Spatial Reuse in Wireless LAN Networks

Khaldoun Al Agha
LRI
Université de Paris-Sud 11 bât 490
91405 Orsay Cedex, France
Khaldoun.Alagha@lri.fr

Laurent Viennot
INRIA- Hipercom
domaine du voluceau - B.P.105
78153 Le Chesnay Cedex, FRANCE
Laurent.Viennot@inria.fr

Abstract The absence of a radio carrier reuse pattern in wireless LAN systems necessities to apply a collision avoidance mechanism in order to manage all collisions that can produce on the medium sharing. Previous studies concerning cellular radio networks are in general focused on the basis of frequency cell partition. We re-investigate this frequency reuse topic for wireless LANs where all nodes use the same channel and are randomly placed. Several measurements are presented to compute all radio parameters in a local radio network. Then, theoretical study and simulation results are introduced to deduce the distance that permits a complete carrier reuse by using a carrier sense mechanism.

Keywords:

Wireless LAN, Propagation model, CSMA

Introduction

Channel utilization in wireless local area networks is, in general, based on the same carrier frequency. No reuse factor or frequency planning is defined. All users tune on the same channel and try to transmit data. However, collision between communications of nearby users could appear frequently. To avoid collisions, several techniques exist like Carrier Sense Multiple Access (CSMA) [1]. In this technique, different thresholds are fixed in order to manage the medium sharing. Each user has to estimate the signal of neighboring users. When the number of neighboring users is relatively high, the user avoids to transmit and waits for another silent period. The CSMA threshold that, indicates to a user when the number of interfering signals is high, represents the key of the system capacity in radio LAN networks.

In Lucent Wave LAN, three threshold levels are defined: low, medium, and high [2]. When the signal measured by the user is lower than the threshold, the user can transmit. A human intervention is needed to modify the threshold between low, medium, and high. In Hiperlan 1 [3, 4, 5], the system defines an adaptive threshold that is fixed as a function of the traffic load. When the traffic is high the value of the threshold is bigger.

An adaptive threshold is crucial in a wireless radio while the capacity of the system and the communication quality depends directly of this threshold. Our approach in this paper consists in computing the maximum distance from a transmitter that guarantees a non-interfering communication in parallel with other transmitting nodes. This distance permits to adapt the threshold in a wireless LAN.

On the other hand, varying the signal power in an *ad-hoc* network [6] is needed to reach neighbors in order to root all packets correctly to the destination. This signal power variation is correlated with our reuse distance. A maximum signal power permits to reach a far node but all nodes in the transmitter neighboring area can not transmit and on the contrary, a minimum signal power allows carrier reuse but necessities more packet routing.

This paper is organized as follows: Section 2 shows results obtained with a set of measurements and simulation, while Section 3 presents a theoretical study of the reuse distance. In section 4, a spatial reuse with and without carrier sense is simulated.

1. LAN radio transmission: measurements and modeling

The carrier reuse in local radio networks depends strongly on the environment characteristics. Path loss and slow fading effects define the reuse factor in LAN environment. Basically, for local radio system, the same carrier is reused every where and has a different employment comparing with a cellular system like GSM [7, 8]. Consequently, all users can use the same frequency band without any constraints. However, the high interference level produced by other user communications in a closed area prevents a continuous utilization of the used carrier. The

Table 1. Environment characteristic values.

Measurement environment	Linear correlation coefficient	α	*b*(*dB*))
Corner-office	0.95	4.63	-11.45
Corner-wall	0.98	2.86	-40.09
Office-office	0.997	3.99	-38.53
Corridor-moving	0.998	2.87	-40.89
Road	0.88	2.31	-31.75
Road with cars	0.94	2.35	-36.60
All points (indoor)	0.99	2.67	-44.24

carrier sense technique resolves this constraint and permits all users to share the medium avoiding almost all collisions.

