Client Channel Selection for Optimal Capacity in IEEE 802.11 Wireless Networks

John T. MacDonald
Sapient Systems, Inc.
456 West Frontage Road
Northfield, IL 60093
Email: macdjoh@iit.edu

Udayan Das
Computer Science Department
Illinois Institute of Technology
Chicago, IL 60616
dasuday@iit.edu

Dennis A. Roberson
Computer Science Department
Illinois Institute of Technology
Chicago, IL 60616
robersond@iit.edu

***Abstract*—In wireless networks, clients are often presented with several access points to open a channel to the infrastructure network. A client can optimize its channel performance by selecting the access point that registers the lowest interference. The interference metric in wireless networks depends on several factors including: the signal quality of the access point, the competing clients associated with the access point, and the impact of other adjacent networks in the same spectrum space. In this paper we demonstrate radio scene analysis in terms of the spatial geometry of networks, the spectrum occupancy in the band, and the temporal load of multiple clients in the network, to evaluate the interference metric. We use this criterion to optimize the client channel capacity. A case study is evaluated in a congested 802.11 wireless local area network. This has implications for wireless network optimization and efficient spectrum utilization.**

I. INTRODUCTION

The IEEE 802.11 protocol for wireless networking is a well engineered standard that allows many clients to access the infrastructure network through a wireless access point [1]. It makes provisions for the asynchronous nature of channel requests and allows multiple clients to share the same spectrum space in the unlicensed ISM bands by means of carrier sensing multiple access and collision detection (CSMA/CD). This works well enough but the communication channel performance of the client can be degraded if it must compete for packets with other clients. When networks overlap, a client must often compete for packet slots with signals coming from adjacent networks. Thus the capacity of the local network can be degraded by the competition for spectrum space from an independent adjacent network. This can be alleviated to some degree by good spectrum planning on the part of the network administrators (mapping distinct channels for adjacent access points) but this type of optimization is rare and is often defeated by overlapping networks that are managed by separate entities. In such cases, where multiple access points are available to the client node, it becomes incumbent upon the client to select the network that maximizes its own channel performance. To select the best channel requires some due diligence on the part of the client seeking network resources. It must be cognizant of the wireless environment in which it operates. It should be able to determine the location of the available access points, the number of clients associated with each access point, and any interference, from competing networks or other sources, that may degrade the channel capacity in a wireless network.

The standard model for wireless networks is that they are tightly managed by a central authority in order to maximize the availability of the network for the user. This is the model of a subscriber network, where a service provider offers access to as many clients as possible to maximize its revenues. With the growth of open networks in the unlicensed bands, clients are free to choose whatever network gives them maximum access to the network resources. In order to optimize the channel performance of the client node, the client must first evaluate the available networks and choose the service that provides the best capacity. In the cognitive radio literature this is known as ”water filling”: spectrum users find access, wherever available, and take as much as they need [2].

We offer a means for channel state estimation that will allow the client to choose the network that will maximize its own capacity. While this may suggest a means for network optimization in an information theory and game theory approach [4], we will defer such considerations for the moment and assume that the client makes his choice, and that choice does not affect the decisions of other clients in the network. In this way, the intelligent client can exploit ignorant networks.

Consider the scenario illustrated in Figure 1. A wireless client node finds itself in a position to choose among any of three access points in order to access the infrastructure network. The coverage range of all three overlap in the space of the opportunistic client. If they are all on separate channels, and the only active client is the one under study, then any access point offers an equally excellent choice to the client. If they are all on separate channels, but two of the access points have several active clients and the third has none, then the choice is obvious: the capacity and performance will be optimal where there are no competing clients for the channel. If on the other hand, the unused access point shares the channel spectrum of one of the busy access points, then the decision becomes complicated by the competition for spectrum space from client nodes from the busy channel. In that case, the client needs some measure of the expected capacity that it can achieve on any of the available clients and select the best access point accordingly.

The manner in which the client weighs the data available, and determines which access point will most likely deliver the optimal performance is the subject of this paper. With that in mind the paper is organized in the following manner. In Section II, we will consider the data available to the client and consider how that can be used to estimate the available channel capacity of the network. In Section III, we simulate several scenarios to demonstrate that the metric behaves in a logical manner. We conclude in Section IV by considering how this work can be applied to future cognitive radio systems.

