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A distance-aware model of 802.11 MAC layer

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Abstract: We present in this paper an analytical model that accounts for the positions of stations with respect to the Access Point while evaluating the performance of 802.11 MAC layer. Our model is based on the Bianchi's work where the performance of 802.11 MAC layer is computed using a discrete time Markov chain, but where all stations are implicitly assumed to be located at the same distance to the Access Point. In our model, given the position of one station, we compute its saturation throughput while conditioning on the positions of the other concurrent stations. Our model also gives the total saturation throughput of the medium. We solve the model numerically and we show that the saturation throughput of one station is strongly dependent on its own position and on the positions of the other stations. One station achieves a high throughput when it is close to the Access Point and loses when it moves away. There is some distance threshold above which the lost in the throughput is quick and important. When a station is far from the Access Point compared to the other stations, it will end up by contending for the bandwidth not used by the other stations. We believe that our model is a good tool to dimension 802.11 wireless access networks and to study their capacities and their performances.

Key-words: 802.11 MAC layer, distance to the Access Point, Markov chain, saturation throughput.

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Un modèle pour la couche MAC de 802.11 prenant en compte les positions des stations par rapport au point d'accès

Résumé : Nous présentons dans ce papier un modèle analytique pour le calcul des performances de la couche MAC de 802.11 qui prend en compte les positions des stations. Notre modèle est basé sur le résultat de Bianchi qui calcule les performances de 802.11 en utilisant une chaîne de Markov à temps discret, mais qui suppose implicitement que toutes les stations se trouvent à la même distance par rapport à la station de base. Dans notre modèle, étant donnée la position d'une station, nous calculons son débit de saturation tout en conditionnant sur les positions des autres stations. Notre modèle donne aussi le débit total de saturation de tout le milieu sans fil. Nous résolvons notre modèle numériquement et nous montrons que le débit de saturation d'une station est dépendent de sa propre position et des positions des autres stations par rapport à la station de base. Une station réalise un débit élevé quand elle est proche de la station de base et son débit baisse quand elle s'éloigne d'elle. Il existe une distance à partir de laquelle le débit d'une station baisse rapidement. Lorsqu'une station est loin de la station de base, elle finit par lutter pour le reste de bande passante non utilisée par les autres stations. Nous croyons que notre modèle est un bon outil pour dimensionner les réseaux 802.11 et pour étudier leurs capacités et leurs performances.

Mots-clés : Couche MAC de 802.11, distance par rapport à la station de base, chaîne de Markov, débit de saturation.

1 Introduction

Nowadays, the IEEE 802.11 WLAN technology offers the mostly used wireless access to the Internet. This technology specifies both the Medium Access Control (MAC) and the Physical Layers (PHY) [1]. The PHY layer applies the correct modulation scheme given the channel condition and provides the necessary bandwidth, whereas the MAC layer decides in a distributed manner on how the offered bandwidth is shared among all stations (STA).

Different analytical models and simulation studies have been elaborated the last years to evaluate the performance of 802.11 MAC layer [2, 3, 4]. These studies mainly aim at computing the saturation throughput of the MAC layer and focus on its improvement. One of the most promising models has been the so-called Bianchi model [4]. It provides closed-form expressions for the saturation throughput and for the probability that a packet transmission fails due to contention. The model is based on a simple and elegant discrete-time Markov chain and analyses the case of saturated STAs, i.e. STAs that always have packets to send.

The modeling of the 802.11 MAC layer is an important issue for the evolution of this technology. One of the major shortcomings in existing models is that distances between STAs and the access point (AP) are not considered. The distance is an important factor in wireless technology given the well known fast attenuation of the power with the distance. The existing models for 802.11 assume that all STAs have approximately the same power at the receiving STA, so when two or more STAs emit a packet in the same slot time, all their packets are lost, which may not be the case if one STA is close to the receiving STA and the other STAs far from it. This fact can be analyzed by considering the spatial positions of the STAs. In [5] the spatial positions of STAs are considered for the purpose of computing the capacity of wireless networks, but only an ideal model for the MAC layer issued from the information theory is used.

Our work reuses the model for 802.11 MAC layer from [4] and extends it such that the interference from other STAs is considered. Our aim is to compute, for a given topology, the throughput of any wireless STA using the 802.11 MAC protocol. Without loss of generality, we only consider in this paper traffic flows starting at the mobile STAs and ending at the AP. Further, we assume that all STAs use the Distributed Coordination Function (DCF) of 802.11 and that all STAs can hear each other, so the hidden terminal problem does not exist. The other scenarios (duplex transmission, hidden terminal, etc.) can be considered using the same approach.

