Air5™ In-Home Field Testing Results

Report 2

Document Number A10027

Version 1.1

James A. Crawford

Chief Technical Officer

Magis Networks, Inc.

April 2003

Advance Information
This product is in a formative or design state. The document contains design target specifications for product development.

Copyrights and Trademarks

Document Number:	**A10027**
Document Version:	1.1
Document Date:	April 2003

Magis Networks, Inc.
12651 High Bluff Drive
San Diego, CA 92130
USA
(858) 523-2300
apps@support@magisnetworks.com

Introduction

Extensive in-home and in-office field testing of the Air5™ system is an on-going component 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.

For the testing described in this document, Magis' Core Module (CM) hardware demonstration platform, version 1.1 based on the MSG6100[1] chipset, was used. The following is a summary of the testing performed.

- CM version 1.1 demonstration hardware was used for both the Access Point (AP) and Remote Terminal (RT) stations.
- 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.
- The maximum allowable data-packet time jitter was set to 9.1 msec.
- Microstrip bow-tie patch antennas (with omni-directional patterns) organized in a linear array with approximately 1.5-inch spacing were used (see Figure 1).
- Two different types of antenna arrays were used at the RT end of the link: (a) two-element quasi-yagis organized in a linear array with approximately 1.5-inch spacing (see Figure 2), and (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.

This paper presents field testing results from two different homes:

- Home #1:
  - Approximately 2,700 square feet
  - Two-story, stucco construction (southern California)
  - Large open stairwell in the center of the home; elsewhere 8 foot ceilings
- Home #2:
  - Approximately 3,500 square feet
  - Two-story, stucco construction (southern California)
  - Large, open entryway and living room, with 30+ foot ceiling, remainder of home with mostly 8 foot ceilings

1. Test Methodology

Even though the data throughput rates used during the field testing ranged from approximately 3 Mbps to approximately 25 Mbps, the time variability of the 5 GHz communication channel made it necessary to conduct measurements over a time span of minutes at each data collection point to obtain reliable results. In the test results reported here, performance was so good throughout the homes that, with the exception of one collection point, no video transcoded rates below 15 Mbps were ever required. The AP was left unchanged in a fixed location in 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.

To ensure reliable results, it was also important to conduct the field testing cognizant of the differences between video and data-only distribution. The quality-of-service (QoS) aspects needed for video transmission are considerably more demanding than those required for data-only communications. Accordingly, actual transcoded video MPEG2 streams ranging from 3 to 25 Mbps[2] were used with all the appropriate IEEE802.11a physical layer (PHY) signaling rates, accumulating a wide range of link statistics from which video performance could be computed. Furthermore, testing of each transcoded video rate at each

[1] First-generation Magis chipset

[2] Actual transcoded video rates used were 2,4, 6, 8, 12, 15, 19, 22, 23, and 25 Mbps.

appropriate PHY signaling rate was completely automated.

1.1 Performance Criteria

Data-only and video-only performance criteria are fundamentally different, because video delivery requires that tight QoS constraints on time jitter and latency be maintained. Accordingly, this paper uses different criteria for the two modes to report system performance.

1.1.1 Video Mode Delivery

Unlike many other IEEE 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. Time latency must also 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.

> **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 transcoded video rate supported independent of the PHY mode used.
>
> The transcoded video source rates allowed in the testing were 2, 4, 6, 8, 12, 15, 19, 22, 23, and 25 Mbps. The maximum time jitter allowed over the air interface was 9.1 msec.

1.1.2 Data Only Delivery

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

> **Data-Only Mode Criteria:** Disregard the number of required data packet retransmissions 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 clarifies the relationship between the data-mode and video-mode criteria.

When an RT requests network resources, 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 Automatic Repeat Request (ARQ) activity (i.e., packet retransmission). In the case of a MPEG2 stream operating at 25 Mbps, a minimum of roughly 27 Mbps must be allocated. 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 Medium Access Control (MAC) for that stream. In contrast, this same stream would only be capable of supporting up to 25 Mbps of MPEG2 video, due to the QoS-related margins that are associated with video.

2. Field Testing Results

All the field testing results are based on using Magis' CM Version 1.1. The CM is a complete engineering development system. Because of this, no efforts were made to reduce the size of the platform or the bill of material.

The objective of the CM-based field testing was to exhibit the Air5 technology in its best light, with reasonable constraints on antenna size and form factors. Customers will 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 key component[3] of good system performance at 5 GHz, and Magis offers a wide range of support in this area.

2.1 Home #1 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 were simple to make, even

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

though no attempt was made in this configuration to eliminate the coaxial lines and connectors.

