



## **Fragment Adaptive Reduction: Coping with Various Interferers in Radio Unlicensed Bands**

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This paper studies the impact of common interferers found in unlicensed bands on 802.11 and other CSMA systems. First, we describe those interferers and the MAC techniques used to combat them. Then, we present Fragment Adaptive Reduction, a scheme to overcome the effect of non CSMA repetitive interferers, and its implementation in the SWAP protocol. We also describe a simple model of domestic microwave oven interferences. We finish by some exhaustive simulations of the impact of microwave oven and other interferers on 802.11, which illustrate the benefits of the Fragment Reduction scheme.

# Fragment Adaptive Reduction : Coping with various interferers in radio unlicensed bands

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## 1 Introduction

When designing a radio system, it is important to know in which kind of environment the system will operate. Some frequency bands are dedicated, but others are unlicensed or subject to interferences or background noises. Of course, the system needs to adapt to the actual conditions in the band.

The physical layer is already doing a lot to combat those interferences, through clever modulation techniques (Spread Spectrum, OFDM) and reception techniques (diversity, equalisation). But, some MAC layer schemes can also improve performance and avoid losing connectivity.

## 2 Interferences at 2.4 GHz

Most of the current generation of Wireless LANs are operating in the 2.4 GHz band, and interferences in this band represent a good example of what can be expected when designing a Wireless LAN.

### 2.1 The 2.4 GHz ISM band (unlicensed)

The frequency band between 2.4 and 2.47 GHz has been allocated in most countries for unlicensed operation of devices conforming to the ISM band rules.

The fact that the band is unlicensed means that the deployment of such systems doesn't require any planning permissions, so system may be deployed in an anarchic way and interferer with each other if they are within range.

The ISM rules allow a wide variety of products to operate in the band, such as standard 802.11 wireless LANs [1], fast hopper systems (such as BlueTooth [3]), cordless phones or TV redistribution systems, which make use of it in different ways even if they obey the same basic rules.

### 2.2 Microwave interferers

The 2.4 GHz band is precisely the frequency band used by microwave oven to heat the content of the oven. Those oven are enclosed and regulated, but significant radiations leak from microwave ovens that interferer with other systems.

Domestic microwave ovens are more predictable and easier to characterise (we describe a model of it in *section 5.4.3*). However, industrial microwave ovens (like in factories) may be much stronger and wider emissions, and a few microwave ovens on different phases might create permanent interference in the band.

## 2.3 Standard channel impairments

The 2.4 GHz band is subject to the same kind of conditions as any other bands, and those are well known...

Attenuation is due to the distance and obstacles on the path between transmitter and receiver, a good sensitivity allows the system to work at higher attenuation.

Fading is due to obstacles and reflections, the channel alternating between "good" and "bad" state. Antenna diversity significantly reduces the effect of fading.

Delay spread is due to the different components of the signal not arriving at the same time at the receiver, it is overcome by using equalisation and OFDM.

## 2.4 The 5 GHz UNII band

Compared to the 2.4 GHz band, the 5 GHz band doesn't contain any microwave oven radiations, but the rules are much more open, allowing in theory a much wider type of systems, so interference is less predictable.

At this point, because there is virtually no product deployed, it is difficult to say if the 5 GHz band is better than the 2.4 GHz band with respect to interference...

## 3 MAC level techniques

The task of the MAC layer is to present an interface and behaviour that suits the higher layer, such as TCP/IP. This means that we must overcome all the effects of interference that are not already dealt with at the physical layer.

### 3.1 MAC retransmissions

Because FEC is very inefficient to overcome fading and interferers (errors are clustered), most wireless LANs use some form of retransmission at the MAC level, usually a stop and go mechanism using immediate MAC level acks.

Retransmission eventually overcomes all kind of interference. Other techniques are only minimising the amount of retransmissions and the overhead.

There is only one exception : some repetitive interferers may hit all retransmissions of a packet, up to the point where the MAC drops it (see *section 6.1*).

### 3.2 Carrier sense

The goal of carrier sense is to detect when transmissions or interferences are happening on the channel, to withhold of

our own transmissions until a better time (we also avoid corrupting other people transmissions). Carrier sense uses the measure of energy strength at the antenna.

CSMA/CA [1] is based on carrier sense and a slotted contention, the initial number of slots fixed, with exponential increase. It would benefit from a distributed adaptive scheme [6] to select the optimal initial contention window (CW<sub>min</sub>).