In the next section we present an overview of the Bianchi model. Section 3 introduces our model and derives the characterizing equations for two different scenarios. We illustrate the obtained numerical results in Section 5 and conclude the paper in Section 6 with some pointers to our future work.

2 Bianchi model

The Bianchi model describes the dynamics of a 802.11 STA with a discrete-time Markov chain [4]. The time is divided into slots of variable duration based on what event occurs in a slot. Either there is a no transmission, a successful transmission or a collision. The model computes the probability τ that an STA transmits a packet in a random slot and the probability p that a transmitted packet collides. The probabilities τ and p are then used to compute the saturation throughput of the STA. The packet loss probability p can be seen as the probability that at least one other STA transmits a packet in the same slot, therefore p can be expressed as:

$$p = 1 - (1 - \tau)^{n-1}, \tag{1}$$

where n is the total number of STAs. The Bianchi model relates p to the transmission probability τ by solving the Markov chain that describes the system. We denote this relation with the function B. Let $m = 5$ be the maximum number of backoff stages in 802.11 and $CW = 32$ be the minimal contention window. The following expression results for B [4]:

$$\tau = B(p) = \frac{2(1 - 2p)}{(1 - 2p)(CW + 1) + pCW(1 - (2p)^m)}. \tag{2}$$

Equations (1) and (2) are solved for the values of p and τ (a non linear system with two unknowns). Once these probabilities are obtained, the saturation throughput of an STA is computed as the probability that the STA correctly transmits a packet in a slot time divided by the average slot time duration. The expression of the throughput is given in Section 4, where we adapt Bianchi's result to our context.

3 Our distance-aware model of 802.11

Our model computes the packet loss probability p considering the interference from the other STAs and the background noise. The expression for the transmission probability τ remains the same as that in (2). The computation of p is done under the assumptions we presented above.

Consider an STA k that transmits a packet to the AP and let us compute the probability that this packet is lost (i.e. cannot be decoded correctly). Suppose that this STA k is located at distance d_k from the AP. We denote its packet loss probability by $p_k(d_k)$. Let BER_k be a random variable defining the bit error rate (BER) of a packet (sent by STA k) after being detected by the AP. Knowing BER_k, the packet loss probability P_k can be computed as follows:

$$P_k = 1 - (1 - BER_k)^l, \tag{3}$$

where l is the total packet length in bits (including all headers, l equals 8784 bits). This expression for P_k assumes that the bit error process is iid during the reception of the packet and that the data is not protected by any channel coding scheme. As we need the packet loss probability averaged over all values of BER_k, we will focus on the computation of the expected value $p_k(d_k) = \mathbb{E}[P_k]$. To do so, we need the probability density function (pdf) of BER_k. As we will see, by decomposing BER_k more and more this task becomes feasible.

The random variable BER_k is a function of d_k, as well as the positions of the STAs that are transmitting at the same time as STA k. These parameters are present in the signal to noise ratio (SNR), which can be related to be BER by the following function valid among others for BPSK and GMSK modulation schemes:

$$BER = \frac{1}{2}\text{erfc}\left(\sqrt{SNR \cdot W/R}\right), \tag{4}$$

where R (1 Mbps) is the physical bit rate, W (2 MHz) is the width of the frequency band and erfc is the complementary error function defined as $\text{erfc}(x) = \frac{2}{\sqrt{\pi}}\int_x^\infty e^{-x^2}\text{d}x$.

We now decompose SNR into identically distributed elements for which a pdf can be defined. Once such pdf is found, we can obtain $p_k(d_k)$ by substituting (4) in (3) then taking the expectation. In order to decompose SNR, we first introduce the Bernoulli random variables Y_i, $i = 1 \ldots n$, being equal to 1 when STA i transmits a packet in a slot time, and equal to 0 otherwise. In a next step we look for the power of STA i at the AP. We denote such power with X_i and we define it as $X_i = Y_i \cdot L(D_i)$, where $L(D_i) = P_0/(1 + D_i)^\alpha$ expresses the power with which the signal of STA i arrives at the AP after being attenuated over distance D_i. P_0 (20 mW) denotes the STA transmission power. Having the power of each STA at the AP, we can compute the interfering power a packet transmitted by STA k faces. We denote this power by I_k and write it as $I_k = \sum_{i \neq k}^{n} Y_i \cdot L(D_i)$. This allows to write the following expression for the SNR at the AP of a packet/signal coming from STA k at given distance d_k:

