Measured Performance of 5-GHz 802.11a Wireless LAN Systems

IEEE 802.11a systems take advantage of higher data rates and more frequency spectrum to deliver good range and improved system capacity performance.

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Abstract

Wireless Local Area Networks (WLANs) have come a long way from their humble roots. What started out as a way for vertical industries to transmit data in warehouses and on the factory floor has grown into a cost-effective means for enterprises to network increasingly mobile workers for increased productivity. Last year approximately 7 million WLAN units were sold generating an estimated $1 billion market. While such results seem impressive, WLANs have yet to realize their full potential. Systems built to the IEEE 802.11a standard will soon appear in the market to take advantage of higher data rates and more frequency channels for even greater performance. In this paper, we will present, for the first time, measured 5-GHz 802.11a performance data. The range performance of 5-GHz 802.11a systems is measured in terms of data link rate and throughput. These results will then be used to calculate 802.11a system capacity. Here, 802.11a provides not only higher end-user speeds but also allows reductions in WLAN deployment costs.

Published 08/27/01

1 Introduction

Many events have conspired to produce the success of Wireless LANs. The advent of the IEEE 802.11b standard that achieved nearly Ethernet-equivalent speeds, the creation of the Wireless Ethernet Compatibility Alliance (WECA) as an industry forum that pushed for Wi-Fi™ interoperability amongst equipment vendors, and the decision by major notebook makers to integrate WLANs into mobile PCs for the mass market all played pivotal roles. Such efforts and trends will continue for 802.11a and for the future of WLANs. As Table 1 shows, U.S. F.C.C regulatory and IEEE standards bodies have laid a solid foundation for this future. Certain inherent advantages for 802.11a are evident in terms of more frequency spectrum, higher data rates, and more advanced modulation techniques. As such, the resulting benefits to 802.11a users are very compelling and should be carefully studied and understood.

	802.11a	802.11b	802.11
Standard Approved	September 1999	September 1999	July 1997
Available Bandwidth	300MHz	83.5MHz	83.5MHz
Unlicensed Frequencies of Operation	5.15-5.35GHz, 5.725-5.825GHz	2.4-2.4835GHz	2.4-2.4835GHz
Number of Non-Overlapping Channels	4 (Indoor) 4 (Indoor/Outdoor) 4 (Indoor/Outdoor)	3 (Indoor/Outdoor)	3 (Indoor/Outdoor)
Data Rate per Channel	6, 9, 12, 18, 24, 36, 48, 54 Mbps	1, 2, 5.5, 11 Mbps	1, 2 Mbps
Modulation Type	OFDM	DSSS	FHSS, DSSS

Table 1. Table of approved IEEE standards. Note that the 802.11a standard is just as mature as 802.11b. U.S. frequency spectrum regulations and number of non-overlapping channels are listed. Only U.S. F.C.C. regulations and frequencies are shown.

This paper seeks to address two of these benefits – range and system capacity. We begin by presenting measured 802.11a range performance in a typical office environment. Details with regards to the measurement setup and measurement environment are described. Measured data for link rate and throughput performance are presented. These are compared to measured 802.11b performance data as well. The measured range data is then used to calculate system capacity. These calculations are based on a published IEEE model and are repeated for both WLAN systems. The results point to the importance of having more non-overlapping channels, which allow 802.11a systems to have more system capacity due to less likelihood of interference from neighboring cells. Finally, we conclude with discussion on the benefits of 802.11a systems for the end user and IT manager in terms of higher speeds and lower deployment costs.

2 802.11a Range Performance

Many studies of 802.11a range performance have used theoretical link models and radio wave propagation characteristics to support their claims. While theoretical models allow for predictive capability, they nonetheless still do not offer real-world validation. This is especially true in environments where people and multi-path (i.e. a condition in which a transmitted signal reflects off many surfaces before arriving at the receiver) are present. Furthermore, all models depend on the performance of theoretical rather than real radio implementations.

This paper will present, for the first time, measured 5-GHz 802.11a range performance data collected in a typical, office environment. Details of the measurement setup and resulting measurement results are explained below. Identical tests were repeated for a popular 802.11b product as well. The results indicate that 802.11a systems have similar range as 802.11b systems in a typical office environment but with 2 to 5 times higher data rate and throughput performance.

