1.0 Overview

We tested enterprise wireless LAN systems based on Cisco infrastructure deployed in a conventional microcellular architecture and the same system was also deployed using the InnerWireless Horizon™ Distributed Antenna System (DAS). In both cases, the same Cisco access points and wireless LAN controller were used. The main difference being the physical layer - how the wireless signals are distributed throughout the coverage area.

Horizon™is a DAS that can accommodate a broad range of wireless services operating from 400 MHz to 6 GHz including paging, public safety, 2-way radio, cellular/PCS, WMTS and Wi-Fi. Horizon™ implements Wi-Fi, 802.11 a, b, g, or n wireless LANs as layers of independent wireless service. This layered architecture is known as a layered DAS or L-DAS. The Horizon™ L-DAS provides pervasive coverage, and layering increases capacity in the same area by using multiple Wi-Fi access points (APs) operating on different channels. The layering capability is unique when compared to the conventional microcellular architecture for wireless LANs, where a single access point (AP) provides both coverage and capacity in an area.

In the L-DAS approach the RF coverage is engineered ahead of time. The access points are located in a wiring closet (or other convenient location with other telecom gear) on each floor and multiple antennas are placed throughout the coverage area such that the wireless signal level for each channel used is spread consistently throughout the entire area. In the discrete microcellular approach, the access points are placed out in the coverage area and each one has its own antennas. The channel and signal level of each AP are set independently by the Wireless LAN controller and can change dynamically. Usually, the resulting coverage pattern is that adjacent access points operate on different channels. In an L-DAS, all channels are available at all locations.

We compared the difference in performance for a system deployed in the conventional manner and a system deployed using InnerWireless Horizon™ Distributed Antenna System (DAS). We tested two configurations - a small configuration with only three access points and a larger configuration, covering the entire floor, using nine APs.

1.1 Key Findings

• The L-DAS exhibited lower interference between APs in the same system than the microcellular system.
• The L-DAS allowed us to organize client traffic into different isolated layers, and this led to better performance.
• The L-DAS delivered more than double the data capacity of the discrete microcellular system in our tests.
• The clients on the L-DAS exhibited more uniform and predictable performance.
• On all of the voice tests, the clients on the L-DAS had much lower jitter and slightly better MOS scores.
• The L-DAS did not compromise the basic functionality of the Cisco Wireless LAN system. All of the expected features worked well on the L-DAS.
• Roaming, voice support, QoS mechanisms and 802.11a/b/g and 802.11n (with 20 or 40 MHz channels) worked on the L-DAS with the same clients and software as the discrete microcellular system.
• To get maximum benefit, the L-DAS requires upfront engineering to design the guaranteed RF coverage and to organize the traffic into layers.
2.0 Wireless LAN Configurations

We tested two different wireless LAN configurations - a conventional microcellular architecture with discrete access points using Cisco APs and wireless LAN controller; and the same equipment implemented on top of the InnerWireless Horizon™ L-DAS. Horizon™ is a broadband, in-building, distributed antenna system designed for the transmission of multiple RF signals simultaneously over a single antenna infrastructure that supports multiple wireless services operating in different RF bands from 400 MHz to 6 GHz. Paging, public safety, 2-way radio, cellular/PCS, WMTS and 802.11 a/b/g/n are combined on the same Distributed Antenna System.

We tested only the wireless LAN portion of the system that supports both the 2.4 GHz and 5 GHz bands. Most of the testing was conducted in the 2.4 GHz band which is widely used in wireless LAN deployments in the enterprise.

2.1 Microcellular Architecture

A conventional enterprise wireless LAN deployment uses a microcellular architecture where multiple access points are installed out in the area to be covered. In the 2.4 GHz band, there are three non-overlapping channels available for Wi-Fi networks. A simple network could be deployed as shown at left, where each color represents coverage on a different channel. The strategy for microcellular deployments is to lay out the APs such that adjacent APs are operating on different channels and avoiding situations where neighboring APs use the same channel. This is not always possible with only three independent channels available in the 2.4 GHz band. AP placement is planned to ensure that the coverage area from adjacent APs overlaps in order to provide a continuous area of wireless coverage.