Note: Design details for a very low-cost, equivalent-performing bow-tie array are available separately to Magis partners.

The bow-tie antenna elements provide a good omni-directional gain pattern, which is desirable for the AP since the angle of arrival from any specific RT is completely unknown.

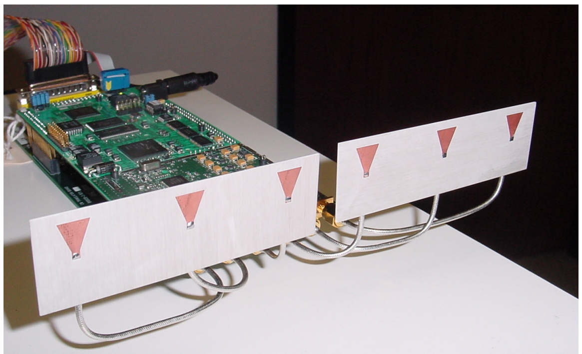

Figure 1: Three-Element Bow-Tie Antenna Arrays developed at Magis (Omni-Directional for AP)—Hosted With CM 1.1.

A more aggressive antenna approach was used for the RT in the Home #1 test because, in many relatively fixed-point in-home applications, the direction toward the AP is easily discernable to within ±60 degrees. The simple, printed yagi antenna elements have a very wide beam width[4] and, therefore are not overly directional while also providing about 4.5 dBi gain.

Many home applications will also be portable, making the omni-directional bow-tie antennas the preferred choice for the RT as well as for the AP. The Home #2 test 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.

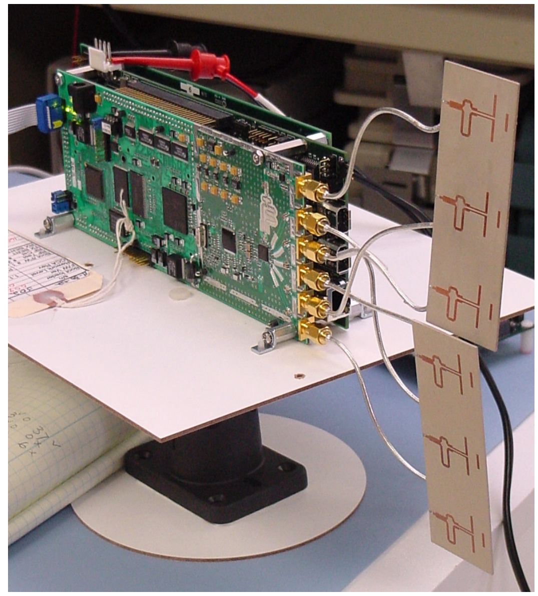

Figure 2: Example of the Yagi Antenna Arrays Developed at Magis (Directional for RT) —Hosted With CM 1.1.

2.1.1 First Home Video Results

The supported MPEG2 video rate by home location is shown in a color-coded format in Figure 3 and Figure 4. The link coverage is remarkable in that a minimum of 23 Mbps is deliverable everywhere within the home, and only 19+ Mbps is required for US-HDTV. All the 25 Mbps MPEG2 delivery represented by the blue dots was accomplished using the highest IEEE 802.11a signaling rate (54 Mbps, 64-QAM R=¾). Substantial throughput resources were 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, which will begin volume shipment in June 2003, perform even better (see Section 3). The raw field-test results for this first home are provided 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 been provided throughout the entire home.

Field test results for Home #1 show that full 19+ Mbps US-HDTV reception (plus additional streams) is easily supported throughout the entire home.

[4] More are details available in A10026 Magis Air5 Antenna Array Development Work.