$$SNR_k = \frac{L(d_k)}{N_0 + I_k} = \frac{L(d_k)}{N_0 + \sum_{i \neq k}^{n} Y_i \cdot L(D_i)}, \tag{5}$$

where N_0 defines the power of the background noise. We let N_0 have the following form $N_0 = N_f \cdot kTW$, where N_f (7 dB) denotes the circuit noise figure, k the Boltzmann constant and T (290 Kelvin) the device temperature.

We can see that to compute P_k using (5) in (4), the only random variable is I_k. Hence, having the pdf of I_k, which we denote by $f_{I_k}(x)$, one can compute $p_k(d_k) = E[P_k]$. Assuming independence of Y_i as in the Bianchi model, $f_{I_k}(x)$ can be expressed as an n-1 convolution:

$$f_{I_k}(x) = f_{X_1} \otimes \ldots \otimes f_{X_{k-1}} \otimes f_{X_{k+1}} \otimes \ldots \otimes f_{X_n}(x). \tag{6}$$

In the analysis above we kept the distance from STA i to the AP random denoted by D_i, except for STA k for which we are computing p_k. We next compute p_k for two cases. First, we compute it when the positions of STAs are known (the D_i are deterministic). The only randomness in this case lies in the dynamics of the MAC layer. Second, we compute p_k for a more general case where nodes are uniformly distributed in the plane.

3.1 Fixed topology

Suppose we are given the distance vector $\underline{D} = \{d_1, \ldots, d_n\}$, where d_i describes the distance of STA i to the AP. Since all distances are fixed, we omit in this section the index of distance from loss and transmission probabilities. For an STA k, we aim at finding the pdf of I_k. Remember that I_k gives the interfering power produced by all the other STAs at the AP. We need $f_X(x)$, the pdf of the power at the AP of an individual STA. For an STA i, $f_{X_i}(x)$ can be written as:

$$f_{X_i}(x) = \delta(x)(1 - \tau_i) + \delta(x - L(d_i))\tau_i, \tag{7}$$

where $\delta(x)$ is the delta function and τ_i denotes the transmission probabiltiy of STA i. $f_{I_k}(x)$ can be easily computed by means of (6). Note that the τ_i in $f_{I_k}(x)$ are kept unknown. Using (4) and taking expectation in (3), we get the packet loss probability of STA k,

$$p_k = \mathbb{E}\left[1 - (1 - BER_k)^l\right] = 1 - \int_{x=0}^{\infty} \left(1 - \frac{1}{2}\text{erfc}\left(\sqrt{\frac{L(d_k)W}{(N_0 + x)R}}\right)\right)^l f_{I_k}(x)dx. \tag{8}$$

This expression of p_k is a function of the transmission probabilities of the other STAs τ_i via the pdf functions f_{X_i}. From the Bianchi model, the transmission probability of an STA is related to its collision probability via the function $B(\cdot)$ in (2) (by substituting p by p_k and τ by τ_k). Thus, using (8) and (2) we set up a non linear system of equations, which can be solved numerically for all p_k and τ_k, $k = 1, \ldots, n$. Having the p_k and τ_k, the throughput of any STA k can be computed. This computation is shown in Section 4.

3.2 Random topology

We consider now the case where the STAs are uniformly distributed in a disk of radius r around the AP. Thus, the pdf of D (the distance to the AP of an STA) has the following form:

$$f_D(d) = 1_{\{0 \le d \le r\}} \frac{2d}{r^2}. \tag{9}$$

We focus on STA k which is located at distance d_k from the AP, and we aim at computing its average performance over all possible positions of the concurrent

