Air5^{TM} In-Home Field-Testing Results

March 2003 Tests

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Air5 In-Home Video Field-Testing Results

Report No. 2[1]

1. Introduction

Extensive in-home and in-office field testing of the Air5 system is an on-going ingredient of Magis' engineering philosophy. The difficulties presented by the indoor wireless channel, specifically multipath, make it necessary to evaluate any real-world solution in a truly representative environment.

The results presented here made use of the Core Module (CM) hardware demonstration platform, version 1.1 based upon the MSG6100[2] chipset. The high-level details of the testing performed were:

- CM version 1.1 demonstration hardware was used for both the Access Point (AP) and Remote Terminal (RT) stations based upon the MSG6100 chipset.
- MPEG2 transcoded video rates from 25 Mbps down to 3 Mbps were used in the field testing
- Effective AP transmit power was set to +14 dBm
- Maximum allowable data-packet time jitter set to 9.1 msec.
- AP antennas used were microstrip bow-tie patch antennas (with omni-directional patterns) organized in a linear array with approximately 1.5 inch spacing (See Figure 1)
- Two different types of antenna arrays were used at the RT end of the link: (a) 2-element quasi-yagis organized in a linear array with approximately 1.5 inch spacing (See Figure 2); (b) bow-tie omni-directional antennas organized in a linear array with approximately 1.5 inch spacing (See Figure 1).
- Cable and test connector losses resulted in a receiver noise figure of approximately 10 dB.

Field testing results from two different homes are presented within this memorandum:

Home # 1:

- Approximately 2,700 square feet
- Two-story, stucco construction (southern California)
- Large open stair-well in center of home, but otherwise mostly all 8 foot ceilings

Home # 2:

- Approximately 3,500 square feet
- Two-story, stucco construction (southern California)
- Large open entry way and living room with 30+ foot ceiling, remainder of home with mostly 8 foot ceilings

2. Test Methodology

Even though the data throughput rates used during the field testing can range from approximately 3 Mbps to approximately 25 Mbps, the time-variability of the 5 GHz communication channel makes it necessary to conduct measurements over a time span of minutes at each data collection point in order to obtain reliable results. In the test results reported here, performance was so good throughout the homes that no video transcoded rates below 15 Mbps were ever required except for one collection point. The AP was left unchanged in a fixed location within each home whereas the RT was mobile on a small equipment cart and moved throughout each home to the different collection points. The antenna heights for both the AP and RT were held constant at the cart height of 30 inches.

In order to get reliable results, it is also important to conduct the field testing cognizant of the differences between video versus data-only distribution. The quality-of-service (QoS) aspects needed for video transmission are considerably more demanding than those required for data-only communications. This was accomplished in part by using actual transcoded video MPEG2 streams ranging from 3 Mbps up to 25 Mbps[3] working with all of the appropriate IEEE802.11a physical layer (PHY) signaling rates and accumulating a wide range of link statistics from which video performance could be computed. Furthermore, testing of each transcoded video rate at each appropriate PHY signaling rate was completely automated.

2.1 Performance Criteria

Data-only and video-only performance criteria are fundamentally different because video delivery requires that tight QoS constraints on time jitter and

[1] Data collected March 2003
[2] First-generation Magis chipset
[3] Actual trans-coded video rates used were 2,4, 6, 8, 12, 15, 19, 22, 23, 25 Mbps

latency be maintained. As such, different criteria for the two modes are used within this memorandum to report system performance.

Video-Mode Criteria: Recognizing that different MPEG2 decoders will conceal errors differently and perform differently in general over a wireless link, adopt the criteria that the link must be ***perfect*** over a 2 minute time interval and report the maximum trans-coded video rate supported independent of the PHY mode used.

The trans-coded video source rates allowed in the testing were {2, 4, 6, 8, 12, 15, 19, 22, 23, 25} Mbps. The maximum time-jitter allowed over the air interface was 9.1 msec.

Unlike many other 802.11-based products, Air5 does not use large data buffers to smooth out large bursts of errors. Consequently, the link reliability must be much greater in order to support video and this also means that time latency must be kept extremely small, on the order of a few msec. These same criteria also dictate that the data packet error rate (PER) be typically less than 3 to 5% maximum.

For data-only delivery, a simplifying assumption is made that any number of data-packet retransmissions can be used.

- **Data-Only Mode:** Disregard the number of required data packet re-transmissions for any given data packet (unbounded QoS), and report the maximum average throughput rate observed from all possible PHY modes. As done with the video-mode criteria, the throughput rate was averaged over a 2 minute time interval.

The field test data was collected with sufficient information to deduce the video-only and data-only mode throughput rates. Owing to the QoS constraint on the video-only mode, the supported video throughput rate at any given measurement point within the home is always less than or equal to the data-only throughput rate. The following example may help clarify the relationship between the data-mode and video-mode criteria.

When network resources are requested by a RT, it must specify (a) the needed throughput rate and (b) the level of QoS required. The requested throughput rate must include some throughput allocation for ARQ activity (i.e., packet retransmission). In the case of a MPEG2 stream operating at 25 Mbps, it is necessary to allocate a minimum of roughly 27 Mbps. In this example, since the Air5 system generally operates with a PER of typically < 1% even in 64-QAM R= ¾ mode, the reported sustainable data throughput rate would be very nearly whatever was originally allocated (i.e., 27 Mbps) by the MAC for that stream. In contrast, this same stream would only be capable of supporting up to 25 Mbps MPEG2 video due to the QoS-related margins that are necessarily associated with video.

3. Field Testing Results

All of the field testing results are based upon using Magis Core Modules (CM) Version 1.1. The CM is a complete engineering development system and as such, no efforts have been expended to reduce the size of the platform or the bill-of-material. (Magis' first production product releases fit well within the MiniPCI form-factor for instance.)

The perspective taken with the CM-based field testing is to exhibit the Air5 technology in its best light with reasonable constraints on antenna size and form factors. Every customer will most likely have their own form-factor constraints when it comes to antennas in particular, and many different options and trade-offs are possible. Antennas are a very key ingredient[4] for good system performance at 5 GHz and Magis offers a wide range of support in this area.

3.1 First-Home Results

The first set of field testing results used a fixed AP with a linear array of very simple printed "bow-tie" omni-directional antenna elements. A representative picture of the AP configuration using the Magis CM is shown in Figure 1. The antenna elements are extremely simple to make even though no effort was expended in this configuration to eliminate the coax lines and connectors (Design details for a very low-cost equivalent-performing bow-tie array are separately available to Magis partners.) The bow-tie antenna elements provide a very nice omni-directional gain pattern which is desired for the AP since the angle of arrival from any specific RT is completely unknown.

