Transmission Probability Strategies for Cluster-based Event-Driven Wireless Sensor Networks

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***Abstract*—In the literature, it is common to consider that sensor nodes in a clustered-based event-driven Wireless Sensor Network (WSN) use a Carrier Sense Multiple Access (CSMA) protocol with a fixed transmission probability to control data transmission. However, due to the highly variable environment in these networks, a fixed transmission probability may lead to extra energy consumption. In view of this, three different transmission probability strategies for event-driven WSNs are studied: optimal, fixed and adaptive. As expected, the optimum strategy achieves the best results in terms of energy consumption but its implementation in a practical system is not feasible. The commonly used fixed transmission strategy is the simplest but does not adapt to changes in the system's conditions and achieves the worst performance. In the paper, we find that the adaptive transmission strategy, pretty easy to implement, achieves results very close to the optimal one. The three strategies are analyzed in terms of energy consumption, and cluster formation latency.**

***Index Terms*— Transmission probability, clustering, event-driven WSNs.**

I. 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 sensors within the event area. 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 paper, a clustered-based architecture is considered partly based on the encouraging results presented in previous works, such as [2], [3]. In a cluster-based architecture, there are two distinct phases:

1) **Cluster formation phase**, where all the active nodes (the nodes that detect the event) transmit a control packet among each other and the sink node in order to be part of the event cluster. Specifically, when the event is detected, the nodes inside the event area transmit their control packet with probability τ in each time slot. If there is only one transmission, that is, only one node transmits, the control packet is successfully received by the sink node and the node that successfully transmitted this packet is considered to be already a member of the cluster. As such, this node no longer transmits in the cluster formation phase. The remaining nodes continue this process until all the active nodes successfully transmit their control packet. If there are two or more transmissions in the same time slot, all transmissions are considered to be corrupted and the control packets involved in this collision have to be retransmitted in future time slots. Hence, when a collision occurs, non of the involved nodes is aggregated to the cluster.
2) **Steady state phase**, where all the nodes in the event cluster transmit their data packets to the Cluster Head, which in turn transmits the aggregated data packet to the sink node.

In the cluster formation phase, the active nodes transmit using a random access protocol where the channel is shared among all nodes and hence, as stated before, collisions are possible. In this work, the slotted NP-CSMA scheme is considered due to its superior performance compared to other variations of the CSMA protocol for WSN applications [2]. On the other hand, in steady state, the Cluster Head assigns resources by clarifying which sensor nodes should utilize the channel at any time through a Time Division Multiple Access (TDMA) protocol, thus ensuring a collision-free access to the shared data channel. One important characteristic of this phase is that only the transmitting node is awake while the rest of the nodes enter the sleep mode in order to save energy. For reasons of clarity, the packets used to form the clusters are referred to *control packets* while the packets used in the TDMA scheme will be referred to as *data packets*.

The main contribution of this work is to provide general guidelines on the selection of the transmission probability in the cluster formation phase on event-driven clustered WSNs. This issue has been largely neglected in the literature [8]. For simplicity, most previous works consider a fixed value of the transmission probability which is selected independently of the network density [4], [6]. This entails a considerable energy wastage as it is shown in the following sections. Previous works on event-driven WSNs attempt to reduce the collision probability by reducing the number of active nodes. For example, [9] 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 [10] is to use multiple paths in order to reduce the collision probability. Yet another recent approach for reducing energy consumption in WSNs aims at using game theory to achieve an adequate performance, such as the works reported in [11]. However, non of these works propose a suitable value of the transmission probability of the messages. As such, three different strategies for selecting the transmission probability in the cluster formation phase are studied here:

- **Optimal transmission probability**. For this strategy, the transmission probability that maximizes the success transmission probability is used. This requires that all nodes in the event area must be aware of the number of nodes that remain to transmit their control packet. In other words, all nodes in the event area have to know the exact number of nodes that can potentially transmit in the next time slot. In a practical system, this is not feasible because there is no simple way to know the exact number of nodes inside the event area since it is usually not fixed. Moreover, in many cases the nodes are randomly deployed through the network. However, one way to implement it practically is to estimate the number of nodes inside the event area by any means, if this is possible. Therefore, the average number of nodes inside the event area is considered for the simulations of the system presented in Section II.