Most systems also perform virtual carrier sense through the use of RTS/CTS [4], which improves carrier sense information, eliminates hidden node effects and reduces the penalty of collision (shorter collisions).

Carrier sense and RTS/CTS are very efficient when interferers are also CSMA/CA based, but much less with microwave ovens or non CSMA systems.

### 3.3 Frequency diversity

Changing frequency improves the probability of getting away from an interferer (or coming back to it). To minimise the number of retransmissions of a packet, we want to increase the number of frequencies used by those retransmissions. For Frequency Hopping systems, this is usually done through reducing the dwell size [11].

### 3.4 Packet Scheduling

Using packet scheduling can improve the temporal diversity of the retransmissions. By waiting a bit of time, we improve the probability that the fade has gone or the interferer emissions are over.

Systems based on TDMA and Polling can naturally control the scheduling of packets. The contention of 802.11 has a memory effect (nodes having waited the most have a lower count of slots), so tend to schedule packets as well, but this supposes that there are multiple active nodes at once.

Channel State Dependant Packet Scheduling [5] complements this by having a node scheduling packets based on destination addresses. A much simpler version of it is, after a failure, to just pick and transmit the first packet in the transmit queue with a different destination address, before retransmitting the failed packet (without any attempt at scheduling). Of course, this supposes that the node has traffic for many other nodes and not just a single destination.

### 3.5 Auto rate selection

Increasing the bit-rate decreases the range and vice versa, so most products implement multiple bit-rates. When transmitting a packet, the node tries the fastest rate and falls back to lower rate (more robust) in case of failures. This is usually very efficient to overcome attenuation and pretty good with fading.

But, this is not always the best strategy, because decreasing the rate increases the transmission time. If the packet was lost because of an interferer, increasing the transmission time will increase the probability of collision, which is not what we want.

In fact, auto rate selection algorithm should not only take into account packet failure but also received signal strength and RTS/CTS failures to make the decision (see section 4.4).

## 4 Fragmentation and adaptive fragmentation

All the MAC techniques described above are very efficient at mitigating the effect of range, fading and other nodes using CSMA. Retransmissions overcome most the effect of microwave ovens and non CSMA systems, however this is not very efficient, and some packets might get dropped by the MAC due to repetitive corruption of all retransmissions.

### 4.1 Fixed fragmentation (802.11)

The problem with microwave oven and non-CSMA systems is that they emit without warning while our transmissions are ongoing. Of course, the probability of collision with such a system is proportional to the size of our transmissions. As we can't change the size of IP packets, we need to use fragmentation to split those large IP packets into small independent transmission.

802.11 [1] provides a very efficient fragmentation mechanism, where fragments are sent as a contention free burst. However, fragmentation is fixed (no variation of fragment size) and adds a significant overhead when we don't need it (no interferers), so most 802.11 products don't use it.

### 4.2 Adaptive fragmentation

However, there is absolutely no requirement for the fragment size to be fixed, and we have already shown that 802.11 could support adaptive fragmentation [11].

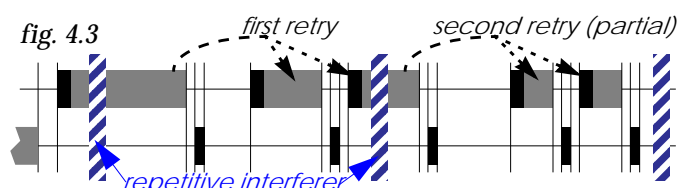
When there is no interferer, packets are sent unfragmented to minimise overhead, and in presence of repetitive interferer the fragment size is reduced until the packet can fit between the bursts of the interferer. The scheme doesn't make any assumption about the nature of the interferer and just adapts to it, so that it works well for all kinds of interferers.

There are two types of adaptation, long term adaptation and short term adaptation. Transmission conditions and interferer emissions do change a lot and quickly, especially with frequency hopping, which usually defeats long term adaptation. The lifetime of the packet in the system is short, so if we want every packet to benefit from it and not to loose any packet, we need short term adaptation.

### 4.3 How to reduce fragments

The easiest solution to reduce fragments is to link the maximum fragment size to the number of transmission failures (acks not received) experienced by a packet, so having an exponential number of fragments (see fig. 4.3).

