Forced Transmissions for Coping with the Effect of Blocked Stations in 802.11 Wireless Networks

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Abstract

In this paper, we consider the problem of blocked stations *that appears in some spatial configurations of multi-hop wireless networks based on the 802.11 DCF (*Distributed Coordination Function*). The problem leads to starvation of at least one station caused by the presence of neighbor stations within its carrier sensing range that do not hear each other. We propose* Forced Transmissions*, a simple and efficient solution to this problem. It consists of detecting that a station is blocked by others stations and forcing a transmission. This results in a collision that increases the contention windows of blocking stations and leaves some channel time to the blocked station for transmitting. The blocked station forces transmission only with some probability adjusted in function of the time spent waiting for the channel. Our simulations show that the proposed method increases the minimal throughput of the blocked stations at the expense of a slight degradation of the total throughput, which is unavoidable in any DCF based solution.*

1. Introduction

We consider the IEEE 802.11 [1] wireless networks in the ad hoc mode. When stations with omnidirectional antennas use the mandatory *Distributed Coordination Function* (DCF) access method to the radio channel, several performance problems may arise due to spatial positions of stations. The problem of *hidden stations* is the most familiar one [19]: two or more stations that are outside carrier sensing range (they are *hidden* with respect to each other, e.g. stations A and C or A and D in Figure 1) try to send a frame to the same destination (station B).

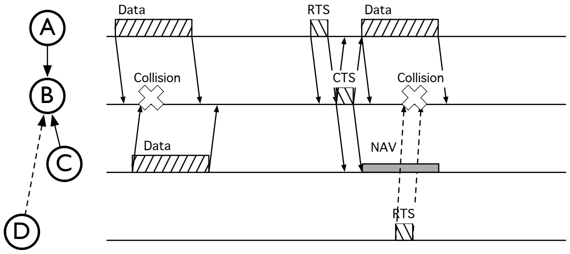

Figure 1. Problem of hidden stations.

The problem appears in certain spatial positions of stations and leads to degraded performance, because transmission attempts collide at the receiver. The RTS/CTS (*Request To Send/Clear To Send*) option may alleviate this effect [13], but it only works if a hidden station is in the range that allows to correctly decode the RTS or CTS control frames, which is not the case for example for station D in Figure 1 (the solid arrow corresponds to two stations within their transmission range while the dashed one represents communication between two stations within their carrier sensing range).

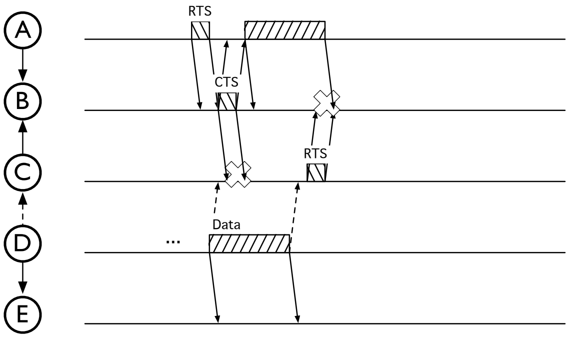

Figure 2. Problem of masked stations.

The problem of *masked stations* is similar, because it also leads to unnecessary collisions and degraded perfor-

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mance [16]. In this case, a station is *masked* (station C in Figure 2) if it cannot interpret the control CTS frame from its neighbor (B), so its transmission can collide at B. Station C is masked, because a neighbor station (D) transmits to another one (E), which overlaps the CTS control frame sent from B to A. When C tries to transmit, it may collide with the ongoing transmission by A.

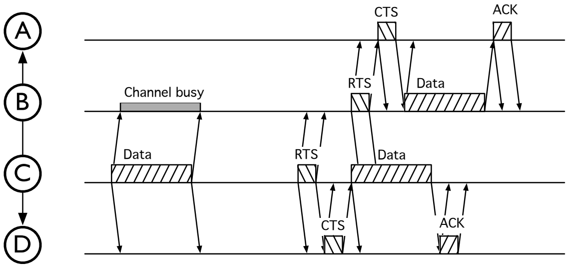

Figure 3. Problem of exposed stations.

Another type of problems may limit network performance, because stations have less transmission opportunity. In the problem of *exposed stations* [13] illustrated in Figure 3, when station C transmits to another station (D), an *exposed* station (B) cannot send its frame to a neighbor (A), because it receives a signal from (C). MACA proposes to solve the problem with the RTS/CTS option, but the solution relies on several assumptions (symmetrical links, the RTS frame does not set the NAV, *Network Allocation Vector*) and only works for a specific placement of stations with respect to their transmission and carrier sensing ranges: when C sends its RTS frame, the exposed station B will not receive the CTS frame sent by D, so it can proceed with its transmission (cf. Figure 3).