In this section, we try to compute parameters that model signal propagation. Measurement parameters are carried out by using Lucent Wave LAN Cards (IEEE 802.11) in different cases including indoor environment (offices, corridors, inside buildings, etc.) and external buildings environment (roads between buildings with many hurdles). These results are compared with simulation results. In fact, the propagation model considered uses as received signal power [7, 8]:

$$P_{tr} \frac{K}{R^{\alpha}} 10^{\frac{\xi}{10}} \tag{1}$$

where P_{tr} is the transmitted power, K is a constant, ξ is related to the log normal shadowing effect with a standard deviation that takes values up to *12dB*. A normal distribution is used for ξ values. R is the transmitter to receiver distance and α is the power attenuation exponent.

The idea is to use one Wave LAN transmitter and receiver and to compute a very high quantity of received signal power. Then, a linear correlation between all points permits to calculate components of the line equation $y = -ax + b$; where a is equal to α and b is a constant (in *dB).* Indeed, mapping the Equation 1 in *dB* implies: $E[10 log(\text{received power})] = -\alpha * 10 log R + KP_{tr}$. Table 1 gives values of the linear correlation applied on measurement files. The correlation coefficient indicates how true values are closed to the computed correlation line. This coefficient has to be very close to 1 in order to exhibit a high correlation quality. Each line of Table 1 consists of a measurement series. Details on measurements are described below:

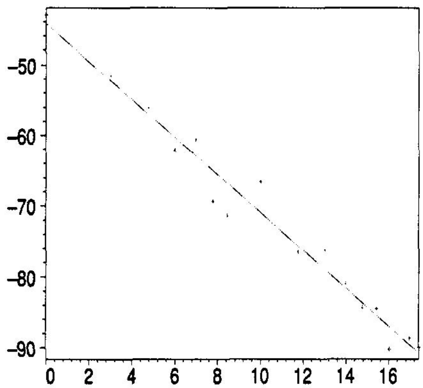
- Corner-office: transmitter behind the corridor corner and receiver is moving from office to office in the same building;
- Corner-wall: transmitter behind the corridor corner and receiver behind all walls in the building;

- Office-office: transmitter in an office and receiver is moving from office to office in the same building (in each office, about 200 measures are taken moving around);

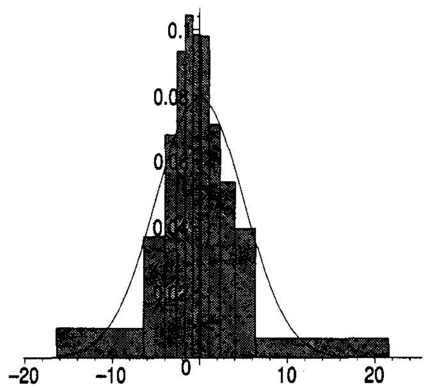
- Corridor-moving: transmitter behind the corridor corner and receiver is turning during measures in each office entrance of the building.

- Road: transmitter and receiver are on a road without cars;

- Road with cars: transmitter and receiver moving around cars parked on the road.



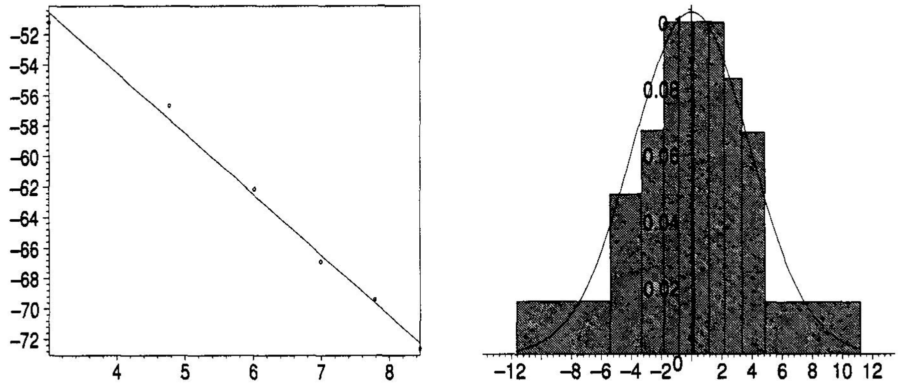
(a) Computing of attenuation components: $\alpha = 2.67$ and $b = -44.24$; (received signal power versus distance).



