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EMERGING COMMUNICATION TECHNOLOGIES (ECT) PHASE 2 REPORT
Volume 1
MAIN REPORT

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September 2003

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Executive Summary

The National Aeronautics and Space Administration (NASA) is investigating alternative approaches, technologies, and communication network architectures to facilitate building the Spaceports and Ranges of the future. These investigations support the Second Generation Reusable Launch Vehicle (2nd Gen RLV), Orbital Space Plane (OSP) and other associated craft presently under development or under consideration in Government, academic, and private sectors. These investigations also provide a national centralized R&D forum for next-generation Spaceport and Range technology development. Together, these sectors all share the common goal of changing the historic risk/reward equation for access to space, with the intent to:

- Dramatically reduce launch cost
- Greatly improve launch system reliability
- Significantly reduce crew risk

The shared and tacit goal is to achieve routine access to space.

A fundamental paradigm shift is required to accomplish the desired goal. The historical approach of using dedicated and custom Range information equipment situated at relatively few and widely dispersed Spaceports as the only access to space must change before routine access to space can occur. This change is analogous to the historical transformation that occurred in aviation; moving from dedicated, remote test sites where test pilots first experimented with jet-propelled aircraft to today's thriving international and regional airports.

Information networks at Spaceports and Ranges must transition to a total integration of existing, new, and emerging technologies that provide a new and robust way of interconnecting the Range assets, Range operations, and Range users during the launch event. This paradigm shift must occur despite the legacy of how the networks have evolved to this point. Instead of the dedicated, immobile, inflexible information infrastructures of today's Ranges and Spaceports, a more flexible approach is needed. Implicit in this flexibility is the need for modularization, to allow incorporation of newer technologies not yet imagined, without requiring scrapping future systems not yet even defined. The key is to envision a transition to a Space Based Range Distributed Subsystem, while enabling mobile and easy-to-reconfigure communication techniques around the edges of fixed, existing, information infrastructures.

To enable this, the Emerging Communication Technology (ECT) research task documented in this report provides a keen vision of so-called First Mile technologies in support of NASA's Advanced Range Technology Working Group (ARTWG) and the Advanced Spaceport Technology Working Group (ASTWG) with the purpose of interconnecting mobile users with existing Range Communication infrastructures. Consistent with the goals originally identified for RISM (Range Information System

Management) during the first year of this task, and continuing with the detailed research conducted on ECT during the second year of this ongoing research, this report details the results of researching and documenting the technical needs and technical characteristics of future Ranges, Range systems, and Range users. Specifically, this report explores Wireless Ethernet (Wi-Fi), Free Space Optical (FSO), and Ultra Wideband (UWB) communication technologies.

The ECT project grew directly out of the earlier RISM Phase I Project, which generated recommendations based on inputs from the RISM team, comprised of:

- NASA and NASA-contractor engineers and managers, and
- Aerospace leaders from Government, Academia, and Industry, participating through the Space Based Range Distributed System Working Group (SBRDSWG), many of whom are also
- Members of the Advanced Range Technology Working Group (ARTWG) subgroups, and
- Members of the Advanced Spaceport Technology Working Group (ASTWG)

Together, this group envisioned a future set of technologies for implementing future Ranges and Range systems that builds on today's cabled and wireless legacy infrastructures while additionally seamlessly integrating both today's emerging and tomorrow's building-block communication techniques. As mentioned previously, the fundamental key is to envision a transition to a Space Based Range Distributed Subsystem. The further enabling concept is to identify the specific needs of Range users that can be solved through applying emerging communication technology.

As envisioned by these aerospace leaders, the future Spaceport and Range will constitute a single, global, communication and data-networking system, partially space-based, which will:

- Contain mobile, portable, and fixed elements
- Provide an always on, 24/7, communication environment
- Provide high bandwidths, achieved without wires or cables, that will form the majority of new extensions to today's infrastructure, to permit flexibly accommodating change, and to avoid stuffing more physical cables into the crowded cable trays and ducts that exist today
- Be pervasively connected, in terms of linking wirelessly and without fibers (e.g., a "fiberless" extension to the existing infrastructure) nearly everything that is new or that is added to the Spaceport and Range environment
- Provide seamless connections to today's wired communications infrastructure, as well as to future systems