2.1 Measurement Setup

The measurement environment was Atheros' Sunnyvale office in California. This is a 265 foot by 115 foot rectangular facility with conference rooms, closed offices, and walls as well as semi-open cubicle spaces. For the 802.11a system, data was sent between two Atheros 802.11a PC Card reference designs. One card served as the fixed Access Point (AP) while the other served as a mobile station. Distances of up to 225 feet were measured. The 802.11a reference design used the Atheros AR5000 chipset and had an output power of 14dBm to the antenna for both the AP and the mobile station. The PC Card reference design used for the 802.11a AP included a reference design external antenna with an average gain of 4dBi. The 802.11b system under test comprised an Access Point and PC Card from a leading 802.11b manufacturer. This system had an output power of 15dBm to the antenna for both the AP and the mobile station.

For both systems, the mobile station was moved to the same 80 random locations, which included open cubicle areas, various closed offices and conference rooms. At each location, the placement of the laptop followed a random orientation in order to be representative of actual use (i.e. users do not manually adjust the orientation of their mobile stations). A random orientation also lessened the advantages for any antenna gain with respect to a particular orientation. The same orientation at each location was used for both 802.11a and 802.11b systems in order to maintain a uniform comparison between the two systems.

At each location, 100 broadcast (i.e. non-acknowledged) packets at each data link rate were sent from the Access Point to the mobile station. This was done in order to obtain statistically meaningful results. The packet size was fixed at 1500 bytes and no fragmentation was used. The mobile station then recorded how many of these packets were received successfully to compute a Packet Error Rate (PER). This measurement technique allowed close monitoring of the physical, link performance of both systems without being subject to performance effects due to variability in software (i.e. rate adaptation) or higher layer protocols and applications (e.g. FTP file transfer using TCP/IP). Again, the same measurement methodology was used for both the 802.11a and 802.11b systems.

After all packet error rate measurements were taken, an optimal rate adaptation algorithm was used to determine the data link rate and throughput performance. This was applied to both 802.11a and 802.11b systems. Recall that at each of the 80 measurement locations, packets were sent at all data link rates (i.e. 6, 9, 12, 18, 24, 36, 48, 54 Mbps for 802.11a and 1, 2, 5.5, 11 Mbps for 802.11b) and associated PERs were recorded. These PERs were then used to compute an effective MAC throughput for each of the data link rates. This calculation accounted for the MAC and PHY overhead and effect of packet retries. This calculation was based on 802.11 specifications for inter-frame spacings, slot times, PHY overhead, etc. (An example of this calculation can be found in Appendix A and is summarized in Appendix B.) The best throughput was selected for each location and this process was repeated for all 80 locations.

2.2 Data Link Rate Results

For each location, the optimal data link rate is defined as the link rate yielding the highest throughput. This determination was repeated for all 80 locations. This process was applied to both 802.11a and 802.11b systems to remove the effect of different software rate adaptation algorithms. For the data link rate measurement, a median filter was applied to the data from each of the 80 locations to smooth the data. The purpose was to produce results that provided a fair representation of the overall range performance. The use of the median filter means that at each link rate there are equal numbers of measured ranges that are less than as well as greater than the median values. The 802.11a and 802.11b median range performances are plotted in Figure 1 below.

There are two main conclusions that can be readily drawn from Figure 1:

1. 802.11a has similar range compared to 802.11b up to 225 feet in a typical office environment.
2. For all distances up to 225 feet in a typical office environment, the data link rates of 802.11a are 2 to 5 times better than 802.11b.

Other notable observations are that at the maximum measured distance of 225 feet, 802.11a yielded a 6 Mbps rate versus 2 Mbps for 802.11b. At the highest 802.11b 11 Mbps range (i.e. 107.5 feet) 802.11a still operated at a higher data link rate of 18 Mbps. Of course, at closer distances this improvement becomes larger. In actual use, many enterprises are deploying smaller cells with 65 feet radii. This is done in order for each AP to serve a smaller number of users thereby providing each user a higher speed. At 65 feet, Figure 1 shows that 802.11a furthers its speed advantage by delivering a 36 Mbps data link rate.