When more wireless capacity is needed, additional APs are added to the system covering the same area. The power for each AP is reduced so that it covers a smaller area. The alternating pattern of APs operating on different channels is repeated as much as possible. The actual coverage is not as uniform as shown in the figures. In modern enterprise wireless LANs, a Wireless LAN Controller (the Cisco 4402 for example) is used to coordinate the management and security of the distributed APs. One of the functions of the WLAN controller is radio resource management (RRM), which sets the channel and power level of the APs in the system. The RRM tries to ensure a continuous coverage area with minimum interference from APs in the system operating on the same channel.

Once the Cisco system is configured, the APs act independently, with no awareness of their neighboring APs in terms of Wireless LAN access, other than the low level 802.11 medium access protocol.
2.2 Layered DAS Architecture

Horizon™ is made up of multi-coverage diversity antennas that are engineered to provide uniform signal-level RF coverage throughout a facility. Each coverage area uses a single coaxial cable with multiple RF radiating elements (antennas) to provide a typical coverage area of 6,000 square feet, about three times the size of the coverage area expected from a discrete access point in a microcellular deployment. This coverage area is called a segment.

An access point is connected to the antenna segment using an access point combiner. Access points for each segment are collocated in a common location (e.g. a telecommunication closet or recessed ceiling cabinet) so that they are secure and easy to maintain.

Multiple segments can be combined to provide coverage throughout an entire facility. In this architecture, a single channel of Wi-Fi covers the entire area. If more capacity is needed, more APs can be added to the antenna segment and tuned to a different channel. Each new channel provides an independent layer of wireless LAN service. At any specific location, all channels that are in use are available.

In the 2.4 GHz, band there are three unique channels and the L-DAS distributes signals for each channel throughout the entire coverage area. More channels are available in the 5 GHz band, depending on which version of 802.11 is being used. Horizon™ supports from one to six layers on a single L-DAS segment for wireless LAN coverage, - three channels of 2.4 GHz and up to three channels in the 5 GHz band.

A fully loaded L-DAS, with three layers operating in the 2.4 GHz band, would have three access points per 6,000 square foot segment; one for each channel. A microcellular deployment supporting the same applications and designed for the same capacity will usually require the same number of APs.

Our testing configuration used three L-DAS segments with three APs each for a total of nine APs. The microcellular system we tested used nine APs to deliver coverage and capacity to the same area, however one of the APs was off during the large scale testing.
2.3 Actual Test Configurations

The actual test configuration is shown above. On the left is the L-DAS, consisting of three segments. Because of the floor plan for this 15,000 square foot space, we divided the coverage into three segments with each segment covering roughly 5,000 square feet. Each segment is supported by three APs operating on different channels. On the right is the microcellular system configuration with nine discrete APs providing coverage for the entire area. The APs are shown in their actual locations throughout the floor.
3.0 Test Environment

3.1 The Facility

We conducted the testing at an office building in Richardson, Texas. The office space was fully built out, but only about half of the offices and cubicles in the area under test were occupied. The floor plan is shown below. The area is approximately 15,000 square feet with a mix of hard walled offices and cubicles.

None of the people working in the test area were using wireless LANs. We did detect other wireless LAN traffic from neighboring businesses and other parts of the building. We made no attempt to isolate our testing from these low level signals. Both configurations tested were subject to the same background noise.
3.2 Infrastructure System Equipment

Cisco Wireless LAN
- (6) Cisco 1252 Access Point, AIR-LAP1252AG-A-K9
- (4) Cisco 1242 Access Point, AIR-LAP1242AG-A-K9
- (1) Cisco 4402 Controller, AIR-WLC4402-12-K9
- (2) Cisco 4402 Controller, AIR-WLC4402-25-K9
- (1) Cisco Catalyst 3560G PoE-48 Switch, WS-C3560G-48PS-S
- (1) Cisco Standard WCS-50 AP, WCS-APLOC-50

We used the InnerWireless Horizon™ L-DAS which included three access point combiners, ten bi-cone broadband antennas and the associated cabling.

We used Chariot Console 4.2 to generate the traffic for these tests and gather performance statistics.

Wildpackets AiroPeekNX 2.0.3 was our 802.11 packet sniffer

The Chariot console was running on a laptop PC connected to the Ethernet network at one gigabit. The same laptop acted as an endpoint for the Chariot data tests. In this mode, the laptop PC running Chariot is acting as a server on the wired network. The voice calls were bi-directional calls initiated from the Chariot console to wireless clients.

3.3 Wireless LAN Client Equipment

We used 32 laptops and two Wi-Fi voice handsets to generate the traffic for the testing.