- **Fixed transmission probability**. In this scheme a suitable value for the transmission probability is selected and remains unchanged during the operation of the system. As opposed to the optimal strategy, this scheme is very simple and easy to implement in a practical system. However, the selection of the value of the transmission probability is not straightforward and it has a major impact on the performance of the system. This is because for high node's densities, the transmission probability should be small in order to avoid a high number of collisions and for low densities, the transmission probability should be high in order to avoid long idle listening periods (that is, periods where there are no transmissions and the nodes have to continually listen to the channel). As such, once the transmission probability is appropriately selected for some particular conditions, the fixed transmission probability has a fair performance. The main problem with this strategy is that in WSN's, the system's conditions are highly variable due to the death of nodes (nodes that consume all their battery's power or are destroyed in the normal system operation) and to the aggregation of new nodes to the system. As such, when the number of nodes in the network changes, the performance of the system is degraded.
- **Adaptive strategy**. In this scheme, 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. In order to simplify the procedure and its tuning, the increment and decrement of the transmission probability is done according to a factor γ that has to be carefully selected. The performances achieved by this strategy are pretty close to those of the optimal one. It also has the advantage of constantly adapting to the conditions of the system. Hence, the death or aggregation of nodes has no important impact on the operation of the network. Finally, its practical implementation is easy since the nodes only have to distinguish between a successful, collided or idle time slot which is commonly used in previous works such as [7]. It is important to notice that this scheme does not only adapt to different node's densities but it also adapts throughout the cluster formation procedure. Indeed, as the cluster begins to form after the detection of the event, the initial number of nodes is relatively high while at the end of the cluster formation phase, the number of nodes that can transmit is very low. Therefore, the transmission probability at the beginning of the cluster formation phase should be relatively small while at the end of the cluster formation, the value of τ should be close to 1. This behavior is close to that of the optimal strategy but with the advantage that there is no need to know the number of remaining nodes to transmit their control packets.

A complete system simulation has been developed in order to compare these strategies considering both the cluster formation and steady phases for different parameter values. The transmission strategies are studied in terms of energy consumption, and cluster formation latency. The rest of the paper is organized as follows. Section II describes in detail the simulation models to study the complete WSN. Section III presents some relevant numerical results. The article concludes with a summary of conclusions and contributions.

II. Simulation 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 [4]. At the beginning of the simulation, all nodes have the same energy level. Each sensor node remains in the sleep mode until it senses an event. In this case, it wakes up, takes part in the formation of the cluster with the rest of the 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_a meters and is called the *event area*. C_a is considered to be an exponentially distributed random variable with mean 20 meters. Whenever an event occurs, all sensor nodes within the event area attempt to transmit a control packet with probability τ. The first sensor that successfully transmit 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 as it is considered in [4]. Namely,

$$E_t(l,d) = \begin{cases} \ell E_{\text{elec}} + \ell \varepsilon_{\text{fs}} d^2, & \text{if } d < d_0 \\ \ell E_{\text{elec}} + \ell \varepsilon_{\text{mp}} d^4, & \text{if } d \geq d_0 \end{cases} \tag{1}$$

where E_{elec} is the electronics energy, $\varepsilon_{\text{fs}} \times d^2$ or $\varepsilon_{\text{mp}} \times d^4$ are the amplifier energies that depends on the distance to the receiver, and d_0 is a distance threshold between the transmitter and the receiver over which the multipath fading channel model is used (i.e., d^4 power loss), otherwise the free space model (i.e., d^2 power loss) is considered. The energy consumed at the reception of the packet is calculated according to $E_r(\ell) = \ell E_{\text{elec}}$. 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_a. Hence, the initial number of active nodes is not constant. Additionally, whenever the number of nodes that have deployed all its energy 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 1x10^6 times and then the simulation is finished.

The Non Persistent Carrier Sense Medium Access (NP-CSMA) protocol is selected by means of random access protocol mainly because its intrinsic capacity of continuously listening to the channel. 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.

III. Numerical Evaluation

In this section, the different transmission probability strategies are numerically studied and compared. The parameters used in these numerical evaluations are as follows: $\varepsilon_{\text{fs}} = 10$ pJ/bit/m^2, $\varepsilon_{\text{mp}} = 0.0013$ pJ/bit/m^4, $E_{\text{elec}} = 50$ 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. Also: total nodes in the system N_T, event area C_a (meters) and event duration T_{dur} (reports per active node). The default values considered in these experiments are $C_a = 20$ meters, $N_T = 500$ nodes in the system and $T_{dur} = 20$ reports per active nodes unless specifically stated otherwise. This set of simulations considers a realistic energy consumption model that depends on the distance between the nodes and the length of the packets. Specifically, when the nodes are communicating among each other, the concerned nodes use a low power transmission. On the other hand, when the CH communicates with the sink node, it uses a higher power level transmission. For the case of the packet length, in the cluster formation phase, nodes transmit a very small control packet that is formed only by the *Id* field. Conversely, in the steady phase, the nodes transmit the complete packet.