STAs. As for fixed topology case, we have to find the pdf of I_k. However the computation of $f_{X_i}(x)$, the pdf of signal power at the AP of a random STA i, becomes slightly more tricky. We first write the cumulative distribution function of X_i (for $x \geq 0$):

$$\begin{aligned} F_{X_i}(x) &= \mathbb{P}\{Y_i \cdot L(D_i) \leq x\} = (1 - \mathbb{E}[\tau_i(D_i)]) + \mathbb{E}[\tau_i(D_i)]\,\mathbb{P}\{L(D_i) \leq x\} \\ &= (1 - \mathbb{E}[\tau_i(D_i)]) + 1_{\{P_0/(1+r)^\alpha \leq x \leq P_0\}}\mathbb{E}[\tau_i(D_i)]\left(1 - \frac{(L^{-1}(x))^2}{r^2}\right) \end{aligned} \quad (10)$$

$\mathbb{E}[\tau_i(D_i)]$ is the transmission probability of an STA i averaged over all its possible locations. By differentiation and using the expression of $L(D_i)$, we find the pdf of X_i,

$$f_{X_i}(x) = \delta(x)(1-\mathbb{E}[\tau_i(D_i)]) + 1_{\{P_0/(1+r)^\alpha \leq x \leq P_0\}}\frac{2}{\alpha r^2 x}\left(\frac{P_0}{x}\right)^{1/\alpha}\left(\left(\frac{P_0}{x}\right)^{1/\alpha} - 1\right)\mathbb{E}[\tau_i(D_i)]\,. \quad (11)$$

Assume that the transmission probability of a random STA i is only dependent on its own position and independent of that of the others. Only the number of the other STAs is supposed to influence the transmission probability of STA i. This is the case when the number of STAs is large (our numerical results will show that this assumption almost holds). Under this assumption, the variables X_i are independent of each other. We can therefore compute the pdf of I_k by using (6). Note that f_{I_k} is a function of one unknown $\mathbb{E}[\tau_i(D_i)]$. The packet collision probability can be obtained by plugging $f_{I_k}(x)$ in (8). We substitute then the expression of $p_k(d_k)$ in (2) to get $\tau_k(d_k)$, the probability with which STA k transmits a packet in a slot time averaged over all possible positions of the other STAs. Finally, the throughput of STA k averaged over all locations of the other STAs can be computed in a similar way to the fixed case as explained in Section 4.

Something is still missing in the above analysis, that of the expression of $\mathbb{E}[\tau_i(D_i)]$. To solve for this expectation, we write an implicit equation with $\mathbb{E}[\tau_i(D_i)]$ as a variable, then we solve this equation numerically. Equations (11) and (8) give us the expression of $p_k(d_k)$ for STA k as a function of $\mathbb{E}[\tau_i(D_i)]$. Denote by $p_k(d_k) = G(d_k, \mathbb{E}[\tau_i(D_i)])$ this expression. Using (2), we can write $\tau_k(d_k) = B(p_k(d_k)) = B(G(d_k, \mathbb{E}[\tau_i(D_i)]))$. We get our implicit equation in

$\mathbb{E}[\tau_i(D_i)]$ by summing over all the values of d_k,

$$\mathbb{E}[\tau_i(D_i)] = \mathbb{E}[B(p_k(d_k))] = \int_0^r \frac{2\pi\rho \mathrm{d}\rho}{\pi r^2} B(G(\rho, \mathbb{E}[\tau_i(D_i)])). \qquad (12)$$

Once we obtain $\mathbb{E}[\tau_i(D_i)]$, all transmission probabilities, collision probabilities and throughputs can be obtained using our above analysis. In summary, for an STA located at distance d_k:

- The packet collision probability $p_k(d_k)$ can be obtained by plugging (11) in (8), where the value of $\mathbb{E}[\tau_i(D_i)]$ is computed numerically with the implicit equation (12).
- The packet transmission probability $\tau_k(d_k)$ is computed by substituting p by $p_k(d_k)$ in (2).
- Given $p_k(d_k)$ and $\tau_k(d_k)$, the throughput of STA k can be obtained in a similar way to the Bianchi model (Section 4). The throughput of a random STA can be computed as well.

4 Throughput calculation

We now derive the throughput of an STA k located at distance d_k based on the Bianchi model. The throughput of an STA is simply the average volume of data the STA transmits in a slot divided by the average slot duration. An STA can transmit at most one packet in a slot and the slot duration depends on what happens during the slot: idle, successful transmission or collision. In the case of a fixed topology (Section 3.1), the throughput of STA k depends on the positions of all other STAs via their transmission probabilities τ_i, whereas in the case of a random topology (Section 3.2), this throughput depends on the transmission probability $\mathbb{E}[\tau_i(D_i)]$ of a random STA averaged over all its possible locations and the locations of the other STAs.