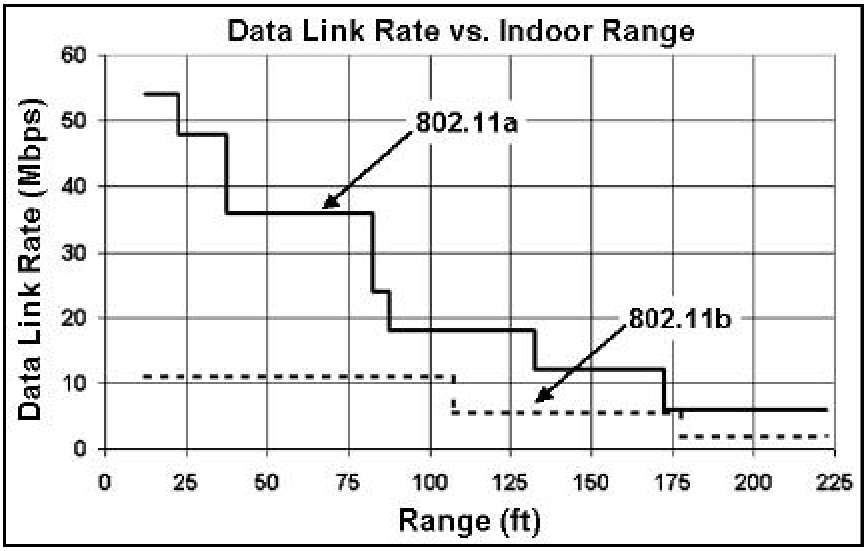

Figure 1. Measured median range performance data for 1500 byte data packets indicates that the range of 802.11a is similar to 802.11b up to 225 feet in a typical office environment. At 225 feet, 802.11a systems were measured at 6 Mbps while 802.11b systems were at 2 Mbps.

2.3 Throughput Results

Data link rates provide an insight into how WLAN systems trade performance for range. However, another important metric is throughput versus range. Throughput is the actual rate of information that can be transmitted accounting for various overheads. Throughput is dependent on several factors: data link rate (54 Mbps, etc.), MAC efficiency, measured packet error rate (PER), and packet size. Other factors such as efficiency of higher layer protocols (e.g. TCP/IP), collisions, and the number of users can also affect throughput but were not considered in this analysis.

As previously described in Section 2.1, throughput performance was determined by selecting the best throughput at each location. This process was repeated for all 80 locations. The resulting set of 80 throughput data points was then binned and averaged to smooth the data. This methodology was repeated for both 802.11a and 802.1b systems under test and is plotted in Figure 2.

There are two main conclusions that can be readily drawn from Figure 2:

1. 802.11a has higher throughput than 802.11b up to 225 feet in a typical office environment.
2. For all distances up to 225 feet in a typical office environment, the throughput of 802.11a systems are 2 to 4.5 times better than 802.11b.

More specifically, at the maximum measured distance of 225 feet, 802.11a yielded a 5.2 Mbps rate versus 1.6 Mbps for 802.11b. At more realistic deployment distances of 65 feet, 802.11a extends its speed to 21 Mbps versus 5.1 Mbps for 802.11b. These throughput results will be used in calculations on system capacity in the subsequent sections.