In Fig. 1 the fixed transmission strategy performance is shown. It is clear that the simple model observations can be applied to the complete model. Specifically, for small network densities, a relatively high transmission probability renders the lowest energy consumption and cluster formation delay due to the low collision probability. On the other hand, a small transmission probability is better suited for high network densities. Note that as the event area increases, the number of active nodes per event also increases. Hence, for an environment where the monitored event has a highly variable coverage area, a fixed transmission probability leads to excessive energy drain. Another interesting observation is that, as expected, the cluster formation latency is independent of the event duration. Meanwhile the energy consumption per event increases as the event duration increases.

In Fig. 2 the numerical results for the optimum strategy is presented. Remember that for this strategy, the initial value of τ is 1/(*Average # of nodes inside the event area*). Even if the initial value of τ is an approximation that degrades the system performance, this strategy still achieves the best results in terms of energy consumption and cluster formation latency as it will be discussed in detail later in this section. Similar observations can be made for the adaptive strategy results presented in Fig. 3. Indeed, in this strategy, the initial value of τ is also 1/(*Average nodes inside the event area*). As such, the initial value of the transmission probability may not be adequate in case of many death of nodes or aggregation of new nodes. However, this scheme continuously adjusts the value of τ in such a way as

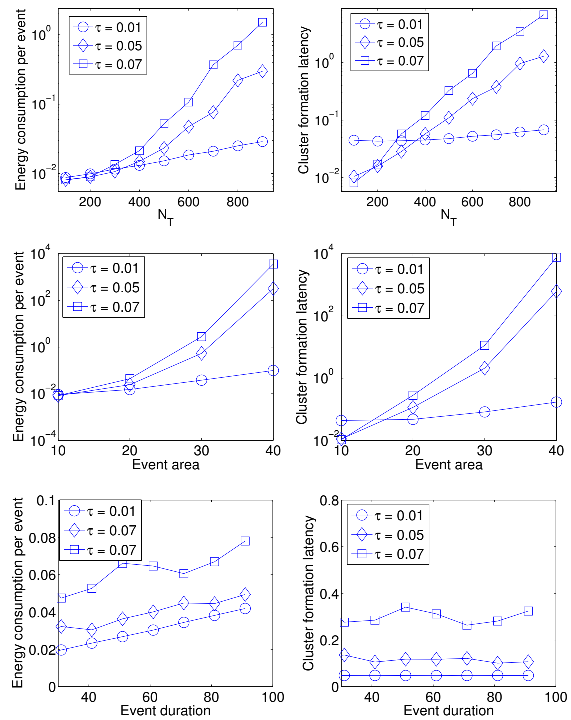

Fig. 1. Simulation results for fixed strategy

to achieve a good system's performance. From these results we can also see that, as the analytical results showed, a low value of γ renders a better system's performance.

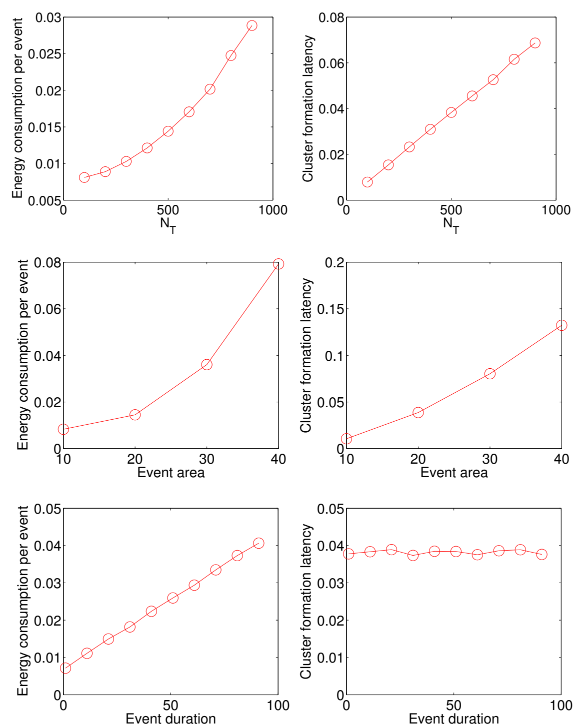

Fig. 2. Simulation results for optimum strategy

From the previous results, it is clear that the selection of the parameters in the random access protocol used in the cluster formation phase is very important. This issue has been largely overlooked in the literature. Observe for instance the energy consumption in Fig. 1. As the event duration increases from