(b) Slow fading component measurement; standard deviation=5.03.

Figure 1. All indoor values.

Figure 1.a presents mean signal power measurements compared to the linear correlation line. All measurements are very close to the correlation line. Deviations from the mean value are shown in Figure 1.b and compared to the PDF (Probability Distribution Function) of the normal distribution with the same standard deviation. The histogram represents all measurement points that are inserted into boxes with equal surfaces. This represents a discrete analog of the PDF. Basically, we can observe that all values tend to form a normal distribution silhouette while respecting the same standard deviation issued from the measurement values. Note that values are measured in several indoor environments.



(a) Computing of attenuation components: α = 3.99 and b = −38.53; (received signal power versus distance).

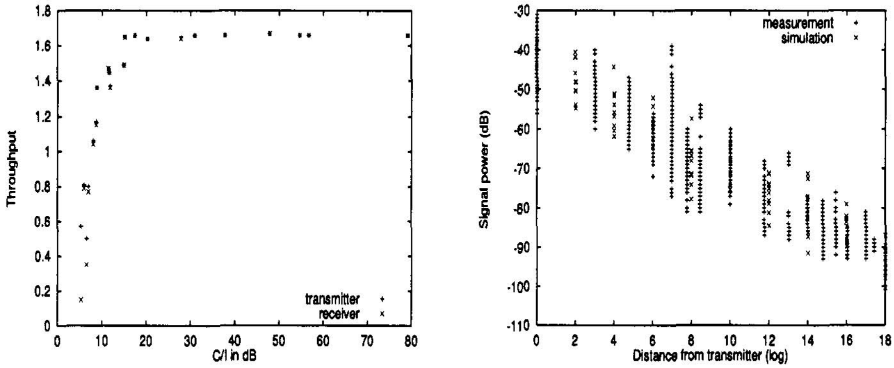
(b) Slow fading component measurement; standard deviation=3.86.

Figure 2. Measurement in building offices only.

In order to zoom into values and to estimate a better standard deviation of the log-normal shadowing, we show only values that measured in the same environment conditions. Figures 2.a and 2.b depict only measurements carried in an office-office (referred to Table l) environment. Clearly, one can see that values are more coherent and the form of the histogram is ideally similar to the PDF of the normal distribution and show the relevance of the model.

After doing measurements and computing all simulation model parameters, the idea consists in reporting all these values in the simulation model and compare results with measurements. All indoor environment values are plotted in Figure 3.a (see Table 1 also). The shadowing log-normal standard deviation is estimated to 5*dB*. Figure 3.a illustrates measurement values and simulation results for the received signal power. We can observe that the path loss attenuation and the deviation from the mean value are very similar. This conclusion confirms the validity of the log-normal distribution for the shadowing modeling or the slow fading effects.

Finally, the system throughput (at transmitter and receiver) is exhibited in Figure 3.a as a function of the received *C/I* ratio. Measurements were made by using a UDP (User Datagram Protocol) stream of l*Kbytes* packets. Recall that the maximum throughput supported by Wave LAN cards is supposed to be 2Mbps (in a theoretical way!). The



(a) System throughput (Mbps) versus *C/I*(*dB*) ratio.

(b) Received signal power.

Figure 3. Throughput measurements and a comparison between simulation and measurements.

figure suggests that the minimum *C/I* ratio required to maintain a high throughput should be about 15*dB*. This value will be used later to compute the reuse distance in our radio model. Also, the transmitter and receiver throughput are very approximately equal to each other when the *C/I* is bigger than 15*dB*. This is due to the high quality of the radio communication. In the other case, below 15*dB,* Figure 3.a displays the difference between throughput at the receiver and the transmitter end point (due to packet loss). Evidently, when the bit error rate is high (small *C/I),* the re-transmission protocol will reduce the bit rate.