In our scheme, each packet is initially transmitted without fragmentation and for each failure the fragment threshold is divided by two until reaching the minimum adapted fragment size (to prevent ridiculously small fragments). We are only reducing the fragment threshold, so small packets will be fragmented only if and when the fragment threshold gets lower than their size.



However, we can't assume that packet failures are always due to interferers, in fact the contention process is the source of many collisions [10]. Because of the exponential increase of the contention window, the first failure is very likely to be a contention, and subsequent failures more likely to be due to interferers. Therefore, a good strategy is to postpone fragment reduction after the second or third failure.

In our model, we tried both after 1 failure (*Autoreduce 1*) and after 2 failures (*Autoreduce 2*), which work as follows :

**Fragment threshold (2048 maximum packet size)**

Packet failures	Autoreduce 1	Autoreduce 2
0 - Initial transmission	2048 B	2048 B
1 - After one failure	1024 B	2048 B
2	512 B	1024 B
3	256 B	512 B
4 or more failures	256 B	256 B

Now, if after reducing fragment size a fragment is successful, we could assume that we have reached the correct fragment size. So, I have simulated a modified scheme, where when a fragment is successful, fragment reduction is held off for the next failure and resumed only at the second failure after this successful fragment. In practice, this didn't make much difference, so I only present schemes that always reduce fragment size on failure (apart from the very first one).

**4.4 Interaction with other schemes**

Decreasing the bit rate increases the transmission time (see section 3.5), so the reduction scheme must compensate for that effect. For example, when dividing by 2 the bit-rate, we should divide the fragment threshold by 4 (and not by 2).

My current model doesn't distinguish between RTS/CTS failures and packet failures, because I wanted to have results valid also for networks not using RTS/CTS. Distinguishing the two types of failure can significantly improve the performance of fragment reduction (and adaptive bit rate). If the RTS/CTS fails, it is likely a contention issue, so no action should be taken. However is the main transmission protected by the RTS/CTS fails, this is likely a interference issue, and fragment size should be reduced (and bit-rate as well).

In another paper I present adapting fragment size to fit in the dwell [11]. These two adaptation schemes are compatible, in fact my simulations implement both adaptive schemes.

**4.5 SWAP fragment reduction implementation**

The SWAP protocol [2] offers 1 Mb/s and 2 Mb/s bit-rate and use a CSMA/CA protocol without RTS/CTS. Fragment reduction is part of the standard and combined with bit rate adaptation, following these patterns :

**Maximum fragment sizes (SWAP)**

Packet failures	1 Mb/s	2 Mb/s
0 - Initial transmission	512 B	1024 B
1 - After one failure	512 B	1024 B
2 - <i>reduce bit-rate</i>	256 B	<i>Forbidden</i>
3	128 B	<i>Forbidden</i>
4 or more failures	64 B	<i>Forbidden</i>

**5 Simulation model**

The models used for these simulations have been carefully chosen to be simple and realistic and to illustrate the impact of the fragment reduction scheme and interferers.

**5.1 MAC model**

The MAC model includes a fairly complete 802.11 channel access mechanism. This model is based on an 802.11 backoff (slotted exponential contention). All management functionalities have been removed to keep the model simple.

The model implements MAC level acknowledgments and retransmissions. The model includes RTS/CTS (for packets larger than 250 B), dwell adaptive fragmentation and when stated fixed fragmentation or fragment reduction. The minimum adapted fragment size is 256 B.

By default, the maximum packet size is 2048 B. All other defaults parameters conform to 802.11 [1] (CWmin = 16 ; SIFS = 28 μs ; Slot = 50 μs ; Hop delay = 224 μs ; Headers = 50 B ; Ack/RTS/CTS = 30 B ; MaxRetries = 7). Some simulations use different values for some of those parameters.

**5.2 Channel model**

The channel model is a simple radio channel model, including node to node attenuation (80 dB by default), Rayleigh fading (calculated on a per packet basis) and antenna diversity. The bit rate is 2 Mb/s, the transmitted power is +20 dBm, and the sensitivity is -80 dBm (in a Gaussian channel). The system is Frequency Hopping with 80 channels of 1 MHz, by default the dwell size is 200 ms.

**5.3 Traffic models**

Various traffic models are used through the simulations. More information on the traffic models and their behaviour may be found in my previous papers [9].

**5.3.1 Random traffic model**

The *random* traffic model generates packets following a Poisson process (random interarrival time with negative exponential distribution) and all packet sizes are uniformly distributed in  $J0 ; max\ packet\ size$ .