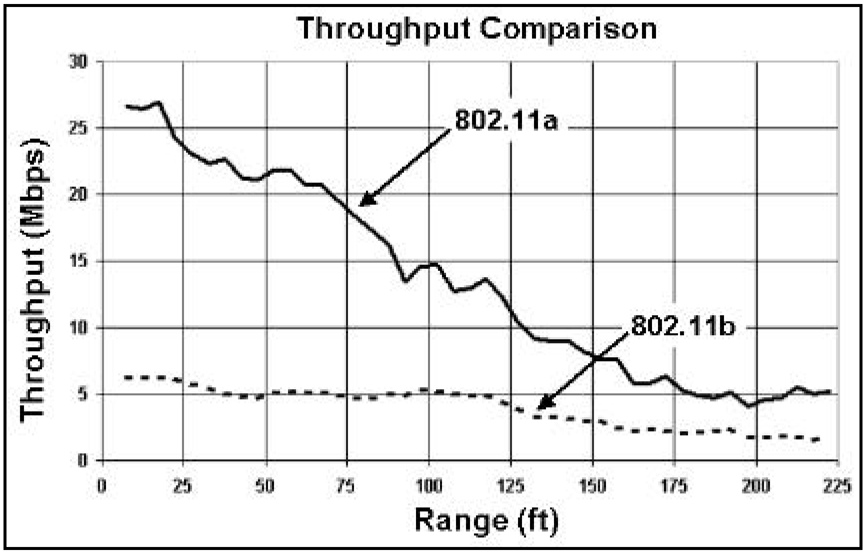

Figure 2. Averaged throughput performance data for 1500 byte data packets. The results indicate that 802.11a throughputs are always at least a factor of 2 times and up to 4.5 times larger than 802.11b systems up to 225 feet.

3 802.11a System Capacity Benefits

So far the discussion has been limited to measured performance between two nodes, one AP and a mobile station. In a real world WLAN deployment, there are many Access Points, each simultaneously serving many stations within a given area or cell. A more meaningful question that should be asked is, 'given a deployment of multiple APs, how much throughput does each user receive?' To answer this question, we will need to introduce and discuss the issue of system capacity.

System capacity refers to the throughput of an entire WLAN system comprised of many cells. Before we can begin a discussion on 802.11a system capacity versus that of 802.11b, we first need to understand the throughput of a single-cell WLAN network.

3.1 Single Cell Throughput

For a single mobile station within a cell, the cell throughput is equivalent to the throughput received by the station. For multiple stations in a cell, the average cell throughput is divided equally among the stations (assuming equal sharing among stations). Based on the measured results of Figure 2 above, throughput of the cell is the highest when the mobile station is closest to the center of the cell, or AP, and lowest when it is farthest away. In between these extremes is an average throughput for the entire cell. This average cell throughput represents an average value that the cell can provide to a mobile station irrespective of its location within the cell. Based upon the measured results of the previous section, the average cell throughput of an 802.11a cell with a 225 feet radius in a typical office environment is 9.41 Mbps. This is a 3 times increase over the throughput of an 802.11b system (3.13 Mbps) in the same office environment. For a more realistic cell radius of 65 feet (or a cell size of 130 feet), 802.11a average cell throughput is 4.5 times that of 802.11b -- 22.6 Mbps versus 5.1 Mbps. In other words, for an 802.11b system to provide the same amount of total throughput as an 802.11a system, more than four 802.11b APs would have to be deployed (each operating on a unique frequency) in the same area (see Figure 3 below).

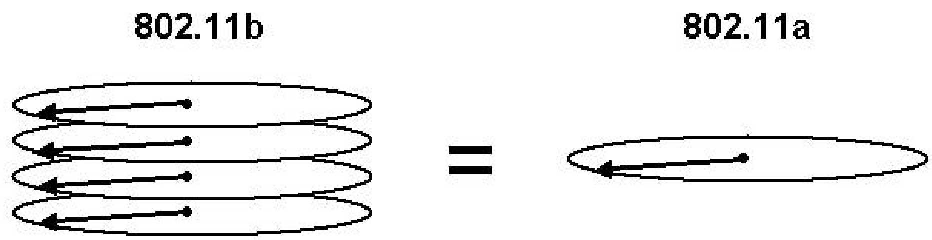

Figure 3. For a cell radius of 65 feet, more than four 802.11b cells would have to be overlaid on top of each other to achieve the same average throughput of a single 802.11a cell. This assumes that each 802.11b Access Point can operate on a unique frequency. In reality, this can never be accomplished since 802.11b systems can only operate on 3 distinct channels as mandated by the U.S. F.C.C regulations for the 2.4-GHz unlicensed band.

3.2 Impact of Co-Channel Interference (CCI)

Unfortunately, the deployment scenario described in the previous section is not possible for 802.11b systems. The reason is that the fourth 802.11b cell would have to operate using one of the previous three channels. The sharing of the same channel between two adjacent cells reduces their average throughput. This effect is referred to as Co-Channel Interference (CCI). Conceptually, it is easy to understand that the key factor in eliminating or reducing CCI is to increase the number of available channels. Figure 4 illustrates this point for an 8-cell system deployed using 802.11a and 802.11b. The 8 indoor WLAN channels allotted for 802.11a by U.S. F.C.C regulations prevent any CCI in this 8-cell system. This is not the case for the 8-cell 802.11b system. Each channel has at least one additional CCI cell for an average of 1.67 CCI cells over all 3 frequencies.