- 19 HP Compaq nc62xx laptops with Intel 2915abg card and integrated antenna.
- 8 Dell 600s with Cisco CB21 abg PC Card adapters.
- 2 Dell 400s with Cisco CB21 abg PC Card adapters.
- 3 Dell 630 with integrated Intel 4965 agn
- 2 Cisco 7921 Voice Handsets
4.0 Testing Scenarios

4.1 Small-Scale Testing
We focused on a 5,000 square foot area at the bottom of the floor plan, corresponding to segment 3 shown above. This region has more hard walls than the rest of the test area. We configured each access point on a separate channel using channels 1, 6 and 11 in the 2.4 GHz band. This is the ideal case for a discrete microcellular system operating in the 2.4 GHz band - each AP is on a different channel and there are no interfering APs on any of those channels nearby. The L-DAS equivalent configuration is a single segment covering the same area. Only one AP is needed to provide coverage for the segment. Other APs are added on different channels to add more capacity and enable traffic segregation. For these tests we used three layers - three APs on the three different channels.

4.2 Larger-Scale Testing
We moved the same set of wireless clients to spread them evenly throughout the entire 15,000 square foot test area. The L-DAS configuration used 9 APs. It was designed as three segments with 3 APs each. When using a DAS in this fashion, each of the channels is available at every location.

The microcellular configuration used eight discrete APs to cover the entire floor. We did not use AP7 from the figure in section 2.3. That AP was in a separate conference room which did not contain any clients during the large scale testing. Every client in the large scale testing was associated to an AP with good signal levels.

The recommended configuration for this multi-AP deployment would normally use Cisco's Radio Resource Manager (RRM) to automatically assign channels and power levels to the APs. We tried RRM with poor results. After running RRM, most APs were assigned to the same channel, and we got very low system throughput in the capacity tests. We were unable to resolve the RRM configuration problem, so we manually set the channel and power level of the APs and created the alternating pattern of channels 1, 6 and 11. This manual configuration had much better performance compared to the configuration when we ran RRM, so we used it for the remainder of the testing.

4.3 Multiple Application Testing
We created a traffic mix that is similar to the applications running in a hospital - voice, mission-critical data, and guest access. The voice clients were two Cisco 7921s and several laptop PCs running a Chariot script that generates voice traffic using the G.711 codec and timing that is similar to the Vocera system. The mission-critical data is upstream data traffic that is 500 byte packets sent twice a second. This simulates the type of traffic you might get from a heart monitor or an infusion pump - low data rate, with packets occurring at regular intervals. The guest access traffic is FTP download traffic with a small amount of upload traffic. We configured the QoS on both systems to assign voice traffic to Platinum QoS, mission-critical traffic to Gold QoS and the guest access traffic to best effort.

For the discrete microcellular system, all applications are supported by each AP and available on every channel. This is required since there is no guarantee that RF coverage from every channel is available at all locations throughout the test area. We configured the L-DAS so that each class of service was isolated to its own channel. All of the voice traffic was on channel 1, all of the guest traffic was on channel 6 and all of the mission-critical traffic was on channel 11. We configured this by assigning different SSIDs for each traffic type and then organizing the APs to only support a particular SSID. The ability to organize traffic in this manner is a key differentiator of the L-DAS.
4.4 Multiple Protocol Capacity Tests
The 802.11 standard continues to evolve and most wireless LAN installations will support a mix of wireless clients based on different generations of the standard. 802.11b and 802.11g have been sharing the same wireless LAN systems for years and now 802.11n clients are being introduced. The 802.11 protocol has mechanisms for backwards compatibility and coexistence of the different protocols on the same system. When a network is comprised entirely of 802.11 clients and APs based on the same generation of the standard, the performance of the system can be much better. We were able to take advantage of the layering of the L-DAS to isolate clients using the different 802.11 protocols into separate layers.

4.5 Performance Expectations
When measuring throughput using the Chariot scripts we developed for the capacity testing, it is possible to get about 5 Mbps per channel for an 802.11b network and about 20 Mbps per channel for an 802.11g network. When 802.11b and 802.11g clients are mixed on the same network, the overall throughput drops to 8 or 9 Mbps depending on the mix of 802.11b and 802.11g clients. In order to achieve this level of performance, all the clients must be within range of the AP and have very good signal quality.

