Wireless Local Area Network for Data Telemetry from Fast Moving Nodes

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ABSTRACT

A Wireless Local Area Network (WLAN) based system called 2-Way Robust Acquisition of Data (2-RAD) is being developed to telemeter data from a number of fast moving airborne platforms to ground collection points distributed over a large test range. The Johns Hopkins University Applied Physics Laboratory (JHU/APL) is analyzing a 2-RAD prototype currently in operation at the U.S. Army Yuma Proving Ground (YPG) that uses an IEEE 802.11b WLAN infrastructure. Preliminary analysis efforts at JHU/APL indicate that the Doppler shift from fast movers, and the system radio link margin, do not preclude IEEE 802.11b from being used for 2-RAD.

KEY WORDS

Telemetry, Wireless Local Area Network, IEEE 802.11b, Doppler, link margin

INTRODUCTION

Commercial off-the-shelf (COTS) technologies such as WLANs offer high data rates, quick setup times, configuration flexibility, and relatively long ranges. These technologies may be readily adapted for data telemetry from sensors on mobile and airborne platforms. At YPG, IEEE 802.11b wireless bridges (WBs) and access points (APs) are currently being used to remotely control and telemeter data from video, meteorological, and other data collection equipment throughout the proving ground. The current YPG wireless network is considered to be a prototype for 2-RAD, a system that is being developed to support data telemetry from a number of fast moving airborne platforms such as missiles, munitions, and aircraft to collection points on the ground.

An effort is underway at the JHU/APL to analyze the current YPG system, and to investigate the feasibility of using this system for data telemetry from multiple fast moving airborne platforms. JHU/APL is attempting to determine the effect of fast moving platforms on the IEEE 802.11b system performance. The analyses consider maximum coverage area of the 2-RAD system, the effects of Doppler shift and Doppler shift rate, handovers of fast moving platforms from one AP/WB to another, the scalability of the 2-RAD system, and the ability of the network Management Information Base (MIB) to change network management information as fast moving platforms move in and out of the network. Some of these analyses are underway and have yet to be completed. Therefore, only the Doppler shift effects and area coverage analyses are summarized in this paper.

IEEE 802.11b SYSTEM DESCRIPTION

The IEEE 802.11b WLAN is a flexible data communication system that uses radio frequency (RF) to transmit and receive data over the air. IEEE 802.11b is implemented as an extension to, or a replacement of, a wire/cable/fiber local area network (LAN). In addition to eliminating the wire/cable/fiber infrastructure, this system allows network nodes to be mobile.

WLAN systems can be configured as either an ad-hoc or infrastructure network. In an ad-hoc network, the system nodes form a network "on the fly" when they are brought together. There are no fixed points, and every node can communicate with every other node. In an infrastructure network architecture, the nodes (mobile and fixed) communicate with fixed network APs. These APs are usually connected to wire or fiber optic land lines which act as the connection to wired networks (e.g., the internet). Nodes that travel from one AP service area to another AP service area are transferred via handoffs. This handoff method is similar to that used by mobile phone cellular systems. AP service areas can be linked to each other using WBs.

The IEEE 802.11b system consist of two primary layers: the Physical (PHY) layer and the Medium Access Control (MAC) layer. The MAC layer is a set of protocols responsible for maintaining order in the use of the shared medium. The PHY layer is the physical wireless link between nodes and uses RF transmissions. This PHY layer is considered to be the most susceptible to Doppler effects.

IEEE 802.11b supports data rates of 1, 2, 5.5, and 11 Mbps, and spreads its spectrum using Direct Sequence Spread Spectrum (DSSS). It operates in the 2.4000 to 2.4835 GHz frequency band, which is an unlicensed industrial, scientific, and medical (ISM) frequency band. In DSSS, the carrier is modulated using differential binary phase shift keying (DBPSK), which produces the 1 Mbps data rate, differential quadrature phase shift keying (DQPSK), which produces the 2 Mbps rate, or complementary code keying (CCK), which produces the 5.5 and 11 Mbps rates. Detailed information on the system can be found in the IEEE 802.11b standard (ref [1]).

In the U.S., IEEE 802.11b transmitters operate on 11 channels spaced 5 MHz apart. The channelization is shown in Table 1. The maximum allowable transmit power is 1000 mW (+30 dBm) in the U.S. Radiated emissions conform with American National Standards Institute (ANSI) uncontrolled radiation emission standards (IEEE Std C95.1-1999). The maximum allowable antenna gain is 6 dBi. Use of higher gain antennas are accompanied by a proportional decrease in transmit power. For fixed point-to-point applications, the antenna gain can be higher than 6 dBi with no associated decrease in transmit power. The transmitted center frequency tolerance is ± 25 ppm maximum. For 2.4 GHz, this corresponds to a frequency tolerance of ± 60 kHz.