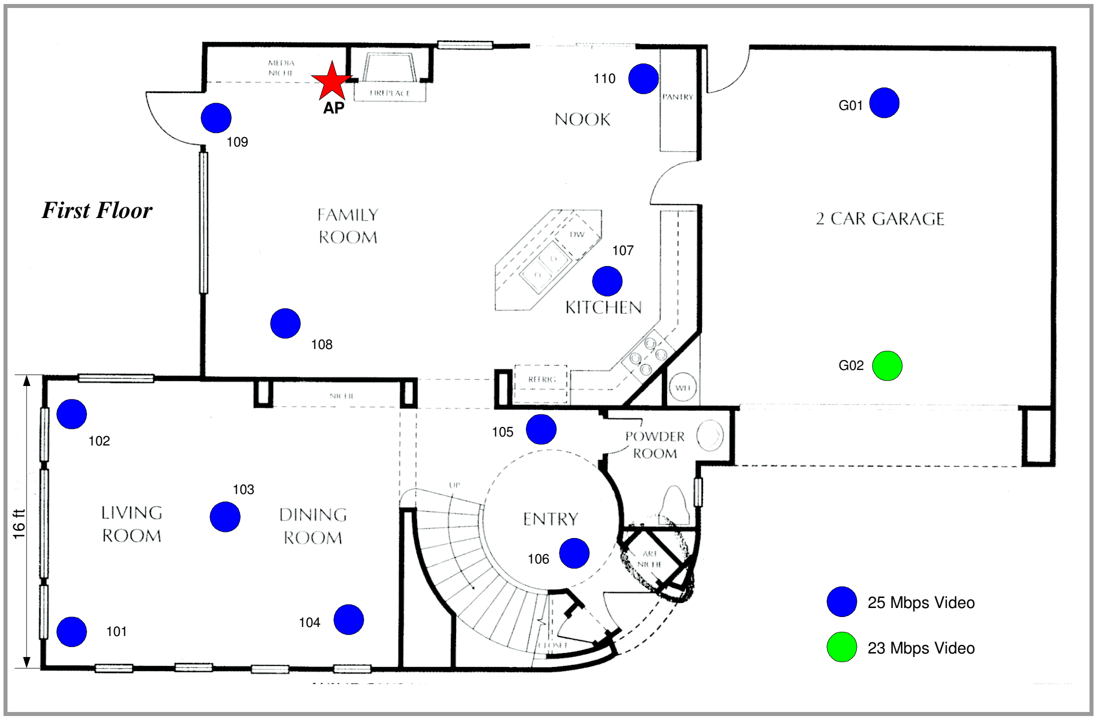

Figure 3: Supported MPEG2 Video Rate Versus Location (Home #1, First Floor)

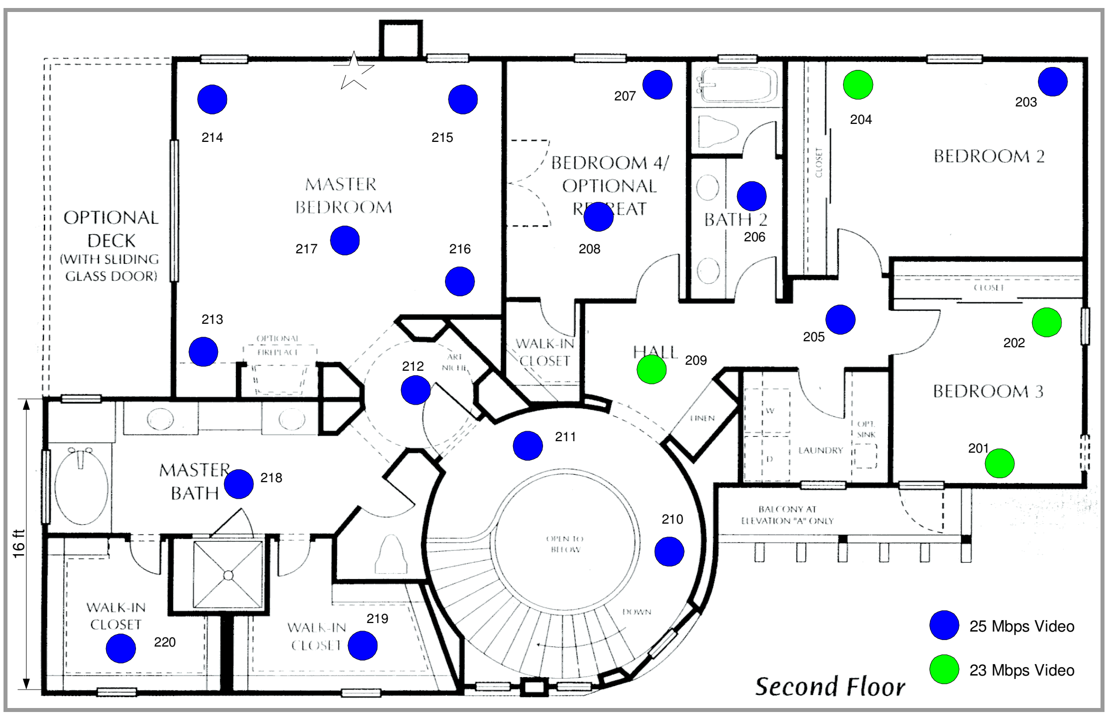

Figure 4: Supported MPEG2 Video Rate Versus Location (Home #1, Second Floor)

