Adaptive In-band Full-Duplex Collision Detection for Balancing Sensing and Collision Costs

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Abstract—**An undesirable side-effect of network densification is a reduced quality of service due to increased contention. One interesting solution to address this issue is full-duplex medium access control (MAC) with collision detection. By detecting collisions early on, a considerable amount of energy can be saved in dense networks. However, when traffic demand and, as a result, the collision rate decrease, the reduced collision time does not compensate for the increased power consumption of the full-duplex physical layer. This paper therefore investigates the trade-offs between two MAC protocols (i.e. full-duplex CSMA/CD and half-duplex CSMA/CA) proposing closed-form formulas to calculate the equilibrium point in terms of power consumption. Knowing this equilibrium, we propose a distributed algorithm that independently switches the MAC protocol of each node reducing the energy consumption of each node up to 33%.**

I. INTRODUCTION

The increased usage of devices with wireless capabilities is generating an ongoing densification in existent wireless communication networks. This densification, in conjunction with an increased data exchange between users, is introducing great challenges for network managers to continue providing good quality of service. These issues are particularly challenging in the industrial, scientific and medical bands, where many devices and protocols contend for scarce resources.

Different solutions have been proposed to allow multiple nodes sharing a common communication medium. Of these, maybe half-duplex carrier sense multiple access (CSMA) is the most well-known. However, half-duplex CSMA requires to complete each packet transmission even when collisions occur, wasting valuable spectrum and energy. Current state-of-the-art solutions trade in resources like time and bandwidth to reduce the time spent in collisions. In [1], each node randomly interrupts the transmission to listen for collisions. This protocol increases performance but requires significant overhead due to occasionally switching between the transmit and receive states. Also spectral efficiency can be traded for increased network performance. In [2], an out-of-band control channel is used to detect collisions, exchanging extra bandwidth for increased performance.

To reduce transmission time wasted with corrupted packets, a novel CSMA scheme based on in-band full-duplex (IBFD) [3] has been proposed in [4]. IBFD allows a transmitter to cancel its own transmitted signal in order to simultaneously receive data or, in this case, to detect collisions without extra time or bandwidth. When the intended receiver detects a packet, it will transmit a real-time acknowledgment (RACK). If the receiver experiences interference or collisions , the transmitter will preemptively abort the transmission, thus saving energy and resources.

It has been shown that the benefits of this full-duplex scheme are significant in scenarios with high interference, but the extra consumption caused by additional hardware makes it suboptimal for scenarios with less relevant interference [5]. Therefore, to address realistic contexts where interference can change dynamically, we propose an adaptive scheme that can switch on or off the full-duplex capabilities depending to the context.

This paper complements our previous work by investigating in depth in which conditions each scheme performs optimally. As a result, this paper provides a closed-form formula to calculate the critical amount of nodes to switch. With these formulas in mind, a distributed algorithm is proposed that enables each node to switch locally between the half- and full-duplex CSMA schemes to optimize node power consumption.

We have tested the performance of our algorithm in ns-3 [6]. The simulation results show that it is possible to devise a practical algorithm to decide which protocol should be used at runtime. Using our switching algorithm it is possible to save up to 33% of energy per successfully transmitted bit compared to half-duplex CSMA and up to 17% compared to a IBFD CSMA for a concrete simulated scenario.

This paper is organised as follows, Section II explains the need to adaptively switch between both protocols, including an energy model to compare both protocols. Section III derives closed-form formulas for the critical number of nodes, while Section IV describes our practical algorithm. Section V discusses the simulated results and energy savings and finally Section VI summarizes our conclusions.

II. THE NEED FOR ADAPTIVITY

In this section we give a short overview of the in-band full-duplex collision detection protocol. Furthermore, we summarize the main aspects of the energy model in [5] for half-duplex collision avoidance, referred to as HD-CSMA/CA, and full-duplex collision detection, referred to as FD-CSMA/CD. We then extend this model by determining the analytical critical network size N where the energy consumption of both schemes is equal, in Section III.

