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Throughput optimization of a multihop CSMA mobile ad hoc network

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Abstract: A lot of research has been done in routing protocols for ad-hoc network especially at the IETF in the working group MANET. These studies have mostly focused on the conception of routing protocols for mobile radio networks where the radio channel capacity is generally limited. The present article does not target the study of these routing protocols but investigate how carrier sense multiple access (CSMA) protocols can be tuned to optimize the network throughput. We build two models of interference of simultaneous transmissions and conduct simple computations to guide our optimizations. The first interference model only considers the strongest interferer as the second one takes into account all the contributions. We use simulations to test our optimizations results. The result of this paper is a guide to optimize CSMA multihop networks; the obtained results show that a good tuning of CSMA protocols in term of carrier sense threshold and transmission range allows one to gain a lot of network throughput (up to 90% depending on scenarios)

Key-words: Ad hoc Network, performance evaluation, CSMA protocol, routing protocol, interference, IEEE 802.11, hidden nodes, spatial reuse.

(Résumé : tsvp)

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Optimisation du débit d'un réseau mobile ad hoc CSMA multisaut

Résumé : De nombreuses études ont été menées sur les protocoles de routage dans les réseaux ad hoc et spécialement à l'IETF dans le groupe de travail MANET. Ces études concernent principalement la conception de protocoles de routage pour des réseaux mobiles radio où la capacité du canal est généralement limitée. Cet article ne concerne pas l'étude de ces protocoles de routage mais vise à optimiser le débit du réseau. Nous construisons deux modèles simples d'interférence des transmissions simultanées et nous conduisons des calculs simples pour guider nos optimisations. Le premier modèle ne considère seulement que la plus forte interférence alors que le second prend en compte toutes les contributions possibles. Le résultat de ce papier est un guide pour optimiser les réseaux multisaut CSMA. Nous utilisons des simulations pour tester nos optimisations. Les résultats obtenus montrent qu'un bon paramétrage des protocoles CSMA en terme de seuil de détection de porteuse et de portée permet de gagner jusqu'à 90% de la bande passante du réseau suivant le scénario.

Mots-clé : Réseau ad hoc, évaluation de performance, protocole CSMA, protocole de routage, interférence, standard IEEE 802.11, noeuds cachés, réutilisation spatiale.

1 Introduction

The major progress in wireless modem has opened a new technical area around Wireless LAN e.g. IEEE 802.11 [10], HiPERLAN [9], Bluetooth. Mobile ad hoc networking is a new research area which has benefited from this emerging wireless technology. Contrary to LANs where the propagation constraints usually do not impose stringent restrictions, in WLANs the transmission range is very limited. The network connectivity has to rely on a routing algorithm which allows packet exchange between nodes not directly within radio reach, see figure 1. Thus, in ad-hoc networks, the routing issue is a very important subject. This area has received a strong interest from the academic world. At the Internet Engineering Task Force (IETF) a new working group MANET (Mobile Ad hoc NETwork) has started in 1997. This group has produced numerous routing proposals [1, 2, 3, 4, 5]. A lot of publications have compared various routing algorithms for ad-hoc networks.

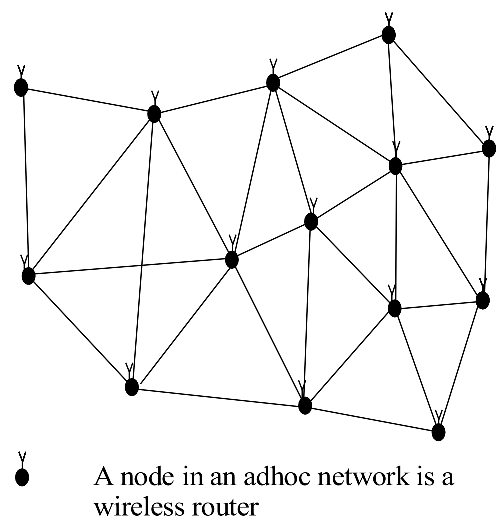

Figure 1: An ad hoc network which needs routing to ensure a proper connectivity

On multihop networks we cannot avoid the hidden collision issue. After the initial paper from Tobabgi [11] numerous papers mostly in the 90s proposed dedicated protocols to cope with this problem [12, 13, 14, 15, 16]. The general idea of these protocols is to implement a mechanism in the receiver to protect its reception. Since the busy tone technique requires a complex modem, another way is to require a packet a handshake before the actual transmission of the packet. This technique had been adopted by the IEEE 802.11 standard as an option called RTS/CTS (Request To Send / Clear To Send), acronym of the two packets exchanged between the source and the destination before the actual transmission. The benefit of this method is questionable. First it incurs a significant overhead due to radio switching times and synchronization delays. Second a recent publication mentions congestion with this scheme [17]. As it will be shown in details in this paper, CSMA protocols ensure in principle that no concurrent transmission occurs in the vicinity of an already transmitting node. The range of the "exclusion area" around the transmitter can be tuned by the carrier sense threshold; by neighbor effect CSMA protocols which are "protecting the transmitter" are then also protecting the receiver against concurrent transmission. Since CSMA protocols are generic, simple and do not show the above mentioned problems, we have decided to focus our study on these protocols.

In this article our goal is to investigate the global throughput of a multihop CSMA ad hoc network. Although we may have different variants in CSMA protocols e.g. rule for the first transmission attempt, backoff strategy... the main performance of these protocols are driven by the exclusion effect induced by carrier sensing. In the present study we aim to optimize the global throughput of the network by tuning the parameters of the carrier sensing mechanism.

This paper is organized as follows: the next section introduces our study. We review results obtained in [6] and we explain how our work can be related to them. We develop a simple model to evaluate the maximum throughput of a CSMA multihop network and we deduce that there are at least two parameters: the carrier sense range and the transmission range to optimize the throughput of an ad hoc network. Section 3 will be devoted to the study of the throughput optimization with respect to these two parameters. We will use two models. The first one only considers the strongest interferer. The second one considers the contribution of all the interferer. In section 4 we present simulation results of an ad-hoc network using an IEEE 802.11b wireless interfaces and running OLSR [4] as routing protocol. The medium sharing of the widespread IEEE 802.11 standard [10] is a CSMA protocol with special additional features : MAC acknowledgement, optimized backoff time update, binary exponential backoff... It is the ideal candidate to carry simulations to test our optimizations of CSMA protocols. Section 5 presents other possible optimizations and future work.