Table 1. IEEE 802.11b Frequencies

Channel	Frequency (GHz)	Channel	Frequency (GHz)
1	2.412	7	2.442
2	2.417	8	2.447
3	2.422	9	2.452
4	2.427	10	2.457
5	2.432	11	2.462
6	2.437		

YPG WLAN IMPLEMENTATION

At YPG, an IEEE 802.11b based COTS WLAN is being used to remotely control and telemeter data from equipment throughout the proving ground. This wireless backbone operates in the 2.4 GHz region and supports data rates as high as 11 Mbps over ranges up to 30 km (19 mi) between links. This current YPG wireless network is considered to be a prototype for the 2-RAD system.

YPG is a U.S. Army proving ground encompassing over 1300 square miles in the southwest Arizona desert. It consists of three areas: the Cibola, Laguna, and Kofa Regions. The Kofa Firing Range is the primary location for test and evaluation of long-range artillery weapon systems, mortars, mines, and munitions for the U.S. Army. Various prepared impact areas are available for evaluating the deployment, functioning, and recovery of submunitions and other munitions for post-firing analysis. With a maximum firing range approaching 75 km (47 mi), a wide range of production and developmental ammunition/weapon systems requiring long ranges and extensive airspace envelopes can be tested. These weapons systems range from small arms and mortars to a 16-inch Naval gun.

A 2-RAD system implementation would require that ground stations be capable of receiving telemetered data from platforms along the entire firing range. Currently, numerous IEEE 802.11b ground stations, each consisting of an AP or WB, are distributed throughout YPG. A map of these locations is shown in Figure 1.

Projectiles proposed for the initial munitions testing using 2-RAD will have velocities approaching Mach 3, or 994 m/s for dry air at standard temperature and pressure (STP). Projectile velocities tested in the future may be as high as Mach 5 (1655 m/s at STP). Conservatively, Mach 5 is assumed for the Doppler effect calculations.

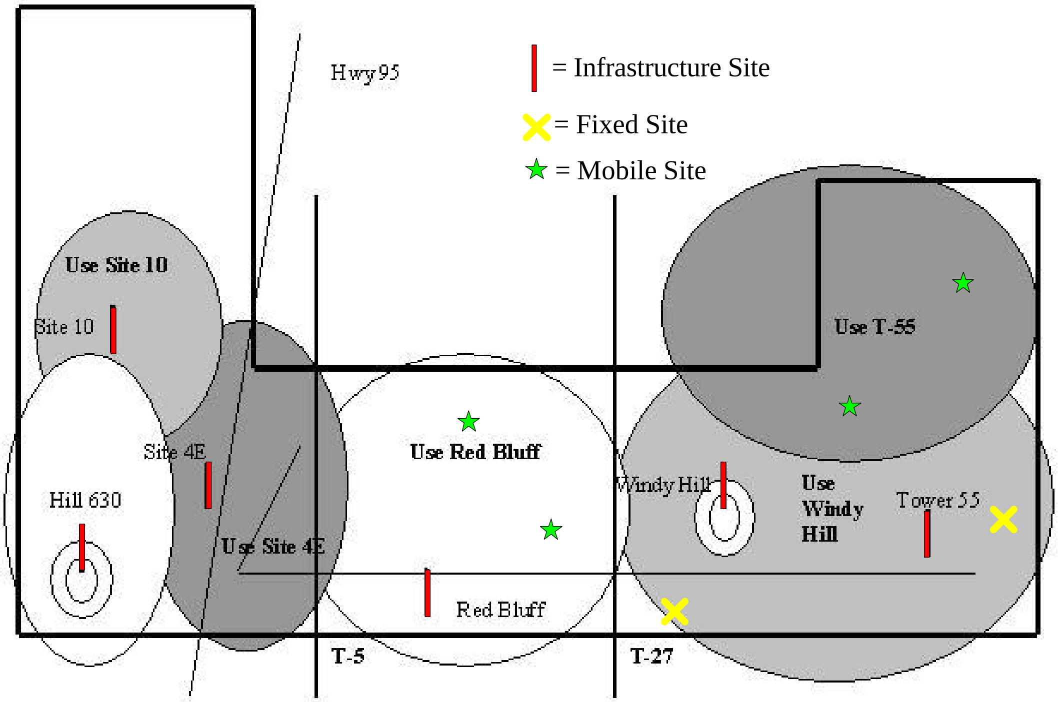

Figure 1. YPG IEEE 802.11b WLAN Sites

DOPPLER SHIFT ISSUES

The Doppler shift equation for a platform moving away from the ground station is

$$f_{gs} = f_t \cdot \frac{(1 - v/c)}{\sqrt{(1 - (v/c)^2)}} = f_t \cdot \sqrt{\frac{(1 - v/c)}{(1 + v/c)}} \qquad (1)$$