Table 1: Field Test Results for First Home

Locations	Video Rate	Measured Data Flow	Scaled Data Thru
101	25	29.83	40.8781
102	25	29.92	41.0015
103	25	29.88	40.9467
104	25	29.86	40.9467
105	25	29.94	40.9196
106	25	29.95	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	26.70	26.7
202	23	26.84	36.7807
203	25	29.00	39.7407
204	23	27.99	38.3567
205	25	29.92	41.0015
206	25	29.60	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	40.8979
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

2.1.2 Home #1 Data Results

The criteria for assessing the supportable data throughput in the home are described in Section 1.1. 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 of data-only mode. As discussed in Section 1.1, 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 (a) the MPEG2 video stream used in the testing (even with additional throughput for ARQ servicing) does not consume all the throughput resources available over the channel and (b) there is a fixed packetization loss associated with video that is not present with data-only operation for a specific stream. The resulting data-only throughput rate achievable for a single link is given by the table column labeled “Scaled Data Thru” in Table 2. As Table 2 shows, only location 201 exhibited a throughput rate that was significantly less than that of all 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.

> With the exception of one collection point, the mean data-only throughput rate for the entire home was 40.6 Mbps, with a standard deviation of only 0.45 Mbps.

2.2 Home #2 Results

The same test procedures used in Home #1 were used in testing Home #2. In Home #2, 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 bow-tie elements. As supported in the results that follow, this approximate 3 dB difference in gain is helpful along the range perimeter.

More testing points were used in Home #2 in order to more thoroughly investigate the fine structure of the multipath throughout the home. Some 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 test 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 on 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, (a) the yagi antenna array used with the RT, and (b) the bow-tie array used with the RT. The bow-tie antenna array was used at the AP in both cases.

On the first floor of Home #2 including the garage, full US-HDTV is supportable everywhere except for a single point in the garage. Every measurement point on the first-floor easily supports DVD-quality video.

The slightly reduced throughput points represented by the green dots in the kitchen area (e.g., point 34) primarily result from the large number of heavy metal appliances that surround 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, a dual oven, a range, and a microwave.

In the garage, points 101 and 103 are disadvantaged because, not only are they located a large distance from the AP, but signals must also pass through several load-bearing walls of the home to reach the garage. In addition, there is 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 directly behind the two side-by-side filing cabinets 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.

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 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.

2.2.1 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 (approximately 40 Mbps), except for only four measurement points out of 67. Even at these points, the lowest data throughput rate is almost 18 Mbps.

2.2.2 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. Even in the garage, it 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.

2.2.3 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 worst-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.

2.2.4 Comparing Bow-Tie and Yagi Antenna Array Results

In semi-fixed wireless applications like large flat-panel displays, antennas with yagi-style performance can be incorporated with very little cost or difficulty.

Note: No effort has yet been made to miniaturize or productize the antenna arrays used with the demonstration platforms, because product form-factors vary widely.

In high-mobility applications, such as a webpad or small display, the omni-directional, bow-tie-style antenna will likely be needed to prevent customers from having to reorient the antenna position whenever they move the 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.

2.2.5 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 in the living room where the AP was located (30 feet), there was a direct line-of-sight path from the AP to the broadside wall of the room. Although the signal only had to pass through one interior wall to reach the interior of the room, the signal first had to pass through the evenly 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 wave front, which causes very severe frequency-selective fading within the 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. In each case, we used real-world channel situations to further improve our end system performance.

3. Second-Generation Air5 Product

The second-generation Air5 product begins volume shipment in June 2003. This product provides:

- A higher level of integration (two chips instead of three).
- Additional digital interfaces (most notably, a built-in PCI interface).
- A number of performance improvements, including (a) lower power consumption, (b) improved phase noise and linearity performance, and (c) better receiver sensitivity.

In total, the CMs based on the second-generation chipset are expected to exhibit approximately 12 dB better link margin performance than the CM units used in the field testing described in this paper. This additional performance margin will make the Air5 wireless connections even more reliable. As clearly evidenced by the yagi versus bow-tie results, a 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 presented in this paper.

4. Antennas

Casual observers will note that the Air5 technology uses multiple antennas. As supported in a separate Magis white paper[5], the nature of the indoor multipath channel combined with fundamental laws of estimation theory mandate that multiple antennas be used to achieve high throughput and link reliability. 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 paper, it may be possible to use fewer antenna elements, with some trade-offs 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 to help our customers adhere to our antenna engineering guidelines while achieving their industrial design and cost goals.

5. 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 on 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.