Consider first the case of fixed topology. The throughput of STA k is equal to:

$$Z_k = \frac{\tau_k(1-p_k)L}{(1-P_{tr})\sigma + P_{tr}P_sT_s + P_{tr}(1-P_s)T_c}, \qquad (13)$$

where L (8000 bits) is the payload size and σ (20 μs) is the physical slot time of 802.11 (idle slot). P_{tr} is the probability that at least one of the n STAs is transmitting: $P_{tr} = 1 - \prod_{i=1}^{n}(1-\tau_i)$. P_s is the probability that there is a successful transmission in a slot given that at least one STA is transmitting: $P_s = \frac{\sum_{i=1}^{n}\tau_i(1-p_i)}{P_{tr}}$. The expressions for T_s and T_c, representing the slot duration for a successful and unsuccessful (collision) transmission, are shown in [4]:

$$T_s = 2t_{PLCP} + DIFS + \frac{H+L}{R} + SIFS + \frac{ACK}{R}, \quad (14)$$

$$T_c = t_{PLCP} + DIFS + \frac{H+L}{R}. \quad (15)$$

In these expressions, H is the total header length seen at the application layer (74 bytes for TCP). It includes the header information of the transport, network and data link control layer, hence H is equal to:

$$H = MAC_{hdr} + IP_{hdr} + TRANSPORT_{hdr}. \quad (16)$$

t_{PLCP} is the Physical Layer Convergence Protocol (PLCP) preamble and header which is of total duration 192 μs at 11 Mbps. ACK is the size of an 802.11 acknowledgment which equals 112 bits. Finally, DIFS and SIFS are the Distributed Inter Frame Space and Short Inter Frame Space time intervals. Their values are 50 μs and 10 μs respectively.

For a random topology, only the expressions of P_{tr} and P_s change. These expressions become:

$$P_{tr} = 1 - (1-\tau_k(d_k))(1-\mathbb{E}[\tau_i(D_i)])^{n-1} \quad (17)$$

$$P_s = \frac{\tau_k(d_k)\cdot(1-p_k(d_k)) + (n-1)\mathbb{E}[\tau_i(D_i)]\,(1-\mathbb{E}[p_i(D_i)])}{P_{tr}}. \quad (18)$$

One can apply the same technique to compute the saturation throughput of a random STA independently of its position as well as the total saturation throughput of the medium.

5 Numerical results

We implement our analytical model in MATLAB. We first consider a fixed topology, i.e the D_i are deterministic. We place 5 STAs at 1 m from the AP, and the other 5 STAs are placed on a circle centered at the AP whose radius is changed from 0 to 8 m. We compute the saturation throughput of one fixed STA and that of one moving STA. The throughputs (in kbps) are shown in Fig. 1. We also plot in the same figure the throughput obtained by an STA if the Bianchi model was used. The results are very interesting. When the STAs are all close to the AP (less than 2m), they all have the same throughput and it is equal to the one given by the Bianchi model (which supposes that two colliding packets are automatically lost). When the moving STAs are far from the AP (more than 5m), their power level at the AP starts to be very low compared to that of the close STAs, so they lose their packets when they contend for the medium with the close STAs. The close STAs get then a high throughput and the moving STAs get a low throughput approximately equal to the bandwidth not used by the close STAs. The Bianchi model is no longer good in this case. We also notice in the figure the fast throughput shift of the moving STAs between 2 and 5 m. This results from the fast attenuation of the power when an STA moves away from the AP.

To better illustrate the above results, we plot in Fig. 2 two conditional probabilities: (i) the probability that one moving STA loses its packet when it contends to the medium with one or more fixed STAs, and (ii) the probability that one fixed STA loses its packet when it contends to the medium with one or more moving STAs. Both probabilities are equal to 1 when all STAs are close to the AP (same as assumed by the Bianchi model). Probability (i) remains equal to 1 when the moving STAs are far from the AP since their power level at the AP is low. On the other hand, probability (ii) drops to 0 at around 5 m, which means that fixed STAs always win when they contend to the medium with a moving STA at more than 5 m from the AP.