2 Throughput of a multihop wireless network

In a recent paper [6] Gupta and Kumar show that the actual throughput in a multihop wireless network with n randomly located nodes is actually $O(W\sqrt{S}/\sqrt{nlog(n)})$ where W denotes the bandwidth in bit/s of the shared medium, S the area in square meter of the network and the assumption is the non-interference protocol. They actually prove this result demonstrating that this bound is an upper bound and exhibiting a scheduling scheme and a routing scheme which actually offer this figure. Although this result is quite technical, we can offer a simple understanding of this result. Let us assume that the range for one hop is $r(n)$. If we assume that with a non interference protocol a circle of radius $r(n)$ is consumed for a single transmission, then we have at most $O(WS/\pi r(n)^2)$ simultaneous transmissions. Let us call L the mean number of hops that a packet will experiment to reach its destination.

Obviously we have $L = O(\sqrt{S}/r(n))$ thus we can deduce that the offered bandwidth for the whole network is $O(\sqrt{S}/\pi r(n))$. To complete the computation we just have to choose $r(n)$. This transmission range has to meet two criteria. The first one is to connect the network. The second is to optimize the throughput. In [6] it is shown that these two requirements lead to the same range $r(n) = O(\sqrt{log(n)/n})$ thus the throughput that can be achieved in the network is $O(W\sqrt{Sn}/\sqrt{log(n)})$ which indeed gives the expected throughput for a single network node.

These results are of interest because they give general bounds for the throughput of a multihop network. However, these results are asymptotic. Most of them hold only for networks with a large density of nodes. Additionally, they are not directly explaining how to optimize a CSMA protocol in a multihop ad hoc network. The goal of this article is precisely to investigate in these two directions.

2.1 Carrier Sense multiple access modelisation

In multihop ad hoc network the access technique may belong to two different kinds: random access technique and controlled access technique. However due to the complexity led in multihop ad hoc network by phenomenon like spatial reuse or hidden collision, the use of controlled access techniques seems very difficult and the random access techniques are to be preferred. Ad hoc networks are generally open network where nodes often enter or leave the network. This genuine property of ad hoc network is also in favor of random access. The ancestor of the random access technique is "Aloha". This scheme has been widely improved the carrier sensing and the obtained CSMA (Carrier Sense Multiple Access) is the usual access technique used in WLANs. For instance the access technique used in IEEE 802.11 and in HiPERLAN type 1 is based on a CSMA scheme.

The CSMA scheme can be simply modeled. It is well known that it is impossible to transmit and receive in the same time in a CSMA system. Therefore whenever a node A transmits, this node will block the transmission access for other nodes in the vicinity of A. We call this area around A the “carrier sense area”. However, the data signal sent by A can not successfully be received in all the exclusion area, the data will be successfully received in a smaller area called the “reception area”, the range of this area can be tuned by the carrier sense threshold which determines the level of signal above which a transmission has to be differed. In a simple model with no obstacles and with a signal decay function of the distance, the carrier sense area and the reception area will be disks of radius respectively noted R_{cs} and R, see figure 2.

Let us assume that we have the following function $P(r) = \frac{P_0}{r^\alpha}$ where $P(r)$ denotes the power at distance r and P_0 the power at the source node; α is usually called the decay factor. There is another very classical assumption concerning correct reception of packet. It is usually assumed that a correct transmission implies two conditions. The first one is that the signal strength of the received transmission is above a given threshold P_{thres}. The second one is that the ratio of the signal strength by the noise is greater than the capture level. The noise N experienced by the transmission is the sum of the thermal noise and of

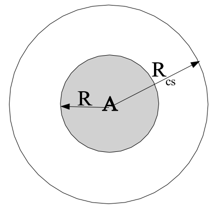

Figure 2: Carrier sense area and reception area

the potential concurrent transmissions in the vicinity. In the following, we will denote by K the capture level. We can summarize these two conditions

$$P(r) \geq P_{thres} \text{ and } \frac{P(r)}{N} \geq K.$$

2.2 Estimation of the maximum throughput of a multihop network with a simple model

Computing the exact throughput of a multihop ad-hoc network seems to be extremely complex. Our aim in this section is to compute an estimation of the network throughput with a simple and to derive the parameters which will influence this throughput.

For the sake of simplicity we will use, the following assumptions:

- the ad-hoc network is deployed on an area of S square meters (to simplify we will assume that S is infinite or at least large)
- the location of the network nodes follows a Poisson point process of intensity λ,
- for a given node its neighbor nodes will be in a a disc of radius the transmission range R; only neighbor nodes can forward packets for a node,
- the bandwidth (air rate) of the shared radio medium is W in bit/s,
- the time is slotted, the duration of the slot is adapted to the packet size,
- the network node queues are always full; at each time slot each network node has a packet to send,
- each network node will follow a CSMA rule to send its packet, thus a transmitting node will block concurrent transmission within a carrier sense range modeled as a ball of radius R_{cs},

- the effect of collision for nodes within carrier sense range and starting "nearly simultaneous" transmissions will be taken into account by a correcting term issued from usual single hop CSMA model,
- the mean distance for a packet in hops to reach its destination is known. We denote it L.

Our first goal is to estimate the maximum number of simultaneous transmissions in our ad hoc network with respect to the carrier sense range R_{cs}. It is easy to compute this figure if the transmitters are in regular pattern on a grid or on equilateral triangles. For the grid we find $\frac{S}{R_{cs}^2}$ and for the tessellation with equilateral triangles it is $\frac{S}{\frac{\sqrt{3}}{4}R_{cs}^2}$.