A more aggressive antenna approach was used for the RT in this first home test because in many relatively fixed-point in-home applications, the direction toward the AP is easily discernable to within ±60 degrees. The very simple printed yagi antenna elements have a very wide beam width[5] and are therefore not overly directional while also providing about 4.5 dBi gain.

[4] See "Making OFDM Work at 5 GHz" at www.magisnetworks.com

[5] More details available in E10612 Magis Air5 Antenna Array Development Work

Many home applications will also be very portable making the omni-directional bow-tie antennas the preferred choice for the RT as well as the AP. The second home testing was done with bow-tie and yagi antennas at the RT end in order to provide a measure of performance comparison between these two options.

Figure 1 Three-element bow-tie antenna arrays developed at Magis (Omni-directional for AP) hosted with CM 1.1.

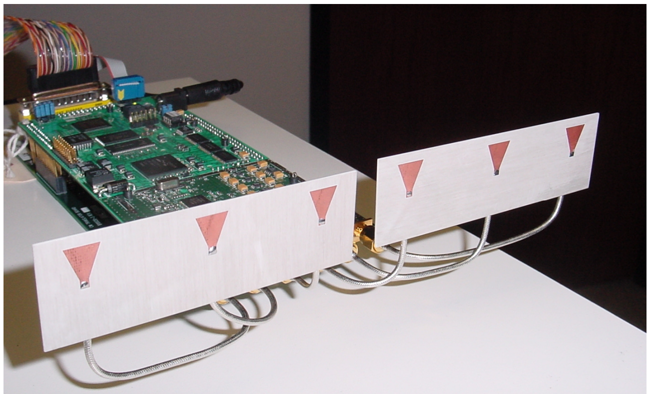
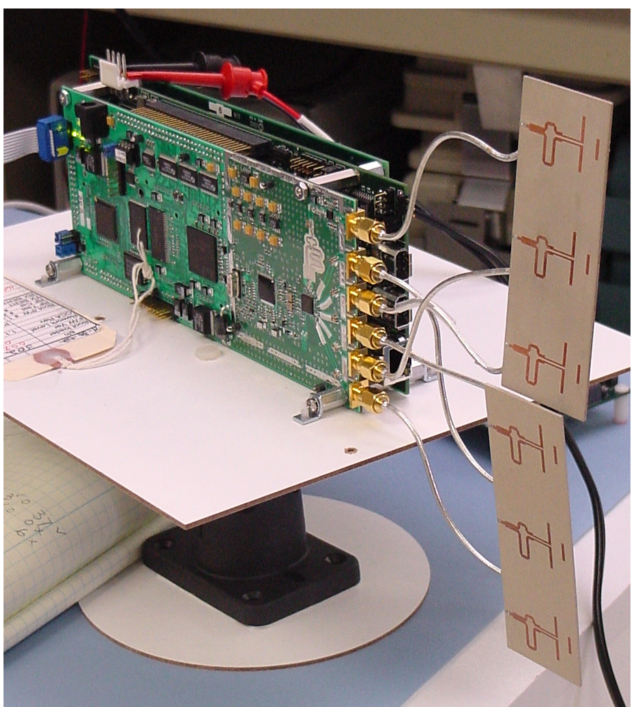


Figure 2 Example usage of the yagi antenna arrays developed at Magis (directional for RT) hosted with CM 1.1.



3.1.1 First Home Video Results

The supported MPEG2 video rate versus home location is shown in a color-coded format in Figure 3 and Figure 4. The link coverage is quite remarkable in that a minimum of 23 Mbps is deliverable everywhere within the home whereas only 19+ Mbps is required for US-HDTV. All of the 25 Mbps MPEG2 delivery represented by the blue dots was accomplished using the highest IEEE802.11a signaling rate (54 Mbps, 64-QAM R= ¾) thereby leaving substantial throughput resources still available for other streams like computer networking and other audio/video activity. The 23 Mbps MPEG2 delivery at the few green dots in the figures was achieved using the 16-QAM R= ¾ PHY mode. Second-generation Air5 devices that will begin volume shipment in June 2003 perform even better (See Section 4). The raw field-test results for this first home are provided here in Table 1.

Had a more centralized location for the AP been selected within the home, it is likely that the full 54 Mbps signaling rate could have provided maximum system throughput for the entire home.

Field test results for the first home clearly show that full 19+ Mbps US-HDTV reception (plus additional streams) is easily supported throughout the entire home.

3.1.2 First Home Data Results

The criteria for assessing the supportable data throughput in the home was described earlier in Section 2.1. Since the field testing was orchestrated to assess the performance of the more difficult video-only mode, an additional scaling factor must be applied in order to correctly capture the throughput capability in data-only mode. Recall in the earlier example provided in Section 2.1 that the requested MAC resources were sized for a 25 Mbps video stream whereas the full Air5 throughput capability in data-only mode is approximately 40 Mbps. The needed scaling factor comes into play because (i) the MPEG2 video stream used in the testing (even with additional throughput for ARQ servicing) does not consume all of the throughput resources available over the channel and (ii) there is a fixed packetization loss associated with video that is not present with data-only operation for a specific stream. The resultant data-only throughput rate achievable for a single link is given by the table column labeled “Scaled Data Thru” in Table 1. As shown in that table,

Figure 3 Supported MPEG2 video rate versus location (Home #1, First Floor)

