International Journal of Computer Science and Information Security (IJCSIS),
Vol. 15, No. 1, January 2017

Prototyping of a new Multi-channel Multi-hop Access Method without RendezVous

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***Abstract*— One of the most important issues for wireless LANs is the access and the share of wireless radio medium. Several single-channel MAC protocols have been proposed and address this issue with interesting solutions, but some major problems related to channel access (hidden node, synchronization, propagation of RendezVous…) still persist in a multi-hop transmission context and are still the subject of intensive studies by the scientific community, especially when it is related to extended topologies on distributed Wireless Sensors Networks. This article proposes a new multi-channel MAC for all types of multi-hop wireless network topologies, without RendezVous, its prototyping and performance analysis.**

***Index Terms*— Multi-channel medium access; Multi-hop without RDV; Prototyping; Performance evaluation; Medium Access Control; Wireless Sensors Networks; WiNo.**

I. Introduction

In order to find more effective solutions to the access problems and sharing of wireless medium, some research has proposed multi-channel MAC protocols, often addressing the ideal case, where all nodes in the network are within range of each other, or when the transmissions and receptions of the data frames are preceded by controls frames for the establishment of RendezVous (RDV), i.e. a common time and frequency shared between several nodes. We define the RDV, when a peer of nodes concludes after exchange of control frames to switch on the same channel at the same time. Multi-channel access methods still remain confronted to the some specific problems related to the use of multiple channels, such as multi-channel hidden node, deafness, and logical partition problems. The establishment of RDVs requires either a channel dedicated to the exchanges of control frames, which consumes bandwidth; or a phase dedicated to the RDV, which introduces a significant delay in the network. By studying the literature addressing the access to the multi-channel medium, we find that the RDVs do not guarantee the channels reservation coherently (deterministically) without conflict among the nodes in the network, and may make it difficult the multi-hop transmissions. A solution to avoid any conflicts in the use of channels, is to propagate if possible the RDVs beyond from 2 to 3 hops to the neighbors of receiver node, this further significantly complicates the management of RDV (due to additional constraints on making RDV and high cost of time and control bandwidth).

Given this complexity of RDV management in multi-hop that we make our contribution. It is important for us to use a random multi-channel multi-hop access method without RDV, which must be based on the Slotted-Aloha method [1], [2], [3] improved for our multi-channel context. We implemented this multi-channel access method on a real testbed made of multi-channel single-interface “WiNo” nodes, of which we evaluate the performance in terms of: number of received frames ; number of lost frames; and frame error rate (Frame Error Rate, FER) based on the network load. We then compare our solution with the same medium access method, but in a single-channel context with the same performance parameters.

In this paper, we will discuss first about multi-channel access methods with RDV; then we evoke the problems related to RDV in a multi-hop context; and finally we present then discuss about our proposed multi-channel multi-hop access method without RDV, the testbed and its performance study performed and compared with the same single-channel access method, concluding with its advantages and disadvantage.

II. State of the Art and Problematic

Several multi-channel MAC protocols for wireless ad-hoc networks have been proposed, since they allow different nodes to transmit in parallel on distinct channels without collision, thereby increasing throughput and potentially reducing transmission delays. However, most of the proposed protocols are single RendezVous protocols that are subject to control channel congestion. In general, the different protocols are distinguished by the manner in which the network nodes establish RendezVous or in other words, how the nodes negotiate the channels to be used for data transmission.

The first multi-channel MAC protocol that was presented in [4] and [5] is called DCA (Dynamic Channel Assignment); it uses two interfaces: one interface for control frames exchanges and the other for data transfers. In this protocol, each node maintains a list of free channels (Free Channel List FCL) to register the free data channels. With DCA, when source node has data to transmit, it transmits an RTS frame (Request To Send) including the list of available channels (FCL) that are not used by its one hop neighbors. After receiving the RTS, the destination node compares the received

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FCL with its own FCL and selects a common free channel. Then, the destination node indicates to the source node and its neighbors, of the selected data channel by sending a CTS (Clear To Send). By receiving the CTS, each node also informs its neighbors of the selected channel by sending an RES (Reservation) frame. We note that compared to the IEEE 802.11 DCF standard, DCA protocol requires an additional control frame RES to reserve the selected channel.

