Optimized TDMA Multi-Frequency Scheduling Access Protocols for Sensor Networks

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Abstract—**In order to eliminate the interferences between neighbors and reduce the delay, with the respect of the real time constraint, we focus our work on the multi-frequency scheduling access protocols. In this paper, we review the most multi-frequency MAC protocols which deploy more than one frequency to transmit data to neighbors. After that, we propose an optimized TDMA multi-frequency scheduling access contribution for sensor networks which is based on three phases. In the first phase, we assign frequencies based on parent node reception in communication tree structure. The reduction of the number of frequencies is provided, in phase two, based on the principle of the graph coloring. Finally, in the last phase, we reduce frequencies to the maximum number of allowed frequencies with TDMA (Time Division) clustering principle.**

Our results are compared with the other works and have showed that our strategy can remove more interference between neighbors, optimize communication delay and adapt with the maximum number of frequencies in WSN (Wireless Sensor Networks).

Keywords-Wireless Sensor Networks; multi-frequency assignment; Time Division Multiple Access; simultaneous transmission; energy efficient.

I. INTRODUCTION

In Wireless Sensor Networks, the energy consumption presents the real critical issue because it is wasted due to collisions, overhearing packets, control packet transmission and idle listening. The collision issue appears when two nodes transmit their data at the same time. In this case, the sender will retransmit the packet again the fact of which implies more power consumption. The *Overhearing packets* occur when a sensor node listens to all transmissions from its neighbors and receives packets which are destined to other nodes. The control packet transmission presents a factor for losing more power because sending, receiving and listening to control packets consumes energy. Finally, the *idle listening* occurs when a node is listening to the channel in order to receive possible data but the cost becomes higher when nothing is sensed and no data is sent during this period [1].

To resolve these problems, clustering has been proposed as a potential solution to address them. In addition, the medium access control protocols, such as x-MAC [7-11] and TDMA (Time Division Multiple Access) have been proposed to help each sensor node to decide when and how to access the medium or channel [9]. The x-MAC protocols are contention-based protocols such as SMAC (Sensor-MAC), PMAC (Pattern-MAC), GMAC (Group MAC), DSMAC (Data-gathering MAC), DMAC (Dynamic MAC) and BMAC (Berkeley MAC). The main idea of these protocols is to organize the sensor nodes in order to send their data in their own slot time without collisions. In addition, they reduce the energy consumption in each sensor node by permuting it from active state into sleep state, when it has no data to send. The major limit of these protocols is that they are not deterministic. However, the aim of the TDMA scheduling protocol is to organize the sensor nodes to send their data in their own slot time without collision [3]. Since TDMA access method is a deterministic one, we can predict easily the communications' delay in order to verify the real time constraints. This is one among the objectives of our contribution.

The principle goal of our strategy is to eliminate the interferences and to have simultaneous transmissions, on multiple-frequencies, between sensor nodes in order to reduce the delay by respecting the real time constraints. To achieve this objective, we mathematically formulate the problem while basing on three phases. These phases help us to resolve the problem of the interferences and the simultaneous transmissions on multi-frequencies. In addition, we adapt the number of frequencies with the maximum value since they are limited in sensor networks.

The rest of this paper is organized as follows. Section 2 presents a synthesis of most of the related works concerning multi-frequency MAC protocols in WSN. Our contribution, being based on formulating the problem, is presented in section 3. In the section 4, we present the analysis of the delay and the number of frequencies. Our performance evaluation is given in section 5. The paper is concluded in section 6.

II. RELATED WORKS

In this section, we describe the most important MAC protocols which deploy multi-frequency and TDMA to transmit data to sink node without interferences. Among these MAC protocols, we present TFMAC, MMSN, HYMAC and MCSFC for wireless sensor networks.

A. TFMAC

TFMAC [4] is the abbreviation of Time Frequency MAC**.** It is a hybrid MAC protocol in which each sensor node is equipped with a single half-duplex transceiver with multiple-frequency support. Its main idea is to allow different sensor nodes to transmit on different channels simultaneously. It divides the time into a fixed number of slot times and allows each node to use different frequencies within different slot times to send data packets to its neighbors. In fact, it should be noted that the number of the slots and frequencies is fixed manually.