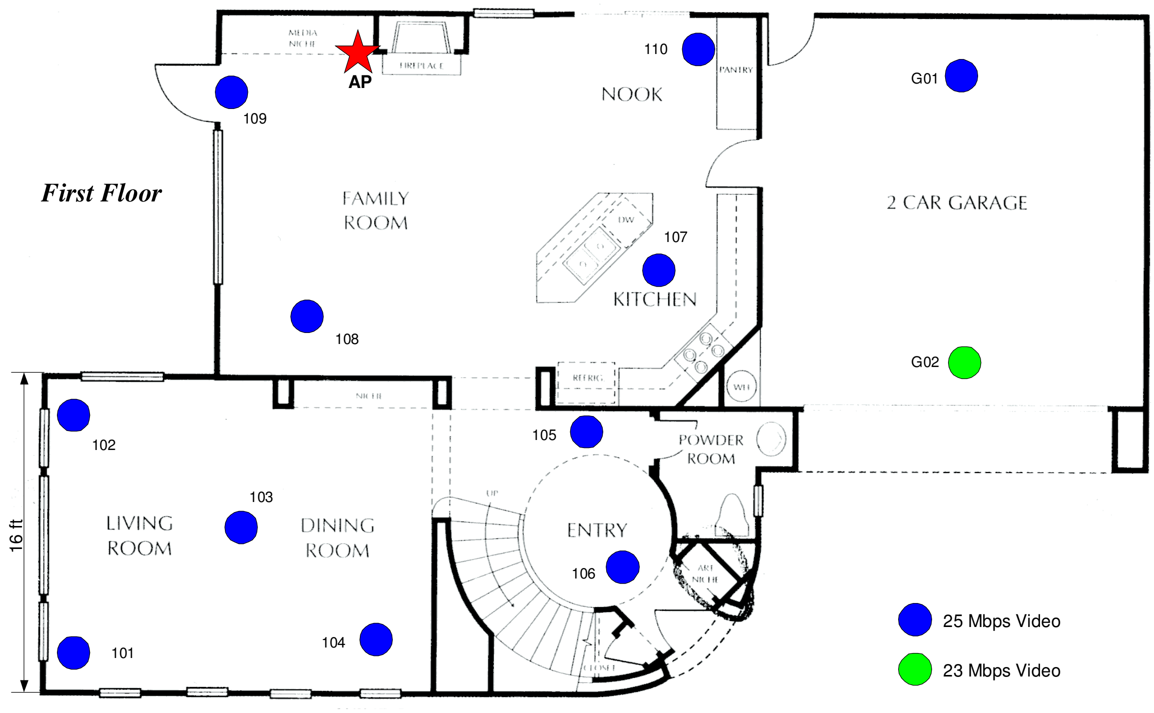
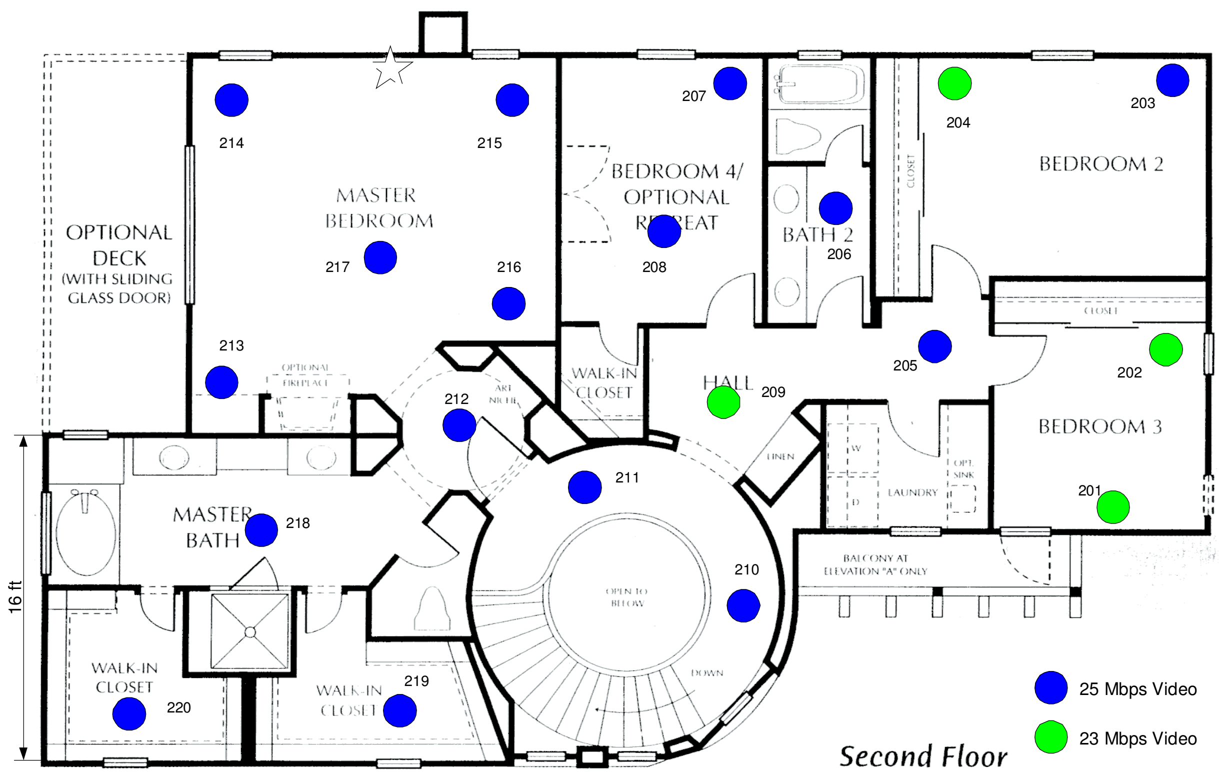


Figure 4 Supported MPEG2 video rate versus location (Home #1, Second Floor)



only location #201 exhibited a throughput rate that was significantly less than that of all of the other collection points within the entire home. If this single data point is excluded from consideration, the mean data throughput rate for the remainder of the home is 40.59 Mbps with a standard deviation of 0.45 Mbps. Given that the maximum achievable throughput of the system is 41 Mbps, these results are exceptionally good.

Table 1 Field test results for first home

Locations	Video Rate	Measured Data Thru	Scaled Data Thru
101	25	29.83	40.8781
102	25	29.92	41.0015
103	25	29.88	40.9467
104	25	29.88	40.9467
105	25	29.86	40.9193
106	25	29.94	41.0289
107	25	29.95	41.0426
108	25	29.84	40.8919
109	25	29.98	41.0837
110	25	29.67	40.6589
201	23	26.7	26.7
202	23	26.84	36.7807
203	25	29	39.7407
204	23	27.99	38.3567
205	25	29.92	41.0015
206	25	29.6	40.563
207	25	29.91	40.9878
208	25	29.89	40.9604
209	23	29.46	40.3711
210	25	29.96	41.0563
211	25	29.89	40.9604
212	25	29.84	40.8919
213	25	29.77	40.7959
214	25	29.84	40.8919
215	25	29.92	41.0015
216	25	29.85	40.9056
217	25	29.84	40.8919
218	25	29.76	40.7822
219	25	28.89	39.59
220	25	29.82	40.8644
g01	25	29.77	40.7959
g02	23	29.67	40.6589

The mean data-only throughput rate for the entire home aside from one point was 40.6 Mbps with a standard deviation of only 0.45 Mbps.