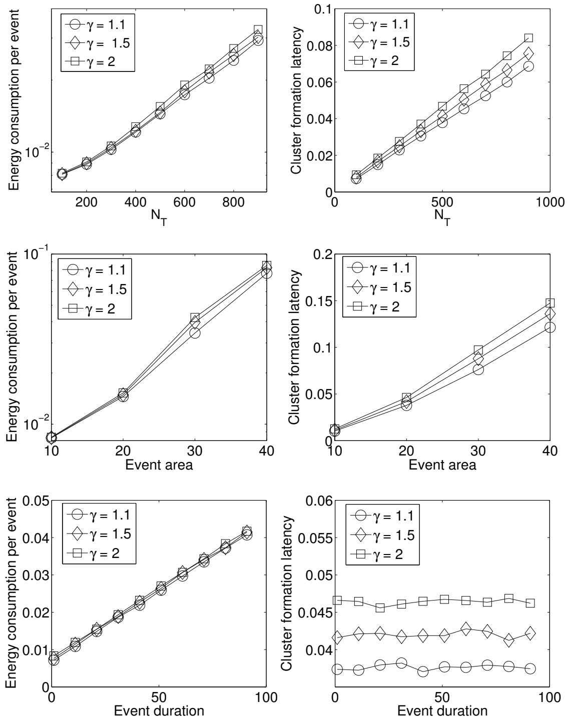

Fig. 3. Simulation results for adaptive strategy

20 to 95 reports per node, the energy consumption is increased form 0.02 to 0.04 J when $\tau = 0.01$. This increment is due to the energy consumption in the steady state since the energy consumed in the cluster formation is not affected by the event duration. Conversely, fixing $N_T = 600$ for different values of τ, i.e., leaving the energy consumption at the steady state phase fixed, the energy consumption goes from 0.02 J using $\tau = 0.01$ to 0.1 J for $\tau = 0.07$. Therefore, a mild variation of the value of τ has a greater impact on the system's performance than the number of reports per active node. As such, the value of the transmission probability has to be carefully selected in order to obtain an acceptable system's performance.

In Fig. 4 we present a comparison of the simulation results for the three transmission strategies. As expected, the fixed strategy with $\tau = 0.001$ has the worst performance specially for low network densities while it has a better performance for high network densities. This is due to the energy wastage of the idle listening of nodes in the cluster formation phase. Conversely, analytical and simulation results show that a higher value of τ achieves better results for low densities while it increments the energy wastage for high densities due to the excessive number of collisions. This figure also shows that the adaptive and optimum strategies produce very similar results. Note that in this model, the optimum strategy no longer produces better results than the rest of the strategies as in the simplified model. Furthermore, for certain values of N_T, the adaptive strategy is slightly better. For example, when $N_T = 900$, the cluster formation latency and energy consumption is lower for the adaptive strategy when $\gamma = 1.1$. The rationale behind these results is that the optimum strategy considers only a rough estimation of the number of active nodes. In a real system, this value is constantly changing and the optimum strategy does not consider this variation into the calculation of τ. On the other hand, the adaptive strategy is able to adapt the value of the transmission probability even if the initial value of τ is not well adjusted.

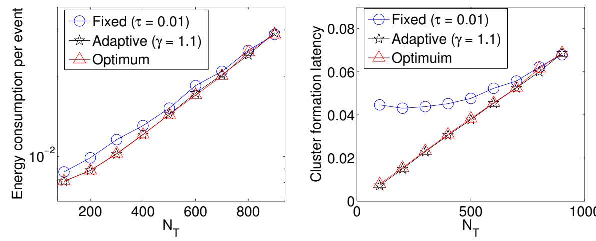

Fig. 4. Comparison of simulation results for different transmission strategies

IV. Conclusion

This work has focused on the study of three transmission probability schemes for clustered-based WSNs. The resulting event driven WSN has been simulated, and studied. The system is analyzed in terms of the energy consumption, and cluster formation latency. A complete model that considers the death and aggregation of nodes in the network is simulated. An analytical model is also proposed, with results consistent with the simulation ones (not enough room to provide details here). From the results derived in this work, it can be seen that a fixed transmission probability is easy to implement in a practical system. However it has the worst performance. The optimum strategy achieves the best results, as expected, but its implementation is not feasible. The use of an adaptive transmission strategy achieves a performance close to the optimum scheme and its practical implementation is possible.

Further work should include other parameters in the study such as the traffic intensity, the link quality, etc.

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