In short, by doing an important number of measurements, we compute all indoor environment characteristics in order to determine the reuse distance and the maximum number of possible simultaneous communicat ions.

2. Spatial reuse modeling and analysis

In time multiplexed cellular networks [7, 8] spatial reuse is generally considered in term of frequency pattern allocation. We consider here a simpler model which is still consistent with the cellular approach. We want to characterize the maximum distance between a transmitter and a receiver (allowing a good transmission) according to the density of simultaneous transmitters. This section is devoted to give a simple analytic analysis of the triangular mesh. It will be used as a reference for comparing the simulation results. The classical triangular mesh is a basic example where transmitters are regularly and densely placed. We characterize a density of simultaneous transmitters in a $L \times L$ square by the inter-node distance of the triangular mesh with same number of transmitters that fit in the square. If N is the number of transmitters, then we have $N = \frac{L}{D} * \frac{L}{D\sqrt{3}/2}$.

In cellular networks [7, 8], frequency reuse pattern is in general based on a frequency reuse distance D proportional to the radius R of the cell [7]. Typically, $D = 3R$ or $D = 3.46R$ for classical GSM reuse patterns. We are going to estimate this factor for the triangular mesh supposing that no shadow fading effect occurs.

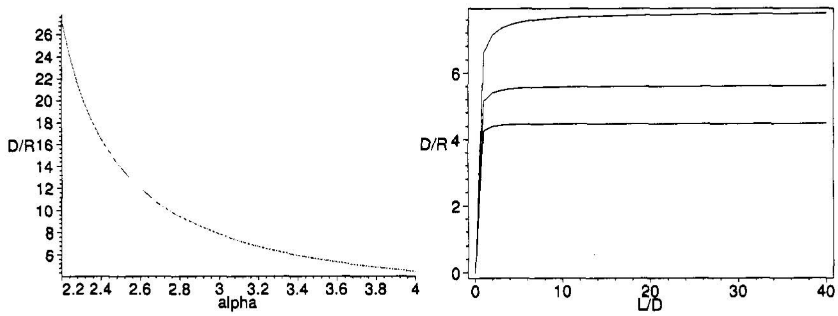


Figure 4. (a) A ratio D/R that guarantees good spatial reuse in a triangular mesh with $Q = 15dB$ according to the attenuation coefficient α. (b) A sharper lower bound on the minimum ratio D/R according to L/D for $\alpha = 3$ (upper curve), $\alpha = 3.5$ (middle curve) and $\alpha = 4$ (lower curve).

A sufficient condition for getting a good transmission between the transmitting node and the receiver is:

$$K\frac{P_{tr}}{R^\alpha} \geq Q\mathcal{B} \quad \text{where} \quad \mathcal{B} = \sum_{e \text{ transmitter}} K\frac{P_{tr}}{\text{Distance}(e)^\alpha}$$

Let HN denotes the hexagon with transmitters at distance nD from the source transmitter (there are $6n$ such transmitters; their distance is greater than $nD\sqrt{3}/2$). By partitioning the sum according to concentric hexagons, we obtain:

$$\mathcal{B} = \sum_{n=1}^{L/D} \sum_{e \in H_n} K\frac{P_{tr}}{\text{Distance}(e)^\alpha} \leq \sum_{n=1}^{L/D} 6nK\frac{P_{tr}}{(nD\sqrt{3}/2)^\alpha} \leq \frac{6KP_{tr}}{(D\sqrt{3}/2)^\alpha}\zeta(\alpha-1)$$

