, the same value of τ that minimizes the energy consumption in the low network density environment, produces high energy consumptions due to a higher probability of collision. In fig. 1 (c), it can be seen that the energy consumption for the complete network model follows the curves of the analytical model for small values of N. Remember that in the simulation model, N_T represents the total network density, while in the analytical model only the active nodes are considered. Note that for any network density considered in these experiments, a suitable value of τ is never higher than 0.4.

In conventional wireless networks, such as cellular systems or Wireless Local Area Networks, a low value of τ could be used since a high successful transmission probability ensures a better channel utilization. However, in WSNs, the main performance parameter is the energy consumption, because it is difficult or impossible to replace the node battery once it consumes its energy. Therefore, for a fixed transmission probability strategy, the value of τ should be very carefully selected. Additionally, since any change in the network's parameters has a high impact on the performance of the system, the effect of nodes that deplete their energy or the aggregation of new nodes would impact negatively the network, leading to higher energy consumption levels.

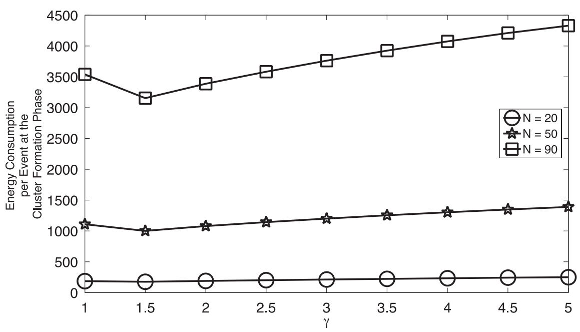
As described above, the initial value of the transmission probability of the adaptive scheme is not relevant since the nodes constantly adapt the value of τ according to the outcome of the last slot. Specifically, whenever a collision occurs, all active nodes decrease the value of τ by a factor γ. Whenever a free time slot is sensed, all active nodes increase the value of τ by the same factor.

However, if there is a successful transmission, the value of τ remains unchanged. As such, the initial value is selected as τ=1/N.

From fig. 2, it can be seen that the value of γ that renders a high success transmission probability is not the same value for which the energy consumption is the lowest. From the experiments performed in this environment, an appropriate value of γ is 1.5.



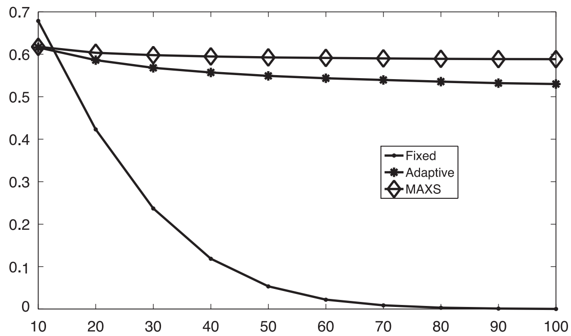
(a) Success Probability



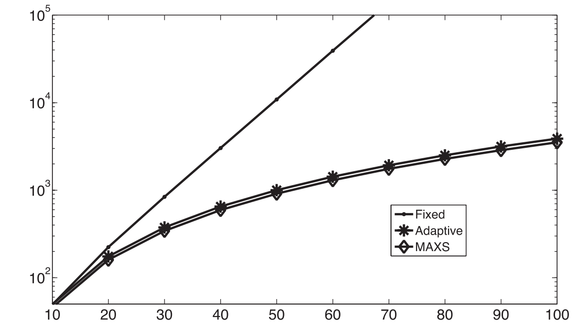
(b) Normalized Energy Consumption (Energy Units)

Figure 2 Adaptive transmission probability with factor γ, Markov Model, a) Success Probability, b) Energy Consumption

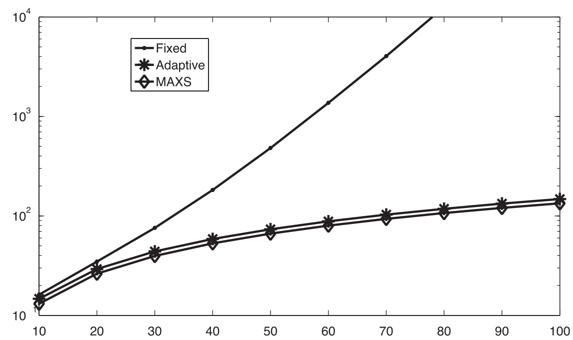
In fig. 3, the three different transmission probability schemes are compared. In these experiments, τ = 0.12 for the fixed retransmission strategy and γ = 1.5 for the adaptive scheme.