We now consider the random topology case, where STAs are uniformly distributed in a disk of radius 10 m centered at the AP. We pick one STA, we move it from 0 to 10 meter, and we compute its throughput averaged over all the possible locations of the other 9 STAs. We also compute the average throughput of any other STA. The results are shown in Fig. 3 and are also very interesting. When the moving STA is close to the AP, it gets a higher throughput than the average throughput of the others and than the throughput given by the Bianchi model (Fig. 1) since with a high probability the other STAs are far from the AP. However, this throughput decreases when the STA moves farther from the AP until it drops below the average throughput of the others. The minimum throughput of the moving STA is again obtained at a distance of 5 m. Note that Fig. 3 also shows the average throughput over 1000 realizations of the 9 STAs. We use the fixed topology method to find the throughput per realization, and we average over all the realizations. The purpose is to validate our analysis in the random topology case.

6 Conclusions

We presented in this paper an analytical model that accounts for the positions of STAs when evaluating the performance of 802.11 MAC layer. The model has different extensions on which we are working and that will be introduced in a future detailed version. One extension considers an AP that transmits packets (see Fig. 4), which would allow us to find the optimal AP placement for a given topology. Further extensions could consider the RTS/CTS mode as well as the ad-hoc mode to numerically approach the wireless capacity found in [5].

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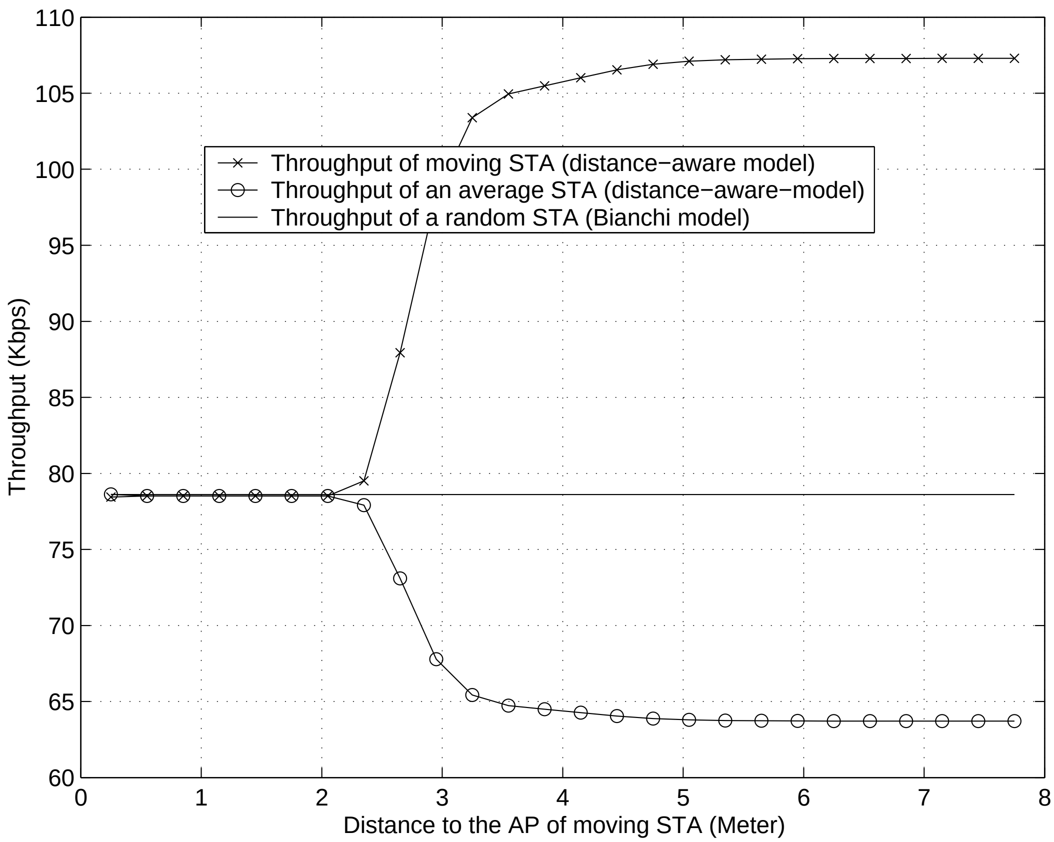

Figure 1: Throughput in the fixed topology case.