where $\mathbf{f_t}$ is the frequency transmitted by the platform, $\mathbf{f_{gs}}$ is the Doppler shifted frequency received by the ground station, **v** is the velocity of the platform with respect to the ground station, and **c** is the speed of light (3 x 10^8 m/s) (ref [2]).

For a transmitted frequency of 2.4 GHz and a platform velocity of Mach 5, the Doppler shifted frequency is 2.3999868 GHz. This corresponds to a Doppler shift of -13.241 kHz. For a platform moving toward the ground station, the Doppler shift is +13.241 kHz. A plot of Doppler shift relative to platform velocity for 2.4 GHz is shown in Figure 2.

For the IEEE 802.11b system, the frequency tolerance is ± 60 kHz. This overbounds any frequency shift caused by a 2.4 GHz transmitter traveling at Mach 5 (± 13.241 kHz Doppler shift) or slower.

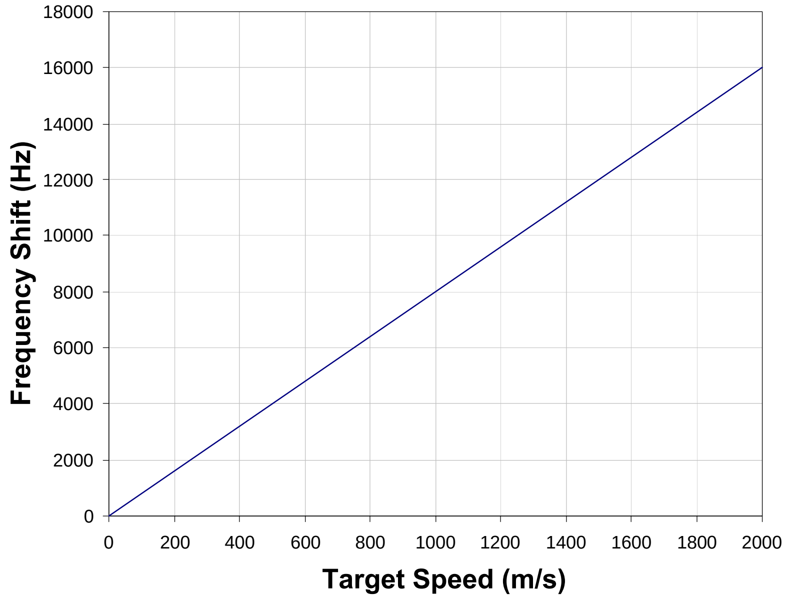

Figure 2. Doppler Shift Relative to Platform Velocity for 2.4 GHz System

Consequently, the IEEE 802.11b specification indicates that Doppler shifts due to platforms flying at velocities of up to Mach 5 should not cause problems to communications with the ground station. In fact, **v** in Equation 1 can be solved to determine the maximum allowable platform velocities based on the frequency tolerance specifications. If the IEEE 802.11b system frequency tolerance of ± 60 kHz is used as the maximum allowable Doppler shift (f_{gs} in Equation 1), velocities of up to 7500 m/s (Mach 22.6 at STP) should not affect system performance.

Note that the calculations assume transceivers transmitting at the exact center frequency. Transceivers with transmit frequencies offset from the center frequency will decrease the tolerance margin, resulting in lower allowable Doppler shifts.

Doppler shifts were calculated for a typical rocket trajectory. GPS tracking accuracy tests were performed by JHU/APL, in cooperation with the Naval Air Warfare Center (NAWC) and the Army Research Laboratory (ARL), using a 2.75-inch HYDRA-70 rocket instrumented with a miniaturized GPS device (ref[3]). One of the outputs of the test effort was a HYDRA-70 rocket flight velocity history, shown in Figure 3. This velocity history was used to generate Doppler shifts for a HYDRA-70 trajectory.