- Provide Data Assurance, comprised of:
    - Data Integrity (i.e., protection against tampering, whether intentional or unintentional)
    - Data Authentication (i.e., anti-spoofing functionality)
    - Data Availability (which can range from minor latency issues (timeliness) all the way to data unavailability)
    - Data Ease-of-Use
    - Data Security (i.e., protection of data content to unauthorized personnel)

The overarching conclusion from the RISM Phase I activities, as further researched this year during ECT activities, culminated in this document and postulates that future communication and data networking will largely grow from the communications baselines that exist today, through customization around the edges of existing information infrastructures through so-called First Mile technologies. This approach is both desirable and feasible, in terms of managing costs, as well as for accommodating the desired functionalities. Starting with what is often called the "First Mile" or "Last Mile" problem of traditional public communication networks, this document makes a strong case that three emerging technologies are likely to provide the majority of the technology additions needed to solve many communication problems, while additionally providing a future upgrade path that will counter obsolescence, operational costs, or performance issues. Wireless Ethernet (Wi-Fi), Ultra Wideband (UWB), and Free Space Optical (FSO) are the three disruptive and emerging technologies that can augment today's communication infrastructure. These three technologies can provide performance over three decades of data rates, while augmenting communications in the near future and while providing the needed flexibility for future expanded needs.

As they exist today, all three of these technologies are clearly not *yet* suitable for wide scale deployment on Spaceports and Ranges, although Wi-Fi has come the closest during the last calendar year. In terms of their underlying strengths, and within the realm of where these technologies are headed, within the next five to ten years these technologies will likely become 'industrial-strength', having all the attributes necessary to meet the combined requirements that will then be desired. Table E-1 lists the key attributes of these three technologies. Among these technologies, an assortment of data rates from less than 10 Mb/s to greater than 10,000 Mb/s, supporting operation over various distances, with a choice of power consumptions (as needed, for example, to select body-worn, battery-powered portable apparatus) are provided, thereby meeting communication needs for Range users over the next few decades.[1]

[1] Although not discussed in this report, it is assumed tacitly that some functions, such as range safety and flight termination, by the virtue of their need not to rely on other communication networks, must, by necessity, remain isolated from other communication and data networks, while having nonetheless to interface with other communication systems. Still, it would be an intriguing idea to consider UWB for use in future flight termination command systems, what with UWB's inherent selectable security and simplicity of implementation as compared to existing systems.

As presented in this document, the time to understand these three technologies and to slightly shift the commercial plans for their ongoing developments is now, while there is still time to effect fundamental changes inexpensively. To introduce desirable no-cost or low-cost features into integrated circuits (ICs) intended for mostly commercial product uses presently being developed is entirely possible. Managing future life-cycle costs is often best done by managing technological developments. Once products are fully designed, adding any change is often not cost-effective, and at that point, the ability to affect life-cycle costs is long lost. It is possible, within only a narrow window of opportunity open over the next few years, to insert performance features for next-generation Wi-Fi, UWB, and FSO related ICs, into what are ostensibly commercial product ICs, since the recurring cost for Spaceport and Range features (once implemented into the ICs) is negligible.

Table E-1 Key Technologies for Communication Network Edge & Core Extensions

Attribute / **Technology**	**Wireless Ethernet (Wi-Fi)**	**Ultra Wideband (UWB)**	**Free Space Optical (FSO)**
Location:			
Portable	**X**	**X**	**X**
Mobile	**X**	**X**	**X**
Fixed	**X**	**X**	**X**
Data Rate:			
Highest: 1000^{+}Mb/s – $10{,}000^{+}$Mb/s			**X**
High: 100 Mb/s – 1000^{+}Mb/s		**X**	
Medium: <10 Mb/s – 100^{+}Mb/s	**X**		
Power Consumption:			
High	**X**		
Medium			**X**
Low		**X**	
Data Security:			
High	**X (When merged with UWB)**	**X**	**X**
Medium	**X (With planned extensions)**	**X**	**X**
Low	**X**	**X**	