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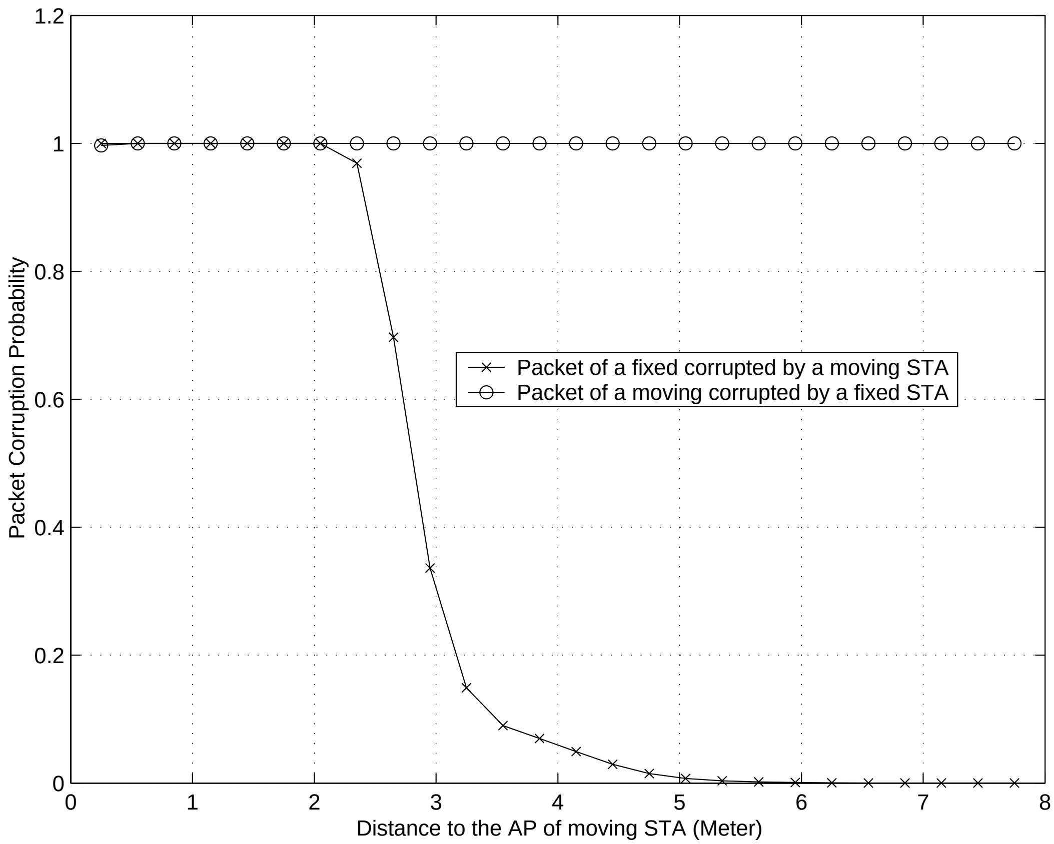

Figure 2: Collision probability in the fixed topology case.