The Matern hard-core process [18] gives a possible answer to this problem with the more realistic assumption of network nodes locations following a stationary Poisson process. To construct it, one gives marks $m(x)$ to the initial Poisson process. The marks will be a random number uniformly distributed over (0,1). The Matern hard-core is a thinned process derived by selecting the nodes with the smallest mark within a disc of radius R_{cs}. The obtained process will have the property that two points of this process are at least R_{cs} apart. We will assume that this Matern hard-core process can represent the selection of active nodes in a CSMA protocol. An interesting feature is that it is possible to compute the intensity of the Matern hard-core process. This intensity $\lambda_{R_{cs}}$ is

$$\lambda_{R_{cs}} = \frac{1 - e^{-\pi\lambda R_{cs}^2}}{\pi R_{cs}^2}$$

see [19]. It can also be noticed that we have the behavior of the intensity of the process with R_{cs}. If the mean number of network nodes in a carrier sense range (i.e. $\pi\lambda R_{cs}^2$) is not small then $\lambda_{R_{cs}}$ varies with $1/R_{cs}^2$. This means that in a CSMA network the number of nodes which can potentially transmit simultaneously varies with $1/R_{cs}^2$. We can thus assume that the maximum number of possible simultaneous transmission is given by

$$\frac{S(1 - e^{-\pi\lambda R_{cs}^2})}{\pi R_{cs}^2.}$$

To capture the total throughput of the network we have to take into account the success rate of a transmission. Let us denote by C the average collision rate of a transmission in our ad-hoc network given that at least two colliding nodes are not within carrier reach. The number of transmission free of hidden collisions is thus $\frac{S(1-e^{-\pi\lambda R_{cs}^2})(1-C)}{\pi R_{cs}^2}$.

To complete our evaluation we have to take into account the network overhead (mostly due to switching and synchronization time) and the collision for nodes within carrier sense reach thus starting transmission in a same small time interval often called collision window. A simple way to evaluate the effect of collision of nodes within carrier sense reach can be found in [23]. It is shown that the dominant factor is the ratio of the propagation delay plus detection time of a packet sent by a node to one of its neighbor node and of the transmission delay of a packet. To consider the overhead a simple rule of three can be applied. The result of this evaluation can be denoted by C^s_{max} the maximum rationalized throughput of the network if this latter were a single hop fully connected network. Let us denote by W the channel bandwidth of the medium in bit/s. The total throughput of the network is thus:

$$\frac{SWC^s_{max}(1-e^{-\pi\lambda R^2_{cs}})(1-C)}{\pi R^2_{cs}.}$$

In order to compute the throughput of the network, we have to make an assumption on the length of an average route. Let us assume that given a traffic and its source/destination distribution, L is the average length in number of hops between a given source and the related destination. The retransmissions of packets from source to destination of course do not contribute to the effective throughput. The previous estimation has thus to be divided by L. Thus, the effective total throughput of the network is:

$$\frac{SWC^s_{max}(1-e^{-\pi\lambda R^2_{cs}})(1-C)}{\pi LR^2_{cs}.}$$

It is easy to extract from the model the variables which can used to optimize the global throughput. The average length L in number of hops between source and destination, is a function of the traffic pattern T. T is given a priori, we will not be able to use it to optimize the throughput. L is also a function of the transmission range R. If the reception range decreases then necessarily the number of hops between a source and a destination will increase. We will denote the average length between a source and a destination by $L(T,R)$ to show this dependence. If R_{cs} is decreased the number of collision will increase because there will be more hidden collisions. If the transmission range is increased it can be well understood that there will be more hidden collision. Thus, C must be denoted by $C(R,R_{cs})$. The bandwidth W is also a function of the transmission range R; it is well known that when the targeted transmission range is increased the transmission rate should be decreased. W is denoted by $W(R)$. According to the remarks of the above discussion C^m_{max} is a function of T, R_{cs}, R.

$$C^m_{max}(T,R_{cs},R) = \frac{S(1-e^{-\pi\lambda R^2_{cs}})C^s_{max}(1-C(R,R_{cs}))}{\pi L(T,R)R^2_{cs}}.$$

2.3 Discussion

The previous equation shows the importance of the carrier sense range on the maximum throughput of a multihop ad hoc network. As a matter of fact if the carrier sense range is large then transmission will forbid other transmissions in a large area. We will not be able to benefit from the same proportion of spatial reuse since an ongoing transmission will block the transmission of every surrounding nodes within carrier sense range. This effect is given in the formula by the $1/R_{cs}^2$ factor. But at the same time with a large carrier sense range there will be less hidden collision. Thus we will have less repetition of the same packet to achieve a successful transmission. We see this effect in the $(1 - C(R, R_{cs}))$ factor. If R_{cs} increases then the collision rate will decrease and $(1 - C(R, R_{cs}))$ will increase. Conversely if the carrier sense threshold is set to a high level then close simultaneous transmissions will be possible (the reuse is increased). But at the same time, the percentage of hidden collision will be much higher. This effect is the first effect that we are going to study in depth.

At the same time the transmission range R can also be tuned. Of course as for the carrier sense range, the transmission range R has two opposite effects. Increasing the transmission range allows to build shorter routes and thus contributes to increase the maximum achievable throughput. Yet, increasing the transmission range may lead to increase the carrier sense range to keep the same success rate $1 - C(R, R_{cs})$; in such a case the reuse factor will be decreased. Conversely, decreasing the reception range will favor spatial reuse as it will at the same time increase the number of hops. Additionally propagation laws link the transmission rate; the larger is your transmission range the shorter is your transmission rate. Thus, there is a tradeoff between the range and the actual transmission rate. In this article, we will first conduct direct evaluations derived from the model we have built in the previous section. Since this model is necessarily simplified and contains approximations we have also conduct simulations to see if they confirm the conclusion of the analytical model. For the simulations, we will use all the assumptions of an IEEE 802.11b network operating in ad hoc mode.

3 Optimization of the network throughput with respect to the carrier sense range

We use the framework previously introduced and we study this optimization with two different interference models. In the first and simplest one, we only consider the strongest interferer to decide if the reception is correct or not. The second model is the total interference model in which the contribution of all the potential interferers is taken into account.