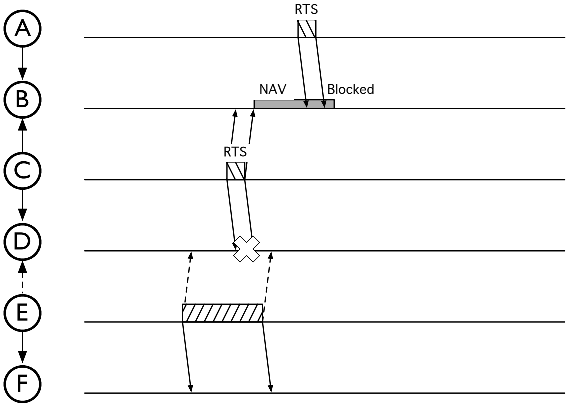

Figure 4. Problem of blocked stations.

The use of the RTS/CTS option may also lead to the problem of *blocked stations* [11,17] in which some stations become *blocked*, because they conform to the NAV of a neighbor station transmitted in the RTS and CTS frames. For instance in Figure 4, E transmits to F, so D is blocked and cannot reply to the RTS frame sent by C, thus C becomes also blocked; in the same way B is blocked, because it respects the NAV of the RTS frame sent by C and similarly A becomes blocked too. In this example, A and C see false collisions, so they enter contention resolution and double their contention windows, which further amplifies performance degradation.

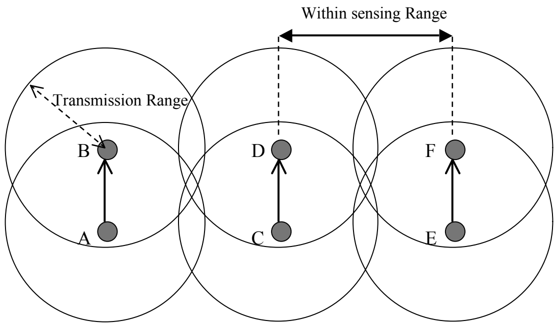

Figure 5. Three parallel pairs.

In this paper, we focus on an exacerbated problem of exposed stations that we class into the category of *blocked stations*. In this problem, three pairs of stations communicate in parallel (pairs are within the transmission range): $A \to B$, $C \to D$, $E \to F$ (cf. Figure 5). Immediate neighbors like A and C are within the carrier sensing range of each other, but they cannot directly communicate. If sending stations are greedy (they always have a frame to send), the external pairs gain much higher throughput than the internal pair C, D, which obtains almost null throughput. Such a spatial configuration of stations under 802.11 DCF leads thus to the starvation of the internal pair [5,6,7,8].

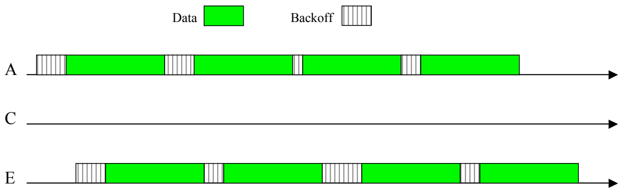

Figure 6. Starvation of the internal sender in the configuration of three parallel pairs.

The performance problem comes from the fact that C contends with two independent senders A and E, while A and E only need to compete with one sender C. Moreover, any successful transmission of an external sender forces C to wait during the EIFS (*Extended Inter Frame Spacing*) interval. In this way, the external senders monopolize the channel and C sees a permanently busy channel. We can observe this effect in Figure 6 (to simplify, we only show contention backoffs and transmissions, data and ACK frames included, without DIFS intervals). When stations A and E send their frames, the channel observed by station C is almost always busy, so C cannot transmit. If we want to give more throughput to blocked station C, the total throughput will decrease anyway, because during the time it sends a frame, the external stations may send two frames in parallel.

With the development of *wireless mesh networks*, performance problems due to spatial positions of nodes become increasingly important. Mesh networks aim at covering large areas with a high capacity communication infrastructure to convey user traffic between access points providing service to mobile nodes and gateways to the wired Internet. To meet their objectives, they need to exploit multiple parallel paths and efficiently use the available capacity of the wireless medium. The topology of a wireless mesh network usually depends on available places for suitable deployment and may vary from some regular structures such as grids to more irregular graphs, but the existence of dense topologies with multiple parallel paths leads to the performance problems due to spatial positions of nodes [14, 20] that we try to address in this paper.