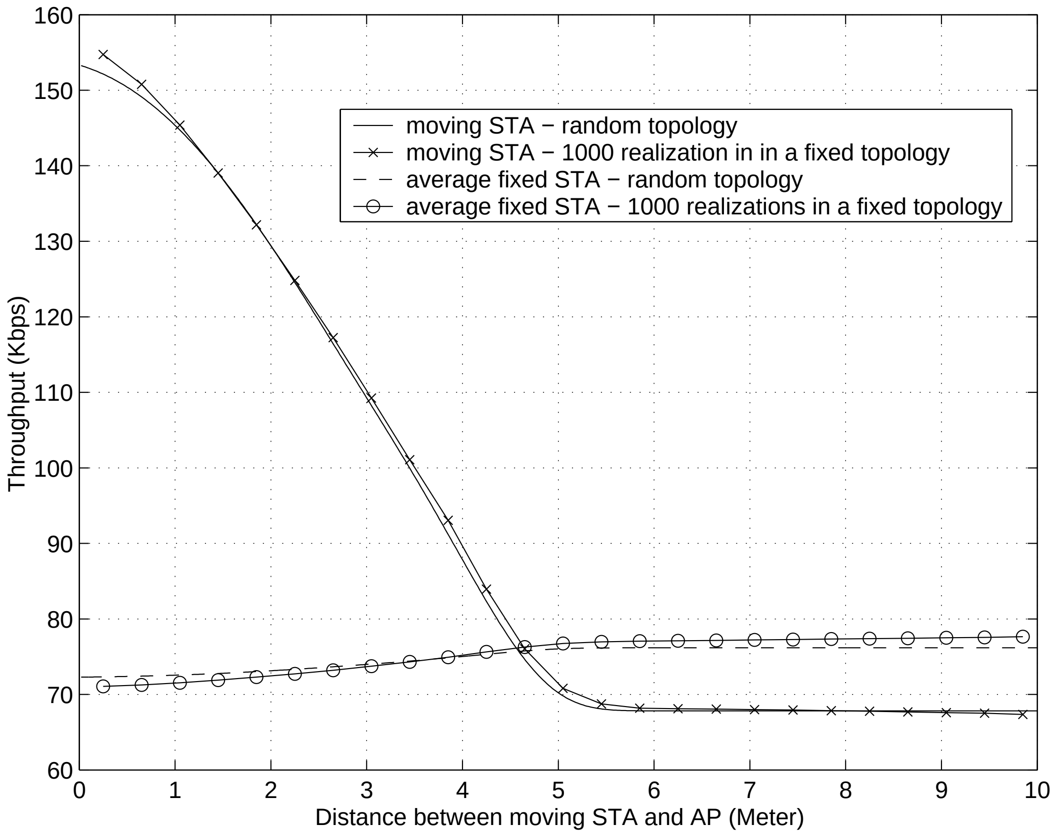

Figure 3: Throughput in the random topology case.

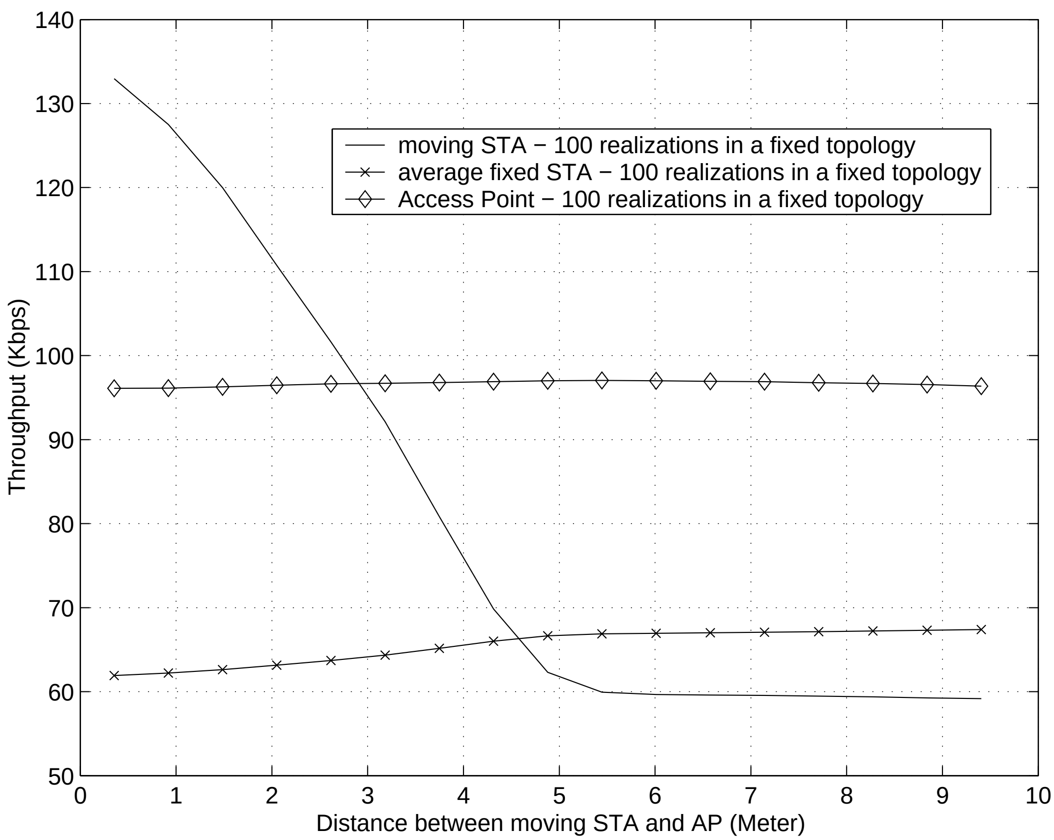

Figure 4: Throughput in the random topology case with duplex transmission. The AP has a 3dB higher transmission power.

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