A. In-band full-duplex collision detection

A typical IBFD transmitter uses knowledge of the transmitted signal to cancel its own transmitted signal (the so-called

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the self-interference) in its receiver chain. This is first done in the radio frequency domain [7], before the analog-to-digital converter (ADC), to enable sufficient dynamic range from this ADC. Then in the digital domain, a second cancellation [3] is applied to further suppress the self-interference below the noise floor. Several state-of-the-art implementations have proven the feasibility of this technology [3], [8].

Leveraging this technology allows to create a noise-free in-band control channel for collision detection. This enables the receiver to sense for collisions and transmit a continuous real-time acknowledgement (RACK) during packet reception, as detailed in [5]. The transmitter can decide based on the RACK to preemptively abort its transmission, freeing the wireless medium from collisions and significantly reducing the collision time.

B. Energy model

The average energy per bit of a half-duplex transmitter can be defined as

$$\bar{\mathcal{E}}_{\mathrm{b}}^{\mathrm{HD/CA}} = P_{\mathrm{HD}} T_{\mathrm{b}} \bar{\tau}^{\mathrm{HD/CA}}, \tag{1}$$

with P_{HD} the power consumption of the transmitter, T_{b} the time per bit and $\bar{\tau}^{\mathrm{HD/CA}}$ the average number of half-duplex transmissions, which consists of three terms

$$\bar{\tau}^{\mathrm{HD/CA}} = \bar{\tau}_{\mathrm{d}} + \bar{\rho}_{\mathrm{i}} + \bar{\rho}_{\mathrm{c}}^{\mathrm{HD/CA}} \ . \tag{2}$$

$\bar{\tau}_{\mathrm{d}}$ is the average number of transmissions due to decoding errors, $\bar{\rho}_{\mathrm{i}}$ is the average number of *transmission trials* due to interference and $\bar{\rho}_{\mathrm{c}}^{\mathrm{HD/CA}}$ is the average number of *transmission trials* due to collisions.

The average energy per bit of a full-duplex transmitter with collision detection can be defined as

$$\bar{\mathcal{E}}_{\mathrm{b}}^{\mathrm{FD/CD}} = P_{\mathrm{FD}} T_{\mathrm{b}} \hat{\tau}^{\mathrm{FD/CD}} + \mathcal{E}_{\mathrm{SIC}}^{(\mathrm{s})} \bar{\tau}^{\mathrm{FD/CD}} \ , \tag{3}$$

with P_{FD} the power consumption of the in-band full-duplex transmitter during a transmission, $\mathcal{E}_{\mathrm{SIC}}^{(\mathrm{s})}$ the energy consumption before each transmission to initialize the self-interference cancellation (SIC) and $\hat{\tau}^{\mathrm{FD/CD}}$ the reduced average number of transmissions in FD-CSMA/CD, defined as

$$\hat{\tau}^{\mathrm{FD/CD}} := \bar{\tau}_{\mathrm{d}} + \gamma_{\mathrm{i}} \bar{\rho}_{\mathrm{i}} + \gamma_{\mathrm{c}} \bar{\rho}_{\mathrm{c}}^{\mathrm{FD/CD}}. \tag{4}$$

Here γ_{i} and γ_{c} represent the reduction in transmission time due to the collision and interference detection. Because of the real-time acknowledgment, collisions can only occur before the receiver has decoded the header and transmitted the RACK, as a result, γ_{c} is equal to the ratio between the header transmit time and the total packet transmit time. Interference on the other hand can occur anytime during the packet, therefore, one can safely assume that $\gamma_{\mathrm{i}} = 0.5$.