3.1 Strongest interference model

In this model we assume that the capture condition is to be verified for the interferer with the maximum power strength. Although simple, this condition is however widely used in simulation works. For instance it is the one that is implemented for the IEEE 802.11 protocol in the ns simulator [21], thus all the simulation works using this tool actually are under this simple model. With such a model it is possible to exactly evaluate $C(R, R_{cs})$. As a matter of fact, a node producing the collision (interferer) is necessarily inside a circle of radius $R_{ex} = RK^{1/\alpha}$. Since we assume that this is an hidden collision the interferer is also outside the circle of range R_{cs} see figure 3

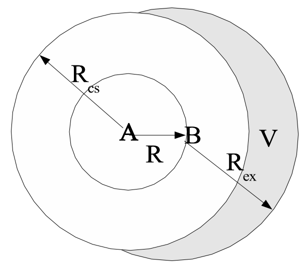

Figure 3: Collision area

To evaluate the effect of carrier sense range we have to consider in C^m_{max} the contribution:

$$G(R, R_{cs}) = \frac{(1 - e^{-\pi\lambda R_{cs}^2})(1 - C(R, R_{cs}))}{\pi R_{cs}^2}.$$

$G(R, R_{cs})$ give the mean number of successful transmission per area unit, we call $G(R, R_{cs})$ the normalized throughput. The probability of a successful transmission can be simply expressed :

$$C(R, R_{cs}) = 1 - e^{-V(R, R_{cs})\lambda}.$$

where $V(R, R_{cs})$ denotes the area of V (see figure 3).

Thus

$$G(R, R_{cs}) = \frac{S(1 - e^{-\pi\lambda R_{cs}^2})e^{-V(R, R_{cs})\lambda}}{\pi R_{cs}^2}.$$

If R and R_{cs} are given, it is then possible to compute explicitly $V(R, R_{cs})$; this computation uses standard trigonometric functions. It is then easy to compute the maximum of $G(R, R_{cs})$. The maximum of $G(R, R_{cs})$ is found to occur when $R_{cs} \simeq R(K^{1/\alpha} + 1)$.

In figure 4 and 5, we have studied $G(R, R_{cs})$ respectively for $\alpha = 4$ and $\alpha = 2$. We have used a density rate λ which leads to a mean number n_R of 1, 3 and 6 neighbors within a disc of radius R, given a fixed node at the center of the disc.

When we use a small carrier sense range, we have a high probability of collision. As in Aloha, we should use a transmission probability to avoid collision with hidden node. When a node wants to transmit, it first senses the channel. If the channel is sensed idle, it transmits with probability p. We call this scheme CSMA with priority p. We may wonder whether using a small carrier sense range with CSMA with priority p can be better than CSMA with the optimized carrier sense range. The throughput of CSMA with priority p can be obtained by maximizing over p the success rate : $pe^{-pV(R, R_{cs})\lambda}$. As a matter of fact a given node will transmit with probability p. This transmission will be a success if no other transmission

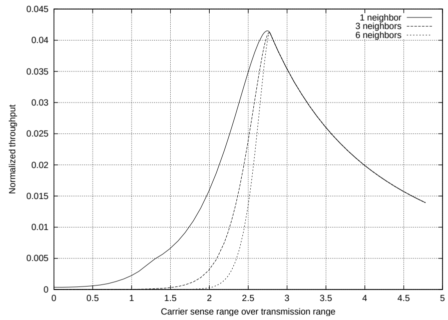

Figure 4: $G(R, R_{cs})$, $R = 1$, $\alpha = 4$

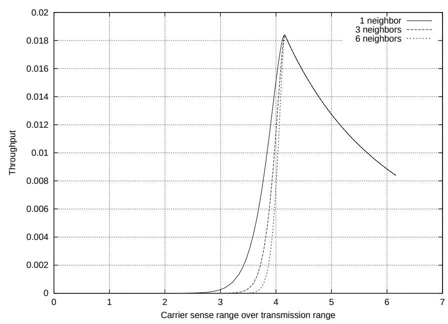

Figure 5: $G(R, R_{cs})$, $R = 1$, $\alpha = 2$

occurs in V. This event has a probability $(1-p)^{V(R,R_{cs})\lambda}$. If one uses the approximation for small x, $(1-x)^n \simeq e^{-nx}$ we have $(1-p)^{V(R,R_{cs})\lambda} \simeq e^{-pV(R,R_{cs})\lambda}$. Thus the success probability which is also the throughput equals

$$pe^{-pV(R,R_{cs})\lambda}.$$

This throughput is optimized for $p = \frac{1}{\lambda V(R,R_{cs})}$ and the obtained throughput is $\frac{e^{-1}}{V(R,R_{cs})\lambda}$.

The results of this optimization lead to another value of $G(R, R_{cs})$ which is presented for $R = 1$ $\alpha = 4$ and $\alpha = 2$ in figures 6 and 7. We can see that CSMA with priority p improves the performance when the carrier sense range is reduced but the obtained performance is not better than the optimal reached by CSMA using a larger carrier sense range.

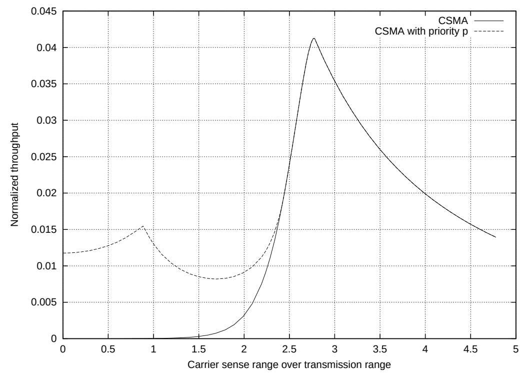

Figure 6: $G(R, R_{cs})$ with CSMA and CSMA with priority p, $R = 1$, $\alpha = 4$

