Packets delivery approach in a clustered Linear Sensor Network using a probabilistic capture model

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ABSTRACT. A wireless sensor network (WSN) consists of a large number of sensor nodes deployed in a fixed or random manner over a wide area, for example for environmental monitoring applications. The sensor nodes communicate through radio links and are usually powered by batteries. In most cases, the information produced by the sensors is assigned to a base station called sink node. In the case of monitored infrastructure such as roads, tunnels, pipelines or rails, the sensor nodes are often deployed linearly. This type of network is called linear sensor network (LSN). In such a network, the data frames are carried from node to node until to reach a sink. One of the major challenges faced in linear sensor networks is to perform a good policy of radio communication interference management that takes into account the environment change and the activity of the nodes. This requires a control of propagation conditions, nodes equipped with an efficient data frame reception unit and a MAC protocol taking advantage of the linearity of the topology.

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KEYWORDS: WSN, LSN, Interferences, Clustering, MAC protocol, Delivery ratio, capture model.

1. Introduction

Linear Sensor Networks [1] [2] can be found in many monitoring applications, such as underground environments monitoring [3], road track or railway monitoring[4] [5], border monitoring [6], Oil and Gas[7], or even water pipeline monitoring[8], etc.

The management of radio interference is a standard problem in WSNs, because it allows reduction of the waste of energy caused by unsuccessful transmissions. Nodes of LSNs are characterized, in particular, by limited neighborhood, and often stretch over long distances. One of the major specific challenges faced with this type of network is the management of interferences induced by the nodes activity over the line. Indeed, according to the MAC protocol, the interferences decrease significantly the network performance such as the delivery rate, throughput and the end-to-end delay.

The purpose of this paper is to control the high interactions between the particularities of a linear sensor network deployed in an environment whose propagation conditions are adequately represented by a Log-normal Shadowing model and exploiting a token-based MAC protocol for the transmission channel access. This involves especially evaluating the minimal distance between two nodes which are token holders in order to avoid interferences according to a new probabilistic capture model. So, the impact of interferences on the network performances is evaluated in terms of probability reception at a given node.

The remainder of this paper is organized as follows. Section II presents a state of the art about the general ambitions of the paper, while the main objectives of this paper are detailed in Section III. Section IV describes the capture model used in this work and is followed by the analytical study in section V. The paper ends by section VI with conclusions and perspectives.

2. State of the art

In the literature, the ways the clusters are established or their establishment algorithms vary according to the desired objectives. Thus, one can find that some clustering algorithms are based on specific sensor node characteristics, such as the range [9] or residual energy[10] of the nodes to establish the cluster grouping process. This smooths out the challenge of proximity when range is the issue, and increases the lifespan of the network when considering residual energy. Other algorithms instead take into account characteristics specific of the network, such as support for sensor mobility using more dynamic approaches to sensor-cluster belonging [11]. The support of a degree of redundancy in terms of the number of sensors deployed to capture identical phenomena across groups, allowing the aggregation or fusion of data [12] is another way of clustering. This type of clustering approach consists of taking advantage of the way sensor nodes are deployed by exploiting the topology of the WSN.

Some new researches focus on partitioning, deployment, and clustering techniques on LSN to improve certain performance metrics. Indeed, in [13], the authors proposed a technique for deploying nodes based on an anchor node. This allows the other nodes of the network to synchronize and calculate their coordinates by using many iterations. Another technique of deployment in order to improve the network life time is presented in [14]. This technique is based on a virtual node concept as defined in the networks. In addition, this technique takes into account the reception messages cost in term of energy, while the related work only accounts for message transmissions. A clustering approach for deployment is proposed in [15]. This technique divides the network into clusters of equal members. Each cluster head communicates directly with its neighbor cluster head. All these techniques focus on the network life time but do not take into account of QoS required. Nevertheless, it is very important to improve the QoS as delivery ratio, throughput and end-to-end delay. Recent research works have focused on clustering in linear networks, but do not well address propagation interference conditions. Indeed, in [16], the authors proposed a method of clustering LSNs, but with deterministic propagation conditions[17]. Consequently, the length of radio links in such a topology is constant and uniform along the entire line. The cluster size was therefore found to not take into account random propagation conditions in the actual environment being considered.

3. Objectives of the study

Let's assume that exchanges between two nodes N_i and N_{i+1} where N_i is the transmitter and N_{i+1} the receiver node. Suppose the radio propagation conditions between receivers and transmitters generate a received power dispersion modeled by a Gaussian distribution [17]. So that all frames have a chance to be received, it is necessary that all components of this distribution in terms of reception power are higher than the sensitivity threshold. This choice has two consequences:

- It requires a transmission power always exceeding the minimum transmission power required according to the sensitivity threshold, which consumes energy,
- Interferences generated by the part of the distribution at the right of the threshold are higher. These interferences depend on many factors as path loss, distance, antenna gain, etc.