During flight, the HYDRA-70 rocket was assumed to be transmitting at 2.4 GHz to three ground receivers, one at the launch point, one at the temporal midpoint of the flight, and one at the impact point. The Doppler shift at all three receivers was determined for the entire flight history.

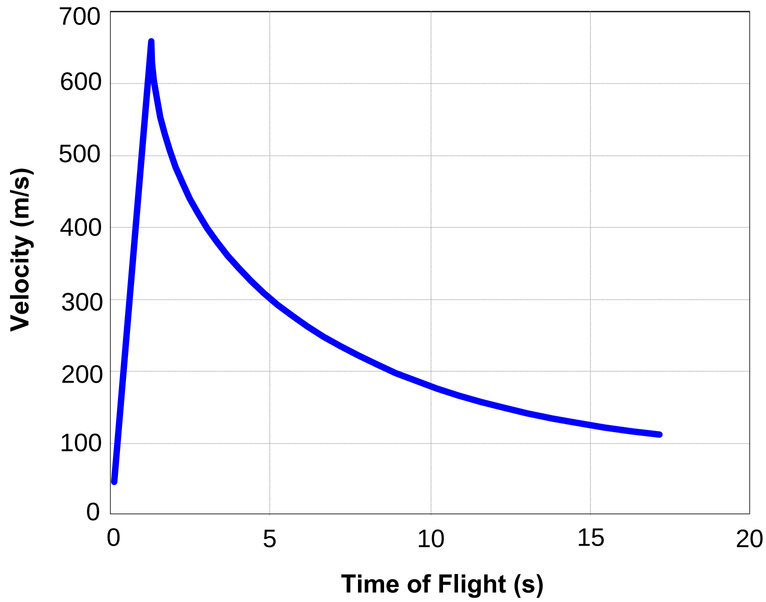

Figure 3. Velocity History of HYDRA-70 Rocket Trajectory

The Doppler shift profiles are shown in Figures 4, 5, and 6, for the landing point receiver, temporal midpoint receiver, and impact point receiver, respectively. As shown in these figures, the largest Doppler shift occurs at the point of greatest velocity, at launch. The shift is negative for the launch point receiver, with the rocket moving away from the receiver, and the shift is positive for the midpoint and impact point receivers, with the rocket moving toward these receivers. The magnitude of the shift is approximately ± 6 kHz, well within the ± 60 kHz frequency tolerance specification.