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

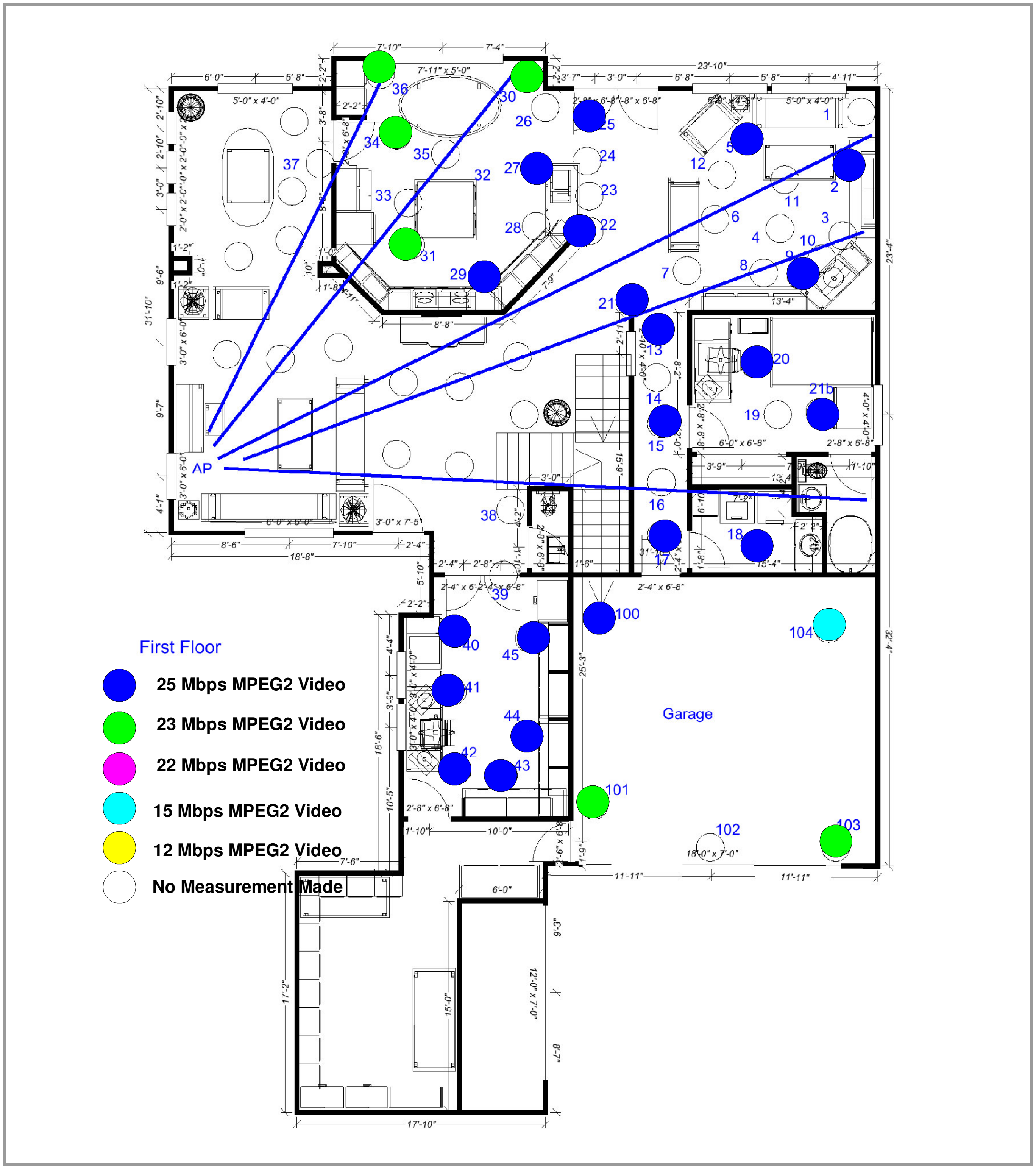

Figure 5: Second Home, Supported Video Rate, First