In particular, we look for a solution to the problem of blocked stations that closely sticks to the standard 802.11 DCF access method, so that required modifications are minor. We propose a simple and efficient method called *Forced Transmissions*. It consists of detecting that a station is blocked by other stations and forcing a transmission. This results in a collision that increases the contention windows of blocking stations and leaves some channel time to the blocked station for transmitting. The blocked station forces a transmission according to some probability adjusted in function of the time spent waiting for the channel. The price for fixing the fairness problem is an increased number of collisions and a slightly lower overall throughput—we observe that our method increases the minimal throughput of the blocked station at the expense of the average and the total throughput of all stations. Unlike other solutions, our method gives the control of channel access to the blocked station whereas in other approaches, it is up to the blocking stations to decide when to yield the channel to the blocked station.

Our method also improves performance in a similar configuration with four pairs shown in Figure 7. In this asymmetric configuration, it is more difficult for the previously proposed solutions [4, 18] to sufficiently improve the throughput of the blocked station. Any proposal that tries to solve the problem of blocked stations needs to test this configuration and show that it provides sufficient throughput to the blocked station.

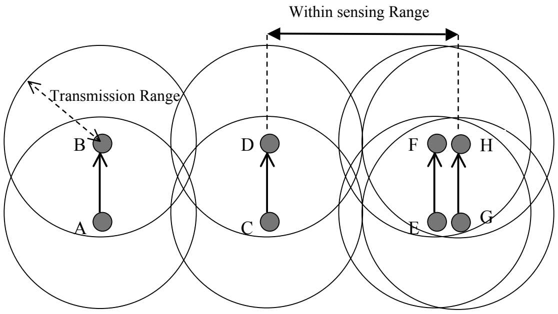

Figure 7. Four parallel pairs.

This paper is organized as follows: we start with the discussion of the related work in the next section. We then describe our proposal (Section 3) and report on simulation experiments to compare our method with DCF and PNAV, a previously proposed solution (Section 4). The last section concludes the paper and presents some future work.

2. Related Work

Spatial problems in wireless networks have already attracted a lot of attention and researchers have considered the problems of hidden and exposed stations for years. The problem of hidden stations was considered as the most crucial one and many solutions have been proposed mostly based on the dual tone approach [9, 11, 19]. Karn has proposed the RTS/CTS exchange for reducing the chances of the hidden and exposed station problems [13]. It was further improved in MACAW, but at the expense of reintroducing the exposed station problem [2]. The problem of masked stations was also studied in the context of ad hoc wireless networks [16].

The problem of blocked stations considered in this paper is a fairly recent one. Dhoutaut identified and studied the configuration of three parallel pairs in his PhD thesis [8]. He has shown that the spatial configuration leads to long-term unfairness between stations and to the starvation of the internal pair. Further analysis and solutions have followed [4, 5, 6, 7].

Chaudet *et al.* have proposed the first solution to this problem called *Probabilistic NAV* or PNAV [4]. It is based on the principle of occasionally giving to a blocked station an opportunity to access the channel. With an adjustable probability p_{nav}, a station sets a NAV of duration δ after a transmission to allow other stations to access the channel. p_{nav}, the probability of yielding the channel depends on its utilization by stations. The method solves the problem of three pairs, but in a more general situation of the asymmetric four parallel pairs shown in Figure 7, it does not provide a satisfactory solution. In this configuration, the internal pair $C \to D$ is almost always starved by the external senders, because E and G are unlikely to set the NAV at the same instant, so that A, E, or G may still monopolize the channel.

MADMAC proposes to address the spatial unfairness problem while maximizing global throughput [18]. The main idea is that an active station periodically senses the channel and when the channel is busy, it reduces its MAC throughput by introducing a waiting time before each frame to send. To cope with the problem of blocked stations in the configuration of three parallel pairs, it introduces the following adaptation: after x consecutive successful transmissions, the contention window for the $(x + 1)\mathrm{th}$ frame is set to $2CW_{\min}$ (x being a parameter of the protocol), to $4CW_{\min}$ for the $(2x + 1)\mathrm{th}$ transmission, and so on. Similarly to PNAV, the proposed method solves the problem of the three pairs, but does not provide a satisfactory solution for the asymmetric configuration in Figure 7 for similar reasons.