In [4], [6] and [7], the authors classify the multi-channel MAC protocols into two categories: the single RendezVous (i.e. the dedicated control channel), the common hopping, Split phase, and parallel RendezVous protocols for example SSCH (Slotted Seeded Channel Hopping) [8] and McMAC (Parallel RendezVous Multi-Channel MAC Protocol) [9].

A new parallel RendezVous multi-channel MAC protocol, called TSCH (Time Slotted Channel Hopping) [10], [11] for 802.15.4e access method was published in 2012 as an amendment to the medium access control protocol defined by the standard IEEE 802.15.4 (2011) and which aims to improve the performance of the standard IEEE 802.15.4 in terms of latency and reliability by exploiting several channels simultaneously.

The single-RendezVous MAC protocols have a common control channel also called RendezVous channel. Nodes can exchange control frames and negotiate channels for data transmission on this channel. This control channel, however, can become a bottleneck if the data traffic increases.

Parallel RendezVous MAC protocols, on the other hand, do not need a common control channel. The main idea of these protocols is that nodes hoping through different channels according to their own sequences and control information are exchanged on different channels. Several RendezVous can then establish simultaneously; nodes stop their hopping when they conclude agreements and begin to transmit data and then resume their hopping sequences at the end of the transmission.

In [6], Crichigno, J., and al. compare single and parallel RendezVous protocols in terms of channels number and throughput; according to their study and considering that all nodes are equipped with a single radio interface, they deduce that the parallel RendezVous protocols such as McMAC and SSCH are more efficient than single RendezVous protocols because they eliminate the control channel bottleneck.

In [12] El Fatni and al propose two multi-channel MAC solutions in order to overcome the control channel bottleneck problem. One protocol is called PSP-MAC (Parallel Split Phase multi-channel MAC), which exploits the split phase by applying parallelism during the control phase. The main objective is to exploit all channels during this phase. The second proposed protocol is PCD-MAC (Parallel Control and Data transfer multi-channel MAC), it exploits the concept of multiple RendezVous and dedicated control channel. This protocol excludes the concept of two phases per cycle. Unfortunately, these propositions do not take into account natively the multi-hop topologies, even if the author thinks that its proposals should still be efficient in a more realistic topology.

Most research work has proposed four main approaches based on two types of RDVs, but several have only addressed the problem in a single-hop context without mentioning the complexity generated by the RDVs in multi-hop transmissions.

III. ISSUES RELATED TO MULTI-CHANNEL MULTI-HOP ACCESS METHOD WITH RDV

The multi-channel access methods that have been proposed to manage the channels allocation to the different nodes in the network, generally address the multi-channel access in a simplistic single-hop network. In these types of networks, it is always considered that the RDVs established by each pair of nodes are signaled to their immediate neighbors and therefore to a single-hop. But, there may be cases where the transmitter will be limited by its radio range. In this specific context, the frames need to be relayed or routed through intermediate nodes to their destination (cf. Fig. 1). If the node R sends frames to the node G, these frames will be relayed by the nodes A, B, D before reaching their destination G. In this case, the RDV established by each pair of nodes in the path must be absolutely propagated by the latter to their neighbors beyond a one-hop before their transmissions through controls frames. If a single channel is used by the network, then the two-hop neighbors of all pairs of nodes in the path between R and G (green dotted) that are already informed of channel occupancy from the received control frames will be penalized by the interference zones do not emit on the channel during the entire transmission.