3.2 Second-Home Results

The same testing procedures were conducted in a second home. In this home, two full sets of test results were made, first with the yagi antenna array used on the RT, and second with the bow-tie antenna array used on the RT. The yagi array elements have a very good front-to-back ratio on the order of 20 dB and also provide about 4 dB of gain as compared to the typical +1 dBi gain of the bowtie elements. As supported in the results that follow, this approximate 3 dB difference in gain is very helpful along the range perimeter.

A larger number of testing points was used in the second home in order to more thoroughly investigate the fine structure of the multipath throughout the home. A number of collection points were purposely positioned where they would be shadowed by walls, appliances and bookshelves from the direct-path back toward the AP.

This was the second time that this home has been thoroughly field tested. The first testing done in late 2002 was done with antenna arrays that were later found to exhibit considerable self-shadowing particularly for the second-floor test locations. Based upon this prior experience with this test home, not every data point was repeated in this effort, particularly points that were physically close to the AP location in the first-floor living room.

The numerical field test results for this home are provided in Table 2. The formatting for the data results is the same as that used with Table 1 except that results are shown for two cases, (i) the yagi antenna array used with the RT, and (ii) the bowtie array used with the RT. The bowtie antenna array was used at the AP in both cases.

3.2.1 Yagi Array at RT Results for Video-Mode

The supportable MPEG2 video rate is shown with a color-key overlaid on the home floor plans in Figure 5 and Figure 6. Notice that the top-3 video rates in the color code are only separated by 2 Mbps and that all of these rates would easily support full US-HDTV. Even the remaining 15 Mbps and 12 Mbps rates would easily support full DVD-quality digital video.

On the first floor of the home including the garage, full US-HDTV is supportable everywhere except for one lone point in the garage. Every measurement point on the first-floor easily supports DVD-quality video.

Table 2 Field test results for second home

Location	Video Rate	Data Thru	Video Rate	Data Thru
p02	25	40.9933	25	40.9408
p05	25	40.9238	25	40.9936
p09	25	40.932	25	40.9069
p13	25	40.858	23	40.8008
p15	25	40.9863	25	40.895
p17	25	40.9995	25	40.627
p18	25	40.947	23	36.0972
p20	25	40.9648	25	40.8589
p21	25	40.9781	25	40.8291
p21b	25	40.9743	25	40.9372
p22	25	40.8741	25	40.96
p25	25	40.9752	25	40.6665
p27	25	40.9394	23	40.5202
p29	25	40.9447	25	40.9335
p30	23	41.0466	25	40.4955
p31	23	41.0219	25	40.7759
p34	23	40.7969	25	40.8928
p36	23	40.9912	23	40.4033
p40	25	40.8749	23	40.3523
p41	25	40.8694	25	40.302
p42	25	40.8239	23	36.5975
p43	25	40.9245	25	40.1392
p44	25	40.9358	22	39.4725
p45	25	41.0358	25	40.3143
p50	25	40.9533	25	40.6584
p51	25	40.7217	25	40.7625
p52	25	39.5708	23	26.5934
p54	25	39.4913	23	26.6946
p55	23	26.3841	15	19.3482
p56	25	40.7417	22	26.4233
p57	23	40.2039	23	26.1927
p59	23	37.6259	22	26.2445
p60	23	38.4954	23	32.2439
p61	25	40.9387	25	40.5622
p62	25	40.6519	23	34.8731
p63	25	40.8754	25	40.432
p64	25	41.0298	25	40.851
p65	23	26.5374	15	18.2329
p66	25	40.831	25	40.6401
p67	25	41.0027	25	40.6108
p68	25	40.964	25	40.3347
p69	25	40.7655	23	40.797
p70	25	40.8874	25	40.8938
p71	25	40.9459	25	40.8728
p73	25	41.0328	25	41.0235
p74	25	40.8493	25	40.9012
p75	25	41.0034	25	40.9248
p77	25	40.7556	23	40.7388
p78	25	41.0059	25	40.1469
p79	25	40.9275	23	40.6229
p81	25	40.8432	25	39.6798
p83	25	40.9605	23	39.3987
p84	25	40.887	23	39.6848
p85	25	40.9255	25	40.7315
p86	25	40.9727	25	40.5469
p87	25	40.8587	22	40.6245
p88	25	40.9054	25	40.7209
p91	25	40.9447	25	41.0048
p92	25	40.9533	25	40.7039
p93	25	40.9272	23	40.0286
p94	25	40.8737	23	26.6949
p96	25	40.9378	25	40.7393
p98	25	40.4431	25	40.6803
p100	25	40.7435	22	26.665
p101	23	26.5544	12	17.5743
p103	23	26.3206	12	24.3505
p104	15	17.7116	6	11.4227

The slightly reduced throughput points represented by the green-dots located in the kitchen area (e.g., point #34) primarily result from the large amount of heavy metal appliances that ring the kitchen area and fall directly between the AP and RT locations. Points 30,31,34, and 36 all fall in the shadow region created by the side-by-side combination of a double-door refrigerator, dual-oven, range, and microwave unit.

In the garage, points 101 and 103 are very disadvantaged because not only are they located a large distance from the AP, signals must also pass through several load-bearing walls of the home to reach the garage as well as a fully-loaded floor-to-ceiling built-in bookcase and side-by-side filing cabinets in the office area (e.g., point 45). Garage point # 100 is immediately behind the two side-by-side filing cabinets located in the home office.

The only real disadvantaged point is #104 in the garage. Although not shown in this floor plan, the garage wall near points #16 and #18 has heavy shelving along the entire ceiling line, two full-size water heaters, a full 6-foot high steel utility cabinet, and 6-foot high deep-freezer. Even with these many encumbrances, full DVD-quality video is supportable at this location in the garage.

The second-floor test results shown in Figure 6 are equally if not even more impressive than the first floor. System performance on the entire second floor easily supports full US-HDTV.

Full US-HDTV video is easily supported everywhere throughout the second floor of the home.

3.2.2 Yagi Array at RT Results for Data-Mode

The supported data-mode throughput rate throughout the home is at nearly the system's full capability (approx. 40 Mbps) except for only 4 measurement points out of 67. Of these 4 points, the lowest data throughput rate is still almost 18 Mbps.