Floor, Yagi Array Used at RT

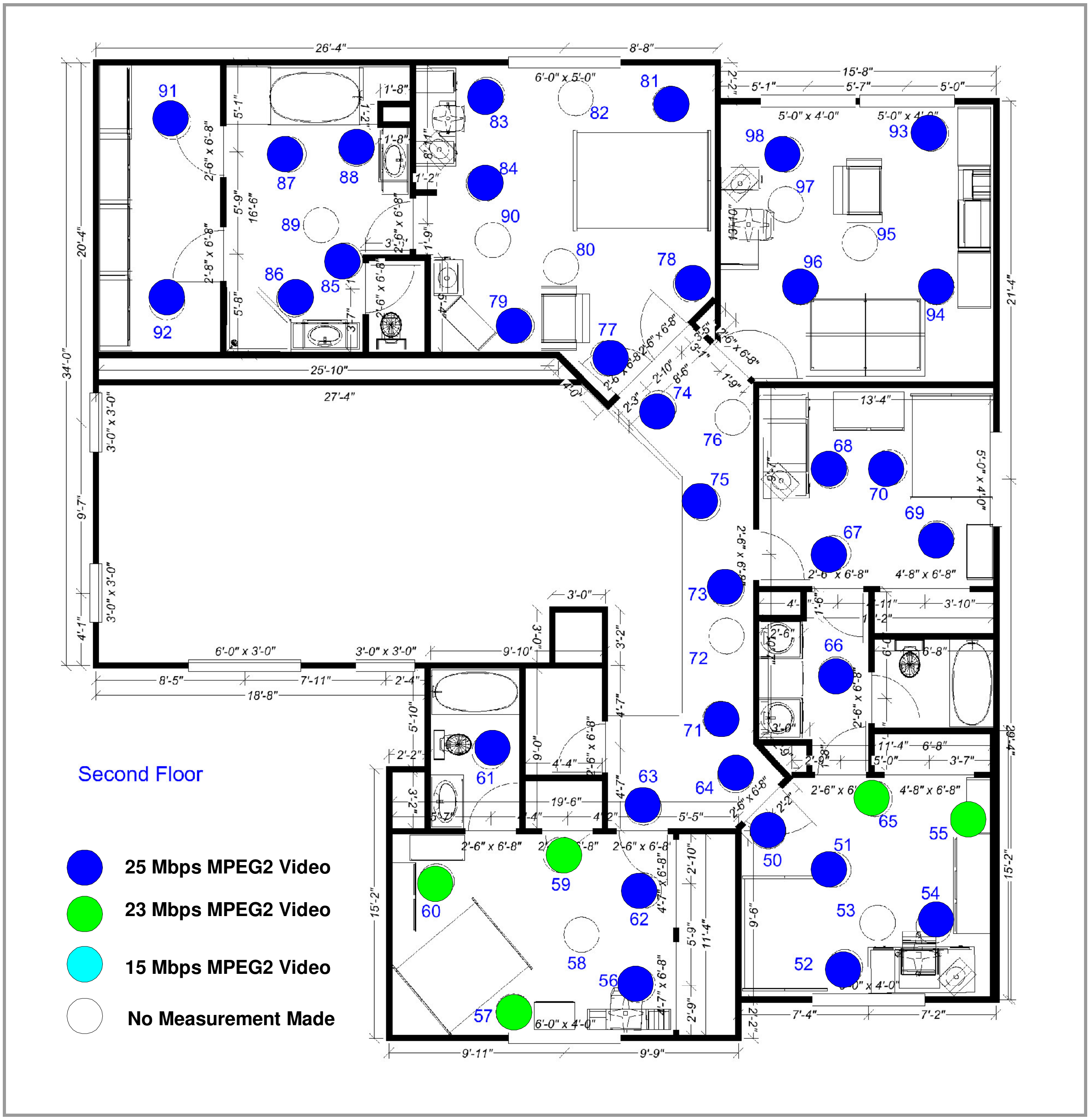

Figure 6: Second Home, Supported Video Rate, Second floor, Yagi Array Used at RT