In such case, the transmission power necessarily used by N_i, is calculated according to a compromise based on the efficiency of the radio link N_i - N_{i+1}, which is expressed by a percentage of the number of frames received by N_{i+1} beyond the sensitivity threshold, relative to the number of frames sent by N_i. This is the principle of the outage probability which is to admit that a certain percentage of frames sent will be received by N_{i+1} with a power below the sensitivity threshold.

Reducing this proportion means increasing the transmission power, causing a shift in the distribution to the right and increases the risk of interference. Frames received with considerable energy (right side of distribution) are those that will generate more interference for N_i and N_{i+1} neighbors. The effects of the interference are dependent on the capacity of the receiver to capture a frame despite the noise.

The major contribution of this paper is the proposal of a calculation method that helps to estimate the number of frames captured according to a probabilistic capture model for a linear sensor network using a token passing access method.

4. The capture model

A linear sensor network consisting of *N* nodes is considered, the node at one end being the sink. A token circulation from node to node is a medium access method that is well adapted to this kind of topology [12] [18]. The energy received being dependent on the geometry of the configuration. In the case of simultaneous activity of multiple transmitters, it is very difficult for a receiver to conclude a collision. It may even be that "he sees only" the signal received with the greatest energy: this is the capture effect [19]. The positive aspect of this phenomenon (capture of a frame despite the collision) is then to be moderated by its inequitable aspect: the farthest transmitters may be hidden.

The model of capture is called binary due to the fact that a frame is captured or not according to the received powers at the receiver from concurrent frames and depends to the SIR (Signal-to-interference ratio [17]) In this case, the conditions of reception for a packet is given for $P_R > P_{threshold}$ by:

- If $SIR \leq SIR_{threshold}$, then the packet is lost
- If $SIR \geq SIR_{threshold}$, then the packet is captured.

Where *SIR* represents the signal-to-interferences ratio and $SIR_{threshold}$ is the threshold. Experiments carried out in [20] [21] have shown that the capture effect is probabilistic rather than binary as announced in the literature. This phenomenon is visible when the useful and interfering signals are close.This observation allows us to recover the formalism introduced for a binary behavior and to refine the approach. The threshold $SIR_{threshold}$ considered above is to be replaced by an interval in which there are capture opportunities and defined by $[SIR_{probathreshold}, SIR_{Guarantedthreshold}]$. $SIR_{probathreshold}$ and $SIR_{Guarantedthreshold}$ respectively represent probabilistic reception threshold and warranty reception threshold. In the case of the probabilistic capture, three segments (intervals) containing the SIR are identified:

- If $SIR \in \left]-\infty, \mathrm{SIR}_{\mathrm{probathreshold}}\right[$, then the frame is lost.
- If $SIR \in [\mathrm{SIR}_{\mathrm{Guarantedthreshold}}, +\infty[$, then the frame is captured.

- If $SIR \in [SIR_{probathreshold}, SIR_{Guarantedthrshold}[$, so the capture probability of the frame is characterized by the capture law $[SIR_{probathreshold}; SIR_{\text{Guarantedthreshold}}[\rightarrow [0,1]$.

The interval of the probabilistic capture is obtained from measurements in [20]. These measurements are performed on three nodes equipped with 802.15.4 physical layer operating in the 2.4 GHz band. These nodes were used in an anechoic chamber to explore the capture conditions. The probabilistic capture interval I $[SIR_{probathreshold}, SIR_{Guarantedthrshold}[$ corresponds to *[-1 dBm, 10dBm]*. This allows us to fix the interval $[i\text{-}SIR_{probathreshold}, i + SIR_{Guarantedthrshold}]$ to evaluate interfering received signals.

5. Analytical study

A simulation made on the NS2 tool which consists of transmitting 10,000 frames at -4.68 dBm gives us the results in Fig. 2., which indicates the distribution of power received by B from A, D, E and F located respectively at 1 hop, 2 hops, 3 hops , 4 hops from B as shown in Fig. 2. The node B is considered as the reference node. In the reference model considered, it is assumed that the nodes use same transmission power. In our study, the reception threshold is set at *90%* which is a reference value in sensor networks. This corresponds to *10%* of Outage probability.

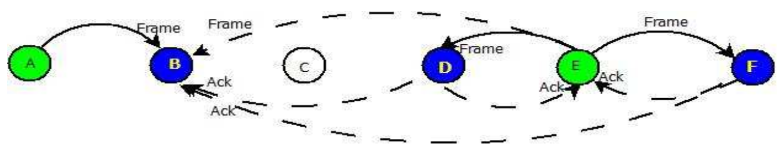

Fig. 1Illustration of the reception at B with interfering nodes

Generally, the number of frames or acknowledgements received at B from N is labelled *CPN*(x_j) . N represents the nodes A, D, E or F and *PRN*(x_j) is the probability associated with such a reception. The simulation results show different distributions of the received power at B from nodes A, D, E and F according to the considered reference model as shown in Fig. 2. These distributions show the Gaussian nature of the propagation model. For 1 hop, the effect of the defined outage probability as *1000* packets are received below the sensitivity threshold is seen to represent *10%* of the total number of transmitted packets.