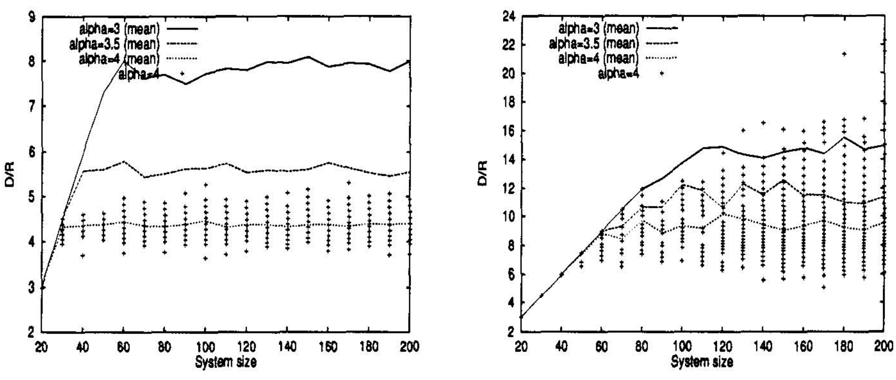
where $\zeta(s) = \sum_{n=1}^{\infty} \frac{1}{n^s}$ is the famous zeta function of Riemann. A sufficient condition for good spatial reuse for the triangular mesh is thus:

$$\frac{D}{R} \geq \frac{2}{\sqrt{3}} \left(6Q\zeta(\alpha - 1)\right)^{1/\alpha}$$

Note that this inequality is obtained by summing up to infinity. It is possible to get a sharper estimation by considering finite sums. See Figure 4 for an illustration. Notice that the *D/R* ratio converges rapidly as the system size increases.

3. Spatial reuse simulation

After presenting measurements that provide radio parameters and a theoretical study that gives an idea about the *D/R* ratio (D is the distance between two transmitters as defined in Section 3 and *R* is the maximum distance from a transmitter that guarantees a good transmission), the paper proposes to execute simulations in order to find the *D/R* ratio as a function of different parameters: system size, silence CSMA threshold, α and nodes distribution (randomly or triangular). First, simulations are executed without any carrier sense and then by using a CSMA mechanism. The CSMA mechanism defines a silence CSMA threshold: if a node needs to transmit, it should listen other user signals. If the sum of these signals is below the threshold, it can transmit. Otherwise, it waits for a more silent period. The simulation model of Equation 1 is taken.

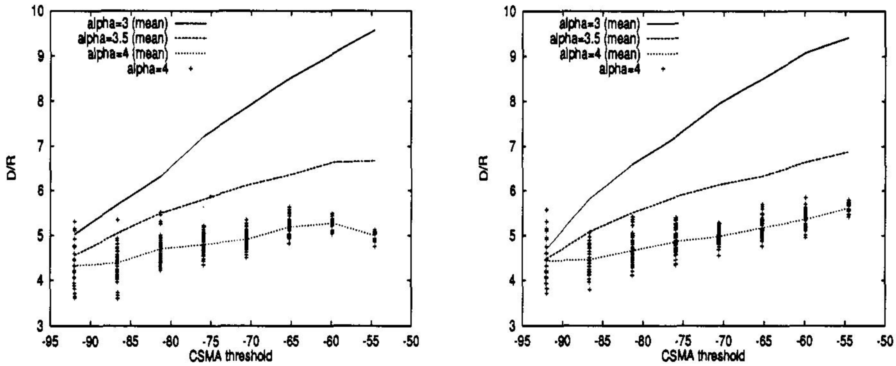


(a) Triangular configuration. (b) Random configuration.

Figure 5. Silence area size versus system size; simulation without CSMA.