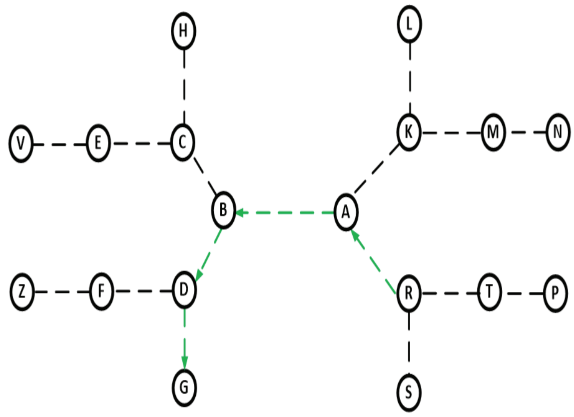

Fig. 1. Topology of a multi-hop network

However, when two or more channels are used, the two hops neighbors (without ACK) or 4 hops neighbors (with ACK) of these nodes in the path can select different channels to send their frames. For example, if node R has chosen channel 1 to transmit to node A, from the control frames exchanged by nodes A and R and received by their neighbors, the node T will therefore be informed of the RDV established by the pair of the nodes A and R and the selected channel, and can then use the channel 2 to transmit to the node P. If we apply the different multi-channel access methods with RDV that we studied, such as the dedicated control channel, the split phase, the common hopping… to this topology of Fig. 1, it is

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necessary that the RDV established by the nodes R and A be known by their immediate neighbors (S and T neighboring R, B and K neighboring A) and that they broadcast it in turn to the neighbors. We are still faced with network flooded by small control frames that will also cause collisions with other data frames, slow down the throughput and therefore degrade the overall performance of the network.

IV. PROPOSED MULTI-CHANNEL MULTI-HOP ACCESS METHOD

We thus noted that multi-channel access methods with RDV are not a simple and optimal solution to the classical problems encountered in single-channel access methods such as the hidden node problem, since the latter still give rise to other problems (deafness …), especially when it comes to a multi-hop network where there are very few optimal solutions because often making use of control frames in order to establish the RDV.

In multi-hop, nodes located beyond a one hop are not often aware of the RDVs taken locally and, thus, can disrupt the transmissions that take place after the RDV.

For such reasons, we are moving towards a simple MAC protocol solution, by proposing a multi-channel access method without RDV based on the Slotted Aloha in order to avoid propagation and negotiation of RDVs, and thus reduce service traffic compared to controlled access.

According to the topology of Fig. 1, using the multi-channel multi-hop access method without RDV, the transmission from R to A does not prevent their neighbors to choose different channels to transmit their data Fig. 2. Thus, several concurrent transmissions take place at the same time on the available channels in the same single-channel interference zone.

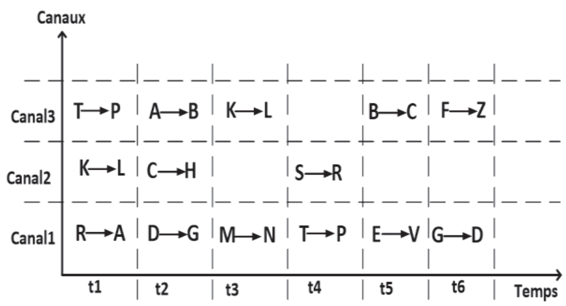

Fig. 2. Topology of a multi-hop network

The operating principle of the proposed multi-channel access method can be described in the following way:

When a node in the network has a frame to send to a destination node, it randomly selects a next slot NS (according to the tests and performance analyzes). It also randomly selects a transmission channel TC (data transmission channel), unless a channel of a previous success is memorized for this neighbor, and transmits its frame data in this slot awaiting the ACK after the data frame in the same slot (and therefore on the same channel). If the sender node of the data does not receive ACK, it repeats the same process by randomly selecting a next data slot and a next transmission channel (simple non-exponential backoff concept, which can then be improved).

When a node has nothing to transmit, it randomly selects a receiving channel RC (data receiving channel) and remain there a number of slots NRS (according to the tests and performance analyzes during our evaluation on testbed).

An important parameter which must be found the most appropriate value is the period of persistence or remanence that a node will pass on the last receiving channel RC.

If the receiving node remains on the same channel for a long time, then at some point there will be a significant number of transmitters that will share the same channel and again faced with single-channel transmission with numerous collisions, hence unsuccessful transmission, we lose the interest of the multi-channel towards which we are oriented.