If each 802.11g AP can deliver 20 Mbps of capacity, adding more APs to the system should increase overall capacity. This works up to a point, as long as the APs can operate on independent channels. One of the interesting things that happens (when you add more APs operating on the same channel in the same area) is the total system capacity usually goes down. In the 2.4 GHz band, after 3 APs are operating on independent channels, adding more APs creates interference in the same area and 802.11 reduces system throughput. The isolation between channels (especially in the 2.4 GHz band) is not perfect. Co-channel interference - other APs and clients on the same channel causing interference - has a much greater impact in multi-AP deployments than most people realize.

For voice calls, we would expect to be able to have 20 active calls on an 802.11g channel, with each call having a Mean Opinion Score (MOS) of 4.0 or better.
5.0 Test Observations

5.1 The L-DAS Delivered Twice the Capacity

We ran several tests where the L-DAS configuration delivered more than double the capacity of the discrete microcellular system. The simplest of these tests was a small scale multi-protocol test in segment 3 with three APs. There were 32 clients - (3) 802.11n, (5) 802.11b and (24) 802.11g. For both systems, the 802.11n clients were using a 20 MHz channel in the 2.4 GHz band. This mix of clients was distributed evenly throughout the 5,000 square foot area. The location of the clients is shown at right.

Separating traffic into different layers is one of the primary benefits of the L-DAS. For the L-DAS tests, we isolated the 802.11n clients on their own layer, configured a layer with 14 802.11g clients and another layer with a mix of 10 802.11g and 5 802.11b clients. The discrete system supported all client types on every AP, which meant that every AP in the system had to support a mix of client types based on different generations of the 802.11 standard.

<table>
<thead>
<tr>
<th>Run</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Download Mbps</td>
<td>30.98</td>
<td>19.1</td>
<td>24.28</td>
<td>13.53</td>
</tr>
<tr>
<td>Data Upload Mbps</td>
<td>28.56</td>
<td>21.75</td>
<td>22.1</td>
<td>24.13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Download Mbps</td>
<td>54</td>
<td>54.32</td>
<td>52.93</td>
<td>53.5</td>
</tr>
<tr>
<td>Data Upload Mbps</td>
<td>62</td>
<td>61.22</td>
<td>60.935</td>
<td>60.598</td>
</tr>
</tbody>
</table>

The L-DAS delivered more than twice the capacity. With all clients running the download throughput tests, the discrete system delivered an average of 21.97 Mbps and the L-DAS delivered 53.69 Mbps. With all clients running the same throughput script to upload data from the wireless clients to the wired server, the discrete system delivered an average of 24.13 Mbps and the L-DAS delivered 61.19 Mbps. What happened?

It appears that two factors contribute to the lower performance of the discrete system in this small scale test - system overload and the behavior of the 802.11 coexistence mechanisms. We were able to overload the discrete microcellular system with 32 clients continuously downloading data.
A closer look at the Chariot results below, for one of the discrete download runs, shows that many of the test pairs do not run to completion and there is a wide variance in throughput during the tests. One of the 802.11g clients (pair 24) averaged almost 12 Mbps during this run, but two of the 802.11n clients (pairs 16 and 17) didn’t complete the test and the third (pair 18) averaged less than 2 Mbps throughput.

By contrast, the L-DAS tests were much more stable and the system did not appear to be overloaded. All of the clients ran the tests to completion in the L-DAS configuration.
We used the L-DAS layers to separate the 802.11n traffic from the 802.11b and 802.11g traffic. Only one of the L-DAS layers had mixed protocols, and it supported (5) 802.11b and (10) 802.11g clients. Looking at the Chariot results in more detail, we can see the benefit of this organization. In the L-DAS results, there are three distinct levels of throughput. The 802.11n clients (pairs 16, 17 and 18) averaged about 11 Mbps each for a total of 33 Mbps; the 802.11g clients averaged about 1 Mbps each for a total of 14 Mbps and the mixed 802.11b/g clients average almost .5 Mbps for a total of 7 Mbps. (33+14+7=54 Mbps) In the discrete tests, all of the clients shared all of the APs. Each AP had to deal with traffic from all types of clients. The slower 802.11b clients were essentially hogging the airwaves, and the 802.11n and 802.11g clients could not operate at full speed.