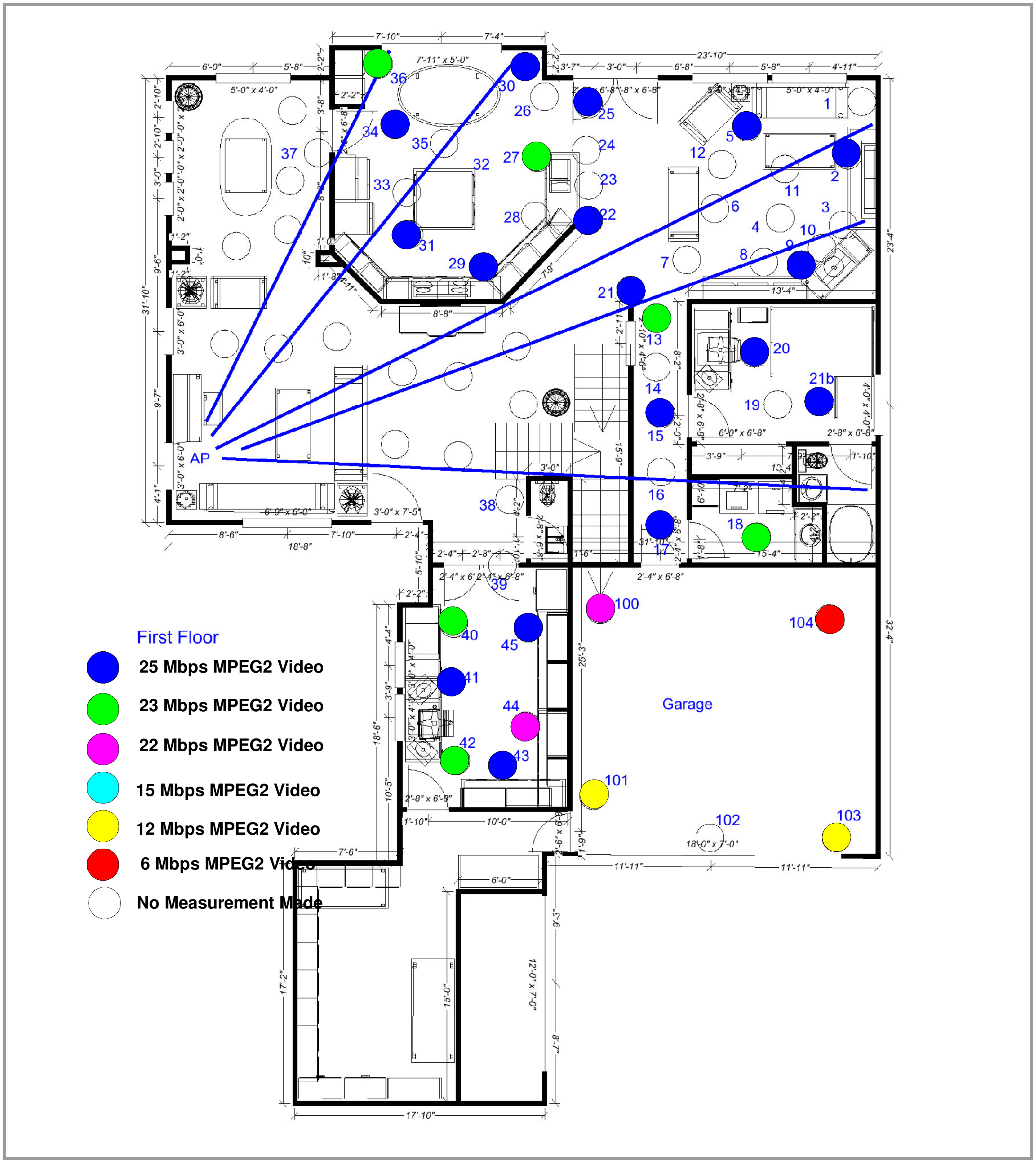

Figure 7: Second Home, Supported Video Rate, First Floor, Bow-Tie Array Used at RT