1.0 INTRODUCTION

1.1 CHANGING NEEDS AND CHANGING PERSPECTIVES

For nearly 50 years, the Ranges operated under a long-held policy of Government ownership and Government control. On September 28, 2000, the Space and Aeronautics Subcommittee, under the leadership of Chairman Rohrabacher, R-California, of the House Science Committee, held a hearing on the commercial space launch industry and the construction of new, private launch ranges. Edward C. Aldridge, Jr., Chairman, Defense Science Board Task Force on Air Force Space Launch Facilities and CEO, The Aerospace Corporation, testified before the U.S. House of Representatives Committee on Science Subcommittee on Space and Aeronautics. The key points from his testimony that pertain to RISM and to ECT are that:

- Access to Space must be recognized as a national priority.
- Space Launch Ranges are "National Assets".
- The future "vision" of the space launch ranges must address the combined needs of Government and commercial users.
- Existing Government Ranges are not "customer friendly".
- The National Airport System (NAS) has the most direct applicability to future concepts for modeling space launch range operations.
- New technologies can increase flexibility and reduce costs. Technology application (such as GPS navigation, Autonomous Flight Termination System, Satellite Telemetry Relay and improved weather forecasting systems) can play a large part in reducing future infrastructure costs by permitting the phase-out of old and expensive ground equipment and avoiding unnecessary weather delays.
- Sufficient information is now available to describe a vision for future range operations.

This ECT report uses the information available today to describe a vision for First Mile/Last Mile communications for improving future range communication functions and operations. This vision is one based on combining appropriate present infrastructure technologies with a likely cadre of emerging communication technologies that together combine to form a total technology capability for the Range.

1.2 WORKING GROUP

1.2.1 Description

As a part of the RISM effort, and continuing through this year's ECT effort, a need for a technical working group was quickly identified. (Originally, solely the Advanced Range Technology (ARTWG) Communications Working Group supported this need. Due to a greater focus on emerging communication technologies than in ARTWG, a separate working group evolved during the early days of RISM in year one and continued in year two on ECT.)

The new working group was created with participants from the following organizations:

NASA – KSC
NASA – Wallops
NASA – other centers
AF 45th Space Wing
AF SMC/CWP
Navy NOTU
Range Engineering Contractor (SLRSC)
FAA
Aerospace Industry
State Spaceport entities
Academia

The original name for the working group during RISM and the early days of ECT was:

SBRDSWG (Space Based Range Distributed Subsystem Working Group).

This was later changed during the first part of ECT to:

FIRSTWG (Future Integrated Range & Spaceport Technology Working Group).

SBRDSWG, and then later FIRSTWG, filled a crucial need to investigate and discuss detailed Range technologies during the Phase 1 and Phase 2 activities, drilling down into communication technologies in considerably more depth and detail than was possible in the general membership ARTWG and the ASTWG. Once its mission was fulfilled (as the detailed investigations within FIRSTWG into so-called First Mile technologies had accomplished their purpose), FIRSTWG was discontinued in late-FY03 as ARTWG and ASTWG grew to fulfill all the ongoing needs at the higher level. Most FIRSTWG participants, though, continue as active members of both ARTWG & ASTWG.

1.2.2 Vision Statement

The vision statement for the SBRDSWG / FIRSTWG is:

> **This working group, comprised of aerospace leaders from government, industry and academia, will promote the development of Communication architectures and advanced distributed networks that meet the needs of existing and future generations of Spaceports and Ranges.**

In support of this vision, it is the intent that the SBRDSWG / FIRSTWG:

- Will be the professional working group of choice for promotion, support, and evolution of advanced communication architectures and networks supporting the combined Spaceport and Range shareholder and partner community
- Will establish an organizational structure facilitating working group membership participation, with position rotation to preclude participant burnout
- Will support the enhanced growth of Range capability by providing a diverse and widely disseminated array of options; including distributed and multiprocessing systems, efficient protocols, Radio Frequency (RF), Laser, Fiber Optic, and additional communications links supporting of Spaceports and Ranges integrating new formats, usage, and data delivery options
- Will encourage members to lead in aerospace technology, participating in both scholarly and civic development communication of Spaceport and Range technologies. To accomplish this, the members should be diverse; with a broad range of knowledge and expertise, to enable clear and effective communication of Spaceport and Range capabilities and issues to a wide range of government, industrial, and public audiences

1.3 OBJECTIVES

The primary objective for the Emerging Communication Technology (ECT) task is to lead the development of a Space Based Range Distributed Subsystem (SBRDS) network providing the concurrent features and growth capabilities necessary for future Spaceports and Ranges to interconnect Range assets, Range operations, and Range users during launch and recovery events, while focusing primarily on the First Mile/Last Mile communication extension to existing, fixed communication infrastructures.