3.2.3 Bow-Tie Array at RT Results for Video-Mode

In the case where the bow-tie antenna array was used with the RT, the results are provided in Figure 7 and Figure 8. With the small loss of antenna gain compared to the yagi array case, more drop-off in system throughput is apparent near the edge of coverage as expected. Even so, full US-HDTV is supportable throughout the first-floor of the home aside from the garage area, but even in the garage it

Figure 5 Second Home, Supported Video Rate, First Floor, Yagi Array Used at RT

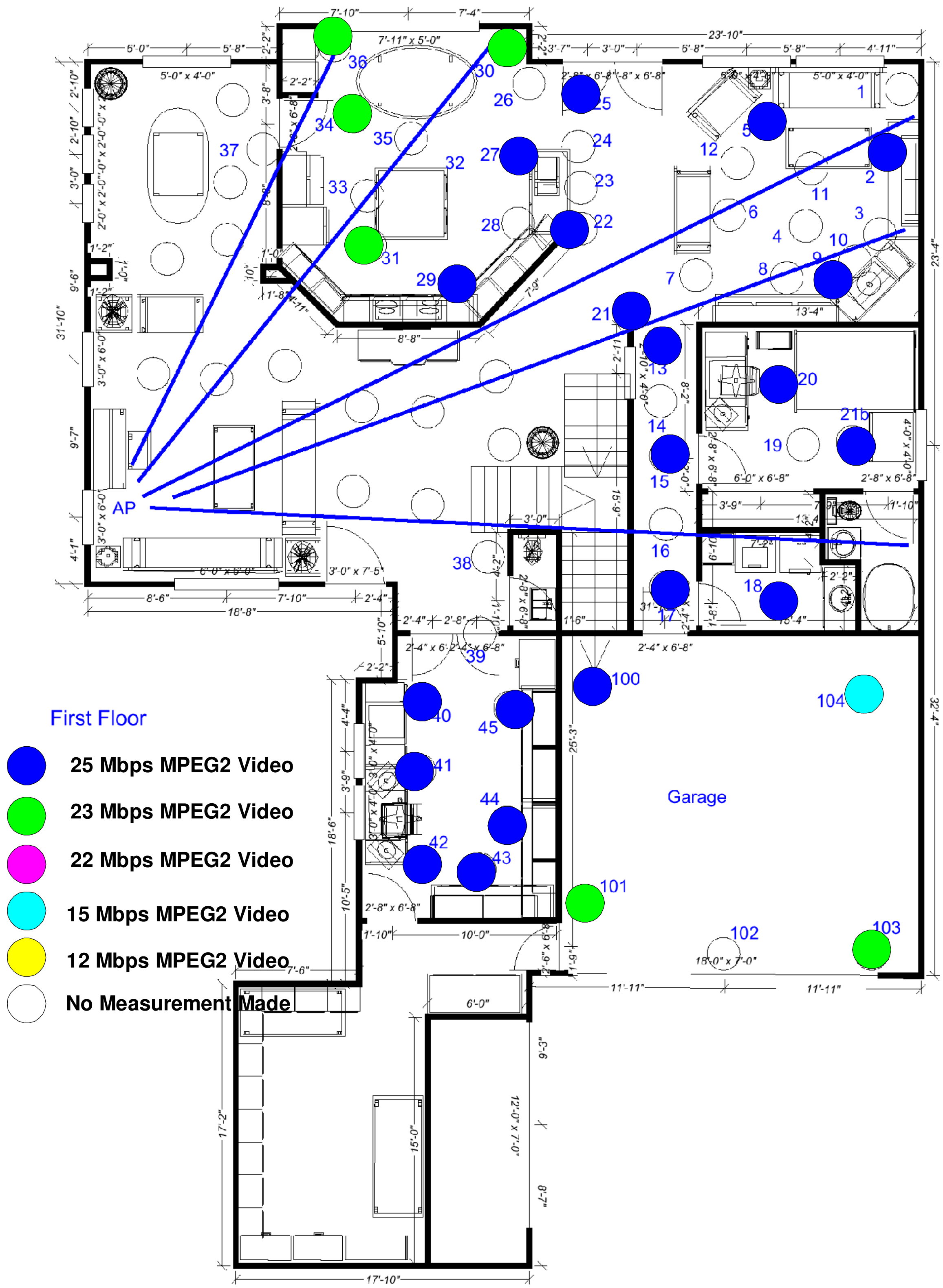


Figure 6 Second Home, Supported Video Rate, Second floor, Yagi Array Used at RT

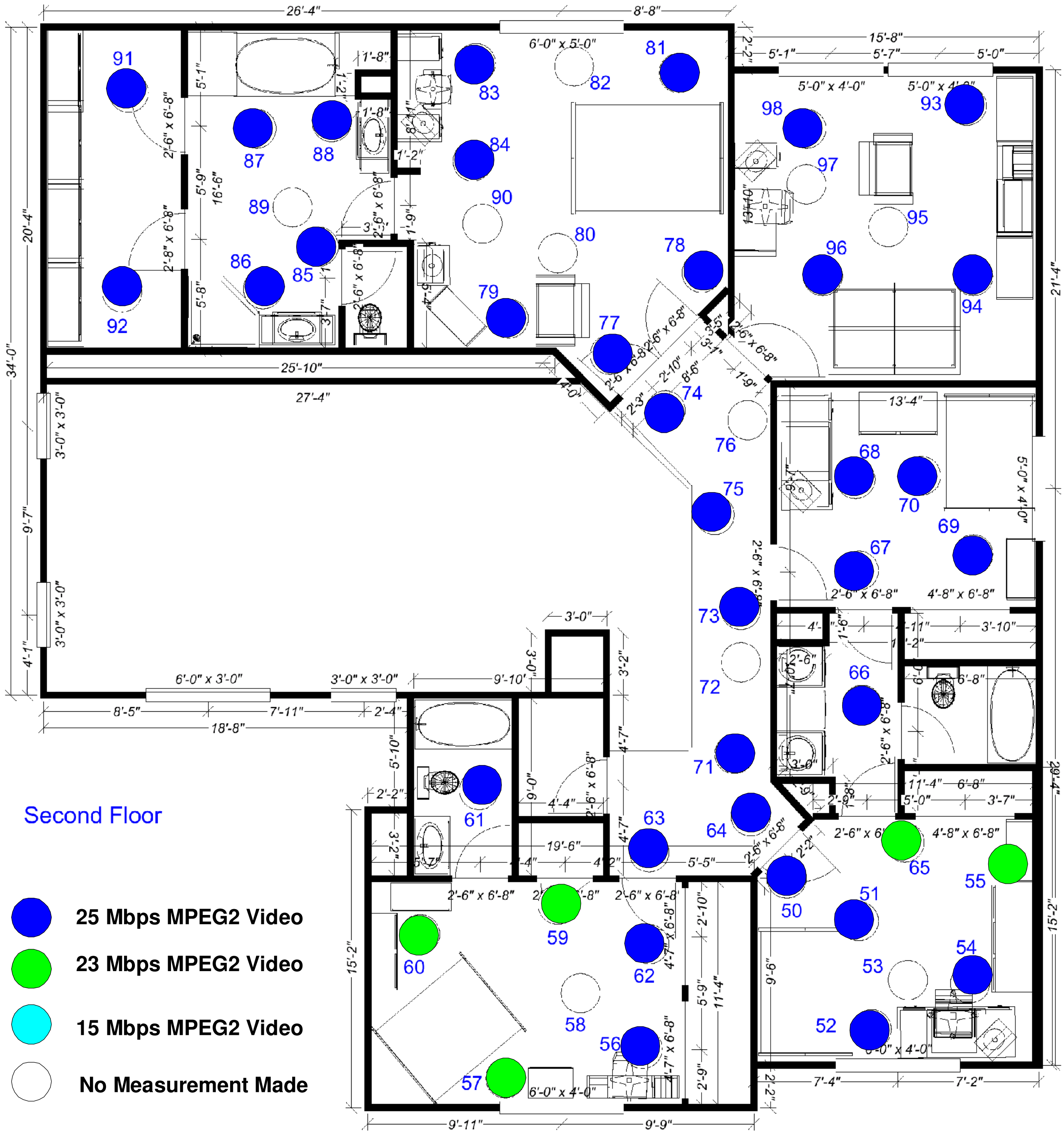


Figure 7 Second Home, Supported Video Rate, First Floor, BowTie Array Used at RT

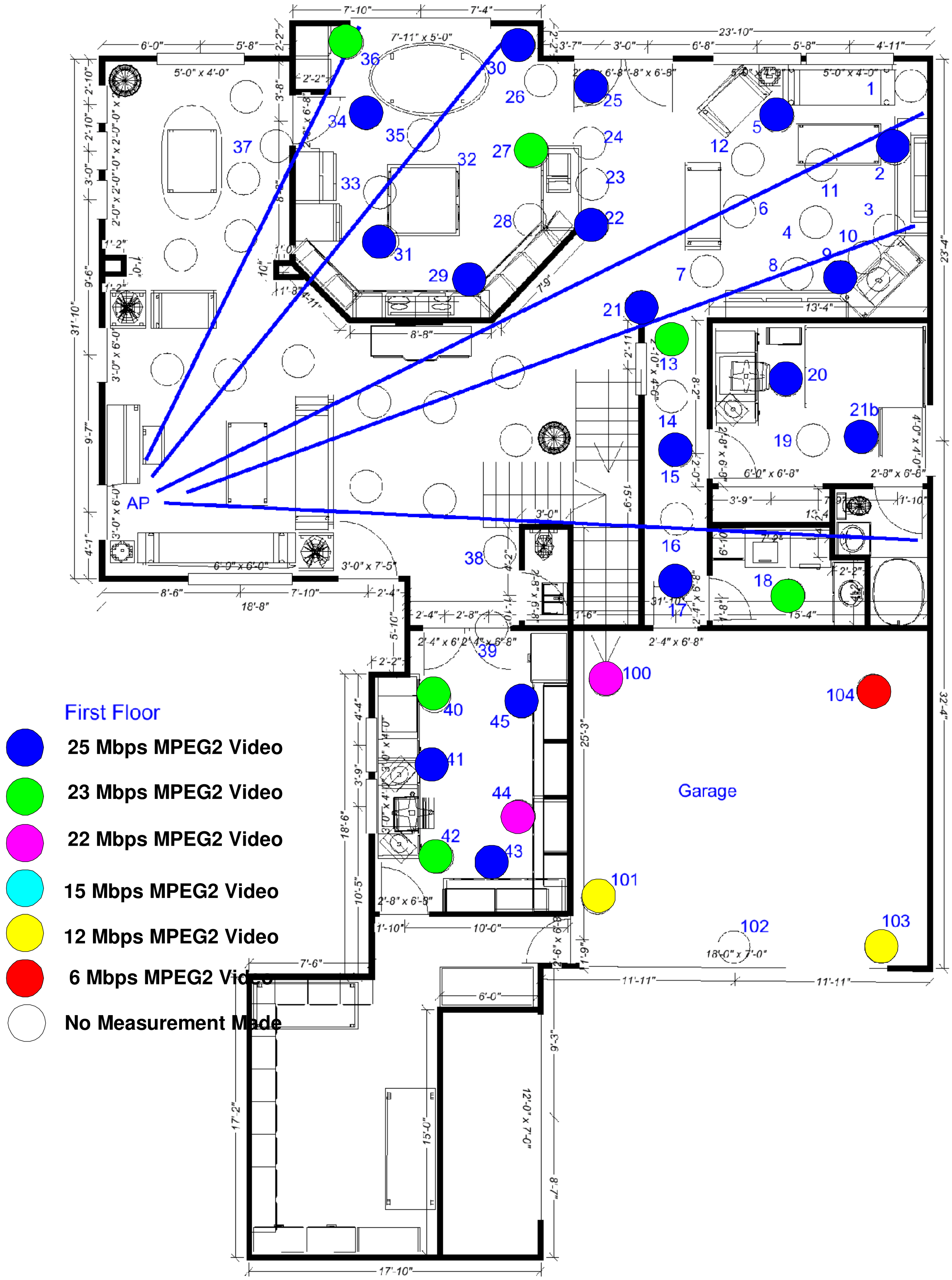
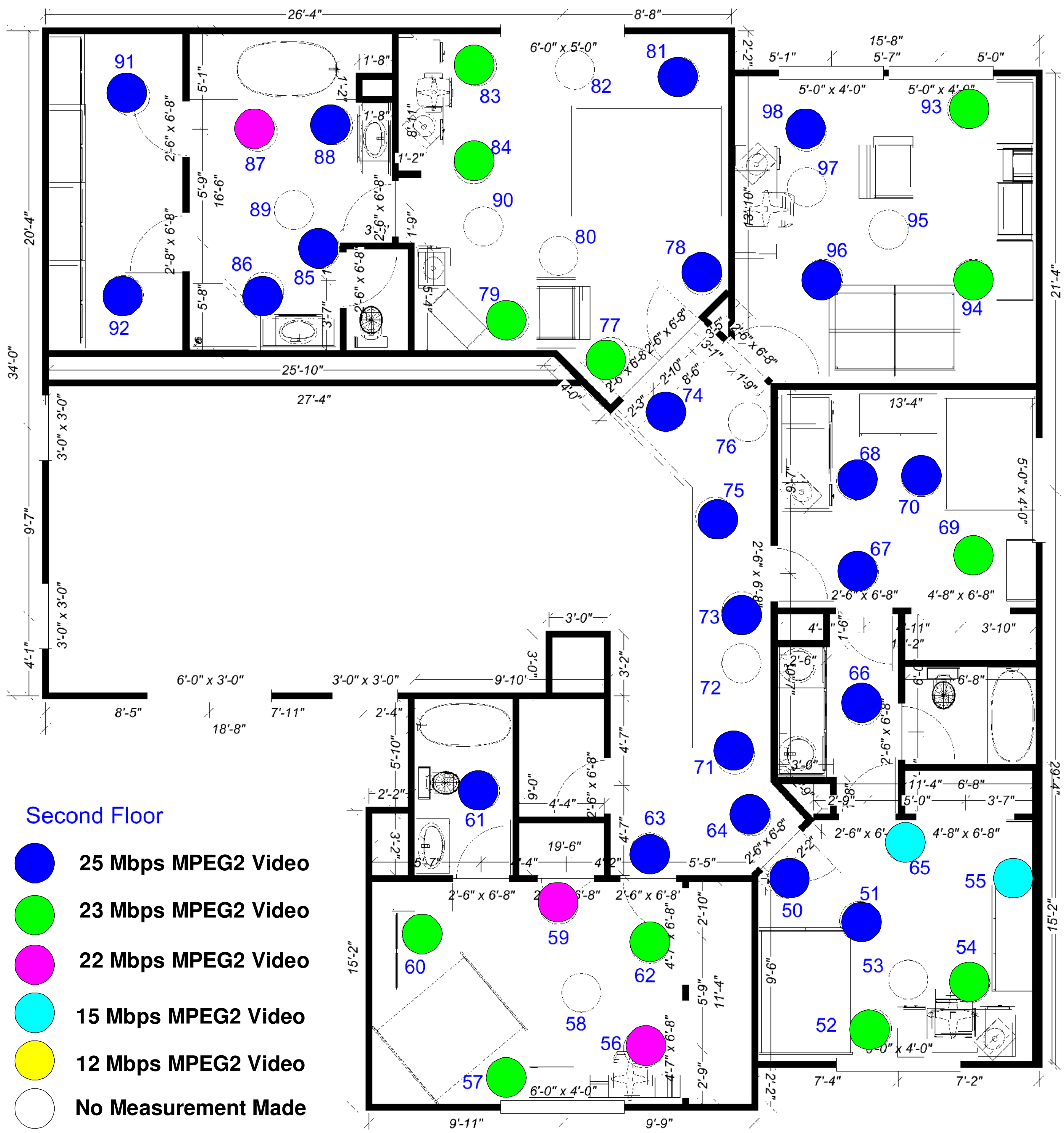