Finally, we want to point out two modified access methods that dynamically adapt the contention window to the current load in 802.11 networks: AOB (*Asymptotically Optimal Backoff*) [3] and *Idle Sense* [10]. The AOB adaptation mechanism uses two load estimates: the slot utilization and the average size of transmitted frames. Without providing a solution to the problem of blocked stations, AOB can serve as a reference method for comparing performance along with DCF, which was done for the PNAV method [4]. In *Idle Sense*, all stations maintain similar values of the contention window CW to benefit from good short-term access fairness. In this method, stations observe the mean number of idle slots between transmission attempts to dynamically control their contention windows. *Idle Sense* proposes an optimal operation of stations with respect to the fairness of channel sharing, but it does not provide a solution to the problem of blocked stations. Nevertheless, it may provide a good method for detecting that a station is blocked.

3. Forced Transmissions

We propose *Forced Transmissions*, a simple and efficient solution to the problem of blocked stations. When a station detects that it is blocked by others stations, it forces a transmission and causes a collision. This is an operation violating the principal rule of CSMA/CA stating that a station cannot transmit when there is an ongoing transmission on the channel. We are aware of this violation, however our simulations show that it results in an improved fairness of stations, i.e. the blocked station gains some channel access and blocking stations slightly lower their throughput.

The *Forced Transmissions* mechanism is simple—the blocked station monitors during a period of T_p whether the channel is monopolized by other stations or not. If so, it transmits during the current transmission of a blocking station with an adjustable probability p_{send}. The ongoing transmission will be thus corrupted and perceived by other stations as a collision. Figure 8 presents a timeline of events that occur when blocked station C forces a transmission (to simplify we do not show the DIFS intervals). As long as node C is transmitting its packet, nodes E and A cannot access the channel. When node C terminates its data transmission, they will wait for an ACK during interval ACK_TIMEOUT. Then, the next backoff will start after ACK_TIMEOUT + DIFS = EIFS—as nodes E and A cannot interpret the data frame sent by C, they should wait for the EIFS interval rather than DIFS before the next backoff.

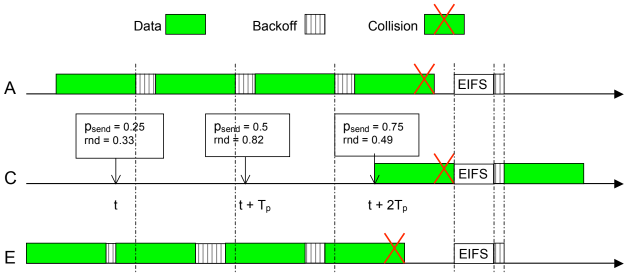

Figure 8. Transmission forced by blocked station C.

Two cases may then arise: first, the blocked station transmits during the data frame of a blocking station. Thus, all receiving stations enforce the EIFS interval (364μs for 802.11b) after the end of the transmission as presented in Figure 8. Second, if the blocked station transmits during the ACK frame, the transmitting blocking station defers during the interval equal to the ACK_TIMEOUT set to EIFS - DIFS. In both cases, all stations will synchronize after these long intervals and then they will contend for the channel. As blocking stations double their contention windows after the collision while in our method the blocked station uses $CW_{\min}$ for the next transmission, it has a greater probability of gaining access to the channel.

Figure 9 presents what may happen next. After having successfully sent its first frame, the blocked station is likely to capture the channel for the next transmissions: as the blocking stations are too far away from the blocked station to interpret its transmission, they will differ access by enforcing the EIFS intervals while the blocked station only waits for the DIFS interval and the backoff chosen from the contention window of $CW_{\min}$. This may even happen several times until the blocked station chooses a backoff longer than the sum of the EIFS interval and the backoff of the external stations (cf. Figure 9).

To maintain an acceptable collision rate, a blocked station uses a probabilistic mechanism to decide on the trans-

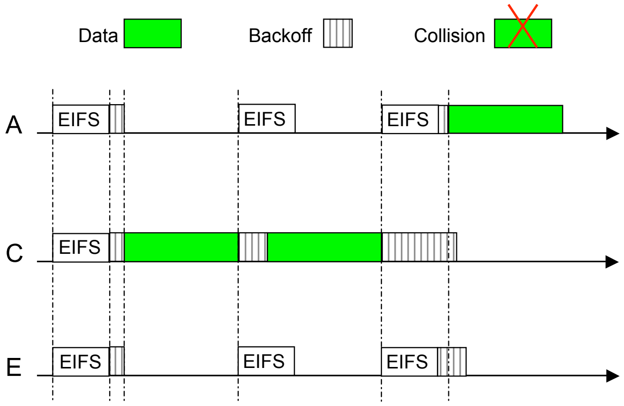

Figure 9. Transmissions after a forced collision.

mission that generates a collision: it transmits with probability p_{send} that depends on the interval during which the station has been blocked. To update p_{send}, a station periodically verifies if it is blocked or not. If it is blocked, p_{send} is increased by p_{step}, otherwise it is decreased by p_{step}.