The transition to 802.11n brings new issues to enterprise wireless LANs. Most enterprises with legacy 802.11 networks who are adopting 802.11n will not use 802.11n in the 2.4 GHz band because of the negative performance impact of the coexistence protocols on the new 802.11n clients. There are not enough channels in the 2.4 GHz band to allow separate operation of 802.11n and legacy 802.11b/g clients in a microcellular system. The L-DAS addresses this issue and is able to support 802.11n operation in the 2.4 GHz band effectively by creating an isolated layer for 802.11n clients and supporting legacy clients in one or two other layers.
We ran the same set of tests without 802.11n to see how the system performed in a mostly 802.11g, environment typical of many enterprises today. We converted the 802.11n clients to 802.11g. The results are similar. For the download throughput tests, the L-DAS delivered an average of 38.73 Mbps and the discrete system delivered 18.06 Mbps on average.

### Layered DAS Multi-protocol Capacity Results - 1 Segment 3 AP, 32 802.11b/g Clients

<table>
<thead>
<tr>
<th>Data Download Mbps</th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>38.965</td>
<td>38.549</td>
<td>38.685</td>
<td>38.733</td>
</tr>
</tbody>
</table>

We also ran the capacity tests on a larger-scale configuration, with the same clients distributed throughout the entire 15,000 square foot test area, utilizing all three segments and nine APs. The overall layout, client locations and AP locations are shown in the figure in section 5.2 below.

### Layered DAS Multi-protocol Capacity Results - 3 Segment 9 AP, 32 802.11b/g Clients

<table>
<thead>
<tr>
<th>Data Download Mbps</th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>37.646</td>
<td>37.161</td>
<td>37.467</td>
<td>38.304</td>
<td>37.650</td>
</tr>
</tbody>
</table>

The results are similar. The L-DAS delivered more than twice the throughput of the discrete configuration.

Did we rig the test to give the L-DAS configuration an advantage? No. In fact, the layering of the DAS test was not optimized for this experiment at all. When we removed the 802.11n clients from the test, we did not change the organization of the layers for the L-DAS. We simply converted the 802.11n clients to 802.11g, so we had (3) 802.11g clients on one layer, (14) on another layer and a mix of (10) 802.11g and (5) 802.11b on the third layer. To optimize the throughput for the L-DAS, we could have spread the 802.11g clients more evenly. We did not do this. During the 802.11n testing, we used a single 20 MHz channel in the 2.4 GHz band for both configurations. In the L-DAS configuration, we could have configured that layer to be a 40 MHz wide channel operating in the 5 GHz band without increasing the number of APs or radios used in the APs. This would have shown even more system capacity for the L-DAS.

### 5.2 Co-Channel Interference

With more APs used for the larger scale testing in both cases, we might expect higher system throughput than the small-scale test. However, the throughput went down for both systems when we tested with all the APs. The L-DAS was 3% lower, 37.6 Mbps compared to 38.7 Mbps, and the discrete system throughput was 16% lower, 15.6 Mbps compared to 18.1 Mbps.

The lower throughput in these tests is the result of co-channel interference. In the microcellular case, the APs are operating on alternating channels 1, 6 and 11 in the 2.4 GHz band, such that adjacent APs do not share the same channel. The co-channel interference problem arises because the interference range of the APs (and the clients too) is greater than their effective communication range. Even though the coverage areas of APs on the same channel in...
the microcellular configuration do not overlap, they still cause interference for nearby APs on the same channel. The 802.11 standard does not include a protocol for coordinating access to the airwaves across neighboring APs. Each AP behaves as if it is the only one around. With the constant load from our throughput tests, the additional APs in the larger-scale testing actually end up creating a lot of interference for each other, which causes more low-level retransmissions and lowers effective throughput.

The real world result of these large scale capacity tests is counter-intuitive. The microcellular system has higher co-channel interference than we might expect, and the L-DAS has lower co-channel interference.

We initially ran small-scale, single-segment or three AP tests that were designed to illustrate the performance when co-channel interference is at a minimum. With only three APs operating on different channels, there is almost no co-channel interference in either the L-DAS or the microcellular system. We then repeated the same tests in the large configuration with the same number of clients. The only difference is the coverage area is larger and more APs are used. By comparing the results of the tests in the small configuration with the same tests in the larger configuration, we were able to isolate the effects of co-channel interference.