Figure 8 Second Home, Supported Video Rate, Second Floor, BowTie Array Used at RT



is possible to fully support full DVD-quality video except at point #104.

On the second floor of the home, every point supports full US-HDTV except for two points (#55 and #65) which still easily support full DVD-quality video.

3.2.4 Bow-Tie Array at RT Results for Data-Mode

As was true for the video-only case, some additional throughput variability occurs for the data-only case when the bow-tie antenna array is used at the RT. Even so, the very worst-case performing point in the entire home (#104) still delivers 11 Mbps genuine payload throughput. Most of the measurement points still exhibit supportable throughput rates very near 40 Mbps.

3.2.5 Comparing Bow-Tie and Yagi Antenna Array Results

In semi-fixed wireless applications like large flat-panel displays, incorporation of antennas with yagi-style performance can be done with very little cost or difficulty. Here again, no effort has yet been made to miniaturize or productize the antenna arrays used with the demonstration platforms because product form-factors will vary widely.

In high-mobility applications like with a webpad or small display, the omni-directional bow-tie style antenna will probably be needed in order to avoid forcing the user to re-orient the antenna positioning whenever they move their terminal.

A side-by-side comparison of the yagi and bow-tie array performance in video-only and data-only modes is provided in histogram form in Figure 9 and Figure 10. In every case, the yagi array performs somewhat better than the bow-tie array as fully anticipated due to the slightly higher gain of the yagi antenna elements.

3.2.6 Field Test Observations

One of the most interesting regions of the home regarding multipath is on the second floor near measurement point #70. In this room, the receive signal strength was well above the minimum needed to support the highest throughput rates deliverable by the system. Owing to the very high ceiling (30 feet) in the living room where the AP was located, there was a direct line-of-sight path from the AP to the broadside wall of the room in question. Although the signal only had to pass through one interior wall in order to reach the interior of the room, the signal first had to pass through the periodically-spaced wooden 2x2 members making up a hand-railing immediately outside the room. The coincidental spacing of the wooden members acts like a Fresnel plate grating for the incident signal wavefront which causes very severe frequency-selective fading within this particular room. Although the net system performance in this room was still excellent, the additional test statistics that are normally accumulated during our field testing showed that the system had to work particularly hard in this region of the home to address the difficult multipath present.

This case is just one of many that our field testing has uncovered over the past year+ and in each case, we make use of these real-world channel situations to improve our end system performance further.

4. Second-Generation Air5 Product

The second-generation Air5 product begins volume shipment in June 2003. The second-generation product provides a higher level of integration (2 chips instead of 3), additional digital interfaces (most notably a built-in PCI interface) as well as a number of performance improvements that include (i) lower power consumption, (ii) improved phase noise and linearity performance, and (iii) better receiver sensitivity. In total, the CMs based upon the second-generation chips set are expected to exhibit ***approximately 12 dB better link margin performance*** than the CM units used in performing this field testing. This additional performance margin will make the Air5 wireless connections even more reliable. As clearly evidenced by the yagi versus bowtie results, 3 dB gain difference affects performance appreciably. Magis is consequently very pleased that our first volume products will be able to deliver link margins that are significantly better than the excellent results provided in this memorandum.