II. CHANNEL STATE ESTIMATION

IEEE 802.11 networks are the wireless outgrowth of the IEEE 802.X wired network standards, were all terminals share the same data pipe. The terminals may access the pipe asynchronously and so there is a means for carrier detection and collision avoidance. In "dot11" networks, there is the addition of an access point which provides wireless clients access to the broader infrastructure network. The access point serves as a gateway to the infrastructure network, hence the sizable data communication flows through the access point. The access point is the gate keeper and can distribute bandwidth to the clients in any manner it chooses. If we assume that the access point treats each client equally, then if several clients seek a large amount of bandwidth, it will distribute packets in equal time slots. If there are N clients associated with an access point, then the channel capacity available to any client C_A will be bounded by

$$C_M \geq C_A \geq \frac{C_M}{N}, \tag{1}$$

where C_M is the maximum capacity available in the wireless network. This quantity will be limited by the technology used ("b" is 11 Mbps, "g" is 54 Mbps) and by the overhead associated with managing the wireless network (signal preambles, collision back-off time, packet headers, etc.). Naturally, if the other clients are not making requests for data, then the opportunistic client can use the full capacity of the network on the left had side of the equation. If the other clients are as greedy as the opportunistic client, then the access point will divide the resources equally and the worst case data rate will achieved by the right hand side of the equation.

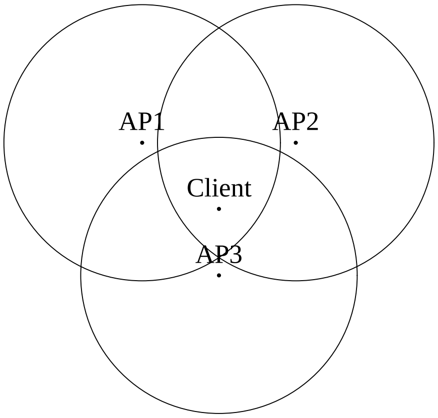

Fig. 1. Overlapping coverage areas in an IEEE 802.11 wireless network. The client may associate any with of three available access points.

In addition to the competition for resources, the capacity of the channel has more fundamental limitations. The capacity of the wireless channel is limited by the technology as dictated in the protocol and by the nature of the wireless interface between the client and access point. The capacity of the channel between the client and the access point will be either the limit set by the protocol, C_M, or the limit set by Shannon's Theorem [5],

$$C_N = \min(C_M, B\log(1+\frac{S_R}{I})) \tag{2}$$

where B is the channel bandwidth, S_R is the received signal power, and I is the interference power. The bandwidth, B (22MHz for the "b" variant), is limited by the protocol. The signal power of the received signal is dependent upon the path loss and Raleigh fading and by shading effects of walls and structures. To estimate the received signal from the transmitter, an empirical model is often used [3] as

$$S_R = \frac{S_T}{4\pi d^m} \tag{3}$$

where $2 \leq m \leq 4$ is the path loss exponent which, theoretically, can be as low as 2, but can often be as high as 4 depending on an elaborate set of circumstances. The interference power, I, is difficult to estimate [6] but if we exclude for the moment jammers in the form of signals in the band that do not operate under the cooperative protocol, then we can view I as a constant which is the noise temperature of the receiver. As the client moves farther from the access point, the signal will be degraded by the noise and the effect will be a renegotiated lower data rate (as with the "g" protocol) or packet errors that will result in retransmission and an effective decrease in the data rate (as with the "b" protocol.)

With the bounds of the channel capacity set in Equations 1 and 2 we can estimate what the worst case capacity of an access point network C_{W_i}, offered to the client

$$C_{W_i} = \frac{1}{N_i}\min(C_{M_i}, B_i log(1+\frac{S_T}{4\pi d^4 I_i})) \tag{4}$$

where i is the index associated with a particular access point network. With this estimate of the worst case capacity, we can then seek the access point that maximizes the available capacity,

$$C_O = \frac{\max}{i} C_{W_i}. \tag{5}$$

So the task for the client device is to find the access point that will maximize its minimum capacity.

All of the parameters required of the optimization are available to the client node without any additional hardware. In Equation 4, the client can determine the bandwidth B_i and the maximum data rate C_{M_i} of any access point by its beacon signal. The number of clients N_i associated with an access point can be determined by monitoring traffic in the channel.

And the signal power from an access point can be determined from the wireless adapter directly. All the ingredients are available to the wireless client to perform this optimization. We will next consider some idealized scenarios to determine the behavior of the procedure.