The L-DAS has lower co-channel interference than the microcellular system in these larger-scale tests. Through the series of distributed antennas, each AP in the L-DAS configuration covers an area three times larger than a normal AP. These areas are called segments. The co-channel interference is limited to areas along the boundary of the L-DAS segments. In the larger scale testing that covered the entire floor, there are two segment boundaries in the L-DAS where we would expect to see co-channel interference. These are shown as shaded areas in the floor plan to the right. Many of the clients in the L-DAS test are in areas that have little or no co-channel interference. The result is the tests for L-DAS configuration show a smaller impact of co-channel interference. Compared to the ideal small-scale tests, the L-DAS system throughput dropped 3% in the three segment nine AP tests, while the microcellular system throughput was reduced by 16% when eight discrete APs were operating in these larger-scale tests.
5.3 L-DAS Client Performance Stable and Predictable

The clients on the layered DAS system exhibited more uniform and predictable performance overall. We observed this on all of the tests that measured throughput. The high capacity tests were unstable on the discrete microcellular system, yet they ran to completion in the L-DAS configuration. At a high level, the performance of the whole L-DAS system was more consistent from run to run in every test that we ran.

The clients in the L-DAS configuration operated within a narrower range of throughput even on the smaller scale lightly loaded tests, and the variance in jitter was much lower for the L-DAS clients, as seen in these detailed Chariot screens from the voice testing. In the discrete voice test run below, the jitter for voice clients averages almost 1.9 milliseconds and there are a few peaks above 15 milliseconds.

![Chariot Test - \LPSFW\untitledTests\Discrete, g, 3AP, MAITTEST5-2 (14, 9, 6).txt](image)

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fin.</td>
<td></td>
<td>325</td>
<td>1.882</td>
<td>37</td>
<td>393</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Fin.</td>
<td>87</td>
<td>0.953</td>
<td>0</td>
<td>2</td>
<td>5</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Fin.</td>
<td>1.005</td>
<td>0</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Fin.</td>
<td>0.774</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Fin.</td>
<td>0.959</td>
<td>0</td>
<td>2</td>
<td>8</td>
<td>9</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Fin.</td>
<td>0.877</td>
<td>0</td>
<td>2</td>
<td>5</td>
<td>6</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Fin.</td>
<td>0.906</td>
<td>0</td>
<td>2</td>
<td>5</td>
<td>6</td>
<td>n/a</td>
<td>n/a</td>
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<tr>
<td>Fin.</td>
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<td>0</td>
<td>3</td>
<td>4</td>
<td>9</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Fin.</td>
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<td>0</td>
<td>8</td>
<td>74</td>
<td>74</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

The clients in the L-DAS voice test have much lower jitter and much less variance in jitter as seen in the Chariot screen below. During these tests, we were able to isolate the voice clients in a separate layer, which made it easier for the 802.11 QoS mechanisms to work well. On the L-DAS, there were no data clients with 1500 byte packets competing for the airwaves on the voice channel.
The average jitter for the L-DAS tests was .3 milliseconds and the variance in jitter was very low after an initial peak. One factor that leads to this consistency of performance is the coverage of the L-DAS. The L-DAS is pre-engineered to cover the desired area at a specific signal level. Our impression was that the RF signal level was very good everywhere. In the system we tested, every 802.11g client was always operating at the 36 Mbps data rate during the L-DAS testing. In the discrete microcellular system, the RF signal level is excellent near each AP and then falls off as you move away from the AP. The coverage of our discrete system (1680 sq. ft. per AP) was designed to provide at least very good RF signal levels at the edge of the coverage area for each AP. In the discrete system, there was much more variance in the signal level, and therefore the clients were operating at different data rates much of the time. Close to the AP, 802.11g clients might be operating at 54 Mbps raw data rate; a little farther away, they operate at 36 Mbps; and many clients near the fringe operate at 24 Mbps or less. The 802.11 protocol addresses this variability and the clients automatically deal with changes in data rate as they move around, but this adds complexity and clearly affects performance.

The value of this more stable client behavior on the L-DAS becomes more apparent at higher system load with more clients sending traffic at higher rates. It is likely that a properly designed L-DAS will support more wireless clients and remain stable longer under higher load than a discrete microcellular network.
5.4 L-DAS Voice Performance Slightly Better

On all of the voice tests, the clients on the L-DAS system had much lower jitter and slightly better MOS scores. This is primarily due to the organization of the traffic that we did to take advantage of the layering on the L-DAS. For the multi-application tests, we defined three classes of traffic. For both systems, we assigned each application to a different QoS level so we could prioritize the voice traffic and the mission-critical data traffic above the guest data traffic. In the discrete case, all APs supported all classes of traffic. In the L-DAS, we used separate layers for each type of traffic - the voice calls were on one channel, the mission-critical data on a different channel and the guest access clients on another. In this example, all of the clients and APs were operating in 802.11g mode. There were sixteen voice clients, nine mission-critical data clients and six guest access clients.