If the remanence delay on the last receiving channel is small, for example a node remains only one slot on the receiving channel, this reduces the probability that the transmitter which has registered the receiving channel of the receiving node will succeed in reaching it during its next transmission, since this delay being too short, the receiving node can quickly switch to another channel.

However, if the remanence delay on the last receiving channel is not very large, for example when a node remains just 2 or 3 slots on the previous reception channel, this will allow the transmitter that has already registered the reception channel of this node to join it at its next transmission, even if the transmitter is on another channel at the first slot, it has the possibility to switch on the receiver channel during the second or third time slot. An adequate slot number also allows to avoid several transmitters sharing the same channel.

V. PERFORMANCE STUDY OF SINGLE-CHANNEL VS MULTI-CHANNEL MULTI-HOP ACCESS PROTOCOL WITHOUT RENDEZVOUS

A. Presentation of the testbed

The proposed protocol has been implemented on a testbed made of "TeensyWiNos" nodes [13]. Fig. 2 shows some types of WiNos: WiNoRF22 (a), TeensyWiNo (b) both are based on HopeRF RFM22b radio, and DecaWiNo (c), which is running a UWB radio. As an Open Hardware Platform, it is very simple, for example, to change the physical layer of a WiNo: it only requires to replace the transceiver and the associated library. The developing environment simplifies the protocols engineering process while enabling fast prototyping and pragmatic evaluation, in real deployment, of the performance of wireless protocols at the MAC and Network levels of Wireless Sensors Networks. Based on the Arduino environment and coupled to the OpenWiNo software [14], WiNo nodes enable the deployment of a self-organized mesh network and also fast prototyping of complete systems such as connected objects, including sensors, actuators, collection protocols, etc. The realistic implementation allows the prototyping of sufficiently integrated solutions allowing proof of concept and test of prototype of the connected object in terms of uses, by real users. WiNos have been developed to provide low-level access for a demanding developer who wants to precisely control the medium access delay, the standby and wake-up mode of the nodes, but also CPU load and management of the restricted memory.

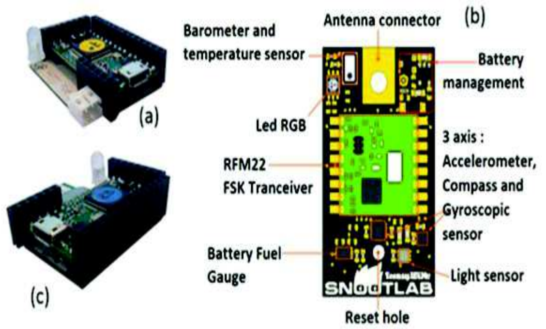

Fig. 3. Image of WiNo nodes

To perform the performance analysis of multi-channel multi-hop access without RDV, we first performed a prototyping using WiNo nodes, and, as a reference, the Slotted Aloha single-channel access method [1] [2]. The time slots are indicated to all the other nodes by a synchronizer node that broadcast beacons every second with a higher transmit power than that used by the other nodes for data transmissions and acknowledgments; the beacon indicates the start of time slot; This allows to easily synchronize all the nodes of the network, even those fairly distant. In order to find the range between two normal nodes, it is necessary to find the fair value of the transmission power. We then proceeded in the same way as for the single channel access to achieve prototyping of the slotted Aloha multi-channel access method. At the beginning of the multi-channel tests, we use two channels.

B. Metrics used

We study the performance of our multi-channel access method considering three essential metrics: The number of received frames, the number of lost frames and the frame error rate which are represented in ordinate on our graph as a function of the network traffic load (represented in x-axis) which is progressively increased, that can be seen in y-axis. These same parameters will be evaluated in single-channel so that we can compare with the multi-channel access. The aim is also to observe the number of hops separating the receiver and a transmitter for a collision to occur.

The data are collected in real time according to the following equations (1) and (2):

$$LOST = LOST + SQNT - RXSQN - 1 \quad (1)$$

LOST is the number of lost frames, *SQNT* is the frame sequence number that has just been transmitted and therefore received, and *RXSQN* is the frame sequence number previously received. This principle is illustrated by the following sequence diagram (Fig. 4).