SBRDWSG / FIRSTWG is a working group aimed toward addressing the day-to-day needs of mobile Range workers who actually use the existing Range systems.

The primary goals of the RISM/ECT research and documentation effort are to:

- Proactively identify and provide reasonably accurate predictions for the evolving communications needs of the SBRDS
- Research, document and understand the equipment, operation, and processes of the current Range architecture
- Research and document the needs and characteristics of future Ranges, Range systems, and Range users
- Research and document technologies that could be associated with future ranges, space operations and information systems
- Identify the characteristics and requirements of a future SBRDS to meet the needs and desired characteristics of future Range users
- Identify the terrestrial, satellite, and vehicle components necessary to interconnect Spaceport Range Systems (SRS), Weather Instrumentation Systems (WIS), Decisions Models and Simulation (DMS), and Space Based Range (SBR) elements; permitting them to communicate with one another, with test and processing facilities, as well as with space vehicles
- Identify communication system architectures that will provide real-time information, on-demand, with minimal latency, to support critical decision processes; insuring public, vehicle, crew, passenger, and mission safety

RISM/ECT further seeks to multiply the knowledge base of the in-house investigators through participation in the active efforts of:

- SBRDSWG / FIRSTWG
- ARTWG
- ARTWG Communication Subgroup
- ARTWG other Subgroups
- ASTWG (Advanced Spaceport Technology Working Group)
- ASTWG Subgroups

ARTWG is a collaborative NASA/US Air Force/Industry/Academia effort to focus interest and investment in Range technologies (Figure 1-1). It is co-chaired by NASA and the US Air Force, and comprised of aerospace leaders from industry, academia, and national, state, and local governments. ARTWG is a multi-layer (Figure 1-2) organization with functional subgroups as its base. ARTWG addresses Range (Figure 1-3) development needs while its companion organization ASTWG (Advanced Spaceport Technology Working Group) addresses Spaceport development needs.