<table>
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<tr>
<th>Small scale, multi-application Results - Discrete 3 APs, 31 clients</th>
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<tbody>
<tr>
<td>Run 1</td>
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<tr>
<td>Guest Download Mbps</td>
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<tr>
<td>Guest Upload Mbps</td>
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<td>Mission Critical Mbps</td>
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<tr>
<td>Voice Jitter</td>
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<td>Min MOS</td>
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<td>Average MOS</td>
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<table>
<thead>
<tr>
<th>Small scale, multi-application Results - Layered DAS 3 APs, 31 clients</th>
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<tr>
<td>Run 1</td>
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Both systems handled the voice traffic and the mission-critical data traffic very well. All of the mission-critical traffic was delivered without unreasonable delays. The MOS for the voice traffic was well above toll-grade in both cases. The voice clients on the L-DAS system had lower jitter and all clients on the L-DAS system exhibited more stable and predictable behavior. Clients on the discrete microcellular system showed a wider variance in throughput and delay.

The discrete system delivered more capacity to the guest access clients than the L-DAS system in these mixed application tests. This is an artifact of the way we separated the clients from different applications into different layers on the L-DAS. We designed the traffic for the mission-critical data clients to simulate a medical monitoring device that generates a small amount of data at a periodic rate. With only nine mission-critical data clients in our testing, the load for this application was very low. On the L-DAS, we had an entire channel dedicated to the mission-critical application, even though the load doesn’t come close to consuming a full channel of 802.11g capacity. In a real world scenario, there would be many more mission-critical data clients (imagine five per patient) and it may make sense to dedicate an entire layer to them.

In the end this is the desired behavior for our example test. The voice clients and mission-critical data clients have priority, with guaranteed delivery of all of their traffic. The guest access traffic is best effort and is allowed to consume whatever bandwidth is left over. In the L-DAS case, we allocated one channel to the guest access application and it can consume no more than that. The discrete system combines all applications at all APs throughout the network. The results show that there was more “left over” bandwidth in the discrete case. The benefit of the L-DAS organization in this example is that there is more headroom available for the priority voice and mission-critical data traffic, and the guest access traffic will never be allowed to reduce the QoS for those critical applications.
5.5 L-DAS Preserved the Functionality of the Cisco Wireless LAN System

We used the same wireless LAN controller and access points for both configurations. All of the expected wireless LAN features worked well on the L-DAS. There is no difference in the operation of security and voice features. The same exact QoS mechanisms were used in the L-DAS and discrete microcellular testing. In all cases, we are using the standard Cisco software.

Roaming works fine on the L-DAS. We tested roaming (BSS transitions in 802.11 parlance.) in the large scale test environment. We generated a light load of background traffic throughout the network. We established a call between the Cisco 7921 handsets and walked around the entire coverage area with both handsets for a few minutes during the call. We were talking continuously and listening to the quality of the call. We tried to force roams by walking around the perimeter of the network and into the most remote offices. Both systems sounded fine. The call did not drop, and we heard no clicks. We could not hear any transitions during the call for either system. We checked the MOS on the 7921s after the test. The discrete system had a MOS of 3.74, below toll grade, but we heard no problems on the call and the subjective sound quality was very close to the quality of the call on the L-DAS. In both systems, the Cisco handsets transition to different APs (they roamed) multiple times. Because each segment is much larger than the coverage area of a single AP, there are fewer roaming events in the L-DAS configuration. This may lead to the better MOS during these tests.

We also informally tested other aspects of 802.11n operation on the L-DAS. We ran tests with 20 MHz channels in the 2.4 GHz band and 40 MHz channels in the 5 GHz band and they worked as expected. The current Horizon™ L-DAS supports one stream per channel for 802.11n APs. The 802.11n clients operating in the 2.4 GHz band on the L-DAS did get substantially higher throughput than 802.11g clients, even though we were not taking advantage of multiple streams or MIMO in these 802.11n tests.
5.7 L-DAS Requires Careful Engineering

There is a cost for better system performance. The RF coverage in an L-DAS deployment is designed up front. When
the system is installed, the placement of the distributed antenna elements is designed such that the entire area to be
serviced has good RF signal levels. Through the use of multiple distributed antennas, each AP using an L-DAS
covers a much larger area than a conventional AP. Once the L-DAS is set up, the power level and channels do not
change. By contrast, a typical discrete microcellular system such as Cisco or Aruba is much more dynamic. The
Wireless LAN controller in the discrete microcellular system adjusts the power level and channel settings of the APs in
the system to respond to changes in the environment.