In TFMAC, each frame is divided into contention access period and contention-free period “Fig. 1”. In the first period, referred as *control slot*, the control messages are exchanged in order to maintain the protocol. In the second period (contention-free period), the nodes transfer data between them. In addition, this period is divided, in its turn, into N_t equal size of slot times which each slot time is long enough to transmit one or more data packets. The aim of the scheduled transmission in slot times is to avoid collisions. In addition, the TFMAC design is presented from two aspects; frequency assignment and media access. In frequency assignment, the nodes are assigned to the available frequencies for the data reception. While the media access establishes a collision-free media assess schedules, in time and frequency domains, for individual nodes.

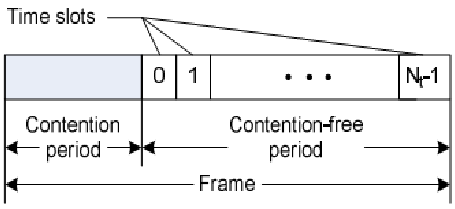

Figure 1. TFMAC Frame structure

The TFMAC strategy is based on the timetables broadcast, which considers that there is N_f frequencies available and only one reception frequency. Its principle is to maintain, at each node, a timetable, which contain an entry (i, t, f), in order to keep current slot time usage information. The slot number is called i, the type slot is t and the index frequency is f. The TFMAC advantage is the synchronization between the transmitter and the receiver which eliminates the interferences. But, it does not fix the maximum number of frequencies which presents an important disadvantage. The simulations results in [4] show that TFMAC provides higher maximum throughput and smaller average packet delay in respect to the basic single-channel TDMA scheme.

B. MMSN

MMSN [2], abbreviated from Multi-frequency Media access control for wireless Sensor Networks, is a multi-frequency MAC protocol which combines CSMA/CA with FDMA. In MMSN protocol, the time is divided into multiple fixed time beacon intervals when the packets are exchanged among nodes, at the beginning of every interval. The packets exchange is doing in order to coordinate the assignment of the appropriate frequencies for use in the subsequent slot times of this beacon interval.

The aim of MMSN protocol is to achieve a parallel transmission among neighboring nodes by using multi-frequency. It provides four frequency assignment schemes in order to meet WSN requirements and each user of MMSN can choose one among these schemes depending on its WSN attributes. The MMSN protocol consists of two aspects: frequency assignment and media access. The frequency assignment is used to assign a physical frequency to each node for data reception which is broadcasted to its neighbors in order to know what frequency to use to transmit data to each of their neighbors. This assignment can be done either at the beginning of the system setup or for adaptation to system aging. The four schemes frequency assignments are exclusive frequency assignment, even selection, eavesdropping and implicit-consensus. The exclusive frequency scheme is deployed when the number of available frequencies is, at least, as large as the node number within two hops, by guaranteeing that nodes within two hops are assigned to a different frequencies. While implicit-consensus requires more physical frequencies by providing the mentioned guarantee, with smaller communication overhead. Even selection and eavesdropping are deployed when the number of available frequencies is smaller than the node number within two hops but they not guarantee the assignment of different frequencies to two hop neighbors. The single difference between these two schemes is that, even selection leads to fewer potential conflicts while eavesdropping is more energy efficient.

In the media access, nodes which are assigned to frequencies coordinate to maximize parallel transmission among neighboring space in this media. In order to provide efficient broadcast support, nodes are time synchronized [6]. A slot time is divided into broadcast contention period (called T_{bc}) and transmission period (called T_{tran}). During the first period, nodes compete for shared unicast frequencies. While during the second period, which provides enough time to transmit or receive a broadcast or unicast data packets, the nodes compete for shared unicast frequencies. The MMSN does not deploy the TDMA access method. In this case, when the number of frequencies is reached, the nodes cannot transmit their data without collision. Through extensive experiments, the simulation results given in [2] show that MMSN exhibits prominent ability to utilize parallel transmission among neighboring nodes. In addition, MMSN achieves an increased energy efficient when multiple physical frequencies are available.

C. HYMAC

HYMAC [5], abbreviated from HYbrid TDMA/FDMA MAC layer protocol for wireless sensor networks which combines TDMA with FDMA. It is a first sensor-net MAC protocol which schedules the network nodes in order to eliminate collisions, principally by taking advantage of multiple frequencies available in current sensor node hardware. HYMAC protocol scheme is based on its basic operation and scheduling scheme. Concerning the basic operation of HYMAC, the communication period is a fixed-length TDMA cycle composed of a number of frames which are divided, in their turns, into several fixed slot times. Each duration of the slot time is able to transmit a maximum sized packet. For each cycle, a fixed number of consecutive slots form the scheduled slots. The remaining slots of that cycle are its contention slots. In HYMAC, the sink node is responsible to assign slot times and available frequency to each sensor node. The slot and frequency assignment is based on the HELLO messages which are exchanged between nodes and sent to the base station (Sink). Therefore, the base station is able to construct the schedule and send it to each node, in a SCHEDULE message. After that, it can send DATA messages to its parents using its assigned slot and frequency.