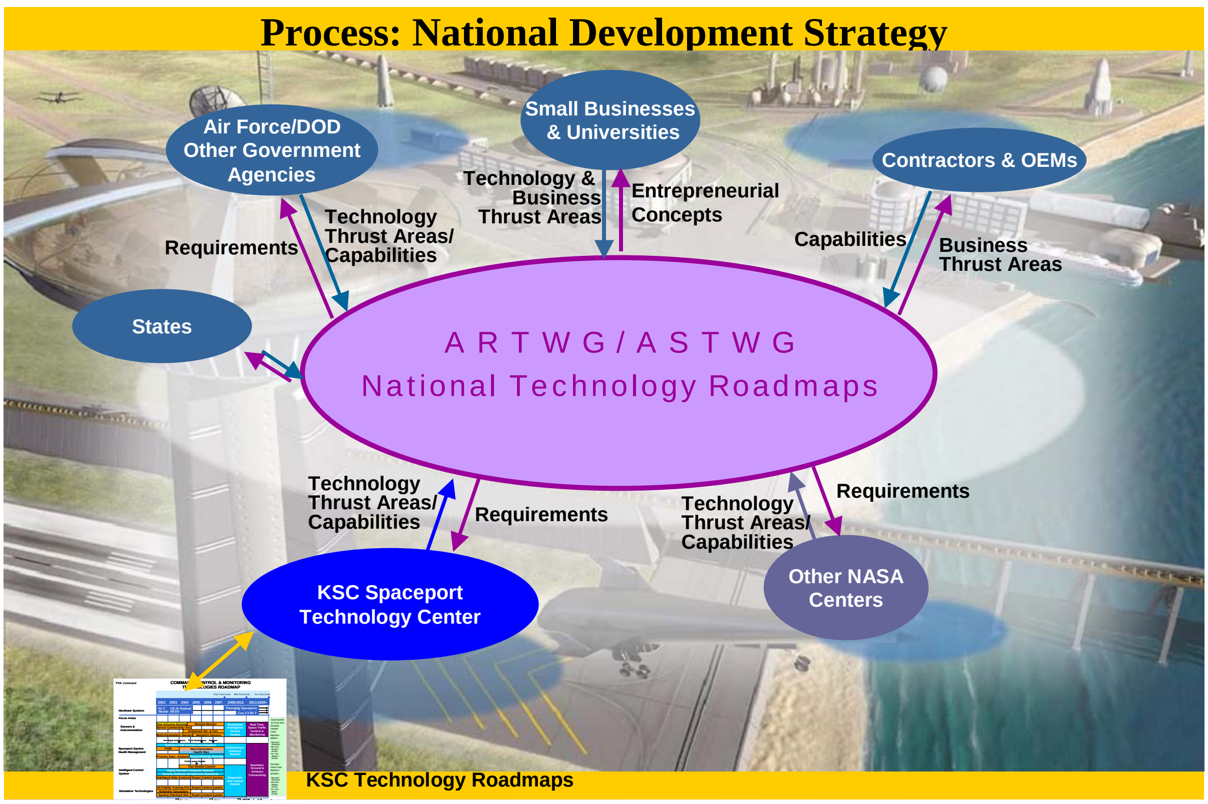

Figure 1-1 ARTWG National Development Strategy[2]