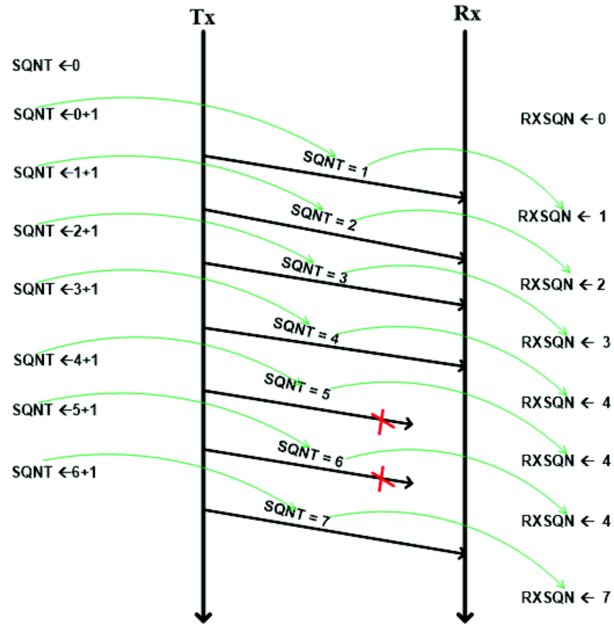

Fig. 4. Sequence diagram specifying the LOST and FER

FER (Frame Error Rate) is the frame error rate, REC being the number of received frames.

When a node receives from different transmitters, then in this case each variable illustrating its metric is divided by the number of nodes from which the receiver has received frames, therefore, we calculate the average values of REC, LOST, FER.

$$FER = \frac{LOST}{LOST + REC} \quad (2)$$

We then implement a single-channel and multi-channel testbed based on this topology (Fig. 5) of 4 WiNo nodes (we designate for **B**: Beacon; **D**: Data; **A**: ACK) where Rx2 is within radio range of two transmitters, Tx1 and Tx2.

The Synch node is a synchronizer that broadcasts every 900 ms a Beacon B to indicate the time slot on channel 0 and all nodes listen to the Beacon on channel 0.

1) **D1_@Rx1** designates the data frames transmitted by Tx1 to Rx1.
2) **A1_@Tx1** designates the acknowledgments (ACK) to the frames emitted by Tx1.
3) **D2_@Rx2** designates the data frames transmitted by Tx2 to Rx2.
4) **A2_@Tx2** designates the acknowledgments (ACK) to the frames emitted by Tx2.

In the single channel scenario, we use channel 0 for Beacons, Data and ACK, while in the multi-channel scenarios, channel 0 is used for Beacons, but it will be reused simultaneously with channel 1 for transmissions and receptions of data and ACK.

C. Results

For this performance study of multi-channel multi-hop access without RDV, we start at the beginning with 2 hops; we

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intend to extend the hops number, the channels number and the nodes number.

The transmitter Tx2 transmits to Rx2 and therefore the signal range reaches only Rx2. Tx1 that is in the range area of Rx1 and Rx2 broadcasts radio to both receivers but only transmits to Rx1.

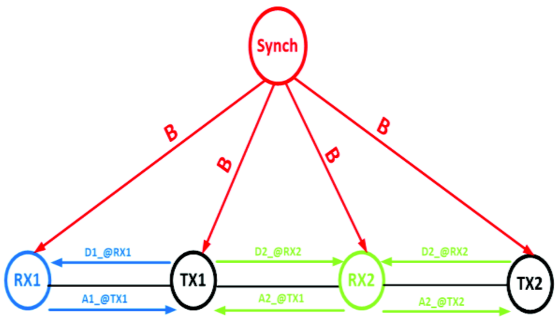


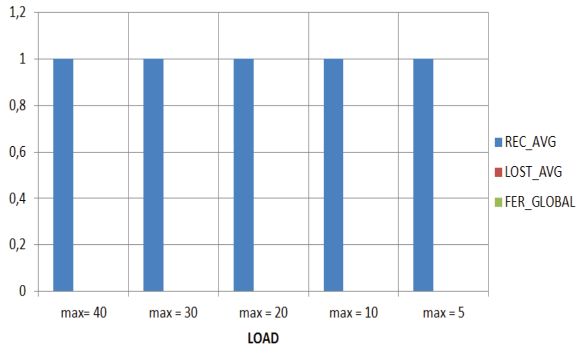
Fig. 5. Receiver (Rx2) within two transmitter's radio range.