Concerning the scheduling algorithm, the authors in [5] propose a heuristic algorithm which aims at achieving a minimum delay schedule by assigning appropriate frequencies and slots to the nodes. The aim of the algorithm is to verify, firstly, if two nodes are siblings. If so, each node will be assigned a different slot time than the other. If they are not siblings then each node will be assigned a different frequency than of the other node, allowing both nodes to send messages to their parents at the same slot time. Note that in a single TDMA cycle, such an assignment, the data packets can be aggregated to the base station. After the extensive simulations, the authors in [5] show that HYMAC provides high throughput, bounded end-to-end delay, for the packets exchanged between each node and the sink, across multiple-hops, collision-free operation and predictable lifetime.

D. *MCSFC*

MCSFC is the abbreviation for Multi-Channel Scheduling for Fast Convergecast in Wireless Sensor Networks. Its main idea is to explore fast convergecast scheduling in WSN where the nodes communicate on a TDMA schedule. The authors in [7] minimize the schedule length, to complete convergecast operations, by using the power control. In addition, they explore some techniques to eliminate the fundamental limitations due to interference and half duplex nature of the radios on the sensor nodes. Therefore, the authors prove, once the interference is eliminated, that with half-duplex radios the achievable schedule length is lower-bounded by max $(2n_k - 1, N)$. The maximum number of nodes on a subtree is called n_k and the number of nodes in the network is N. Hence, the principle in [7] is to assign the frequency per parent node, in reception mode, and eliminate the interferences between the parent nodes (i.e. if there are two interfering parent nodes, then it must be chosen a different frequency). The children nodes, which communicate with the parent node, share temporally the communication slot times (principle of TDMA) using the same reception frequency, in order that the parent node receives data from his children without interferences.

The advantages in [7] are, firstly, the reduction of the number of frequencies when there isn't many interferences. Secondly, they minimize the slot times associated to every child. Generally, the children number per parent is less than the number of neighbors in a graph network. The approach of [7] does not take into account the interferences between children (the case of the hidden terminal problem). In addition, the authors eliminate the interferences just under a restricted condition (announced in the theorem 3 in [7]) and not in the general case.

E. *Limits of the Related Works*

Most of the presented protocols, does not combine the multi-frequency and the TDMA techniques or does not compromise between them to satisfy and to respect the real-time constraint without interference. For example, the MMSN protocol does not combine the multi-frequency transmission and the TDMA techniques to transmit the date in time. While, the TFMAC protocol does not compromise between the necessary number of frequencies and the slot times to send the data in the time to the sink node, since it fixes them manually. So, this affects the real-time constraint when there is more traffic to send.

All these constraints make them not suitable for hard real-time applications. Only MCFSC protocol seems to be adequate to the real-time constraint, the energy consumption and the number of frequencies optimization. That is why we inspire our strategy from it.

The MCFSC protocol is efficient for energy consumption, but the number of frequencies optimization is secondly taken and with less importance. So, the number of frequencies is inefficiently optimized when there are many interferences. This is due, firstly, to the gathering of the clusters by their SINR (Signal-to-Interference-Noise-Ratio) value when there are not other frequencies available to choose. This can cause an increasement of the cluster sizes (i.e. TDMA), and then the pooling cycle of the nodes. Secondly, MCFSC protocol usually assigns a new frequency to the interferent parent without reusing the old frequencies.

In this paper, we try to prove that our strategy can optimize more number of frequencies than MCFSC strategy, when there are more interferences. This provement will be detailed in the next section.

III. OUR MULTI-FREQUENCY CONTRIBUTION

A. *Principle and Problematic*

In Wireless Sensor Networks, when the number of frequencies is limited, the communication delay will be very important mainly when we use the global TDMA (i.e. TDMA for all the nodes in networks).

Our aim is to resolve this problem, by proposing a strategy to optimize the number of frequencies, the power consumption and the communications' delay.