C. Energy evaluation

By implementing the FD-CSMA/CD protocol on top of the existing HD-CSMA/CA protocol in ns-3, it is possible to get numerical results for $\bar{\tau}_{\mathrm{d}}$, $\bar{\rho}_{\mathrm{i}}$ and $\bar{\rho}_{\mathrm{c}}$. Using the above model it is possible to compare the energy efficiency of the two MAC protocols, as shown in Figure 1. It is clear that FD-CSMA/CD is more energy-efficient in large networks. However, in networks with a small number of active nodes, FD-CSMA/CD consumes almost twice the energy per bit. Therefore, finding the crossing point between the two curves in Figure 1 allows the network to efficiently switch between the two protocols, and as a result, to optimize its energy efficiency.

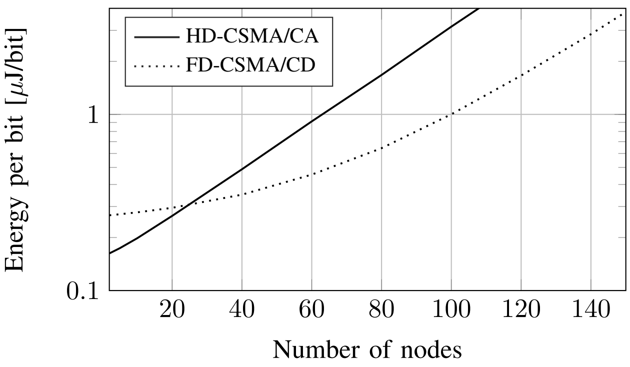

Fig. 1. The average energy consumption per bit without external interference in saturated traffic conditions in ns-3 shows that FD-CSMA/CD, eq. (3), is more energy efficient than HD-CSMA/CA, eq. (1), when more than 20 nodes are in the network.

III. IBFD SWITCHING POINT

Let us consider the energy savings of FD-CSMA/CD with respect to HD-CSMA/CA, which is given by the difference between (1) and (3). From these equations, it follows that:

$$\begin{aligned} \frac{\bar{\mathcal{E}}_{\mathrm{b}}^{\mathrm{HD/CA}} - \bar{\mathcal{E}}_{\mathrm{b}}^{\mathrm{FD/CD}}}{P_{\mathrm{HD}} T_{\mathrm{b}}} &= \\ & \bar{\tau}^{\mathrm{HD/CA}} - \frac{P_{\mathrm{FD}}}{P_{\mathrm{HD}}} \hat{\tau}^{\mathrm{FD/CD}} - \frac{\mathcal{E}_{\mathrm{SIC}}^{(\mathrm{s})}}{P_{\mathrm{HD}} T_{\mathrm{b}}} \bar{\tau}^{\mathrm{FD/CD}}. \end{aligned} \tag{5}$$

Then, it can be seen that the FD-CSMA/CD scheme is more energy-efficient than HD-CSMA/CA when the right hand side of (5) is larger than zero. Using simple algebra, one can re-write this as

$$\frac{\hat{\tau}^{\mathrm{FD/CD}}}{\bar{\tau}^{\mathrm{HD/CA}}} < \frac{P_{\mathrm{HD}}}{P_{\mathrm{FD}}} - \frac{\mathcal{E}_{\mathrm{SIC}}^{(\mathrm{s})}}{P_{\mathrm{FD}} T_{\mathrm{b}}} \frac{\bar{\tau}^{\mathrm{FD/CD}}}{\bar{\tau}^{\mathrm{HD/CA}}} \ . \tag{6}$$