The last detail of the proposed method is to define how a station detects whether it is blocked or not. One way is to observe the channel during a sufficiently long time to see if a station contends with at least two other stations. If during the interval of the transmission time plus DIFS, the idle time is less than DIFS, this means that the station is blocked. The *Idle Sense* access method [10] is particularly well adapted to detect such situations. If the contention window of a station does not oscillate around a value that depends on the network load, but rather it raises indefinitely, this means that the station is blocked. In our simulations, we use the first mechanism that tracks busy periods longer than the one corresponding to the transmission of the MTU plus DIFS.

Compared to other solutions such as PNAV, the advantage of our method is that the decision of reacting to bad spatial conditions is left to the blocked station. A station may use PNAV in two ways. Either it occasionally defers access for a NAV independently of the spatial situation of its neighbors or it uses DCF by default and switches to PNAV if there is a blocked station nearby. In the first way, the performance of the station is degraded even if there are no blocked stations in the neighborhood. The second way requires a signaling protocol through which the station learns that it is blocking another one and starts using PNAV. As the blocked station can hardly access the channel for communication, such signaling may even be impossible. When using *Forced Transmissions*, a station detects that it is blocked and reacts to gain the channel independently of what other stations do. If there are no blocked stations, there is no performance penalty.

4. Simulation and Results

We have implemented the proposed method by modifying the standard implementation of the 802.11 DCF in NS2 (version 2.29) [15]. The PHY and MAC parameters are those of IEEE 802.11b. We have considered a configuration of n parallel sender-receiver pairs as a generalization of the basic three parallel pairs. In this case, when a station uses DCF even pairs are starved and odd pairs monopolize the channel, for instance in the configuration of five parallel pairs, the throughput of the second and the fourth senders is almost null.

We assume that each sender behaves like a greedy CBR source sending 1000 bytes frames. A blocked station sends a data frame of size 1000 bytes to force transmission (it may also send a small dummy frame, but in our simulations, we have assumed the same frame size). We log the amount of data successfully received during the simulation process. The distance between the sender and the receiver is set to 150 m while the distance between neighbor senders is 350 m. The transmission and carrier sensing ranges are 160 m and 400 m, respectively. Each point reported in figures represents the average of 10 simulation runs, each run taking 30 seconds. We present simulation results for transmissions without RTS/CTS exchange, because the results with RTS/CTS are not significantly different.

The objective of our method is to guarantee a minimum throughput for blocked stations. Thus, we use the *minimum throughput* as the main metric for comparing our method with DCF and PNAV. To evaluate the degradation of global network performance, we also report the *average throughput* and the *total throughput* of all stations. The *maximum throughput* allows us to see how the blocking stations decrease their throughput to increase the throughput of blocked stations. We also use the Jain index to evaluate the fairness of the throughput obtained by stations [12].

Figure 10–13 show the simulation results for the configuration of n parallel pairs, $n = 1, 2, 3, 5, 7$. First, we can see that when the problem of blocked stations does not arise, i.e. for $n = 1, 2$, the performance of our method is exactly the same as for the standard DCF, because when all the stations in a wireless network can sense each other, our method degenerates to DCF. Unlike this desired behavior, PNAV incurs performance degradation, because a station occasionally relinquishes the channel so that potentially blocked stations can use it.

For the case of $n = 3, 5, 7$, when the problem of blocking stations does appear, we can observe that the minimum throughput under DCF is almost null and the blocking stations monopolize the channel by obtaining almost 4.9 Mb/s. Our method guarantees the minimum throughput of the blocked stations between 1.4 and 1.7 Mb/s depending on probability p_{step}, a value that barely varies with n (cf.

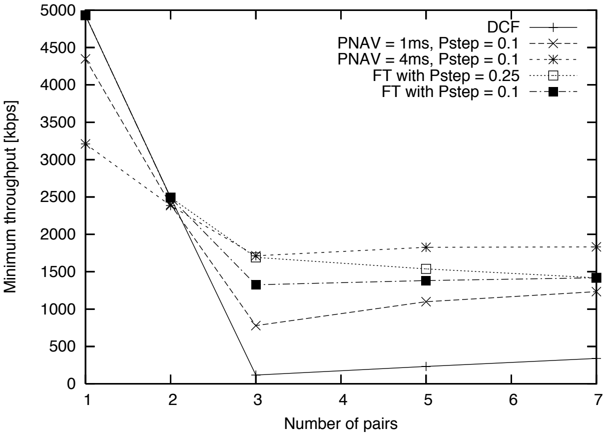

Figure 10. Minimum throughput, n parallel pairs.