III. CHANNEL OPTIMIZATION: SIMULATED SCENARIOS

The formulas in the previous section provide a means to estimate the worst case capacity that the client will experience in a wireless network. Some cases have obvious outcomes. For instance, consider the case where a client is sufficiently close to two access points that the data rate is not impacted by the interference or the path loss. If the two access points have no associated clients and different data rates, then it is always best to choose the access point with the maximum data rate and hence the maximum capacity. (All things being equal one would prefer ”g” to ”b”.) If on the other hand, the two access points have different rates, and operate on separate channels, then the higher rate access point would have to be congested to a certain degree before it would behoove the client to associate with the lower data rate access point. (A ”g” access point with four clients would give a lower worst case capacity than the unused ”b” access point.) As access points become more congested, and the signal quality between the clients and access point degrades, the choice becomes more nuanced.

A. *Choosing between a near and a far node*

In the first case we will consider the scenario where there two available access points with identical maximum data rates: a local node with several associated clients; and a remote node operating on a different channel with fewer associated clients. If the two access points were in the vicinity of the client, then the obvious choice would be the access point to which the least number of clients have associated. This will minimize the competition for capacity in the worst case when all clients demand the maximum throughput. However, if the unused access point is farther away than the congested node, the choice becomes complicated by the quality of the connection and there may be no capacity gain due to the degraded channel. The decision curve will divide the preferred access points when their channel capacities are equal

$$\begin{aligned} C_L &= C_R \\ \frac{C_M}{N_L} &= \frac{B\log(1+\frac{S_T}{4\pi d^4 I})}{N_R}. \end{aligned}$$

where (C_L, N_L) are the capacity and number of clients associated with the local node, and (C_R, N_R) are the capacity and number of clients associated with the remote node.

In this case, we assume that both nodes offer the same maximum data rate, C_M (the “g” data rate), both have the same transmit power S_T (limited by the regulations), both have the same bandwidth B (limited by the protocol spectral mask) and both have the same noise level I (the minimum sensitivity of the receiver). These parameters are listed in Table I.

Parameter	Variable	Value	Units
Maximum Capacity	C_{M_i}	54	Mbps
Bandwidth	B	22	MHz
Transmitter Power	S_T	100	mW
Interference Power	I	-60	dBm

TABLE I
PARAMETERS OF A TYPICAL IEEE 802.11G NETWORK WITH TWO INDEPENDENT ACCESS POINTS

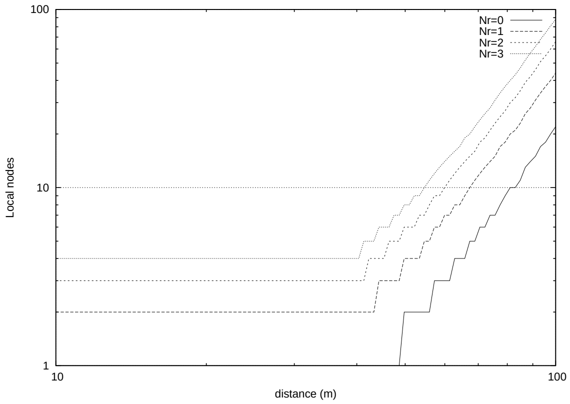

Fig. 2. Curve of equal capacity between a local access point with several clients associated and a remote access point with no clients associated as a function of the distance to the remote access point

As the unused access point moves farther away from the client, at some distance there is no capacity gain to be realized by associating with the distant access point. The graph of Figure 2 shows the distance at which the capacity to be realized from the under-utilized far away node equals the worst case capacity that can be expected in the nearby, occupied, node. As can be seen from the graph, if there is only one client associated with the local access point, and the remote access point is more than 35 meters away, then there is no advantage to associating with the distant access point. As more nodes are associated with the local node, then the advantage falls to the distant access point. At the extreme case, if there are 22 clients associated with the local node, and the remote node is utilized, then it can be 100 meters away and offer better capacity, then the worst case capacity in the local network. Each curve on Figure 2 represents the decision for a different number of clients associated with the remote node. As the number of clients divides the capacity on the remote node, the advantage is reduced and the remote access point must be nearer to the opportunistic client to realize a gain in capacity over the congested local access point.

Of course if the client is nomadic (like a laptop user in a public library), then it would behoove the user to move himself closer to the remote access point. To maximize the capacity, he should move to the left side of the curve.

B. *Remote Access Point with Higher Data Rate*

If we have two access points on separate frequency channels with different data rates, the access point that offers the highest capacity will be preferred. When the nearest access point offers a lower data rate then the client may prefer to associate with the farther access point.

Suppose the near access point operates at the ”b” protocol and the far access point operates with the higher data rate ”g” protocol, then the choice will be based on the signal quality from the far access point. In this case we use the same operating parameters in the previous case except that the both nodes are free (no competing clients have associated with them) and the near access point operates at a lower data rate. Within a certain radius of each access point, the channel capacity is set by the maximum data rate of the protocol. As we move farther from the access points, the noise and path loss will corrupt the signal and reduce the channel capacity.