5. Antennas

The most unmistakable aspect of the Air5 technology to a casual observer is that it employs multiple antennas. As supported in a separate Magis white paper[6], the very nature of the indoor multipath channel combined with fundamental laws of estimation theory mandate that multiple antennas be used if high throughput and link reliability are to be achieved. At 5 GHz, an individual antenna can be extremely small and inexpensive because the signal wavelength at this frequency is only about 6 cm. Although beyond the scope of this brief memorandum, fewer antenna elements may also be used with some tradeoffs in performance and usage.

Since the product form-factor of almost every customer is different, no effort was expended to make the antennas used with the Magis CMs smaller. Antenna spacing of 2 cm in a large plasma video display will certainly not be a problem. Recognizing that antennas can be an issue for our customers, Magis routinely provides extensive technical guidance and support for our customers to help them satisfy our antenna engineering guidelines while achieving their industrial design and cost goals.

[6] "Making OFDM Work at 5 GHz"

Figure 9 Histogram of Supportable MPEG2 Video Rate (Results for Yagi Array Versus Bowtie Array Shown Side by Side)

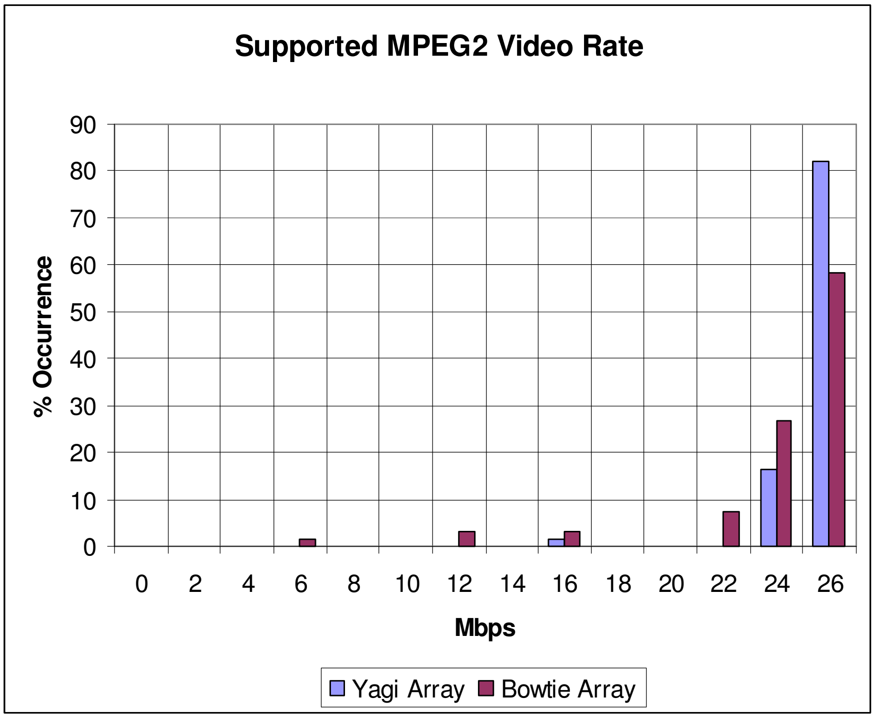
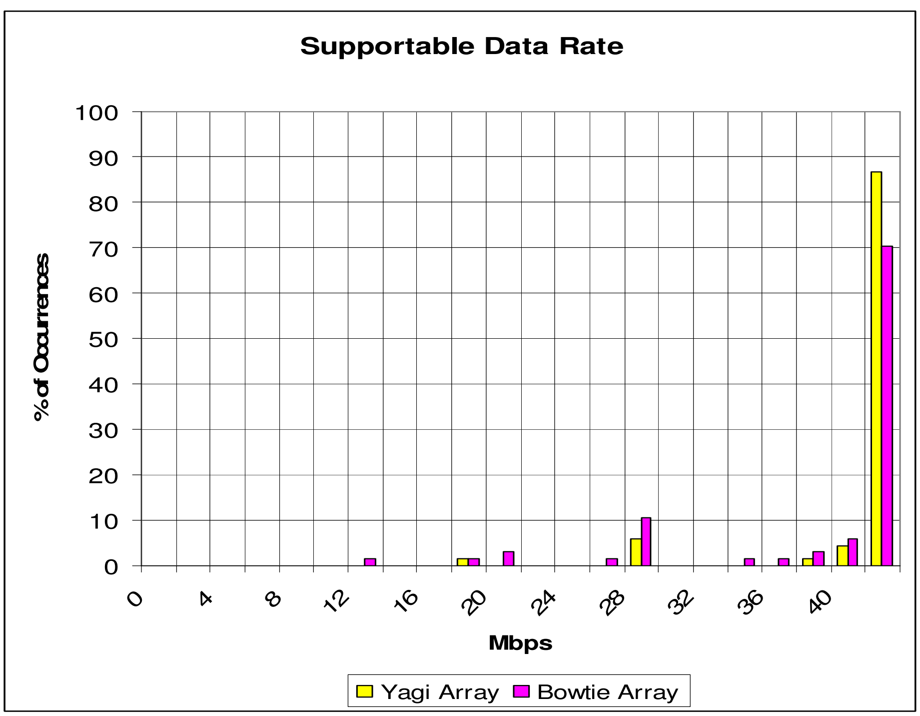


Figure 10 Histogram of Supportable Data Rate Equivalent (Results for Yagi Array Versus Bowtie Array Shown Side by Side)



6. Conclusions

Air5 technology is capable of providing multi-stream video and data services throughout even very large homes. The technology deals with indoor multipath extremely well. Communication range is limited only by signal loss through the home rather than being multipath-limited.

Products based upon the Magis Air5 chipset that begin volume shipping in June 2003 should provide full 40 Mbps data-mode throughput capability and US-HDTV/DVD video capability throughout even very large homes.

7. Appendix: Common MPEG2 Video Rates

Table 3 Standard Digital Video Throughput Rates

Video Type	Throughput, Mbps	Comments
SDTV	3-6	Normally taken to be 6 Mbps
DVD	10.08	
US-HDTV	19.68	Maximum of all US-HDTV rates