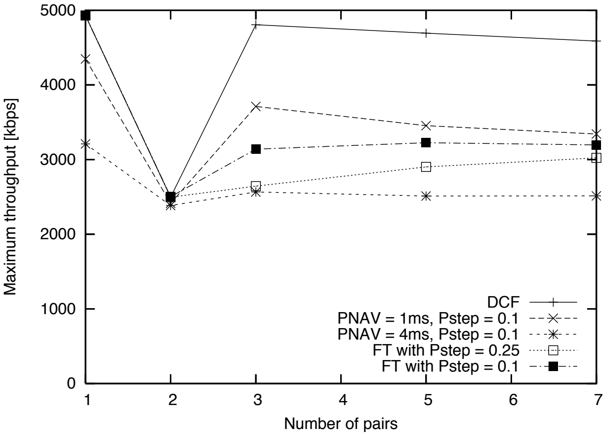

Figure 11. Maximum throughput, n parallel pairs.

Figure 10). Blocked stations obtains this improved minimal throughput at the expense of only a small decrease in the average throughput compared to DCF (e.g. for $n = 3$, 2.5 Mb/s vs. 3.2 Mb/s for DCF, cf. Figure 12). Recall that any method giving some transmission opportunity to the blocked stations decreases the total throughput. In the case of our method, the decrease remains reasonable (e.g. for $n = 3$, 7 Mb/s vs. to 9.5 Mb/s for DCF, cf. Figure 13). PNAV obtains the best results for a NAV of 4 ms—in this case, the minimal throughput is important along with the total throughput. Compared to our method, PNAV with a NAV of 4 ms presents a similar or better minimal throughput with almost equal total throughput.

Figure14 presents the Jain index of the throughput ob-

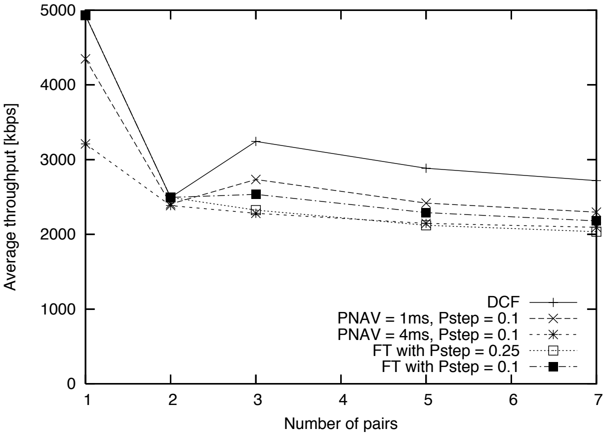

Figure 12. Average throughput, n parallel pairs.

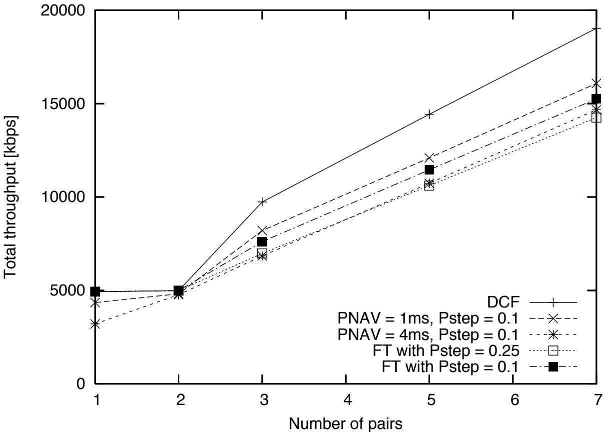

Figure 13. Total throughput, n parallel pairs.

tained by stations defined as [12]:

$$F_J = \frac{(\sum_{i=1}^{n} X_i)^2}{n \sum_{i=1}^{n} X_i^2} \qquad (1)$$

in the configuration of n parallel pairs. It is dimensionless and equal to 1, if all throughput X_i are equal. If $n-k$ values of X_i are zero, while the remaining k X_i values are equal and non-zero, the fairness index is k/n. We can see that for $n = 3$, the Jain index for DCF is around $2/3$, because one value of the throughput is close to zero. We can see that the index is between 0.9 and 1 for our method while the total throughput is still high. PNAV obtains even slightly better results, especially for $n = 5$ and 7.