The L-DAS allowed us to organize client traffic into separate isolated layers to improve performance and quality of
service; or to isolate potentially negative clients from the rest of the system. In our testing, we used this organization
of traffic to keep clients from different generations of 802.11 standard isolated and also to create different layers of
service for different applications. The layering of the L-DAS delivered most of the performance gains. Designing the
layering to optimize performance requires advance planning and an understanding of the types of traffic and wireless
clients that will be supported by a system.

Overall, we observed better performance as a result of the RF planning and traffic organization into layers.
6.0 Conclusions

We tested the InnerWireless Horizon™ Layered Distributed Antenna System in various configurations to understand how it compares to a conventional enterprise microcellular Wireless LAN deployment. Distributed Antenna Systems are usually deployed in very large indoor networks that also deliver indoor coverage for cellular and paging services. We focused entirely on the wireless LAN capabilities of the L-DAS.

We tested a small scenario, covering only 5,000 square feet, with a typical mix of traffic from different applications. We also tested a larger footprint representing an entire floor of a multi-story building. In the large configuration, we generated as much traffic as possible in order to observe how the systems behaved when pushed to the limit.

We saw a number of different performance benefits from the L-DAS. Depending on how the system is configured and the applications used, these benefits can add up to substantial performance gains. Even in smaller configurations, we were able to observe more stable behavior from the wireless clients operating on the L-DAS.

There are many subtle benefits of the layered DAS. Solid, consistent coverage over the entire area means more stable client behavior - consistent data rates, fewer rate changes, less scanning for other APs. Large coverage segments mean less roaming; and all of that adds up to less protocol overhead and slightly better performance. Covering large areas with a single channel allows layering of services that are operating on different channels. Layering enables wireless traffic to be organized. High priority applications can be isolated from other applications and operate independently at full speed.

We organized the traffic from wireless clients by using the layering of the L-DAS according to application type or according to protocol type. We created separate layers for voice and mission-critical traffic and saw slightly better voice performance in that configuration. We were able to get more significant performance improvements on the L-DAS by creating separate layers on different channels for traffic from 802.11g, 802.11b and 802.11n clients. Separating the clients running different versions of the standard from each other allowed each of them to run without being constrained by the coexistence protocols, and led to better performance. The newer clients can run at full speed.

In the larger testing scenario, we were able to observe the effects of co-channel interference. The results of our tests were exactly the reverse of the common perception about co-channel interference in enterprise wireless LANs. The L-DAS, which is explicitly designed with adjacent areas operating on the same channel, had lower co-channel interference than the microcellular architecture. Co-channel interference is worse than people realize in enterprise microcellular deployments. The L-DAS does not have a “magic” mechanism to deal with co-channel interference. It seemed that the lower co-channel interference is simply due to the better control of the physical layer with the L-DAS and the larger coverage area of the segments. The regions with co-channel interference were smaller with the L-DAS. In fact, it is possible to explicitly design the L-DAS coverage and segments in order to place higher co-channel areas where they will have less impact on system performance.

If wireless LAN services are just a “nice to have” add-on to support a few mobile clients, then a Distributed Antenna System is not necessary. When wireless services are core to the operation of an enterprise; when good coverage is required; when guaranteed data delivery or quality of service is required; or whenever there is a high density of wireless users; a Distributed Antenna System, such as the Horizon™ L-DAS, is a compelling addition to the wireless LAN infrastructure that brings control and order to the physical layer of the wireless LAN.
Appendix A - Full Disclosure

These tests were conducted at the InnerWireless offices in Richardson, Texas. InnerWireless engineers configured the infrastructure for both the L-DAS and the microcellular system with discrete APs.

We ran all of the tests with the help of InnerWireless engineers. Novarum created the Chariot scripts for the different test configurations. We jointly developed the test scenarios.

We believe that the systems were designed and configured properly. We did not perceive any attempt to make a “hot” configuration for the L-DAS or to create a less capable microcellular system. We made every effort to operate these systems at their best performance.