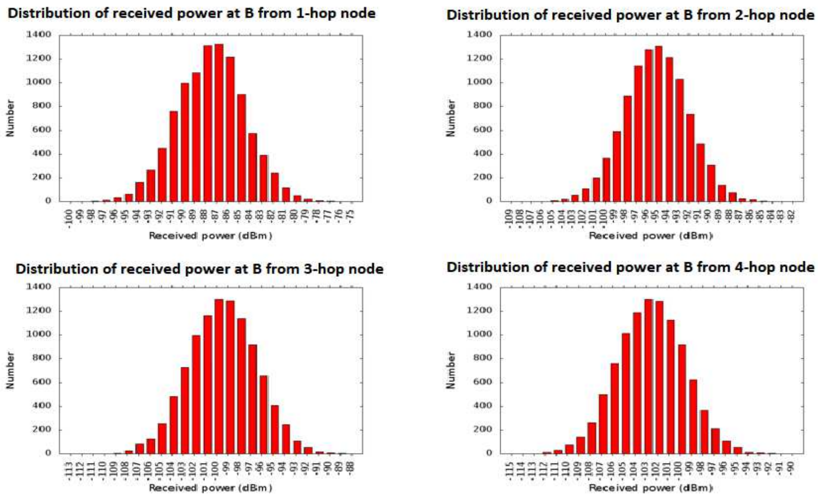

Fig. 2. Distribution of the received power at node B from N-hops nodes

The reception probability at B when D is also token holder is represented in Fig. 3. This corresponds to the exchanges between D and E and between E and F. It increases with the number of hops to node B. So the farthest nodes from B on the linear network create less interference. Indeed, when the interferences in B are created by exchanges between nodes at 2 and 3 hops i.e. acknowledged downlink traffic from E to D, the maximum probability of reception in B is 0.1 (left part). This maximum probability is almost 0.13 in the case of exchanges between nodes at 3 and 4 hops (uplink traffic of E). Note that the maximum probability without interference is 0.13. This probability does not take into account the Outage probability. Therefore, this value shows that the interference is minimal when they are created by the 3 and 4 hops nodes taking into account the Outage probability defined in the simulation parameters.

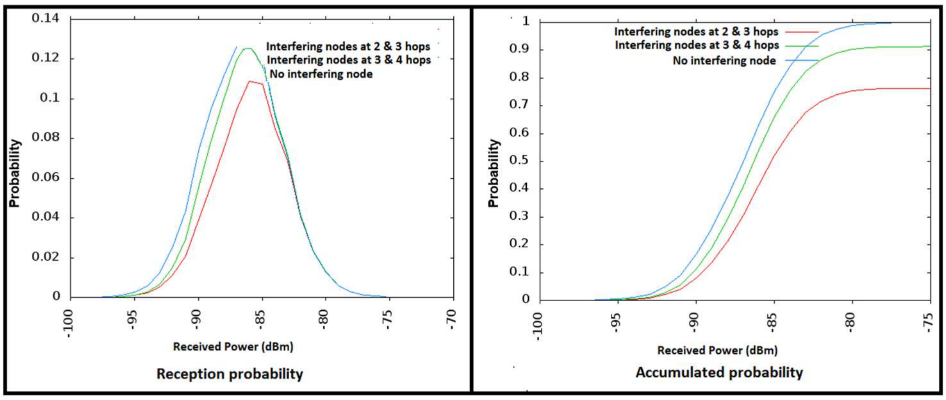

Fig. 3. Reception probability at B in probabilistic capture

The cumulative reception probability at node B can be shown (right part). Thus, one can see that the maximum cumulative probability when the 3 and 4 hops nodes are the sources of interference is 0.9 or 90% of packets received by the node B, while it is 72% when the interferences are created by the 2 and 3 hops nodes.

Considering the defined Outage probability (10%) which justifies this limit at 90%, one can confirm that 3 and 4 hops nodes do not interfere in the reception of packets of node B. Indeed, the accumulated reception probability is equal to 90% corresponding to the percentage of packets above the defined sensitivity threshold. However, the interferences are important when 2 and 3 hops nodes are active. Indeed, there is a total accumulated probability of 76% or 24% of lost packets distributed as follows:

- 10% of packets representing the Outage probability,
- 16% lost by collisions caused by interference created by the 2 and 3 hops nodes.

Exchanges between E and D may correspond to the case of a cluster of 4 and those between E and F to a cluster of 5.

6. Conclusion

This paper proposed a calculation method that allows to estimate the number of frames captured for a linear network according to the assumptions enounced.
This ratio has a significant impact on the capture when the activity of the nodes generates radio interference. Simulations show that probabilistic capture offers significant gain in terms of reception rate for a given cluster size. However, this gain increases when the cluster size increases. This observation leads us to a dilemma because if the cluster is large, the token frequency will be reduced and the capacity of this parallel linear structure also reduced.
In our future works, we plane to focus on the linear LoRa network in order to benefit to the interferences resilience and the ultra-long distance.

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