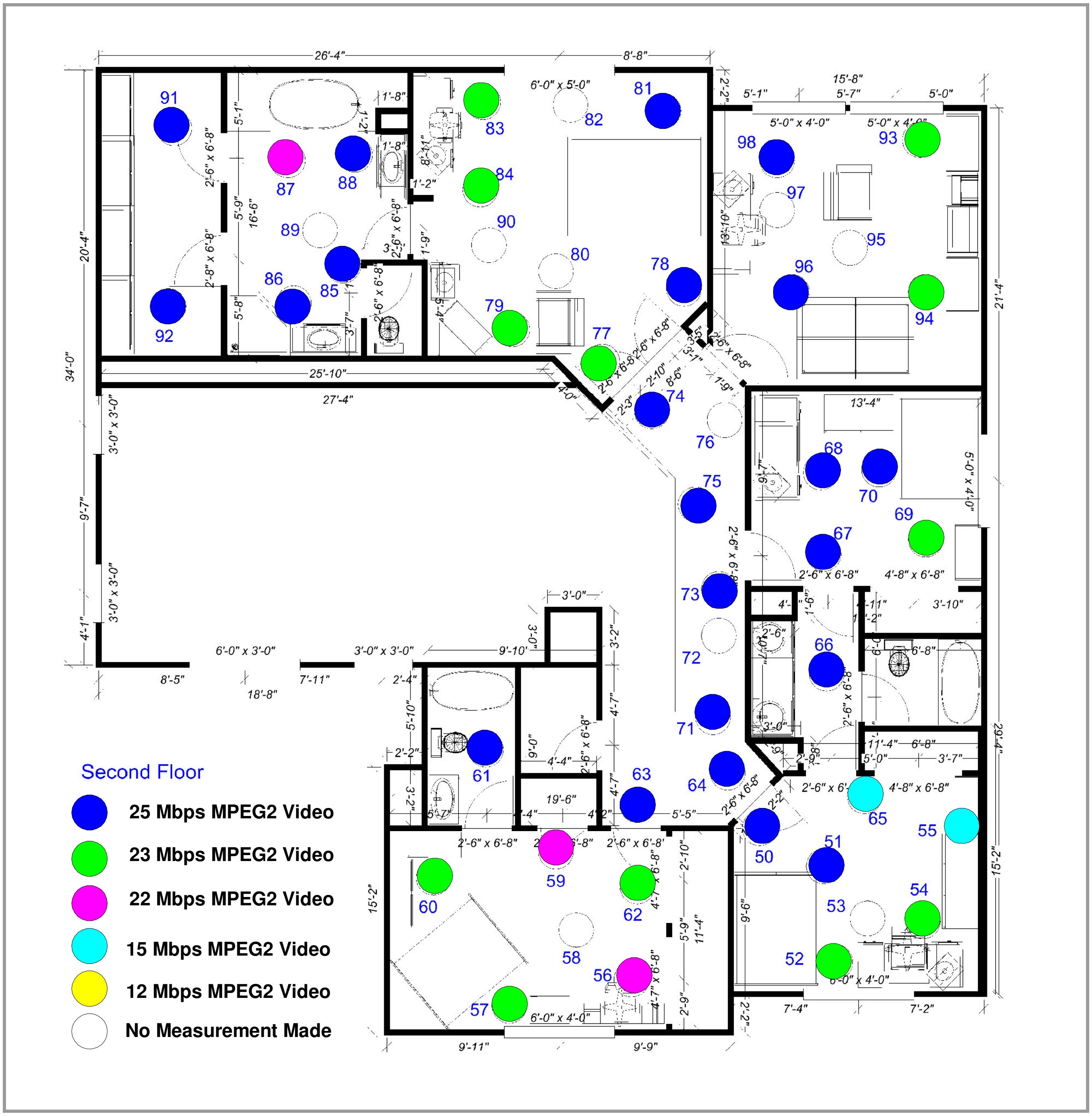

Figure 8: Second Home, Supported Video Rate, Second Floor, Bow-Tie Array Used at RT

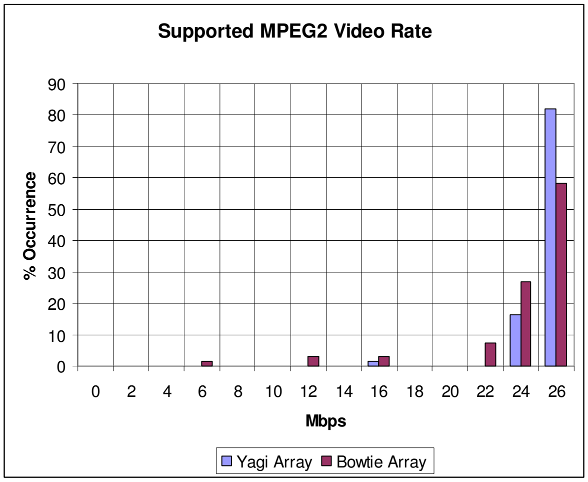

Figure 9: Histogram of Supportable MPEG2 Video Rate (Results for Yagi Array Versus Bow-tie Array Shown Side by Side)

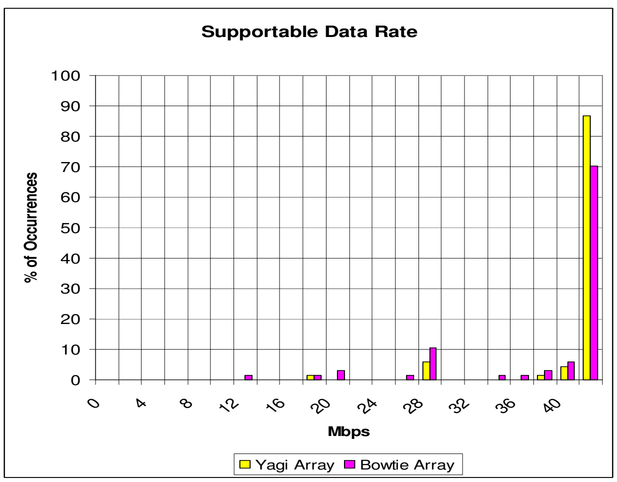

Figure 10: Histogram of Supportable Data Rate Equivalent (Results for Yagi Array Versus Bow-tie Array Shown Side by Side)

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	19.69	Maximum of all US-HDTV rates