Let us define the *relative cost of retransmissions* $\eta_{\mathrm{c}}(N)$ of FD-CSMA/CD with respect to half-duplex as

$$\eta_{\mathrm{c}}(N) := \frac{\hat{\tau}^{\mathrm{FD/CD}}}{\bar{\tau}^{\mathrm{HD/CA}}} = \frac{\bar{\tau}_{\mathrm{d}} + \gamma_{\mathrm{i}} \bar{\rho}_{\mathrm{i}} + \gamma_{\mathrm{c}} \bar{\rho}_{\mathrm{c}}^{\mathrm{FD/CD}}(N)}{\bar{\tau}_{\mathrm{d}} + \bar{\rho}_{\mathrm{i}} + \bar{\rho}_{\mathrm{c}}^{\mathrm{HD/CA}}(N)}, \tag{7}$$

where the second equality uses Eq. (2) and (4). As full-duplex transmissions reduce congestion, $\bar{\rho}_{\mathrm{c}}^{\mathrm{HD/CA}}(N) \geq \bar{\rho}_{\mathrm{c}}^{\mathrm{FD/CD}}(N)$ and therefore $\eta_{\mathrm{c}}(N) \in]0, 1]$ for all values of N. Furthermore, by noting that $\bar{\tau}^{\mathrm{FD/CD}} \leq \bar{\tau}^{\mathrm{HD/CA}}$, from Eq. (7) one can find an inequality that guarantees that FD-CSMA/CD consumes less energy for all values of N that satisfy

$$\eta_{\mathrm{c}}(N) < \frac{P_{\mathrm{HD}}}{P_{\mathrm{FD}}} - \frac{\mathcal{E}_{\mathrm{SIC}}^{(\mathrm{s})}}{P_{\mathrm{FD}} T_{\mathrm{b}}} \ . \tag{8}$$

Please note that condition (8) is sufficient but not necessary for $\bar{\mathcal{E}}_{\mathrm{b}}^{\mathrm{HD/CA}} - \bar{\mathcal{E}}_{\mathrm{b}}^{\mathrm{FD/CD}} > 0$ to be satisfied. Note that the second term of the right-hand side in (8) is usually small, and hence the inequality is dominated by the ratio of the power terms[*]. Therefore, (8) can be reduced to a comparison between the ratios of retransmission versus power savings. Carefully observing this equation reveals that the right-hand side depends only on system parameters[†], being independent of the network size N.

In the sequel (8) is studied in two extreme cases.

A. No contention ($N = 1$)

When there is only one active device then $\bar{\rho}_{\mathrm{c}}^{\mathrm{HD/CA}} = \bar{\rho}_{\mathrm{c}}^{\mathrm{FD/CD}} = 0$. If the interference from other networks is negligible, then $\eta_{\mathrm{c}} \approx 1$. Note that $P_{\mathrm{HD}} < P_{\mathrm{FD}}$, and therefore condition (8) is in general not attained. Therefore, under these conditions half-duplex transmissions are generally more energy-efficient than full-duplex transmissions, as the extra power consumption required by full-duplex transceivers is not being compensated by savings in collision time.

On the other hand, if the network suffers from strong interference then $\eta_{\mathrm{c}}(1) \approx \gamma_{\mathrm{i}}$. If γ_{i} is smaller than the right-hand side term of (8), then the savings due to interference detection makes condition (8) to be attained. This implies that FD-CSMA/CD is more energy efficient than HD-CSMA/CA even for small networks without collisions.

B. Dense networks (large N)

In dense networks the effect of retransmissions due to collisions dominates over the effect of interference and decoding errors. In general, full-duplex CSMA collision detection experiences less collisions than half-duplex CSMA collision avoidance, i.e., $\bar{\rho}_{\mathrm{c}}^{\mathrm{HD/CA}} \geq \bar{\rho}_{\mathrm{c}}^{\mathrm{FD/CD}}$, as the reduction in collision time makes the medium less congested. Moreover, a direct calculation shows that

$$\lim_{N\to\infty} \eta_{\mathrm{c}}(N) = \gamma_{\mathrm{c}} \lim_{N\to\infty} \frac{\bar{\rho}_{\mathrm{c}}^{\mathrm{FD/CD}}}{\bar{\rho}_{\mathrm{c}}^{\mathrm{HD/CA}}} \leq \gamma_{\mathrm{c}} \ . \tag{9}$$

As $\gamma_{\mathrm{c}} \ll 1$ (cf. Section II-B), (9) implies that condition (8) is satisfied for sufficiently large N. This shows that FD-CSMA/CD is always more efficient than HD-CSMA/CA for dense networks.