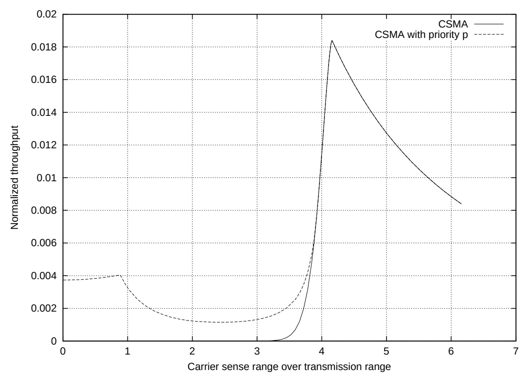

Figure 7: $G(R, R_{cs})$ with CSMA and CSMA with priority p, $R = 1$, $\alpha = 2$

3.2 Total interference model

In this section we use the total interference model in which all the interferers are taken into account. The condition to receive a packet is thus

$$\frac{P(R)}{\sum_i P(r_i)} \geq K.$$

where i denotes the interferer and r_i denotes the distance between the receiving node and the interfer i. To the best knowledge of the authors it is possible to explicitly compute the success rate $1 - C(R, R_{cs})$ when the interferer are in a Poisson point process but is seems difficult to compute this rate when the interferers are in an hard core process. Thus we have taken a simulation approach. A Poisson point process is generated and the emitters are then selected using a Matern selection process. Then the interference is computed for a receiver exactly at distance R from the emitter. Finally the above mentioned reception condition allows one to compute the success rate.

The result of this model is presented in figure 8 for $\alpha = 4$. The Poisson point process is generated in a square 100×100 with an intensity $\lambda = 1$. The simulations conditions have been taken to ensure a precision below 5% for $\alpha = 4$, $K = 10$ dB and an infinite planar Poisson point process. Note that the maximum is reached for R_{cs} around 3.

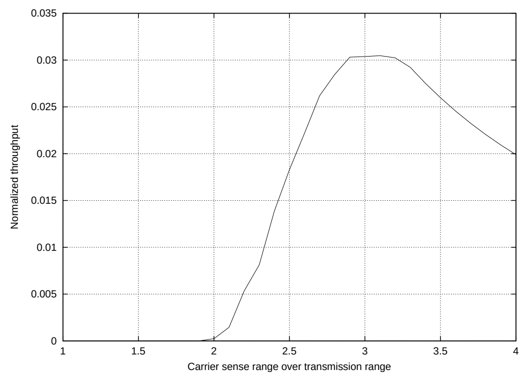

Figure 8: $G(R, R_{cs})$ for $\alpha = 4$

The same result is presented in figure 9 for $\alpha = 2$ with using the same simulation condition. It has to be well noticed that these results do depend on the previous simulation condition since the sum of the interferences will not converge for $\alpha = 2$ in an infinite planar network. For $\alpha > 2$ this sum will converge but the simulation will not give a convenient evaluation of this sum. Figure 9 however shows that for $\alpha = 2$ the results given by the total interference model are very different from those obtained by the strongest interference model.

In figure 10 we compare for $K = 10$ dB the optimized carrier sense range R_{cs} for α ranging from 3 to 6.

In this part we have shown that in the two presented models the throughput is optimized for $R_{cs} = \gamma R$. The value of γ depends on the interference model but is always very close to the smallest figure for which hidden collisions start to be impossible i.e for which $C(R, R_{cs}) = 1$.

4 Optimization of the transmission range

We have to optimize with respect to R the network throughput:

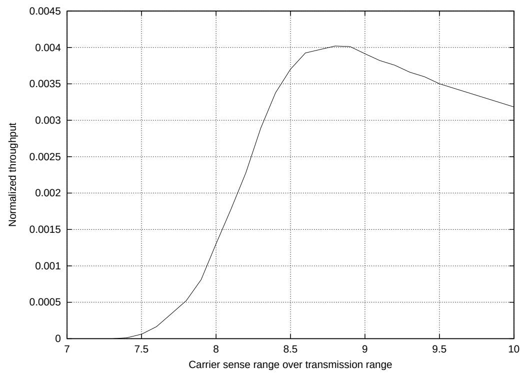

Figure 9: $G(R, R_{cs})$ for $\alpha = 2$

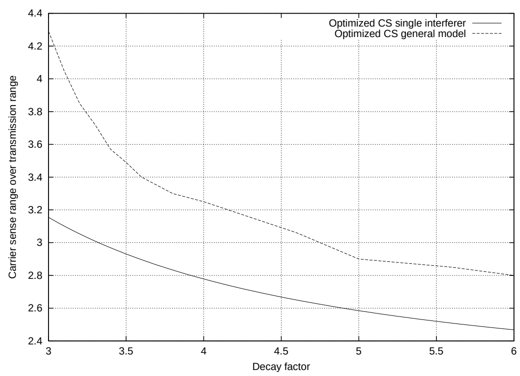

Figure 10: Optimal R_{cs}/R for α between 3 and 6, $K = 10$ dB

$$\frac{W(R)C^s_{max}(1 - e^{-\pi\lambda R^2_{cs}})(1 - C(R, R_{cs}))}{\pi L(T, R)R^2_{cs}}.$$

We will restrict the optimization of the transmission range to values of R for which the mean number of network nodes within the disc of range R is large (e.g. more than 10). We will say that in this case the network is sufficiently connected.

In a first part we will assume that R_{cs} is fixed.