Firstly, the goal is to optimize the number of frequencies without interferences between nodes. This optimization is made by transforming the network from a graph into a tree and applying the clustering mechanism for different chosen frequencies. Secondly, we optimize the power consumption, we employ the suitable method TDMA where the node transmits during its own slot time and sleeps during the others slots. Finally, we optimize the communications delay in order to respect deadlines (i.e. we can predict the time of the communications and verify the deadlines) for real-time applications. To optimize the delay, we combine the TDMA with the frequency multiplexing to get parallel transmissions.

B. Problem formulation and Approach

Our network is presented by a tree in which the data circulates from the sensor nodes (child node) to the Sink, routed by the router nodes (parent nodes). The problem is to know how to reduce the interferences; the solution is either to use a different temporal channel or to use a different frequential channel. For the nodes which are equipped by one transceiver, it's suitable to have a single reception frequency. In this case, the node transmitter can transmit at the same frequency of the reception node. The role of the parent nodes is to collect, to router and to receive the data from the child nodes and then retransmit it to the sink node. To avoid the interferences between nodes, we can make a cluster per parent node and we apply the TDMA principle between nodes in the same cluster. Thus, the global strategy of our approach is to make a clustering per parent node. In this case, all the nodes of this cluster will share the same frequency but with different slot times (TDMA clustering).

Our contribution is based on three phases. The first one presents the transformation of the network from a graph to a tree and the assignement of each parent node to a different frequency in relation to the other parent nodes. The reduction of the number of frequencies is presented, in the second phase, which is based on the principle of the graph coloration [8]. Finally, in the last phase, we try to adapt the number of frequencies compared with the maximum number of frequencies while gathering clusters in the same level.

1) *Phase 1: Transformation of the network from a graph into a tree and assigning frequencies to the tree structure:* is based on two steps. In the first step, we transform our network from a graph, called G, into a tree called T. Each network is composed by a set of nodes called V and a link between them called E. In the second step, we construct a frequency graph.

The transformation of the network is based on the research of the shortest route [10]. This route is found by using the BellmanFort routing algorithm. The construction of the graph is based on the optimization of the energy consumption link (cost) which is given by the following condition :

$$\text{If cost } [E\ (N_i,N_j)] \text{ is minimum Then}$$

$$E_T := E_T \cup \{N_i\}$$
$$E_T := E_T \cup \{V\ (N_i,N_i)\}$$

Where N_j is the parent node, N_i is the sensor node and E_T is the link between two nodes in the tree.

The frequency graph is obtained by assigning for each parent node N_j a different reception frequency called N_{fi}. This frequency graph, called G_f, is presented by the following :

$$G_f = \{(N_j,N_{fi})\}$$

2) *Phase 2: Reduction of the number of frequencies being based on the graph coloration:* Since the number of frequencies is limited in Wireless Sensor Networks, this phase looks for reducing it. This minimization is based on the principle of the coloration of the graph; two neighbors will have different colors and within two hops they can reuse the same color.

The aim of this phase is to aggregate each two linked parent nodes (called N_i and N_j), and assign them the same frequency of N_i *(called* N_{fi}*).* This aggregation is given by the following condition :

$$\text{If } [E\ (N_i,N_j)] \in E \quad \text{Then}$$

$$G_f = G_f \setminus \{(N_i, N_j\}$$

$$G_f = G_f \cup \{(N_j,N_{fi})$$

Where E $(N_{i,}\ N_j)$ is the link between the two parent nodes and G_f is the frequency graph.

3) *Phase 3: Adaptation compared with the maximum number of frequencies by gathering clusters at the same level:* We deploy the phase 3 if the number of frequencies available is limited to N_f. We suppose that, in phase 2, we have N_f frequencies such as $N_{f'} > N_f$.

In this case, we try to reduce the number of frequencies $N_{f'}$, and ensure the resolution of the interference by using TDMA. To reduce the number of frequencies, we make aggregation for frequency clusters. We chose the interferent clusters, that are having the lower cardinality, and assign them the same frequency. To resolve interference, we assign a different TDMA slot times "Fig. 2". We prefer to make clusters in the same level in order to simplify the synchronization of TDMA slot times.