In general, $\eta_{\mathrm{c}}(N)$ is a monotonous sequence that converges to γ_{c}. Therefore, if $\eta_{\mathrm{c}}(1)$ does not satisfy condition (8), then, by considering $\eta_{\mathrm{c}}(\cdot)$ as a continuous function, one can prove there exists a critical number of contending devices N^* that guarantees the following condition[‡]:

$$\eta_{\mathrm{c}}(N^*) = \frac{P_{\mathrm{HD}}}{P_{\mathrm{FD}}} - \frac{\mathcal{E}_{\mathrm{SIC}}^{(\mathrm{s})}}{P_{\mathrm{FD}} T_{\mathrm{b}}} := K \ . \tag{10}$$

In this way, condition (8) guarantees that our FD-CSMA/CD scheme is more energy-efficient than HD-CSMA/CA when there are more than N^* contending devices.

C. N^* for congested networks

Let us now focus on the case of dense congested networks where each node tries to maximally use the wireless channel. This worst case scenario happens when a high number of nodes is trying to transmit data. Also, for simplicity let us ignore the effect of hidden nodes. In this case $\bar{\rho}_{\mathrm{c}}^{\mathrm{HD/CA}} = \bar{\rho}_{\mathrm{c}}^{\mathrm{FD/CD}} := \bar{\rho}_{\mathrm{c}}$, as the shorter collision time of FD-CSMA/CD does not reduce the average number of retransmissions per packet[§]. This assumption was validated using ns-3 simulations. As a result of congestion, the shared medium usage of each contending device will not be affected by the channel fading statistics, and hence the correlation between decoding errors and collisions can be neglected. Therefore, considering fast-fading conditions, the Lemma presented in the appendix of [5] shows that the total number of transmission trials can be expressed as

$$\bar{\tau} = (1 - q_{\mathrm{c}})^{-1}(1 - q_{\mathrm{i}})^{-1}(1 - \bar{P}_{\mathrm{f}})^{-1} \ . \tag{11}$$

Above, q_{c} is the collision rate with packages from the same network, q_{i} is the rate of transmissions which experiences interference from other networks given that there are no collisions and $\bar{P}_{\mathrm{f}}$ is the mean packet error rate when the reception is done without collisions or interference.

Let us study the relationship of q_{i} and q_{c} with $\bar{\rho}_{\mathrm{i}}$ and $\bar{\rho}_{\mathrm{c}}$. Following [9] (Sec II-B), one can identify $\bar{\tau}_{\mathrm{d}} = (1 - \bar{P}_{\mathrm{f}})^{-1}$. Recall that $\bar{\rho}_{\mathrm{i}}$ and $\bar{\tau}_{\mathrm{d}}$ are independent of N, and that if $N = 1$ then $\bar{\rho}_{\mathrm{c}} = 0$ and $q_{\mathrm{c}} = 0$. Hence, using (2) and (11) for the case of $N = 1$, one can find that

$$\bar{\rho}_{\mathrm{i}} = \frac{1}{(1 - q_{\mathrm{i}})(1 - \bar{P}_{\mathrm{f}})} - \bar{\tau}_{\mathrm{d}} = \frac{q_{\mathrm{i}}}{(1 - q_{\mathrm{i}})(1 - \bar{P}_{\mathrm{f}})}. \tag{12}$$

Using again (2) and (11) for an arbitrary value of N, it can now be found that

$$\begin{aligned} \bar{\rho}_{\mathrm{c}} &= \frac{1}{(1 - q_{\mathrm{i}})(1 - q_{\mathrm{c}})(1 - \bar{P}_{\mathrm{f}})} - \bar{\tau}_{\mathrm{d}} - \bar{\rho}_{\mathrm{i}} && (13) \\ &= \frac{q_{\mathrm{c}}}{(1 - q_{\mathrm{i}})(1 - q_{\mathrm{c}})(1 - \bar{P}_{\mathrm{f}})}. && (14) \end{aligned}$$