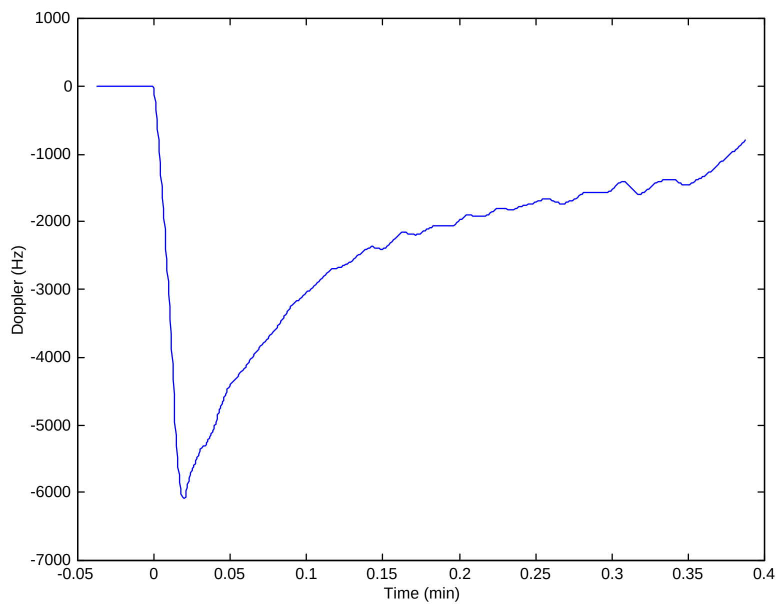

Figure 4. Doppler Shift History for Receiver Located at Launch Point

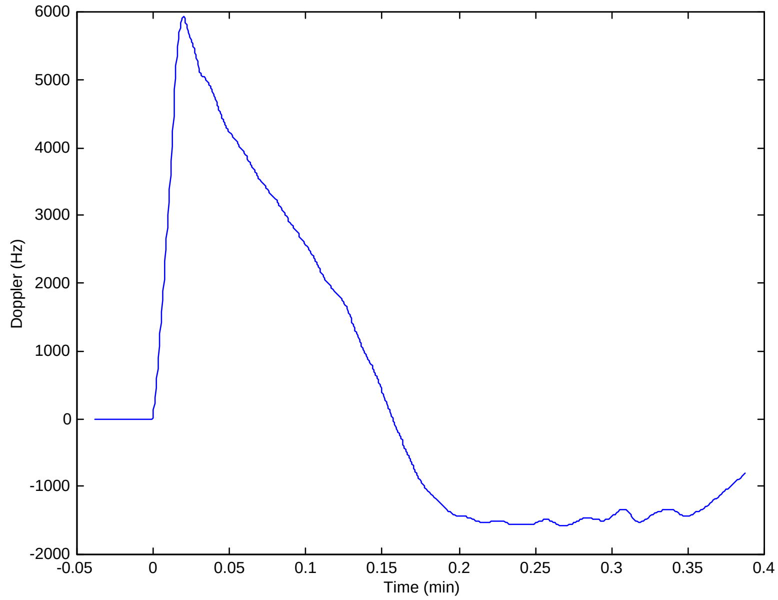

Figure 5. Doppler Shift History for Receiver Located at Temporal Midpoint

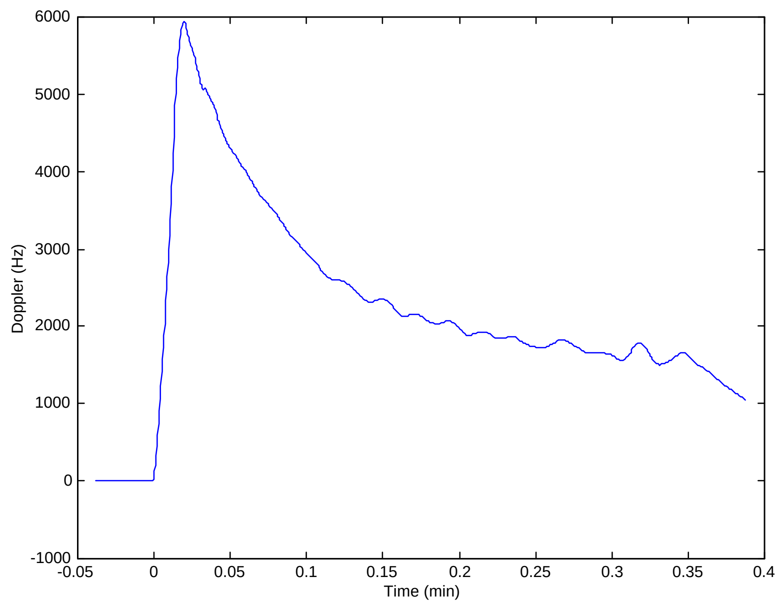

Figure 6. Doppler Shift History for Receiver Located at Impact Point

The rate of change of the Doppler shift was also analyzed. Doppler shift rate depends on the geometry of the platform trajectory. A snapshot of this geometry is shown in Figure 7.

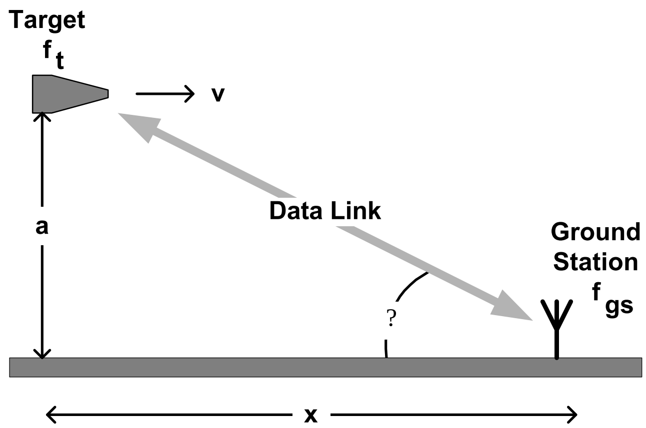

Figure 7. Transmitting Platform With Respect to Ground Station Receiver

The largest Doppler Shift rate occurs when the platform is directly over the ground station, where **?** = 90º, **x** = 0, and the distance between the platform and ground station is the altitude, **a**. In this case, the Doppler shift rate, $\mathbf{df_{gs}/dt}$, is given by Equation 2 (ref [4]):

$$\frac{df_{gs}}{dt} = -f_t \cdot \frac{v^2 \cdot \sqrt{(1 - (v/c)^2)}}{(c \cdot a)} \qquad (2)$$

Using Equation 2, the Doppler shift rate is shown in Table 2 for a 2.4 GHz transmit frequency, a platform velocity of Mach 5, and various altitudes between 20 m and 10 km.