**5.3.2 TCP2 traffic model**

The *TCP2* traffic model is a simple bimodal distribution to simulate TCP traffic. Each packet is either big (maximum size) or small (40 B), the probability of being small is 1/2. Packets are sent as fast as the link can manage (saturated).

**5.3.3 TCP1 traffic model**

The *TCP1* traffic model simulates a node sending a large amount of data over a protocol such as TCP. The sender sends packets of the maximum size as fast as possible.

The receiving node acknowledges incoming packets with short packets (40 B). The probability of small packet is 1/3 (the receiver sends a small packet for each received packet with a probability 1/2).

**5.4 Interferers models**

The main interferer considered is of course the microwave oven, but other interferers are simulated as well.

### 5.4.1 CSMA Frequency Hopping interferer

The Frequency Hopping interferer is in fact just another node, using the same MAC protocol and a random traffic model (saturated). To simulate frequency hopping (with adjacent channel interference), for each dwell the interferer has a probability  $5/80$  to be present in our channel (we assume the receiver bandwidth of our nodes to be 5 MHz).

To worsen the model, the exponential backoff has been removed, the model starts first in the dwell, the pathloss to simulated nodes is reduced to 60 dBm, and the model doesn't implement RTS/CTS or fragmentation.

### 5.4.2 CSMA Direct Sequence interferer

The direct sequence interferer is the same as the Frequency Hopping interferer, with probability of presence being  $22/80$  and transmitted power reduced by  $22/5$ .

### 5.4.3 Domestic microwave oven

Our aim is not to represent accurately the effect of a microwave oven interferer on the physical layer but on the MAC layer, so this is why we accommodate a relatively coarse model. The model is based on measurements of real domestic microwave ovens at HP and Symbionics, on NTIA reports [8] and on analysis of those measurements.

A microwave oven is composed of a magnetron, powered by the AC mains, and producing the radiation. Therefore, emissions have a 50 % duty cycle based on the mains period (60 Hz in the US). Each emission starts by a transition phase, where the emissions swipe across the band, before the magnetron settle on its main frequency, and again a transition phase before shutting off. Those transition phases are the most damaging, because they pollute a wider band, albeit at a lower power, while the main burst is very localised.

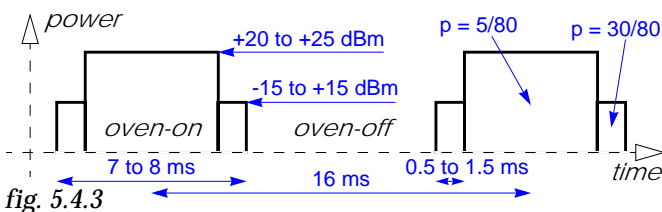


fig. 5.4.3

The model of microwave oven used in the simulations is described in fig. 5.4.3, with timing, signal strength and probability of presence selected using uniform random variables in the described range. Power and timing are calculated for each burst, probability of presence for each dwell (this hack is used to simulate our own frequency hopping by making the interferer come and go). The pathloss between the microwave and the system is 60 dBm.

### 5.4.4 TDMA Fast Frequency Hopper Interferer

We can not assume that all systems operating in the unlicensed band will conform to 802.11, especially that the rules for low power transmission are relaxed. So, we designed another model based on a fast frequency hopper [3].

The model simulates a TDMA link between two nodes in close proximity. The dwell size is 625  $\mu$ s, in each dwell the model transmits a 366  $\mu$ s packet at 0 dBm power (1 mW) and then hop. The hopping rate is effectively 1600 hops/s. Each packet has a  $5/80$  probability to be in our channel.

## 6 Simulation results

Some simulations have been performed to study the impact of microwave ovens. All the simulations have been implemented under the Bones® Designer™ environment.

### 6.1 Influence of packet size

With a repetitive interferer such as a microwave oven, the maximum packet size is very important. First, we want packets to fit between the bursts, and reducing packet size reduces the probability of collision.

We simulate four systems in presence of the microwave oven interferer, a standard 802.11 system (*Standard*), the same system with fixed fragmentation (*2 fragments*), and two fragment reduction schemes (*Autoreduce 1*: reduce fragment size on first failure; *Autoreduce 2*: reduce fragment size on second failure). Each system simulates a TCP transfer between two nodes using the TCP1 model. For reference, the standard 802.11 system is simulated without microwave oven interferer (*No MWO*).