Note that a high mean packet error rate increases both $\bar{\rho}_{\mathrm{c}}$ and $\bar{\rho}_{\mathrm{i}}$, as it increase the number of times the packet needs to be radiated through the shared medium making it more vulnerable to collisions or interference. In a similar way, a high probability of interference increases $\bar{\rho}_{\mathrm{c}}$.

Hence, using (12), (14) and (6) one can show that

$$\eta_{\mathrm{c}}(N) = (1 - q_{\mathrm{c}})[1 - q_{\mathrm{i}} + \gamma_{\mathrm{i}} q_{\mathrm{i}} - \gamma_{\mathrm{c}}] + \gamma_{\mathrm{c}} \ . \tag{15}$$

Then, by using $\eta_{\mathrm{c}}(N^*) = K$ as defined in (10), one can find the following critical collision probability by inverting (15):

$$q_{\mathrm{c}}(N^*) = \frac{1 - q_{\mathrm{i}} + q_{\mathrm{i}}\gamma_{\mathrm{i}} - K}{1 - q_{\mathrm{i}} + q_{\mathrm{i}}\gamma_{\mathrm{i}} - \gamma_{\mathrm{c}}}. \tag{16}$$

Hence, this formula can be used to find N^* for given values of K over different MAC protocols, which determine a specific

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[*] In effect, a calculation based on state-of-the-art parameter values gives a difference of three orders of magnitude between these two terms.

[†] Numerical values of these parameters can be found in [5].

[‡] In the case in which $\eta_{\mathrm{c}}(1)$ already satisfies condition (8) then N^* can be defined as 0.

[§] The total number of transmissions does increase but so does the total number of receptions, equating to an equal collision probability. Due to the higher number of received packets, this does result in a higher throughput.

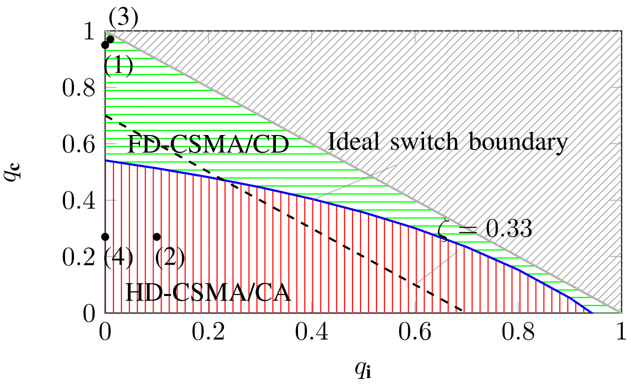

Fig. 2. The ideal switching boundary (——), splits the area where FD-CSMA/CD is optimal (▤) and the area where HD-CSMA/CA is optimal (▥). The ▨ area is mathematically impossible as the packet error rate is greater than 1. In our practical algorithm $\zeta = 0.33$ (- - -) is used as switching boundary. The four dots mark the four scenarios used in Sec. V.

relationship between q_c and N. In particular, let us consider a typical collision probability function given by

$$q_\mathrm{c}(N) = 1 - a\exp\{-bN\}, \tag{17}$$

which for specific values of a and b corresponds to the collision probability of protocols like CSMA/CA. For example, by curve fitting the collision probability from our ns-3 simulations, we found $a = 0.9977$ and $b = 0.0306$. Then, using (16) and (17), the critical number of nodes can be calculated directly as

$$N^* = \frac{1}{b}\ln\frac{a(1 - q_\mathrm{i} + q_\mathrm{i}\gamma_\mathrm{i} - \gamma_\mathrm{c})}{K - \gamma_\mathrm{c}}\ . \tag{18}$$

It can be noted that if one decreases a, then q_c as given in (17) increases while N^* decreases. In a similar way, any change in the parameters a, b or c that makes q_c larger causes a decrease in the value of N^*. This suggests that the critical number of nodes N^* is smaller in networks with less efficient MAC solutions — i.e. networks with larger $q_c(N)$.