Figure 3 shows the maximum channel capacity available to a client in large room (100 meters by 100 meters). On the left side there is an access point with a data rate limited to 11 Mbps. The maximum capacity is constant over a range of 40 meters. On the right side there is an access point with a maximum data rate of 54 Mbps. That access point has its best capacity over a range of 20 meters. The higher rate access point has a smaller radius of optimal operation because it has a lower coding gain. In the middle of the room, Shannon’s theorem is the dominant limitation, and it limits the maximum capacity from both access points equally. In terms of a terrain map, both access points are twin mountains with their tops lopped off at different levels. The saddle of the curve is the region where the capacity is identical between the two access points, and that boundary is the bisecting line in the middle of the room.

If the higher data rate access point is near enough, then it will always be preferred. That is the distance where the Shannon’s capacity will equal the lower data rate of the near access point,

$$d = \sqrt[m]{\frac{S_T}{4\pi I(2^{C_M/B}-1)}}. \tag{6}$$

With the parameters of the simulation, that works out to about 37 meters. So if the client can move to with 37 meters of the ”g” access point, it can get a better channel capacity than that offered by the nearer ”b” access point.

Access Point “b”		Access Point “g”	
coords	(0,50)	(100,50)	meters
maxrate	11	54	Mbps
S_T	100	100	mW
I	-60	-60	dBm

TABLE II
PARAMETERS OF ACCESS POINTS IN FIGURE 3

IV. CONCLUSION

In situations where wireless network users are presented with many communication path options, some simple channel state estimation can be employed to select the best option to maximize the communication performance. The channel estimation means described in this paper requires no additional hardware on the part of the client other than that which is already required to establish a wireless communication channel. It only adds a small network monitoring task to assess the capacity of the available wireless channels and selecting the best choice.

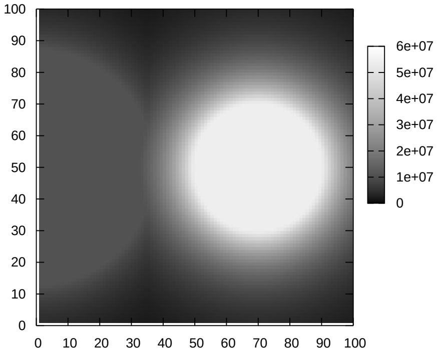

Fig. 3. Terrain map of maximum channel capacity provided by two access points. The AP on the left uses the ”b” protocol. The AP on the right uses the “g” protocol. The dimensions are in units of meters. The color scale indicates the maximum data rate in bits per second.

This provides a small demonstration of the capacity improvements that are possible with cognitive radio systems. In such systems, receiver and transmitter pairs detect available bandwidth and seek out the optimal communication path. In this work, we are concerned with one side of the transaction, the client seeking access to the open infrastructure network (the Internet.) The unlicensed band provides a fertile ground for testing methods to improve spectral efficiency.

While the emphasis of this work has been on wireless network clients, the work suggests methods for wireless network managers to improve their site coverage design to improve the capacity available to their clients. In future work, we would like to improve the algorithm by gathering real-time channel statistics to better assess the best channel option at the moment, rather than simply avoiding the worst choice based on short term survey data.

REFERENCES

[1] “Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications”, *ANSI/IEEE Std 802.11, 1999 Edition (R2003)*,

[2] W.Yu, “Competition and cooperation in multi-user communication environments,” Ph.D. dissertation, Stanford University, Stanford, CA, 2002

[3] A.E.Leu, M.Machinery, B.L.Mark, ”Modeling and Analysis of interference in Listen-Before-Talk spectrum access schemes”,*Intl.Jour.of Network Management*, Vol.16, No.2, pp.131, March-April 2006, ISSN 1055-7146

[4] S.Haykin, ”Cognitive Radio: Brain-Empowered Wireless Communications”, *IEEE Jour.Select.Areas in Communications*, Vol.23, No.2, pp.201, Feb.2005

[5] R.B.Ash, *Information Theory*, John Wiley and Sons, New York, NY, 1965

[6] D.A.Roberson, C.S.Hood, J.L.Locicero, J.T.MacDonald, ”Spectral Occupancy and Interference Studies in support of Cognitive Radio Technology Deployment”, *Proc.IEEE Workshop on Networking Technologies for SDR* Reston, VA, Sept.25, 2006