[2] http://artwg.ksc.nasa.gov/

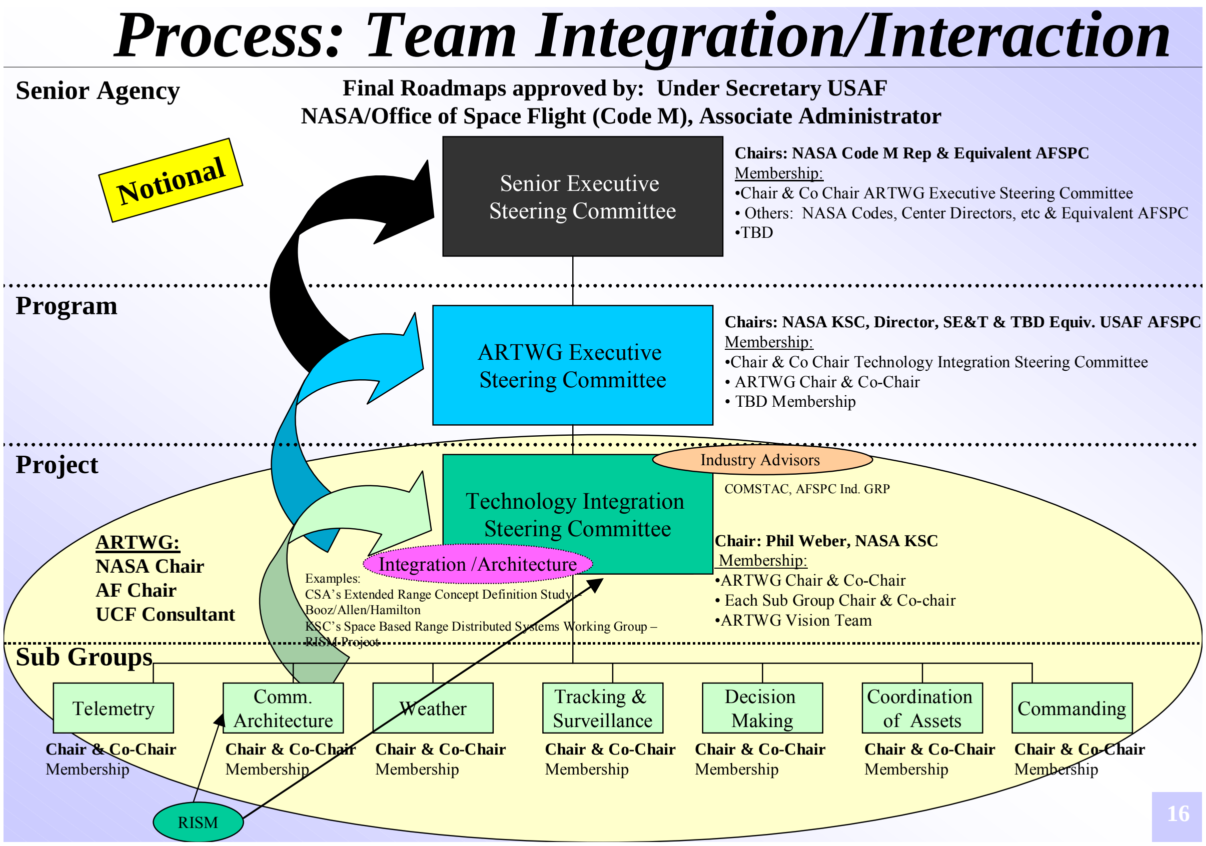

Figure 1-2 ARTWG Integration/Interaction Process

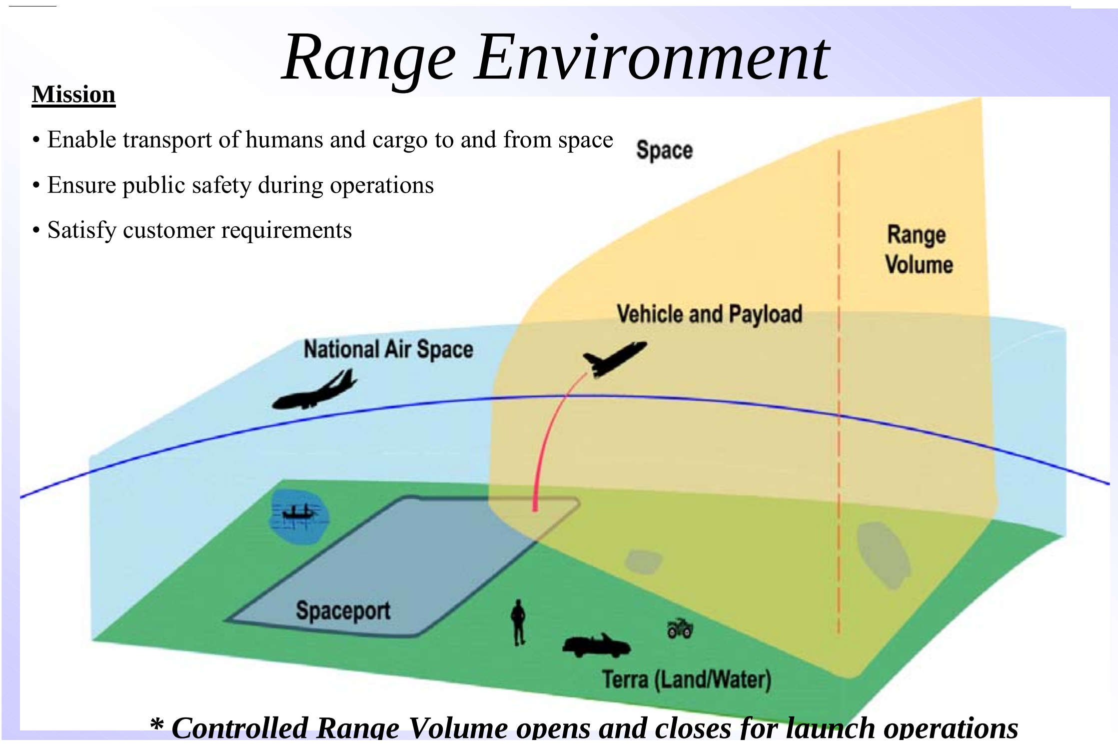

Figure 1-3 Spaceport And Range Environments

1.4 SCOPE

Activities associated with RISM during Phase I provided:

- Identification of technologies that hold the promise of the greatest long term return on investment for the U.S. space program and its associated industries without prematurely choosing winners and losers; this includes identification of technology gaps
- Equitable and open access to technical and administrative information wherever possible, while simultaneously meeting mission security, safety, and reliability needs
- Service to the planned users of future Spaceports and Ranges
- Cooperation, collaboration, and resource sharing to increase reuse of ARTWG and ASTWG generated data and resources
- Redundant Spaceport and Range communication capabilities when needed to improve reliability and safety for the public, shareholders, and partners
- A global perspective supporting the national needs of the United States while facilitating international use of Spaceports and Ranges within the United States through providing a well documented interface to the SBRDS

Activities associated with ECT during Phase II continued this work, and researched theoretical and empirical topics associated with First Mile/Last Mile communication technologies in the three key areas of Wireless Ethernet (Wi-Fi), Free Space Optical (FSO), and Ultra Wideband (UWB) communications.