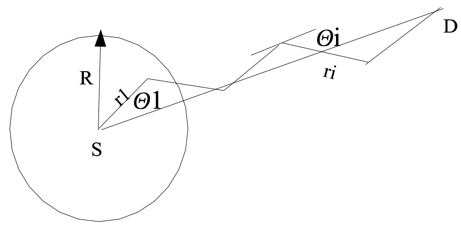

Figure 11: Route from source to destination and number of hop w.r.t. R

4.1 Fixed carrier sense range

Let us analyze figure 11 where we have the successive transmissions from a source node S to a destination node D. If the coordinates of the next hop are given in polar (r_i, θ_i) it can be easily understood that the distribution of r_i is nearly linear w.r.t. the transmission range R as the distribution of θ_i will remain nearly insensitive to R as long as the network remains sufficiently connected i.e. the mean number of neighbors of node within the transmission range R is not too small. In such conditions $L(T,R) \simeq L(T)a(R)/R$ where $L(T)$ is the average Euclidean distance for the traffic T between a source and a destination and $a(R)$ a slowly varying function. A precise computation of $L(T,R)$ taking into account λ appears possible but is not given to keep this paper relatively short. This behavior of $L(T,R)$ leads to the following expression for the throughput where, to simplify, we have adopted $a(R) = 1$:

$$\frac{W(R)C^s_{max}R(1-e^{-\pi\lambda R^2_{cs}})(1-C(R,R_{cs}))}{\pi L(T)R^2_{cs}}.$$

We also know that the effective transmission $W(R)C^s_{max}(R)$ rate depends on the transmission range R and is a decreasing with R. As $W(R)C^s_{max}(R)$ depends on the wireless interface we will only discuss the optimization of $R(1-C(R,R_{cs}))$. Since $1-C(R,R_{cs}) = 1$ for R/R_{cs} below a given threshold and then is rapidly decreasing to reach 0, it can be shown that $R(1-C(R,R_{cs}))$ is an increasing function on the interval $[0, R_{opt}]$ and decreases on $[R_{opt}, \infty[$. In figure 12 we have shown $\frac{R}{\pi}(1-C(R,R_{cs}))$ with respect to R assuming that $R_{cs} = 1$, $\alpha = 4$ and $K = 10$ dB and with the strongest interference model. It has to be noticed that this optimization leads to similar results than the previous optimization in term of obtained ratio R/R_{cs} although the two optimizations are different. As a matter of fact the optimization range will play on the mean number of hops to the destination as the carrier sense optimization will actually play on the spatial reuse. However the effect of the hidden collision is so important that in both case the control of hidden collision is the key factor of the optimization. This conclusion remains valid for the general interference model.

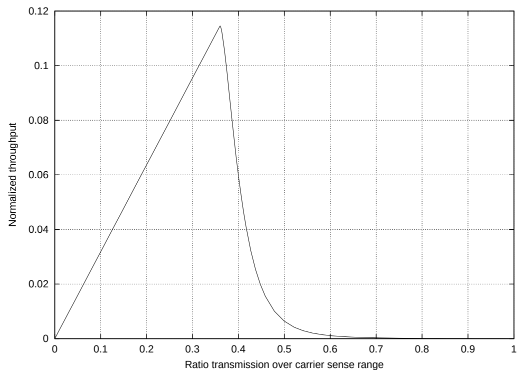

Figure 12: $\frac{R}{\pi}(1 - C(R, R_{cs}))$ w.r.t. R

The complete optimization has also to take into account $W(R)C^s_{max}(R)$. Usually $W(R)C^s_{max}(R)$ is decreasing faster than $1/R$. In such conditions decreasing R may offer a better throughput. But we have to keep in mind that R must be large enough to keep the network sufficiently connected.

4.2 Adaptable carrier sense range

In this part we assume that the carrier sense range can be adjusted. In the previous section we have seen that to optimize the throughput we must have $R_{cs} = \gamma R$. Thus we can do this optimization before optimizing R. In such a case, we obtain the following:

$$\frac{W(R)C^s_{max}(R)(1 - e^{-\pi\lambda\gamma^2 R^2})}{\pi\gamma^2 L(T) R}.$$

The optimization of this expression is straightforward since both $1/R$ and $W(R)C^s_{max}(R)$ are a decreasing function of R. Thus, the maximum throughput is obtained when R is minimum. So R can be decreased as long as the network remains sufficiently connected. Let us call R_{min} the minimum transmission range which ensures this property. The maximum throughput of the network can be written:

$$\frac{W(R_{min})C^s_{max}(R_{min})(1 - e^{-\pi\lambda\gamma^2 R^2_{min}})}{\pi\gamma^2 L(T) R_{min}}.$$

We can compute this figure for the various conditions. We consider: $\alpha = 2$ open, semi open $\alpha = 4$ and close $\alpha = 6$ environment. In IEEE 802.11b products the sensitivity of the wireless interface w.r.t. the transmission rate are usually given with the product characteristics: sensitivity and transmission range. Usual figures for transmission ranges are at 11 Mbit/s: 150 m for an open environment ($\alpha = 2$) and 50 m for a semi open environment ($\alpha = 4$). In figure 13 we show the effective transmission rate $W(R)C^s_{max}(R)$ versus the transmission range. To compute this figure, we have taken into account all the overhead thus, the contribution of $C^s_{max}(R)$ is taken into account. This computation can be found in [22].

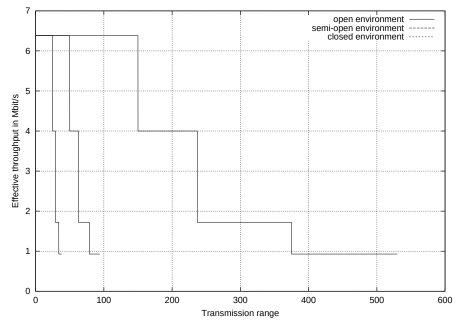

Figure 13: Effective transmission rate of an IEEE 802.11b interface in Mbit/s w.r.t. transmission range

We can thus compute the theoretical maximum network throughput w.r.t. the minimum transmission range R_{min}. We give this computation in figure 14 for $\alpha = 4$ and in figure 15 for $\alpha = 2$.