Figures 5.a and 5.b compare *D/R* versus system size for different Values of α in triangular and random configuration respectively. Note that the standard deviation of the log-normal shadowing distribution is fixed to 5dB. The number of transmitting nodes is equal to 50 and no CSMA protocol is applied. In the simulation, a receiver is placed randomly in a disk of radius *R* centered on each transmitter. Then, *R* is increased (we start with 1 meter) until the overall of failed communications (e.g. $C/I < 15dB$) reaches 5%. As depicted in Figures 5.a and 5.b, when the system size is too small, the number of interfering communications is high and all received power is under 15*dB* (the number of transmitting nodes is relatively high compared to the system size). Consequently, the radius is equal to 1 and the *D/R* (*D* depends on system size) rises according to the system size. When the system size becomes sufficiently big, the *D/R* reaches a stable value and shows the biggest radius that guarantees a communication independently of the system size. This stable value varies as a function of α. Indeed, by varying α with the same shadowing (here standard deviation is fixed to 5), we observe a smaller *D/R* when α is equal to 4 (a strong path loss attenuation). In addition, in a triangular configuration, all values (when varying α) are very close to the theoretical study illustrated in Figure 4. In fact, results join the reuse factor idea in a cellular context because all base stations are, in general, placed in a triangular configuration. On the other side, in an *ad-hoc* context when nodes are placed randomly, the *D/R* mean ratio converges also to a stable value which is less interesting than the triangular configuration value. Moreover, values can be far from the mean value. Indeed, random placing provides a damaging effect on the value of *R* (see Figure. 5.b).

In a CSMA context, simulations are accomplished by placing a receiver nearby each transmitter (randomly placed in the disk of radius *R*). Two cases are considered: 1000 nodes are distributed on a triangular mesh or randomly. CSMA mechanism is applied, e.g. we can transmit a message only if the summation of other signals is inferior than the CSMA threshold. Each node tries to transmit in a random order. Then, the distance *R* is increased as long as 95% of user communications is above 15*dB* as before. Figures 6.a and 6.b depict simulations results and exhibits *D/R* according to the silence CSMA threshold for a system size of 200*m*. Results specify that *D/R* reaches a stable value after a certain threshold and depending, solely, on α. Figures indicates also that random and triangular configuration are equivalent. In short, the use of a carrier sense mechanism reduces the damaging effect produced when transmitters are placed randomly.



(a) Triangular configuration. (b) Random configuration.

Figure 6. Silence area size versus CSMA threshold; simulation with CSMA.

Finally, when comparing to a non-CSMA configuration, we observe that the value of the silence CSMA threshold in our simulation is about $-75dB$ when 50 simultaneous transmissions is permitted in the system (to reach 350 transmitting nodes in the system, a $-55dB$ threshold is needed). A suitable threshold for spatial reuse seems to be around $-70dB$ because it offers small deviations to the mean of D/R values (see Figure 6). In addition, this value concludes the smallest D/R ratio while maintaining the same system size.

4. Conclusion

We have first shown the relevance of a classical radio model in the context of wireless LANs by comparing various measurements from Lucent IEEE 802.11 Wave LAN cards (over 2500 signal power measurements) with analytical analysis and simulations. Moreover, we model the spatial reuse by extending the spatial reuse factor D/R concept (known in cellular radio networks) to wireless LANs which seems especially relevant when a CSMA technique is used to avoid collisions.

Interesting future work resides in the study of self adaptive CSMA threshold tuning policies as proposed in the Hiperlan 1 norm [3]. Such policies may allow to get better spatial reuse. Another interesting study concerns *ad-hoc* networks [6]. A key point resides in finding a good tradeoff between spatial reuse and the number of transmissions needed to route each packet. Our studies could lead to a CSMA threshold policy allowing to reach this goal . . .

On the other hand, our modeling is certainly a good basis for envisioning quality of service in wireless LANs. Indeed, it allows to model, in a simple, way the sharing of the point-to-point radio links: two transmissions are independent if the distance between transmitters is at least D. We can, for example, design a simple bandwidth reservation protocol: a node can reserve some bandwidth b if b plus the sum of all the current bandwidth reservations of the nodes at distance at most D is less than the maximum bandwidth available on the carrier.

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