Additional goals of the ECT participants in the ARTWG and ASTWG are to provide:

- A clear, strategic vision of the goals desired for ECT
- Conservation and preservation of communication architecture and telemetry architecture trade studies performed during ECT
- Widespread dissemination of all information necessary to support the needs of shareholders and partners
- Education of potential users to the technology capabilities initiated, developed, and expanded through the transition to a Space Based Range (SBR) Distributed Subsystem
- A collaborative participation in the ARTWG and ASTWG permitting easy identification of breakthroughs in terms of disruptive[3] technologies, thereby improving mission reliability and efficiency wherever possible, thus improving safety for the public, vehicle, crew, and passengers
- Timely research into alternative communication techniques and communication network architectures that best support initial communication needs while providing long-term growth potential

[3] The phrase d*isruptive technologies* refers to those new discoveries and technologies that represent an order of magnitude improvement, or more, over existing technology and which eventually replace the existing (present) technology.

1.5 STRATEGIC LANS

To support the goals and aims of the RISM/ECT development efforts for a future Space Based Range (SBR) Distributed Subsystem, the following six strategic plans, and enabling goals for each plan, are identified:

Strategic Plan 1.0
The Working Group recognizes the contributions that academic, industrial, and governmental members make in support of future Spaceports and Ranges by communicating Spaceport and Range technologies via their involvement in higher education, scholarly communication, and civic development to ensure public, crew, passenger, vehicle, and mission safety of space vehicles.

Enabling Goals

1.1 Working group members understand their roles as information leaders in their respective institutions.
1.2 Working group members understand the need for the timely, open information sharing to resolve issues as quickly as possible, improving work accomplishment rates and the quality of work accomplished.
1.3 Working group members will promote an atmosphere in their respective institutions that, wherever possible, encourages the consideration of disruptive technological breakthroughs capable of improving mission reliability, safety, and efficiency.
1.4 Working Group Members understand the need for timely resolution of open issues, thereby reducing budget waste, improving the "bang-for-the-buck" of project funding.

2.0 WIRELESS ETHERNET

2.1 WIRELESS ETHERNET DESCRIPTION

Wireless Ethernet, known popularly as Wi-Fi (Wireless-Fidelity), has become the technology of choice for the "first and last mile" of wireless Ethernet connectivity. When connected to a broadband modem or Ethernet hub and when properly installed for the desired area of coverage, its data rate performance fulfills most wireless needs of the home or office. Wi-Fi equipment may be used to set up a wireless Local Area Network (LAN) with data rates of up to 54 Mbps over short distances. Often, multiple base stations or access point will be required for an office environment due to the area of coverage, building constructions design and number of potential users.

Wi-Fi systems operate in either the 2.4 GHz or 5.0 GHz public-use, non-licensed, frequency bands. The 2.4 GHz frequency band is also shared with cordless phones, microwave ovens, Bluetooth devices, and numerous other wireless products designed for public, unlicensed operation. These devices are a part of the ISM (Industrial, Scientific, & Medical) uses permitted in this band. The 5.0 GHz band has less interference, being intended for data links only. It is undisturbed by the wider range of uses that employ the 2.4 GHz band.

Today's Wi-Fi equipment generally conforms to one of three standards. These are as follows:

802.11a: Equipment built to the "a" standard operate at 5.0 GHz and provide data rates up to 54 Mbps using OFDM (Orthogonal Frequency Division Multiplexing) over distances significantly shorter than the "b" standard[4].

802.11b: The "b" standard is the most popular today with multiple manufacturers offering a full assortment of equipment sets as Commercial-off-the-shelf (COTS) hardware. The 802.11b equipment operates at 2.4 GHz using direct sequence spread spectrum modulation. Data rates of up to 11 Mbps are routinely achieved. Effective range is generally better than the 802.11a equipment, but is still very dependent on the building construction environment. When packet loss occurs, the system automatically selects a lower data rate and retries to establish communications. Based on ECT testing, practical ranges within an office environment at data rates of 11 Mbps appear to be limited to 100 feet or less. ECT testing was performed primarily with 802.11b equipment.