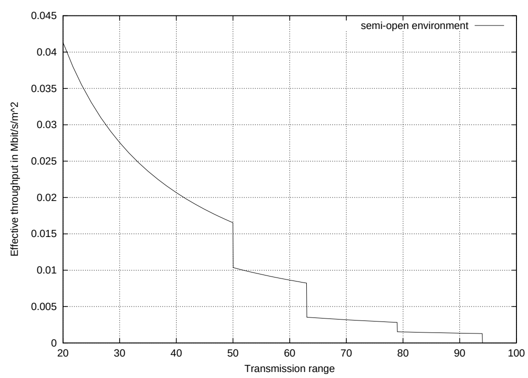

Figure 14: Maximum network capacity in $Mbit/s/m^2$ w.r.t transmission range in a semi-open environment $\alpha = 4$

It is very interesting to mention that the result that we have found can be understood in the framework of [6]. To compute the lower bound of the network throughput comprising n randomly located nodes the authors of [6] exhibit a slotted protocol using at most $1 + c$

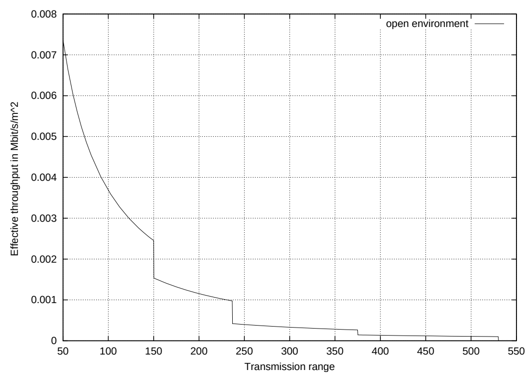

Figure 15: Maximum network capacity in $Mbit/s/m^2$ w.r.t transmission range in an open environment $\alpha = 2$

slots. This protocol derives from a network tessellation in which a node in a cell has at most c neighbors at distance less than $2(1+\Delta)r(n)$. Thus, the slotted protocol ensures that when a node is transmitting there is no concurrent transmission at distance less than $2(1+\Delta)r(n)$ and therefore there is no conflict between concurrent transmissions. Actually, this construction will give close results to those that a CSMA scheme optimized as shown in this article will give. As in the construction in [6] where the constructed protocol ensures that there is no collision, we have shown in the present work that the carrier sense range must be set to forbid collision if one wants to optimize the throughput. To reach the targeted lower bound, the construction in [6] has to compute the minimum range $r(n)$ which ensures the network connectivity; the authors actually show that the transmission range must be $r(n) = O(\sqrt{log(n)/n})$. In the present article, we have also shown that the maximum throughput is achieved when the transmission range is set at the minimum value which ensures the network connectivity.

5 Simulations results

We present simulation results of Ad hoc network equipped with IEEE 802.11b wireless interfaces and running the OLSR routing protocol [4]. We have developed a simple model for the IEEE 802.11b distributed access protocol with the OPNET tool. This model described in [8]; it uses for the interferences the total interference model.

The first scenario that we are considering has the following characteristics

- the network encompasses 36 nodes randomly positioned on a square $260m \times 260m$.
- transmission range is set at $R = 50$ m,

- the air rate is 11 Mbit/s leading to $W(R)C^s_{max} \simeq 6$ Mbit/s (IEEE 802.11b.), the RTS/CTS option is not used.

We are considering two types of traffic. In the first type of traffic, that we call "gateway" traffic, all the network nodes except one (node 36) send packets to a gateway node (node 36). These packets of 1 kbits correspond to request packets. The gateway responds to these request with large packets of 8 kbits. This traffic is a model for wireless nodes accessing distant servers. In the second type of traffic, that we call "random" traffic, wireless nodes are exchanging packets of 8 kbits. For a given sender, the destination is randomly selected in the network.

Running simulation scenarios, we first discover that, if the input load is too high, then a lot of packets are lost no only due to buffer overflow but also suprisingly due to lack of route to the destination. This behaviour can be explained by the collisions encountered by the control packets of the routing protocol. These packets are sent in broadcast mode and can not be acknowledged as point to point packets are. These packets are suffering from a high percentage of packet loss. Thus we had to tune the total network load to be in the neighborhood of the maximum achievable throughput of the network. We found out a figure for the total input load around 2 Mbit/s. On figure 16, we have given the network throughput for different value of the ratio $\frac{R_{cs}}{R}$. For the gateway traffic, the maximum efficiency is obtained for $\frac{R_{cs}}{R} \simeq 2.5$. These figures are slightly less than what is foreseen by the analytical model. The discrepancy can be explained by two reasons. The first and main reason is that since we are in the neighborhood of the network maximum capacity all the network nodes do not have a packet to send; moreover the IEEE 802.11 backoff strategy after a collision also decreases the number of simultaneous potential transmitters. This reason also explains why the slopes of the simulation function are less stiff than the slopes of the models (strongest interference or total interference model). The second reason for experiencing an optimized ratio $\frac{R_{cs}}{R}$ smaller than foreseen by the model is that the model considers reception at the maximum transmission range: R whereas in simulations, receivers can be closer. Thus reception conditions are less stict that those used in the model. We can also point that when $\frac{R_{cs}}{R} \simeq 2.5$ the mean number of transmission attempts of IEEE 802.11 for the data packet is nearly 1. We can infer that with this carrier sense range there is nearly no hidden collision.

If we use the previous analytical model for the throughput, given that $L \simeq 2.6$ for the gateway traffic we find

- 1.9 Mbit/s in the total interference model,
- 2.5 Mbit/s in the strongest interference model.

These figures are a fair approximation of the obtained result and we note that the optimization of R_{cs} allows one to gain up to 40% of channel throughput.

The aim of the second scenario is investigate the influence of topology. We are considering is a grid topology with $6 \times 6 = 36$ nodes. The grid spacing is 40 m. We are using the same types of traffic as for the previous scenario with the same packet payload. On figure 17 we

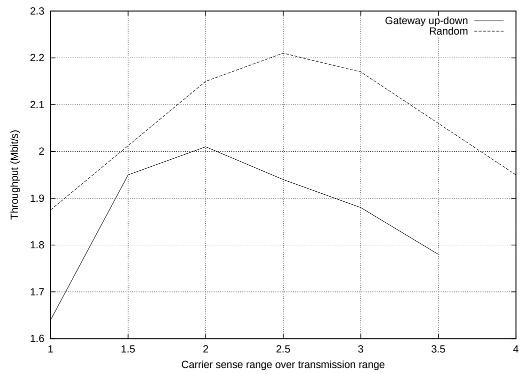

Figure 16: Throughput w.r.t $\frac{R_{cs}}{R}$, random network, $\alpha = 4$

have given the network throughput for different values of the ratio $\frac{R_{cs}}{R}$. We clearly see that for all the scenarios, we have results significantly better with $\frac{R_{cs}}{R}$ between 1.5 and 2. This figure can be explained by the "regular" characteristic of the topology we are considering. The decrease of the obtained throughput can be explained by the increase of mean route length in term of number of hops.