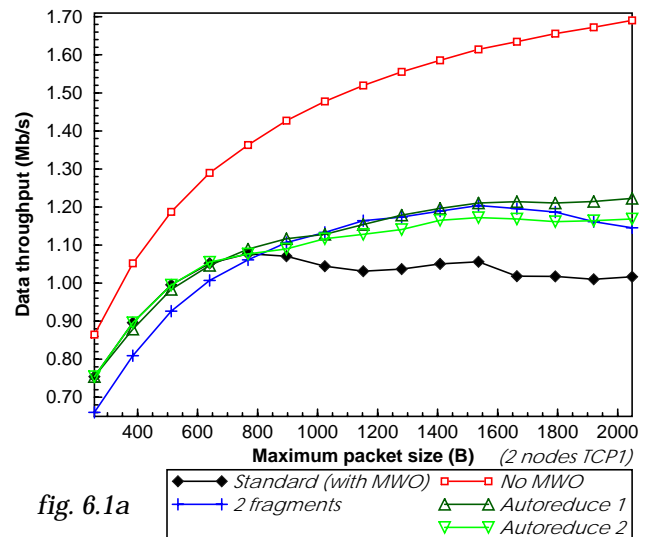


fig. 6.1a

The first curve shows the throughput of each system at different packet sizes (fig. 6.1a). Fragmentation schemes can reduce the impact of the interferer in the band. Fragment reduction always gives the best results whereas fixed fragmentation needs to be tuned up to the interferer.

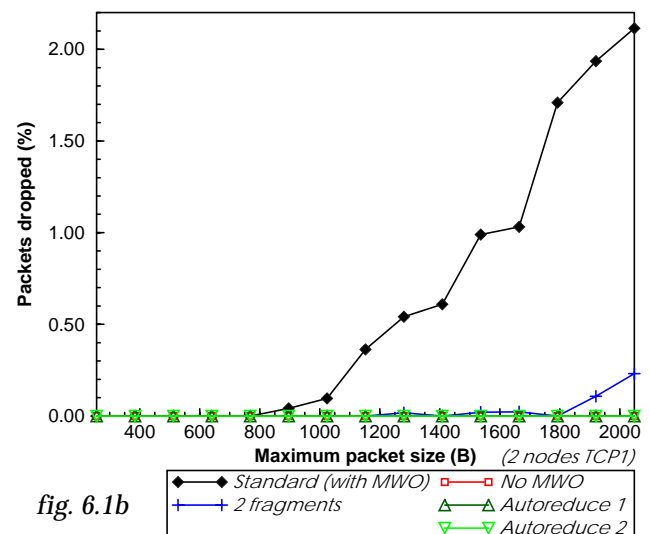


fig. 6.1b

But, the most important measure is the percentage of packets dropped by the MAC. All MACs include up to 7 MAC level retransmissions for every packet, but if the packet fails 8 times it is dropped. TCP/IP is very sensitive to packet drop (it assumes congestion), some small packet drop rate (like 1 %) can reduce significantly the throughput [7], and the loss of some specific packets can break the connectivity.

This measure is also important for multimedia traffic. While the node is “locked” retransmitting the same packet 8 times (around 100 ms), other packets wait in the queue and their latency is impacted. In fact, when the dropping rate is high, the MAC is likely to be blocked for the whole dwell time (200 ms). So, latency is linked to packet drop rate.

At standard packet sizes, the *Standard* system performs poorly (see *fig. 6.1b*), because large packets are repetitively hit by the interferer (the channel is blocked). But even when packet size is half the interval between burst (1000 B) we start to see losses. By automatically reducing the fragment size (*Autoreduce*) we can make sure that packets eventually can get through between interferer bursts and no packets are lost.

### 6.2 Influence of dwell size

In the previous simulations, packets get dropped because the system stays for a long period of time on the same