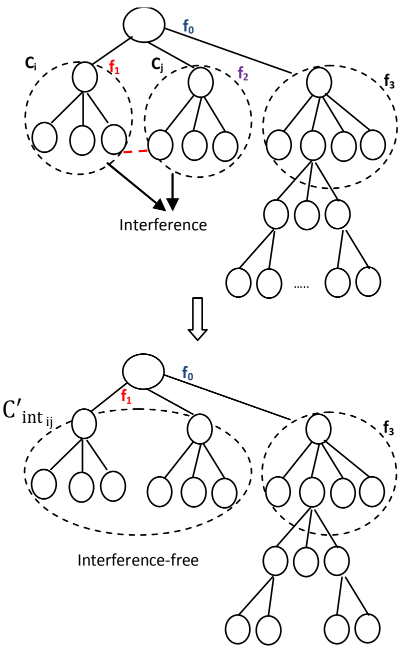

Figure 2. Example of the aggregation for frequency clusters to avoid interference

Before doing the algorithm, based on the clusters' fusions in phase 3, we describe mathematically the fusion.

We have a function C_{int} which defines the interference between two clusters C_i and C_j. This interference is true, if and only if, there is a link between two nodes N_l and N_m where; N_l belongs to C_i and N_m belongs to C_j. The aim of this phase is to adapt the number of frequencies compared with the maximum number of frequencies in WSN with delay optimization. For that, the algorithm of clusters' fusions makes aggregation with minimum cardinality. Once we obtain a set of clusters, we assign them a set of frequencies. To obtain these clusters we are based on two steps, while the cardinality of the clusters is higher than the number of frequencies. In the first step, we look for the fusion of the interferent clusters (for example C_i and C_j). In the second step, we keep just the cluster $C'_{int_{ij}}$ that has a minimum cardinality. To reach these results, we need to apply the following condition:

$$\forall\, i, j \quad \text{Do } C'_{int_{ij}} = \min_{ij}(\text{cardinality}(C_i, C_j))$$

$$C'_{int_{ij}} = \text{fusion\_interf}\,(C_i, C_j)$$

$$C = C \setminus (\{C_i, C_j\} \cup C'_{int_{ij}})$$

$$C = C \cup C'_{int_{ij}}$$

$$\text{Return } \{C\}$$

Where C= $\{C_1 = (N_1, N_2, \ldots), C_2 = (N_6, N_7, \ldots) \ldots\}$, is the set of clusters.

For each cluster, we define a set of frequencies associated to the clusters called $C_f = \{ C_{f_1}, C_{f_2}, \ldots \}$.

IV. FREQUENCY AND DELAY ANALYSIS

In this section, we will analyze two significant factors; the frequency and the delay. The choice of these factors is to prove our strategy's advantages compared with the MCSFC strategy. This comparison is prouved in terms of the number of frequencies and the delay.

A. Frequency analysis

We suppose that sensor networks are represented in a tree structure. Each parent node has *n* children. To avoid the interference from its sensor nodes, the parent node receives their communication with different frequencies. That's in the k^{th} level of the tree; we have n^k different frequencies "(1)".

$$\text{number\_of\_frequencies\_in\_level}_k = \sum_{k=2}^{N} n^k \qquad (1)$$

Where, N is the total number of levels in the tree.

Therefore, we reuse the frequencies within two hops, and we assign the same frequencies of at least two preceding levels. The number of frequencies that can be reused at the level k with n children for each parent node, is expressed in the following "(2)":

$$number\_of\_frequencies\_reused = \sum_{i=2}^{N} n^{k-i} \qquad (2)$$

In fact, the super-bound limit of the number of frequencies is given by the following "(3)":

$$N_f \leq \sum_{k=2}^{N} n^k - \sum_{i=2}^{N} n^{k-i} \qquad (3)$$

Equation (3) is the number of frequencies at each level *k* "(1)" subtracted to the number of frequencies that we can reuse "(2)". We must take into account the level number one of the sink node. In this phase, we have *n* frequencies to receive communication and a different frequency used by the sink node to send the communication. This phenomena is described in the following lemma 1:

Lemma1:
$$N_f \leq \left(\sum_{k=2}^{N} n^k - \sum_{i=2}^{N} n^{k-i}\right) + n + 1$$

B. Delay analysis

The delay is defined as the elapsed time in every level until the sink node, in order to transmit the data. Each node, in a level k_i, has one packet to transmit in its slot time T_s.