We evaluate this performance study by observing the evolution of these three metrics (REC, LOST, FER) as a function of the network load (max=40; 30; 20; 10; 5). The network load is the quantity of data traffics generated by the sending nodes using the RANDOM function to randomly select the time slots number between (1 ; 40), (1 ; 30), (1 ; 20), (1 ; 10), (1 ; 5) before sending the next frame when a collision occurs. We load gradually our network, starting with the small load max = (1 ; 40), and we limit to the maximum load max = (1 ; 5)

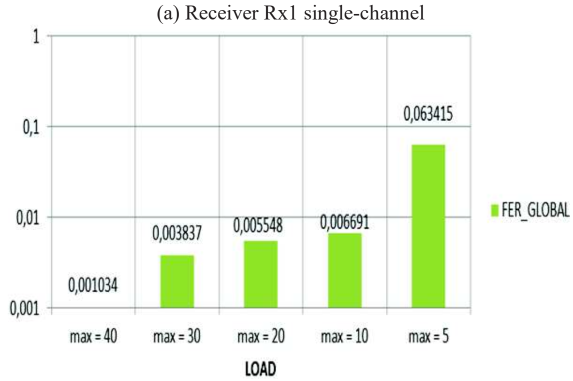
We then evaluate the average value of each metric (REC_AVG, LOST_AVG) at each receiver Rx. Thus the average value is the ratio of this metric value to the number of correspondents of each Rx (number of Tx of which it received frames) and finally we deduce the global FER (FER_GLOBAL) of each Rx.

Note that to find REC_AVG, LOST_AVG, FER_GLOBAL, we first calculate the sum of all received frame and lost frames from all Tx.

According to the graph of Fig. 6, the FER is more important at the receiver Rx2 (Fig. 6 (b)) which mainly comes from frames collisions, since Rx2 is within the range of two transmitters, and sometimes from external noise. However the FER is practically nonexistent at the receiver Rx1 (Fig. 6 (a)) that is only within the range of a single transmitter Tx1 and therefore it is observed only the received frames (REC_AVG, and if there are some times FER, only results from external noises.



(a) Receiver Rx1 single-channel



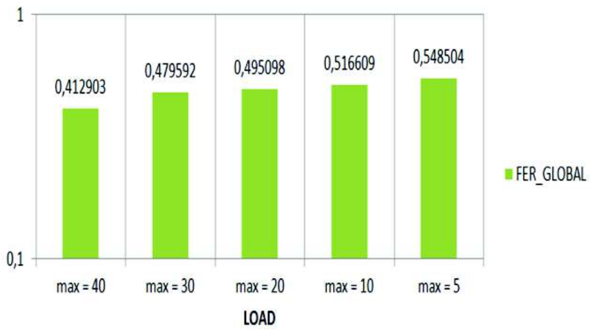
(b) Receiver Rx2 single-channel

Fig. 6. Single-channel FER observed at the receivers Rx1 and Rx2.

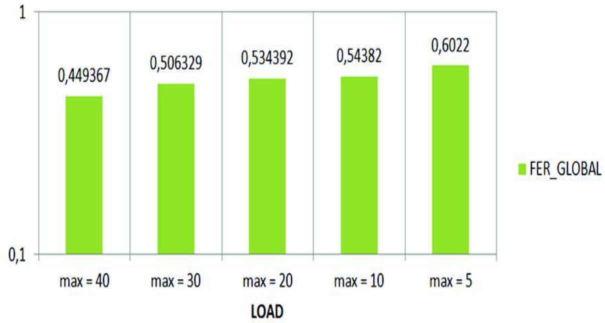
But we observe that the FER is very important in multi-channel at two receivers Rx1 and Rx2 (Fig. 7). At Rx1 Fig. 7 (a), the frames losses result mainly from the lack of reception channel when Tx1 selects a channel randomly to transmit to Rx1 and the latter is on another channel, this disadvantage will be improved by a remanence strategy on the last successful transmission channel that we propose in the following paragraph (VIII).