IV. A PRACTICAL ALGORITHM

Following the analysis above, nodes should determine the number of active nodes N and the interference amount q_i and combined with (18) to decide to either switch to HD-CSMA/CA or to FD-CSMA/CD. However, this determination is practically infeasible as the nodes cannot estimate the number of active nodes in a distributed way. Another way to look at it is by plotting q_c as a function of q_i by filling in (18) in (17), this is shown in Figure 2. For a perfect decision, nodes need to know both q_c and q_i. Again, this is infeasible as nodes are unable to differentiate between collisions and interference.

To avoid this problem, we propose a distributed algorithm, shown in Algorithm 1, where nodes estimate the traffic load (sum of q_c and q_i) on the channel by counting transmitted *(line 19)* and acknowledged packets *(line 22-28)*. If the packet delivery ratio averaged over the last W packets exceeds ζ *(line 13-18)*, it chooses the half-duplex scheme, otherwise it chooses the full-duplex scheme. The parameter W is an adjustable sliding window to avoid excessive switching. ζ is the packet delivery ratio threshold, as shown in Figure 2, ζ is fixed to 0.33 as it is close to the ideal boundary for low q_i. On the other hand a high q_i, i.e. $q_\mathrm{i} > 0.5$, typically only occurs with active jammers.

TABLE I
SCENARIOS USED IN NS-3 SIMULATIONS.

Scenario	1	2	3	4
Time of day (6h)	Morning	Afternoon	Evening	Night
number of sensors	100	10	100	10
WiFi duty cycle	0%	5%	50%	0%
N^* using (18)	25	24	14	25

Algorithm 1 Adaptive selection algorithm

```
Require: Window $W > 0$
Require: Threshold $\zeta > 0$ and $\zeta < 1$
 1: Initialize: $T$ = zeros($W$, 1)
 2: function main()
 3: while AvailablePacket() do
 4:     free ← DoCCA()
 5:     if free then
 6:         TransmitPacket()
 7:         WaitForAck()
 8:     end if
 9: end while
10: end function
11:
12: function TransmitPacket()
13: $C$ ← average($T_{i-W} : T_i$)
14: if $C > \zeta$ then
15:     Transmit with HD-CSMA/CA
16: else
17:     Transmit with FD-CSMA/CD
18: end if
19: $i$++
20: end function
21:
22: functionWaitForAck()
23: if Ack timer not timeout then
24:     $T_i$ ← 1 # Packet arrived successfully
25: else
26:     $T_i$ ← 0 # Packet did not arrive
27: end if
28: end function
```

V. SIMULATION RESULTS

To validate the proposed algorithm, a smart home scenario is considered with IEEE 802.15.4 low power connected sensors to monitor several parameters, e.g. humidity and sound. More specifically, the following scenario, shown in Table I, was simulated in ns-3. This table can be interpreted as follows: The morning scenario includes offline people walking about in their home generating data, whereas the afternoon is defined by a lower, yet online, occupancy of the house and less active sensors. In the evening, the network is severely loaded because of a high and online occupancy. And finally, during the night, the house is quiet. The corresponding q_c and q_i of the different scenarios are shown in Figure 2.