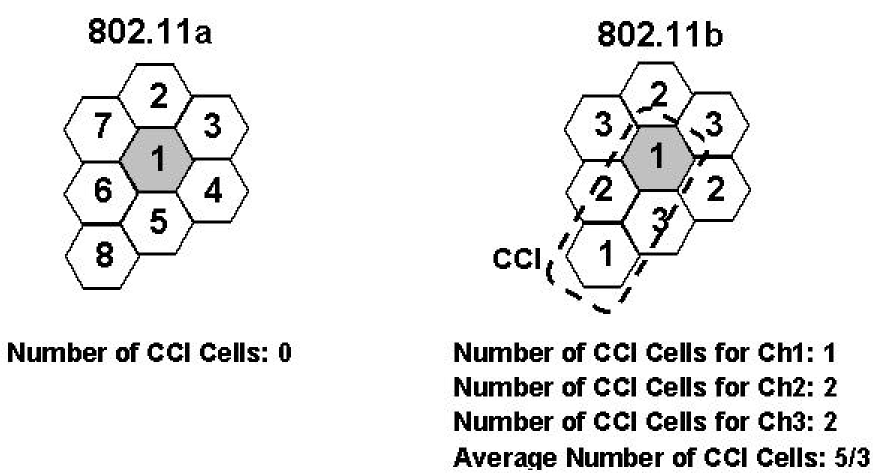

Figure 4. By virtue of having more channels, 802.11a systems will suffer less CCI than 802.11b systems. Hence, cell throughput will not be degraded in an 802.11a 8-cell system as it will in an 8-cell 802.11b system. Numbers inside each hexagon correspond to different channel frequencies.

3.3 System Capacity under CCI

One way to evaluate the impact of CCI on average cell throughput is to use a model for system capacity. A system capacity model proposed in 1998 by NEC[1] to the IEEE WLAN standardization group was used. Measured range performance data from Section 2 was inputted into this model to make its results more indicative of actual 802.11a

[1] Ishii, K. "General Discussion of Throughput Capacity," IEEE 802.11-98, April 23, 1998.

and 802.11b range performance. There are two mechanisms that model the effect of CCI on system capacity. The Clear Channel Assessment (CCA) mechanism describes the decrease in throughput that results when the Access Point inside a particular cell has to wait until the channel is available for transmission. The second, 'Hidden Cell' mechanism models how transmissions from undetected cells can corrupt transmission, thereby lowering throughput.

The system capacity model and measured range data were used to evaluate the system capacity for an 8-cell WLAN system depicted in Figure 4 above. An 8-cell system was chosen because it is representative of deployments in small and medium-sized enterprises (SMEs). Figure 5 shows the result of this analysis. For a typical cell radius of 65 feet (cell diameter of 130 feet), an 802.11a system provides over 8 times the average cell throughput (and therefore, 8 times the system capacity) of an equivalent 802.11b system. For a given number of users, each user on an 802.11a network would experience 8 times the throughput of a user on an 802.11b network. This increase results from the fact that there was no Co-Channel Interference in the 802.11a system due to the availability of 8 channels (802.11a systems have 8 indoor channels versus 3 for 802.11b according to U.S. F.C.C. regulations).