Figure 15–18 show the simulation results in the asymmetric configuration of four parallel pairs (cf. Figure 7): the minimum throughput experienced by the blocked station C, the maximum throughput obtained by one of the blocking

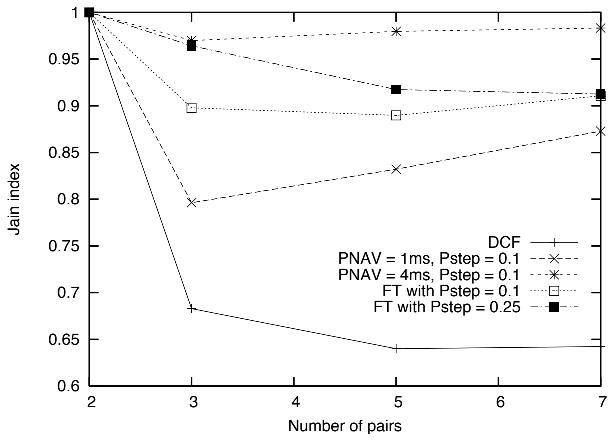

Figure 14. Jain index for n parallel pairs.

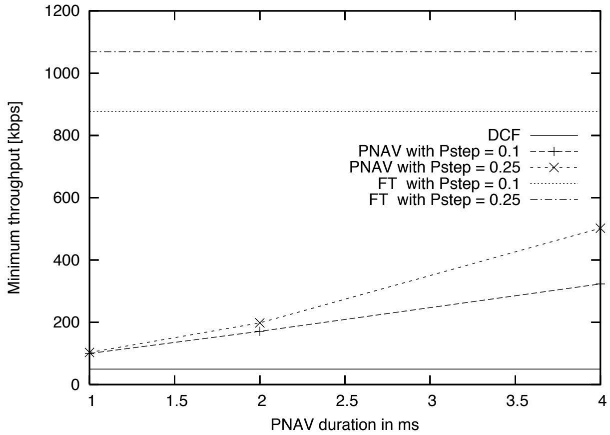

Figure 15. Minimum throughput, four pairs.

stations (A), the average and the total throughput. As previously, we can observe that the minimum throughput under DCF is almost null and blocking station A monopolizes the channel by obtaining almost 4.9 Mb/s. Under our method the blocked station obtains much better minimal throughput than in the case of PNAV with NAV of 4 ms (cf. Figure 15). This is achieved at the expense of only a small decrease in the average throughput compared to DCF as shown in Figure 17 (between 1.8 and 2 Mb/s vs. 2.5 Mb/s for DCF). The total throughput remains important though less than that for DCF (e.g. 7.2 Mb/s vs. 10 Mb/s for DCF, cf. Figure 18). In this configuration, PNAV does not perform as well as for n parallel pairs: the minimal throughput is lower than in our method while the total throughput is almost the same for our method and for PNAV with a NAV of 4 ms.

Figure19 presents the Jain index in the asymmetric configuration of four pairs. We can see that the index is better for our method than that for DCF and for PNAV with NAV of 4 ms while the total throughput remains similar to PNAV (cf. Figure18).

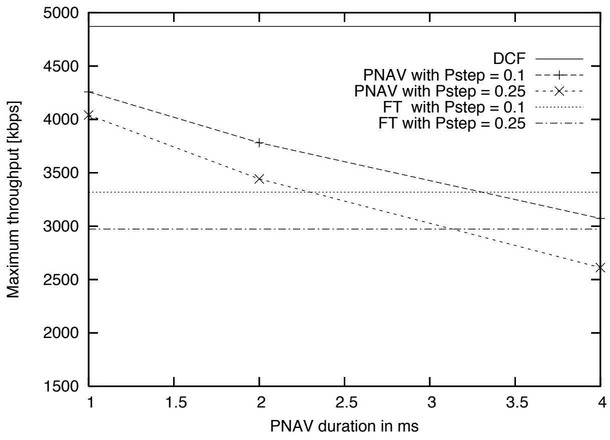

Figure 16. Maximum throughput, four pairs.