Table 2. Doppler Shift Rate for Mach 5 Projectile Directly Overhead Ground Station Receiver

Altitude (m)	Doppler Shift Rate (kHz/s) for Transmit Frequency of 2.4 GHz
20	1095.61
100	219.12
500	43.82
1000	21.91
10000	2.19
30000	0.73
50000	0.44
100000	0.22

The system specification that corresponds to the Doppler shift rate is frequency drift rate. However, this specification is not contained in the IEEE 802.11b standard. It is assumed that the IEEE 802.11b PHY layer uses a type of frequency acquisition or tracking algorithm scheme to compensate for Doppler shift rate. However, an analysis of those techniques is beyond the scope of this preliminary investigation. Future planned field tests and bench tests are intended to determine the effect of this Doppler shift rate on the performance of the IEEE 802.11b system.

RANGE COVERAGE

The range coverage analysis is based on an IEEE 802.11b link budget analysis that specifically takes into account the YPG WLAN equipment and site locations (ref [5]). The link budget was based on an International Telecommunications Union (ITU) recommended template for digital communications systems (ref [6]).

The site specific parameters that were used in the link budget analysis are shown in Table 3. The effective isotropic radiated power (EIRP) is the maximum transmit power plus antenna gain minus cable/insertion loss.

Table 3. YPG Site Specific IEEE 802.11b Radio Parameters

Parameter	Infrastructure Site	Fixed Site	Mobile Site
Transmitter antenna gain (dBi)	11	14	6.5
Cable/insertion loss (dB)	2	2	2
Maximum transmit power (dBm)	30	20	20
Total transmit EIRP (dBm)	39	32	24.5

The IEEE 802.11b radios used at YPG are Cisco Aironet 340 WBs with +30 dB amplifiers on the receive side. The receiver sensitivities for these radios are -90, -88, -87, and -83 dBm for data rates of 1, 2, 5.5, and 11 Mbps, respectively, for a bit error rate (BER) of 10^{-6}. Using these receiver sensitivity values, the site specific radio parameters in Table 3, and the log-distance path loss model, the following maximum link ranges were derived. Note that for projectile testing, the infrastructure site – mobile site model is most relevant.

Table 4. Calculated Maximum Link Ranges for YPG WLAN Sites

Link	1 Mbps	2 Mbps	5.5 Mbps	11 Mbps
Infrastructure site - infrastructure site	165.3 km (102.7 mi)	119.5 km (74.3 mi)	96.9 km (60.2 mi)	70.7 km (43.9 mi)
Fixed site – infrastructure site	79.4 km (49.3 mi)	57.4 km (35.7 mi)	46.6 km (29.0 mi)	34.0 km (21.1 mi)
Mobile site – infrastructure site	36.2 km (22.5 mi)	26.2 km (16.3 mi)	21.2 km (13.2 mi)	15.5 km (9.6 mi)

Note that these maximum distance calculations assume line-of-sight (LOS) communications and thus do not take into account fading or diffraction due to the YPG test range topography. These analysis results also do not consider multipath effects, environmental effects (water vapor density, temperature, barometric pressure), surface ducting, adjacent channel interference (ACI), or intentional interference (i.e. jamming). The contributions of these factors will be evaluated in later phases of this effort.

Although this coverage analysis is incomplete, preliminary results agree with empirical data, which indicates infrastructure site-to-infrastructure site links operating at 11 Mbps over distances of 30.0 km (18.6 mi) to 50 km (31.1 mi). The coverage results in Table 4 and the empirical data indicate that ground stations may have to be added to ensure high throughput (11 Mbps) coverage throughout the projectile test area.

CONCLUSION

Preliminary results of an analysis of an IEEE 802.11b WLAN based data telemetry system operating at YPG are being used to support the use of 2-RAD to telemeter data from fast moving platforms. These results indicate that fast moving telemeters up to Mach 5 will result in Doppler shifts that are well within the specified frequency tolerance of IEEE 802.11b. A coverage analysis of the YPG range indicates that the current IEEE 802.11b infrastructure may be insufficient to cover the area that will be used for projectile testing, and more IEEE 802.11b ground stations may be required. Future tests in the field and on a JHU/APL testbed will be used to support these conclusions, as well as evaluate the effect of Doppler shift rate, handovers of fast moving platforms from one AP/WB to another, the scalability of the 2-RAD system, and the ability of the network Management Information Base (MIB) to change network management information as fast moving platforms move in and out of the network.

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