The WiFi in our simulation is modeled as a duty cycled pattern with a period of 30 ms. With a 50 percent dutycycle,

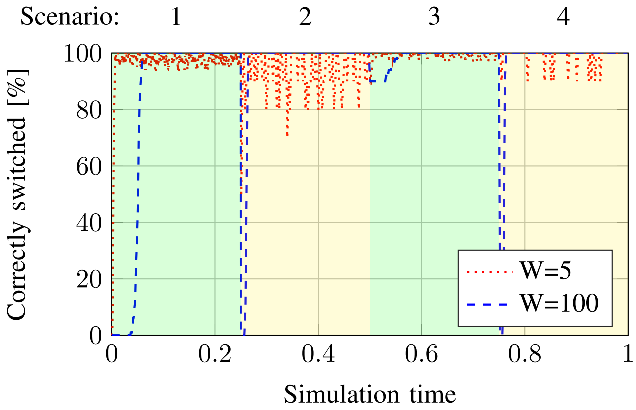

Fig. 3. The amount of nodes that switched to the correct scheme, as shown in Tab. I. This figure clearly shows that a window size of 5 does not converge to the correct solution.

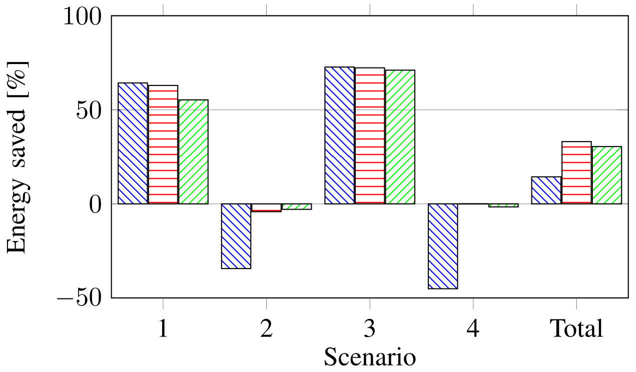

Fig. 4. The average energy saved for FD-CSMA/CD (▧), W=5 (▤), W=100 (▨). The graph shows clearly that a scheme that adaptively enables the full-duplex collision detection ensures lower power. For scenario 1 and 3, the optimal scheme is FD-CSMA/CD, for the other scenarios, that is HD-CSMA/CA.

WiFi interference is turned off and on every 15 ms. The traffic load for each active sensor in the network, i.e., either 10 or 100, is high enough to ensure that every node has always new data to transmit. All sensors are connected in a star topology to the central gateway.

Using (18), the crossing point between the HD-CSMA/CA and FD-CSMA/CD curves can be calculated for different WiFi duty cycles (q_i). From Table I, is it clear that in scenarios 1 and 3, FD-CSMA/CD is more energy efficient. In scenarios 2 and 4, HD-CSMA/CA is more energy efficient.

The algorithm presented in Section IV allows to find the optimal protocol at runtime. Adjusting the window allows to change the tracking speed and steadiness, this is shown in Figure 3. A smaller window is able to respond faster but fails to always select the optimal layer, while a larger window converges better but tracks changes much slower.

Figure 4 shows the energy saved compared to HD-CSMA/CA. In scenarios 1 and 3, 50% less energy is consumed by using collision detection. In less dense scenarios (i.e. 2 and 4), the energy loss is less than 50%. Averaging over the four scenarios, static FD-CSMA/CD saves 14% compared to a static HD-CSMA/CD. When the nodes adaptively pick their preferred protocol, the energy savings depend on the chosen window. For our small window, 33% of the energy was saved while for the larger window this is 30% for the simulated scenarios.

VI. CONCLUSION

This paper analyzed the theoretical energy consumption difference between FD-CSMA/CD and HD-CSMA/CA. Theoretically, the obtained formulas equate to the optimal MAC scheme. However, due to practical limitations, a more applicable switching algorithm for dense wireless sensor networks is described that dynamically selects the full-duplex protocol if high interference is experienced. The tunable window parameter in our algorithm allowed nodes to respond faster to changes in either network usage or interference. The simulated scenarios show the proposed algorithm saves 33% or 17% in energy consumption compared to HD-CSMA/CA or FD-CSMA/CD, respectively.

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