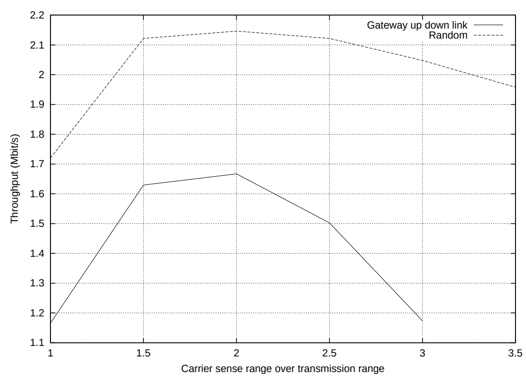

Figure 17: Throughput w.r.t $\frac{R_{cs}}{R}$, grid network, $\alpha = 4$

The third scenario that we are considering has the following characteristics

- the network encompasses 64 nodes randomly positioned according on square 1000 m $\times$ 1000 m.
- the transmission range is set at $R = 150$ m,

- the air rate is 11 Mbit/s leading to $W(R)C^s_{max} \simeq 6$ Mbit/s (IEEE 802.11b.)

We are considering a gateway traffic, node 63 is the gateway. The results of this simulation are given in figure 18. We see that the maximum throughput is obtained when $\frac{R_{cs}}{R} \simeq 3.5$. As the network size is not large enough to allow numerous simultaneous transmissions the strongest interferer model will be accurate. This model foresees a maximum throughput with $\frac{R_{cs}}{R} \simeq 4.2$. The discrepancy between the model and the simulation can be explained by the same already given reasons. The requirement of the simulation in duration and memory space has not allowed us to carry scenarios with a very large network. In this situation the effect of multiple interferers would have been sensible. Given $L \simeq 3.5$ for the gateway traffic the analytical model predicts a global throughput of 1.4 Mbit/s, this prediction is not very far from the obtained simulation result. However edges effects are not taken into account by the model, a larger network size is mandatory to expect close results between simulations and models. Between $\frac{R_{cs}}{R} \simeq 1$ and $\frac{R_{cs}}{R} \simeq 3.5$ the gain for the network throughput is around 90%.

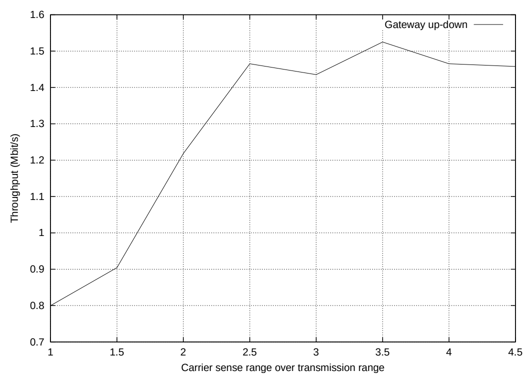

Figure 18: Throughput w.r.t $\frac{R_{cs}}{R}$, random network, $\alpha = 2$

6 Other possible optimization and future work

Another possible optimization of the medium access scheme is the RTS/CTS. With this technique before the “real transmission”, a source node first sends a small packet RTS (Request To Send). If the destination of the packet correctly receives this packet, it replies with a CTS (Clear To Send) packet. Then if the source node correctly receives the CTS, it sends the data packet after the end of the CTS transmission. Moreover, the RTS and CTS packets contain the duration of the data packet which is planned to be exchanged after the RTS/CTS exchange. Thus, nodes receiving the RTS or the CTS become aware of the duration of the forthcoming transmission. This mechanism is called in IEEE 802.11 the

Network Allocation Vector (NAV). Therefore, the RTS and CTS packets induce an indirect carrier sense mechanism, see figure 19. Within a transmission range around the source and the destination, the RTS/CTS packet will forbid alien transmissions during the data transmission of the source. However, according to our carrier sense optimization study, we do see that the coverage area of potential transmitters is small compared to the one we need to cover to optimize the throughput. In such a case the RTS/CTS can not help significantly the carrier sense mechanism and we can not expect either a significant improvement of the throughput or another significantly different choice of the carrier sense range. This conclusion may change if one assumes that the RTS/CTS range is significantly larger than data range R. This discrepancy could result from the two possible reasons: the CTS or RTS packets are significantly smaller than the data packet, the CTS or RTS packets can be sent at a lower data rate than the data packet. In that case a new study to optimize the carrier sense range could lead to different results than the one we have seen in this article.

Another interesting work would be the study of directional antennas. As a matter of fact, directional antennas will reduce significantly the effect of hidden collision. Most of the reasoning that is presented in this article can not be applied with directional antennas and completely new models and simulations would be needed.

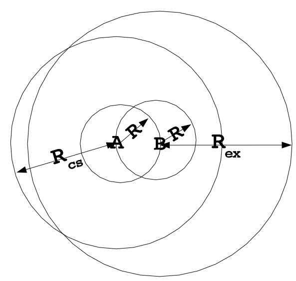

Figure 19: The RTS/CTS mechanism

7 Conclusion

In this article, we have studied the maximum throughput of a multihop network using a CSMA protocol. More specifically, we have deeply investigated the optimization of the throughput with respect to the carrier sense range and the transmission range. We have developed a simple analytical model to study these two issues and we have built two models for the interference: the strongest interference model in which only the strongest simultaneous transmission is taken into account to validate a reception and the total interference model in which the contribution of all the simultaneous transmissions is considered to validate a reception. We have conducted simulations to verify the results of these models. A first result obtained is that the carrier sense range must be set to avoid hidden collisions. This result predicted by the models is also confirmed by simulation results. The second result obtained concerns the transmission range. For a random network, the maximum throughput is achieved when this range is set at its minimum value. This effect is still increased due to the fact that the data rate tends to decrease when the transmission range increases.

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