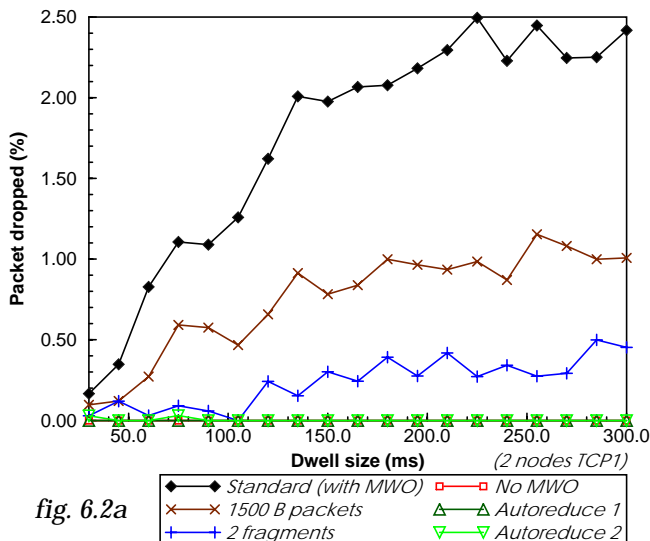


fig. 6.2a

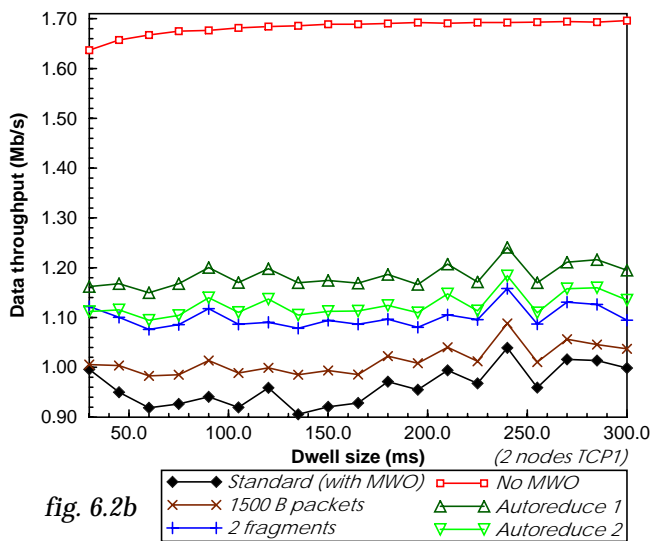


fig. 6.2b

frequency as the interferer. As the system is Frequency Hopping, by reducing the dwell size we minimise the length of time we have to cope with the interferer.

To verify this, we simulate our 5 previous systems with different dwell size (at the maximum packet size, 2048 B). We add another system with a reduced packet size (*1500 B packets*). Reducing the dwell reduces the number of packet dropped by all systems (see *fig. 6.2a*). Of course, only fragment reduction can prevent all losses.

Some people have claimed that reducing the dwell size increase the throughput, and that fast hopper systems [3] should perform better. The hopping rate doesn't change the probability of hitting frequencies polluted by the interferer, as can be seen on the throughput curves (see *fig. 6.2b*).

### 6.3 Influence of contention

Interferers are not the only cause of packet losses, the contention process also contributes to losses [10]. In this simulation, a network of nodes using the *TCP2 traffic model* is used with an increasing number of active nodes. The same MAC configurations as previously are simulated, but this time without the microwave oven interferer. Two additional systems with the microwave oven are simulated (*Standard with MWO* and *Autoreduce 1 with MWO*).

The first thing to notice is that fragmentation does reduce the network performance when no interferer is present in the band (see *fig. 6.3*). Fixed fragmentation has a constant penalty (*2 fragments*), whereas the fragment reduction schemes overhead increases with the amount of contention.

Because it reduces fragments only after the first retry, *Autoreduce 2* performs better than *Autoreduce 1*, which confirms our analysis (see *section 4.3*). Of course, distinguishing failures of RTS/CTS (mostly due to contention) and failures of packets (mostly due to interferer) would allow to remove most of this overhead and the need for the *Autoreduce 2* scheme.

Another interesting thing is that the performance of *Standard 802.11 with MWO* does increase with a higher number of nodes. A higher number of active nodes does a better scheduling of packets and takes advantage of frequency

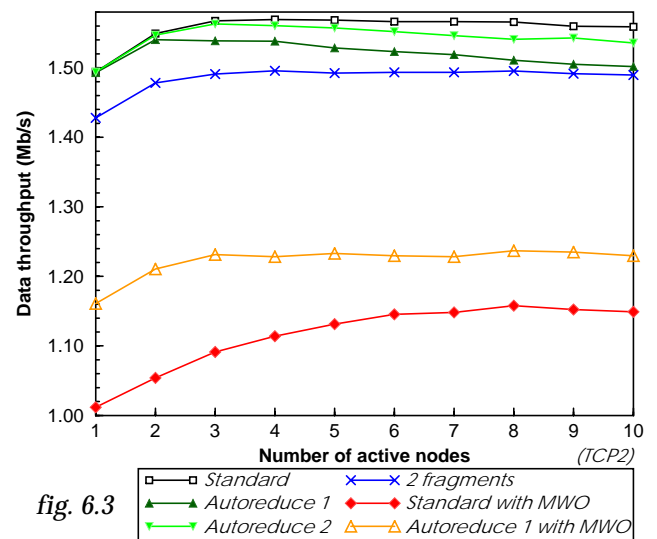


fig. 6.3

diversity (retries are separated by packets from other nodes and pushed to the next hop, see section 3.4).