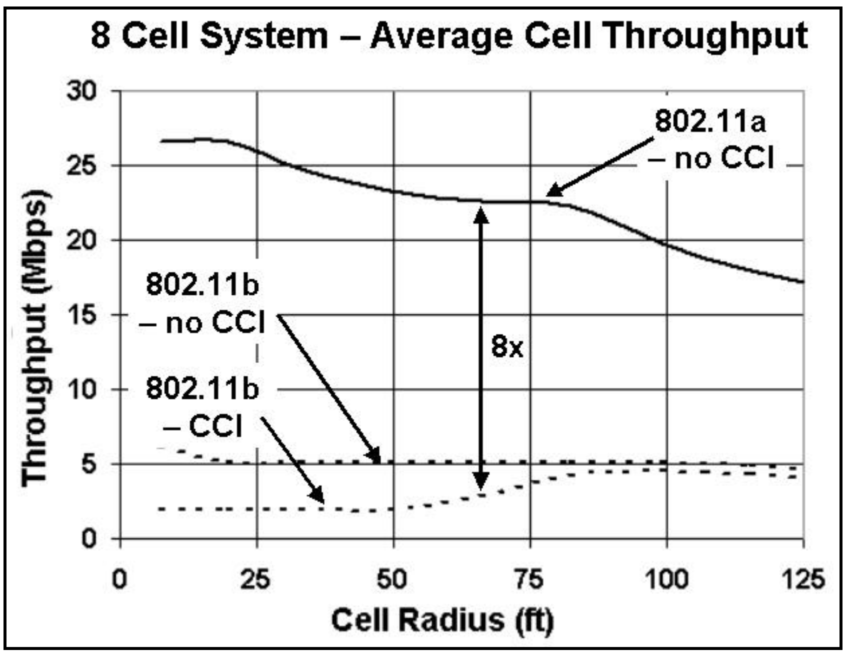

Figure 5. Average cell throughputs for an 8-cell 802.11a system versus an 8-cell 802.11b system. 802.11b systems have Co-Channel Interference and throughput suffers as a result. For a typical cell radius of 65 feet (a diameter of 130 feet), an 802.11a system provides 8 times the average cell throughput of an 802.11b system.

The advantages of having more channels carry over to larger systems as well. In many-cell systems, such as those shown in Figure 6, 802.11a will have CCI cells but a fewer number than 802.11b. If we use channel 1 as the point of reference, the number of CCI cells at one 'cell distance', or first ring, away from the center cell is 0 for both 802.11a and 802.11b systems. If we extend this distance to the second ring, 802.11a continues to have no CCI cells, whereas 802.11b has 6. For the third ring, 802.11a will begin to have 4 CCI cells, but this value is 3 times less than 802.11b systems. The presence of additional channels has another benefit in reducing CCI. As shown in Figure 6, the distance between CCI cells is increased, and the likelihood of packets from different cells interfering with one another is therefore reduced.

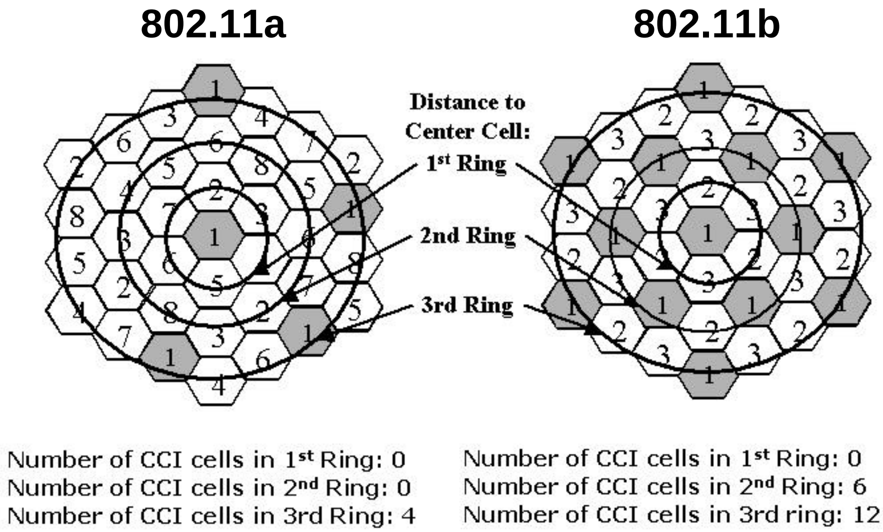

Figure 6. The number of cells that cause Co-Channel Interference is less for 802.11a systems due to the presence of more channels.