Since Rx2 is within range of two transmitters, the FER is more important Fig. 7 (b) than that of Rx1, which results mainly from the lack of reception channel between the transmitter Tx2 and the receiver Rx2 and collisions caused by Tx1 when it selects the same channel and the same time slot as Tx2, but also from external noise.

In both contexts (single-canal and multi-channel), a large number of neighbors of the receiving node will cause several collisions, and thus degrade the network performance, what proves our testbed (Fig. 6 (b) and Fig. 7 (b)). But when the network becomes wider, the multi-channel use with a remanence strategy will be more efficient than the single-channel.



(a) Receiver Rx1 multi-channel



(b) Receiver Rx2 multi-channel

Fig. 7. Multi-channel FER observed at the receivers Rx1 and Rx2

VI. REMANENCE STRATEGY ON THE LAST CHANNEL OF SUCCESS

We have as main objective the multi-channel multi-hop access method without RDV implementation while optimizing the reception success rate without collision, despite the absence of RDV. To achieve this, we thought to adopt a remanence strategy in the last successful channel; this will compensate the rate of non-correspondence between the transmission channel choice and the reception channel of the two communicating nodes identified in the previous pre-versions.

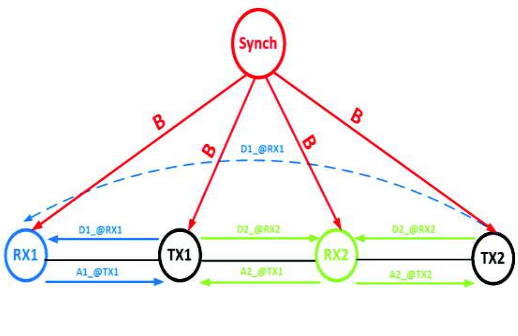


Fig. 8. Remanence topology on the last success channel

Consider the topology of Fig. 8 on which the Synch node is a synchronizer that broadcasts every 900ms a Beacon B on channel 0 and all nodes listen to the Beacon on channel 0.

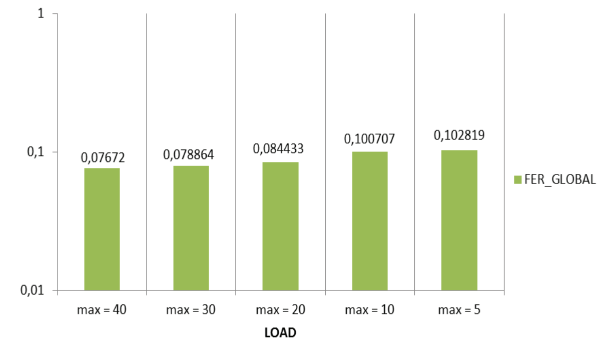
1) **D1_@Rx1** denotes the data frames transmitted by Tx1 to Rx1
2) **A1_@Tx1** denotes the acknowledgments (ACK) to the frames transmitted by Tx1.
3) **D2_@Rx2** denotes the data frames transmitted by Tx2 to Rx2
4) **A2_@Tx2** denotes the acknowledgments (ACK) to the frames transmitted by Tx2.

On this multi-hop topology (Fig. 8), each of the transmitters Tx1 and Tx2 progressively generates traffic to all the receivers. The data frames and acknowledgments are transmitted with the same transmission power. The data frames contain the source address, destination address, sequence number and payload and therefore contain a total of 59 bytes. However, the acknowledgment frame (ACK) is sent only with the source address, the destination address and the sequence number.