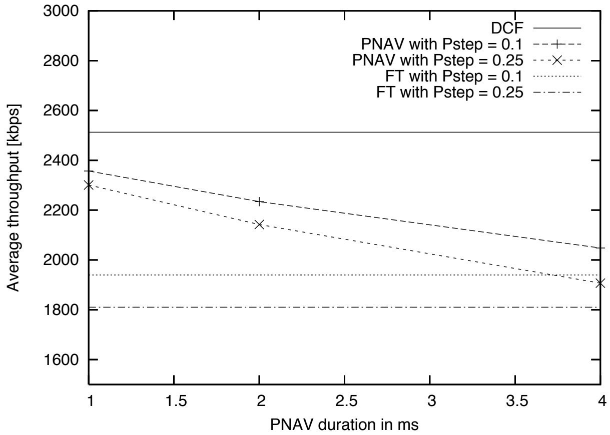

Figure 17. Average throughput, four pairs.

5. Conclusion and Future Work

In this paper, we have proposed *Forced Transmissions*, a simple and efficient solution to the problem of blocked stations. It consists of detecting that a station is blocked by others stations and forcing a transmission. This results in a collision that increases the contention windows of blocking stations and leaves some channel time to the blocked station for transmitting. The blocked station forces transmission only with some probability adjusted in function of the time spent waiting for the channel to become idle.

Our simulations show that the proposed method increases the minimal throughput of the blocked stations in the configuration of n parallel pairs. The price for fixing the fairness problem is an increased number of collisions and a slightly lower overall throughput. PNAV provides a good solution to the problem of blocked stations only if its NAV

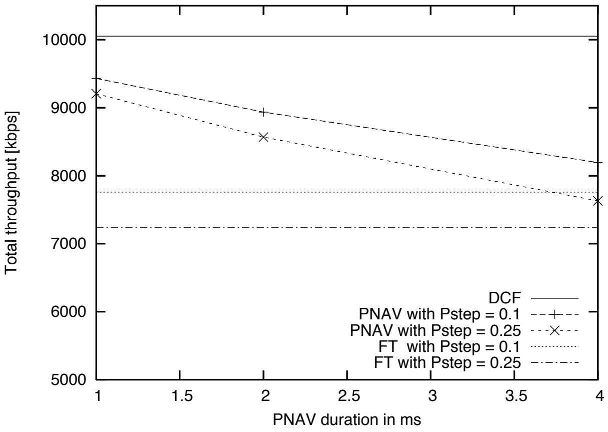

Figure 18. Total throughput, four pairs.

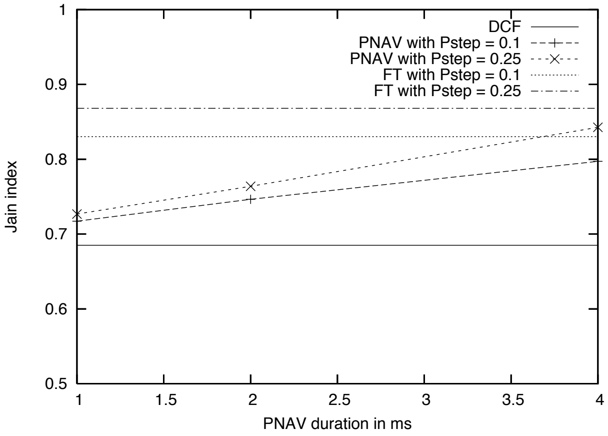

Figure 19. Jain index for asymmetric four pairs.

duration is short, so that the total throughput remains high. For the configuration of n parallel pairs PNAV with a NAV of 4 ms provides slightly better overall performance than our method. However, in a particular configuration of four asymmetric parallel pairs, our method outperforms PNAV.

Our method presents a nice feature: the decision on reacting to bad spatial conditions is left to the blocked station. As described previously, a station operating under PNAV needs to defer access periodically even if there is no blocking stations nearby, thus its performance is lower; or it requires a signaling protocol so that when a blocked station detects its situation, it notifies its neighbors asking for using PNAV. When using *Forced Transmissions*, a station decides itself that it is in an abnormal situation and reacts independently of what other stations do. If there are no blocked stations, then there is no performance penalty.

The proposed method is fairly general and can be deployed in any multi-hop environment (e.g. wireless sensor networks, wireless mesh networks, or wireless ad-hoc networks) in which the problem of blocked stations and their starvation may appear.

There is a still an open issue of a good method for deciding whether a given station is blocked. Our method based on observing the channel for a sufficient time and detecting an idle interval greater than DIFS works correctly in the studied configurations of parallel pairs of senders and receivers, however it may fail in a general scenario of a multi-hop wireless network. One direction to explore is to consider the waiting time before sending a frame—if it is too long, then the station is probably blocked. We plan to study this idea in the context of multi-hop wireless networks.

Acknowledgments

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