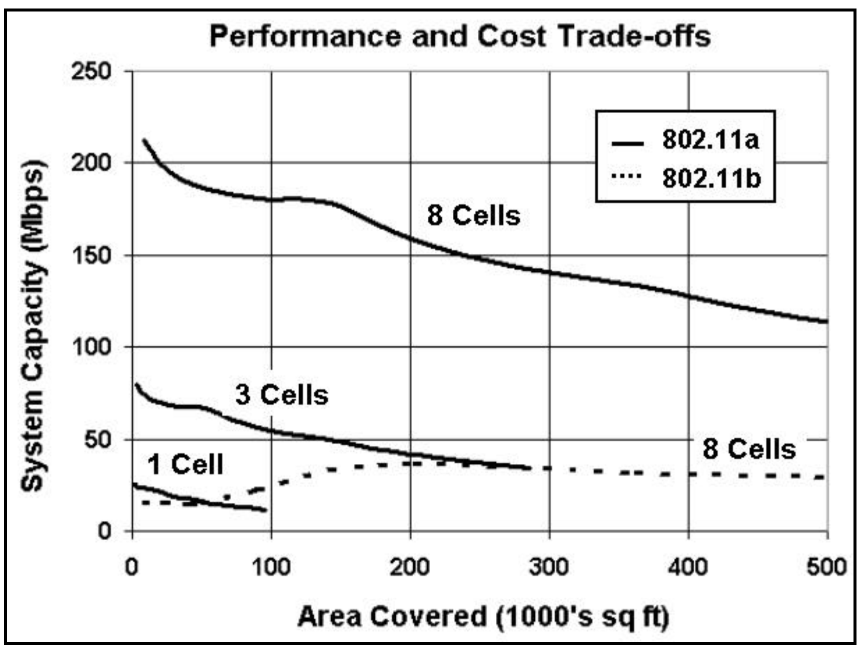

Figure 7. 802.11a system capacity advantages enable IT managers to deploy the same system capacity using fewer APs than an 8-cell 802.11b system. Alternatively, IT managers can deploy a higher system capacity using the same number of APs as an 8-cell 802.11b system.

3.4 Performance and Cost Implications

In the previous section, we demonstrated how 802.11a can provide more system capacity than 802.11b due to the availability of more channels. This increase allows IT managers to trade off increased performance with lower deployment costs. This is illustrated in Figure 7 above. Total system capacity (average cell throughput multiplied by the number of cells in the system) is plotted versus WLAN deployment areas for both an 8-cell 802.11b system and different 802.11a systems with a varying number of cells. For a deployment area of 200,000 ft^2, a 3-cell 802.11a and an 8-cell 802.11b system provide approximately the same system capacity -- 40.4 Mbps and 36.5 Mbps, respectively. However, 802.11a can accomplish this with 3 cells spaced 285 feet apart, whereas an 802.11b system requires 8 cells spaced 170 feet apart. This allows 802.11a systems to be provisioned with less AP infrastructure and lower installation costs. Alternatively, IT managers can also choose to deploy an 8-cell 802.11a system to increase system capacity to 158.3 Mbps for the same 200,000 ft^2 area. In effect, each user now has 4 times more throughput. Figure 7 shows other options that are possible for 802.11a systems.

4 Conclusions

In this paper, we have presented measured 802.11a performance data for range in terms of data link rate and throughput. We have used these measurements with an IEEE model to explain the advantages of more frequency channels on system capacity. To summarize, this paper has produced the following findings:

- 802.11a has similar range compared to 802.11b in a typical office environment up to 225 feet.
- 802.11a has 2 to 5 times the data link rate of 802.11b in a typical office environment up to 225 feet.
- 802.11a has 2 to 4.5 times the throughput of 802.11b in a typical office environment up to 225 feet.
- 802.11a systems have more available non-overlapping channels than 802.11b. This allows 802.11a systems to have higher system capacity than 802.11b systems.
- 802.11a has 8 times the system capacity of 802.11b for an 8-cell WLAN deployment.
- 802.11a system capacity advantages offer choices for IT network managers. They can either provide the same throughput as 802.11b at lower AP deployment costs or provide increased throughput for similar AP deployment costs as 802.11b.