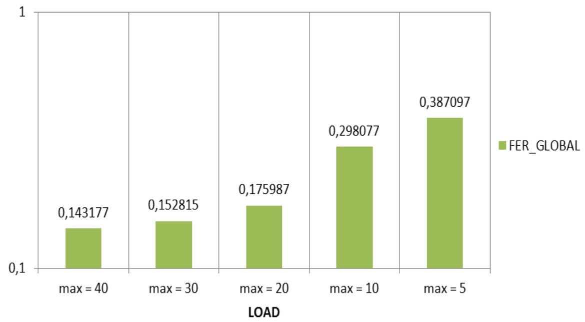
On this topology, it can be seen that Tx1 is within radio range of the two transmitters Rx1 and Rx2, if any obstacle is excluded, the frame transmitted by Tx1 will be received by each of the two receivers; unlike Tx2 which is only within range of Rx2, therefore, the frame transmitted by Tx2 will be received only by Rx2.

If one of the transmitters selects a channel and transmits a frame on this channel, and if it receives an acknowledgment of this frame, then the transmitter stores this success channel for the next transmission to this node, and will select this same channel later if it still wants to address to the same destination. Otherwise, if unsuccessful, it will randomly select another channel. Somewhat in the same way (but unconditionally of course on the source that is not predictable), the receiver also remains in reception on the last reception channel during K time slot (K >= 4 for this testbed). However, beyond this time (K time slot expired), it randomly selects another reception channel. This avoids any starvation phenomenon, because one might be tempted to remain on this same reception channel as long as frames arrive from a talkative transmitter, preventing other potential transmitters on other channels to address this receiver.

Using this method of remanence with the same number of channels (two channels on our test example), it can be seen from the graph of Fig. 9 (a) that the FER at Rx1 which is within range of a single transmitter (Tx1) increases progressively when the network load increases, however the FER is less important than that observed at Rx2 (Fig. 9 (b)). But if we compare it with the FER observed on the testbed without remanence on the success channel (Fig. 7 (a)) it is even less important with very significant different values. This is simply explained by the fact that the probability that the transmitter Tx1 and the receiver Rx1 are on the same channel is significantly improved, however, external disturbances such as: the WiFi network, the other testbeds in our environment that are running at the same time as ours, still disrupt our performance analyzes.



(a) Receiver Rx1 multi-channel with remanence



(b) Receiver Rx2 multi-channel with remanence

Fig. 9. Multi-channel FER with remanence on the last success channel observed at the receivers Rx1 and Rx2

At the Rx2 (Fig. 9 (b)), we see that the FER increases progressively when the network load increases. It may also be simply noted that the FER at the receiver Rx2 is more important compared to the one we just observed at Rx1 (Fig. 9 (a)), this is explained simply by the fact that the receiver Rx2 is subjected to several factors at the same time, in addition to those mentioned at the Rx1, is added the frames collision problem. As we mentioned at the beginning, the receiver Rx2 is in the radio range of two transmitters Tx1 and Tx2, the latter can sometimes selects the same slot and the same channel, consequently the signals of their frames overlap and become undecipherable at the Rx2. However, the FER at the Rx2 is much smaller compared to that observed on the testbed without remanence on the success channel (Fig. 7 (b)).

VII. CONCLUSION

Most of the multi-channel access methods that have been proposed mainly address the case of single-hop networks, and may be inefficient for large multi-hop distributed networks, since it is necessary to propagate the RDV taken locally to neighbors beyond the one hop.

It is therefore important to propose a multi-channel access method adapted to a multi-hop topology, which must be scalable. This study allowed us to first prototype a single-channel MAC wireless access method based on Slotted-Aloha, and then we extended our study to prototype multi-hop multi-channel access without RDV that was improved by the remanence strategy on the last success channel.

According to the performance study we have realized, even if single-channel access offers a better FER (the receiver has very few neighbors) than multi-channel for this testbed with only 4 nodes and 2 channels.

The multi-channel multi-hop access method without RDV that we have proposed, will be a good solution for the large multi-hop distributed networks, and even better when the remanence strategy on the last success channel is used, but it has not great interest for small networks (problems due to the lack of reception channel).

We will test very soon the proposed method with several nodes and we will obviously improve our multi-hop multi-channel access method without RDV in the future.

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ISSN 1947-5500