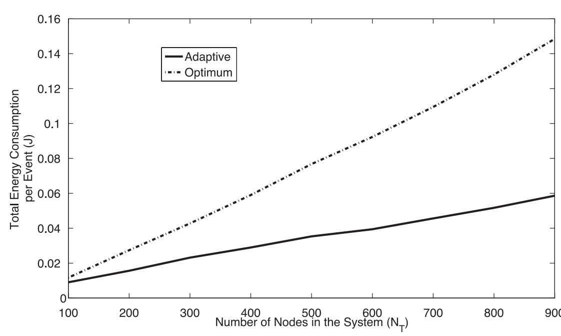
(a) Success Probability, Markov Model



(b) Normalized Energy Consumption (Energy Units), Markov Model



(c) Cluster Formation Latency (Time Slots), Markov Model



(d) Energy Consumption (J), Simulation

Figure 3 Comparison of transmission probabilities, Markov Model

For the success transmission probability, it can be seen that the fixed retransmission scheme has the worst performance, except for very low network densities. The MAXS transmission scheme has the best performance. However, the adaptive mechanism achieves very close results. For the energy consumption and cluster latency the same comments are true. Finally, in fig.3 (d), the adaptive and MAXS strategies are compared for the complete model. Since the fixed transmission probailitiy scheme has the greatest energy consumption in the cluster formation phase, it also has the highest total energy consumption. Additionally, the fixed transmission strategy also entails the longest cluster formation time. As such, the simulation time is also extremly high. For these reasons, we do not present results for this strategy in fig. 3 (d). Note that the adaptive scheme achieves a lower energy consumption than the MAXS scheme. This can be explained as follows: in the simulation model, the nodes in the system do not have the exact value of the initial active nodes. Therefore, when the actual initial number of active nodes is higher or lower than the average value of N, the transmission probability causes either many empty slots or a high number of collisions. This is because, a sufficiently low value is chosen for the case where N=10. However, as the number of initial active nodes increases, this value of τ causes the collision probability to rapidly increase, wasting high amounts of energy in the network.

Continuing the comparison between the transmission strategies, it is worth noting that even if the fixed strategy achieves the worst results in terms on energy consumption and cluster formation latency, it is the simplest strategy to implement. Indeed, the value of τ can be selected even before network deployment and it remains constant for the complete system lifetime. Conversely, the adaptive strategy requires more processsing operations since the value of τ is constantly changed according to the outcome of the previous time slot. However, the performance of the system is much better than for the fixed transmission strategy. Finally, the MAXS strategy corresponds to the ideal strategy but it cannot be implemented in a practical system, since it requires the exact value of nodes attempting a transmission in a given time slot. This value cannot be known since in a wireless channel, effects of noise, interference and propagation losses prevent the exact knowledge on the number of nodes that have transmitted previously. It is important to mention that this strategy could be implemented using an estimation technique such as the ones presented in [14, 15].In a more detailed analysis on the low performance of the fixed strategy, the disadvantage of using a constant transmission probability is that the number of nodes attempting a transmission is constantly decreasing with every successful transmission. For instance, consider the value of a fixed transmission probability. We can see in fig. 1(c) that a suitable value for τ is close to 0.1 when N=90. Meanwhile, when many nodes have finished their transmission of the reports to the sink, say for example 5 remaining nodes, a suitable value of τ would be much higher than 0.1. Since in this strategy the fixed transmission probability is kept constant at 0.1 during the complete cluster formation phase, this value of τ would cause a higher energy drain due to the idle listening proccess at the end of the cluster formation phase. On the other hand, if a higher value of τ = 0.4 where to be used, the number of collisions at the beginning of the cluster formation would be extremely harmful to the system due to the high collision probability.From the results presented above, it is clear that the selection of the transmission probability has a major impact on the performance of clustered based WSNs in terms of both energy consumption and latency. It is important to mention that this issue is also relevant in other networks where random access protocols are used, such as the IEEE 802.11 networks under the CSMA/CA protocol. However, in the WSNs context, the impact of the transmission probability strategy is higher since the number of nodes is a decreasing function of time; while in the case of a wireles local area network (WLAN), the number of nodes attempting a transmission remains constant in average during long periods of time. As such, a fixed transmission probability in a relatively invariant environment does not have the same effect as in the cluster formation pahse in WSNs. This is clearly shown in fig. 3, where the fixed transmission strategy has the worst performance. Also in fig. 3, it is clear that a transmission probability that constantly changes its value is more adequate in these environments. Specifically, a transmission probability with a low initial value at the beginning of the cluster formation phase and a high value towards the end. As a final remark, it is important to mention that different transmission strategies have been proposed in the literature, such as [16], where the transmission probability is a function on the residual energy of nodes. However, this strategy is aimed at very specific cases of WSNs and cannot be used for a general pourpose system. While the strategies studied in this work can be applied to any WSN.

Conclusion

In this paper, three different transmission probabilities are studied for cluster-based event dirven WSNs. From the numerical results, it can be seen that the MAXS and adaptive strategies achieve very close results and they offer a very low energy consumption per event compared to the fixed strategy. The difference between these strategies is that the adaptive mechanism is much easier to implement while the MAXS strategy would require more complex operations to detect the actual number of nodes attempting to transmit. Nonetheless, the complexity of applying the adaptive strategy is that the sensor nodes have to be constantly readjusting the transmission probability after each sensors' transmission. A fixed transmission strategy achieves high energy consumptions due to its inability to adapt to the highly variant system's conditions.

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