Appendix A: Throughput vs. PER Calculation

	Throughput versus PER								
sifs (us)_ =	16								
difs (us) =	34								
slot (us) =	9								
PHY overhead (us) =	20								
data MAC overhead (bytes)=	30								
ACK MAC overhead (bytes) =	16.75								
ACK timeout (greater of actual ack timeout and DIFs time) (us) =	34								
packet error rate =	0.05								
data rate =	54								
packet length =	1500								
try #	probability this try	contention window	ack timeout	time for 1/2 CW	packet time	ACK time (with SIFs)	time this try	accumulated all tries	probability X time
1	9.5E-01	15	34	67.5	248	40	389.5	389.5	3.70E+02
2	4.8E-02	31	34	139.5	248	40	461.5	851	4.04E+01
3	2.4E-03	63	34	283.5	248	40	605.5	1456.5	3.46E+00
4	1.2E-04	127	34	571.5	248	40	893.5	2350	2.79E-01
5	5.9E-06	255	34	1147.5	248	40	1469.5	3819.5	2.27E-02
6	3.0E-07	511	34	2299.5	248	40	2621.5	6441	1.91E-03
7	1.5E-08	1023	34	4603.5	248	40	4925.5	11366.5	1.69E-04
8	7.4E-10	1023	34	4603.5	248	40	4925.5	16292	1.21E-05
9	3.7E-11	1023	34	4603.5	248	40	4925.5	21217.5	7.87E-07
10	1.9E-12	1023	34	4603.5	248	40	4925.5	26143	4.85E-08
11	9.3E-14	1023	34	4603.5	248	40	4925.5	31068.5	2.88E-09
12	4.6E-15	1023	34	4603.5	248	40	4925.5	35994	1.67E-10
13	2.3E-16	1023	34	4603.5	248	40	4925.5	40919.5	9.49E-12
14	1.2E-17	1023	34	4603.5	248	40	4925.5	45845	5.32E-13
15	5.8E-19	1023	34	4603.5	248	40	4925.5	50770.5	2.94E-14
16	2.9E-20	1023	34	4603.5	248	40	4925.5	55696	1.61E-15
17	1.4E-21	1023	34	4603.5	248	40	4925.5	60621.5	8.79E-17
18	7.2E-23	1023	34	4603.5	248	40	4925.5	65547	4.75E-18
19	3.6E-24	1023	34	4603.5	248	40	4925.5	70472.5	2.55E-19
20	1.8E-25	1023	34	4603.5	248	40	4925.5	75398	1.37E-20
Total Odds	1.00						Total Time		4.14E+02
							Throughput (Mbps)		29.0

Appendix B: Throughput vs. Date Rate and PER Summary

	Throughput vs. Data Rate and Packet Error Rate							
PER	**Data Rate**							
	6	**9**	**12**	**18**	**24**	**36**	**48**	**54**
0.00	5.4	7.8	10.1	14.2	17.7	23.9	28.7	30.8
0.05	5.1	7.4	9.6	13.4	16.7	22.6	27.0	29.0
0.10	4.8	7.0	9.0	12.6	15.7	21.2	25.3	27.1
0.15	4.6	6.6	8.5	11.8	14.7	19.7	23.6	25.2
0.20	4.3	6.2	7.9	11.0	13.7	18.3	21.7	23.2
0.25	4.0	5.7	7.3	10.2	12.6	16.8	19.9	21.2
0.30	3.7	5.3	6.8	9.4	11.5	15.2	17.9	19.0
0.35	3.4	4.9	6.2	8.5	10.4	13.6	15.9	16.8
0.40	3.1	4.4	5.6	7.6	9.2	11.8	13.7	14.5
0.45	2.8	3.9	4.9	6.6	8.0	10.1	11.6	12.2
0.50	2.5	3.4	4.3	5.7	6.7	8.4	9.5	9.9
0.55	2.1	2.9	3.6	4.7	5.5	6.7	7.5	7.8
0.60	1.8	2.4	3.0	3.8	4.3	5.2	5.7	5.9
0.65	1.5	2.0	2.4	2.9	3.3	3.8	4.2	4.3
0.70	1.2	1.5	1.8	2.2	2.4	2.8	3.0	3.0
0.75	0.9	1.2	1.4	1.6	1.7	1.9	2.0	2.1
0.80	0.7	0.9	1.0	1.1	1.2	1.3	1.4	1.4
0.85	0.5	0.7	0.7	0.8	0.9	1.0	1.0	1.0
0.90	0.4	0.5	0.6	0.7	0.7	0.7	0.8	0.8
0.95	0.5	0.5	0.6	0.7	0.7	0.7	0.8	0.8