## 6.4 Other interferers

Microwave interferers are not the only kind of interferers in the 2.4 GHz band. So, we have simulated our system in presence of different types of interferers : a CSMA frequency hopping system (*with FH*), a CSMA direct sequence system (*with DS*), a microwave oven (*with MWO*) and a TDMA fast frequency hopper system such as BlueTooth (*with BT*).

The system studied is a TCP transfer between two nodes using the *TCP1 traffic model* and 1500 B maximum packet size. Each interferer is placed at 60 dBm of our system, and the distance between the two nodes varies from very close (50 dB attenuation) to the limit of the range (95 dB).

The best way to deal with other CSMA systems is to use CSMA (and RTS/CTS), and the degradation in the cases *With FH* and *With DS* is quite low (see fig. 6.4). The only way this impact could be greater is if the interferer use a much smaller contention slot or having multiple nodes instead of one. Adding Fragment Reduction may reduce performance due to the increased contention (see section 6.3).

Results with a microwave oven are similar to previous sections. When the two nodes get closer, they gradually capture packets. It's because most of the packet corruptions are due to the wideband transition phase which are relatively low power, so not strong enough to corrupt packet received at high level (in my model, the capture starts to occur when the wanted signal is around 22 dB stronger than interferers).

The fast frequency hopper (*With BT*) brings a lot of performance degradation of the system. The system emit short bursts all over the frequencies, making sure that any packets long enough will get hit. Fragment Reduction (*Autoreduce 1 with BT*) does help a lot, but not as much as in the microwave oven case, because the fast frequency hopper cycles frequencies so fast. Using a periodic model for frequency hopping instead of the current random model would probably help fragment reduction to perform better.

When the two nodes get closer, they of course can capture most packets because the fast hopper is low power, but they

need to get really close. Note that in this case, Fragment Reduction do perform worse, because hits tend to be occasional, so there is no benefit from fragmenting.

## 7 Conclusions

As opposed to dedicated frequency bands, the unlicensed bands used by common wireless LANs is subject to various kind of interferences. Current techniques are efficient to mitigate the effect of propagation (attenuation, fading), background noises and other CSMA/CA systems.

However, 802.11 and most CSMA/CA protocols don't deal very efficiently with the interferences produced by microwave-ovens and fast frequency hopping systems.

By automatically reducing fragment threshold when transmission fail, a system can avoid dropping packets in presence of repetitive interferes and significantly improve performance. This simple technique can be easily implemented in 802.11 and most CSMA/CA systems.

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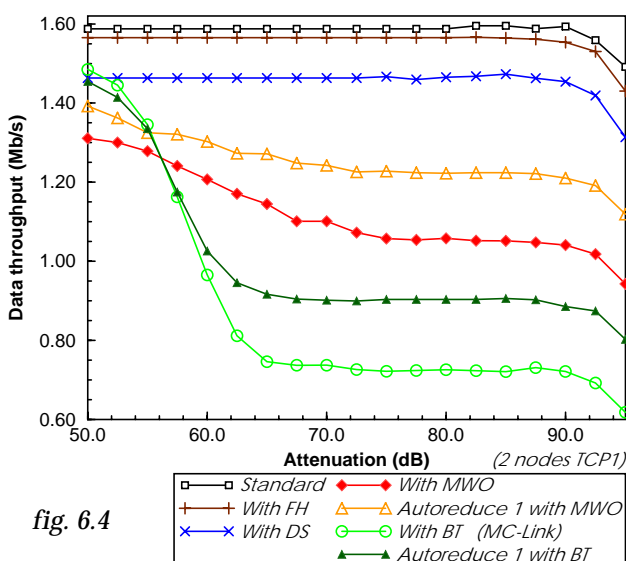


fig. 6.4