So, to transmit the data from the sensor nodes to the sink, we must add all the slot times in each level. Therefore, once the sink node receives the data, the delay is determined in the following lemma 2:

Lemma2: $\quad \text{Delay} = \sum_{i=N}^{1} C_s * T_s$

Where, N is the total number of levels in the tree, T_s is the slot time where each node must transmit one packet and C_s is the cluster size. In our time slotted system, the duration of each slot is long enough to accommodate the successful transmission or reception of a single packet. Thus, this slot time must be larger or equal than the transmission time. The latter is defined as the sum of the packet size P_s and the overhead *Ov* divided by the flow *F* "(4)".

$$T_s \geq \frac{P_s + Ov}{F} \qquad (4)$$

V. PERFORMANCE EVALUATION

In this section, we provide an evaluation of the performance of our strategy and we give a comparison with the MCSFC strategy. We use the number of frequencies and the delay as a performance metric, which are defined respectively in lemma 1 and lemma *2*. We run simulations by varying the following two interference/network parameters: the interference probability and children per parent (i.e. node density). We define the interference probability, as being parent node which interferes with another one. The number of children per parent is an important network parameter since it determines the node density in each level in the tree and thereafter the number of allocated slot times which have an impact on the delay. In our simulations, we take as hypothesis that the number of frequencies to be used is not limited. The Fig.3 illustrates the necessary number of frequencies for different configuration of sensor trees with the variation of the number of children per parent (node density). In the Fig.4, we made the same techniques to determine the delay vs. the number of children per parent. Through these simulations, we notice that our approach uses more frequencies compared to MCSFC in order to improve the delays importance. Moreover, the simulations lead to better communication delays for our approach. In addition, our approach can be well adapted for a limited number of frequencies which depends on the application requirements (see phase 3, section 3.2.3).

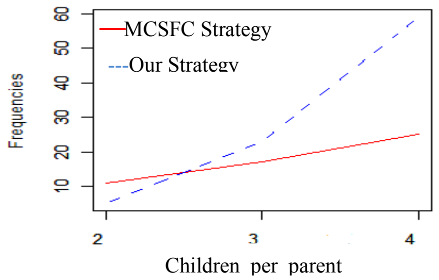

Figure 3. Number of frequencies vs. Children_per_parent

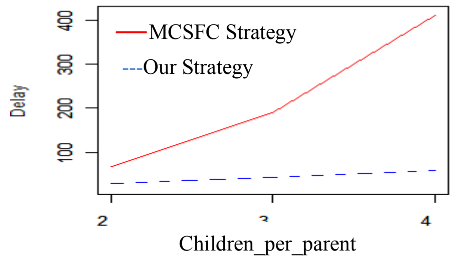

Figure 4. Delay vs. Children_per_parent

In the case of interference, the MCSFC strategy uses the cluster gathering by allocating a different slot time to each node of the cluster. The cluster gathering of the MCSFC strategy, is based on the highest SINR value. However, in our approach, the cluster gathering is based on the minimum cluster size and cluster interference. The interference is considered within a SINR threshold. If the latter is not reached, the interference signal will be low for disturbing the communication.

So, our approach adapts well to the networks having a high interference, as it gathers the clusters according to the lower cardinality in order to minimize the number of frequencies. The nodes in the same cluster use the temporal division technique (TDMA) for the communication. The Fig.5 also shows that the behavior of our strategy with respect to the number of frequencies is more interesting when we have interferences. In our strategy, if the interference probability increases then the number of frequencies will be decreased and we reach the number of frequencies used in MCSFC approach. Our approach gives a better compromise between the delay and the number of frequencies. The delay can be optimized within a limit of the number of frequencies.

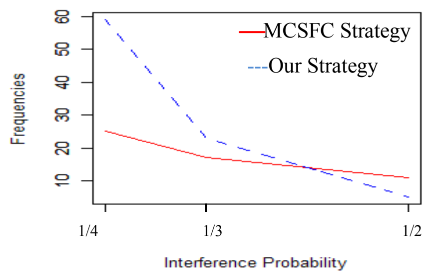

Figure 5. Number of frequencies vs. interference probability between nodes

VI. CONCLUSION

In this paper, we have presented the most important WSN MAC protocols which deploy multi-frequency and TDMA to transmit data to neighbors without interferences. In addition, we have proposed an optimized TDMA multi-frequency scheduling access contribution for sensor networks. The objective of our contribution is to minimize the number of frequencies and the delay to respect the real time constraint.

We evaluate our contribution through simulations and show various trends in performance for different network parameters. As we consider MCSFC strategy as the most appropriate related ones, we compare our strategy to theirs.

On one hand, the delay is minimized by assigning a different frequency to each parent node. On the other hand, the number of frequencies is minimized by gathering the clusters which having a lower cardinality. To prove our strategy, we have compared our results with MCSFC strategy [7]. So, we remark that the number of frequencies decreases more than MCSFC in a concreate context when the interference probability increases.

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