802.11g: The 802.11g standard is the newest of the three standards, but is quickly catching up to 802.11b in terms of total sales. It was approved by the IEEE Standards Board on 6/12/2003[5]. It is considered by some as an extension of the 802.11b standard that has been reworked to provide "a" type performance at the lower 2.4 GHz frequency band. Equipment built to 802.11g has data rates up to 54 Mbps and operates within the

[4] http://www.Wi-Fiplanet.com/columns/article.php/961181 "The BIG Question: 802.11a or 802.11b?"
[5] http://grouper.ieee.org/groups/802/11/Reports/tgg_update.htm

2.4 GHz band using OFDM (orthogonal frequency division multiplexing) technology[6]. The increased data rates come with a distance penalty over the slower 802.11b equipment. Most 802.11g equipment is backwards compatible and will work with existing 802.11b equipment (but not with 802.11a equipment.) The ECT project procured "g" equipment in late July for very limited comparison testing. (Results for "g" equipment are discussed later in this report, in Sections 2.7.8 and 2.8)

Although equipment qualification and acceptance was not a part of these activities; some comparisons were made between advertised performance and observed performance. These are presented in Section 2.8.

The greatest weakness of Wi-Fi is security. Security control ranges from zero to a barely minimal acceptable level. Many individuals and small companies turn off all security features to enable open sharing of internet access. This technique is unacceptable for many larger companies due to liability and other security concerns. Security is discussed at length in Section 2.9.

Wi-Fi has quickly received wide acceptance in today's 24/7 wired economy due to the convenience it provides for mobile lifestyles. Wi-Fi connectivity zones are currently available within public buildings, colleges, restaurants, truck stops, hotels, convention centers and numerous other public places.

A summary of Wi-Fi status and recommendations for follow-on activities are presented in Section 2.10.

[6] http://www.Wi-Fiplanet.com/tutorials/article.php/1009431 "Making the Choice: 802.11a or 802.11g"

2.2 BASIC WIRELESS ETHERNET THEORY

Wireless Ethernet is an outgrowth of early packet radio experiments that commenced in the late 1970's in both the Amateur Radio and, later, in the Military defense contractor arenas. The basic method of operation for all Wi-Fi equipment is that data is first packetized, and then transmitted, one packet at a time. Collisions and lost packets are handled with conventional Ethernet control methods, with only slight extensions being required beyond the original wired transmission protocols of the earliest Ethernet systems. These minor extensions were added to account for the peculiarities of radio transmissions as opposed to wired system transmissions. (The Phase I RISM report previously documented the early days of Ethernet standards in considerable length.)

This packet radio legacy remains today for Wi-Fi, although it is often forgotten. For example, the PRISM® chipset of Intersil (now a wholly-owned subsidiary of Globespan Virata) first was known as an acronym for **P**acket **R**adio over the **I**ndustrial, **S**cientific, and **M**edical band when the acronym was first used at Harris Semiconductor. (Harris Semiconductor was the company from which Intersil was spun.) This technology, in turn, had grown out of early packet radio systems that Harris Government Systems had produced for tactical military radio networks in the early 1980's.

Fundamentally, Wi-Fi is today a largely seamless extension to traditional Ethernet networks. The primary Achilles heel, as discussed earlier, is security. Wired Equivalent Protocol (WEP), initially thought to be relatively secure, has instead been shown to provide no security for Wi-Fi networks except over for very short periods (often measured in only hours). Newer protocols, still being developed, are currently at work to secure Wi-Fi networks, in an attempt to achieve the original security goals set forth for WEP.

2.3 TEST DESCRIPTION

The overall goals of Wi-Fi testing under ECT were to learn more about the emerging Wi-Fi technology and to determine the usefulness and limitations of Wi-Fi operation in an office/industrial environment. ECT tests were configured to address these key concerns in both a quantitative and qualitative fashion, and to assess whether Wi-Fi communication systems are practical for unique Range communication needs. Additionally, the capability of Wi-Fi communication equipment to transport Ethernet data was investigated to assess the robustness of Wi-Fi communication signals. Of prime interest was how the signal would be attenuated within an enclosed building and how Wi-Fi and signals from other products could co-exist in the same vicinity.

Security concerns were initially a part of the strategic objective but were not completely tested due to the Wi-Fi industry's parallel effort to develop new, more secure protocols and standards, which as of yet are not finished. Testing, to the extent that security could be tested, was performed in accordance with a draft Test Plan, included in Appendix A, and with the final Test Procedure, included in Appendix B.

ECT's Wi-Fi testing was conducted in and around the Engineering Development Laboratory (EDL) at KSC. The majority of the testing was performed in the Advanced Network Development Lab (ANDL), EDL Room 124. Some testing was performed in the EDL first floor hallway. Interference testing was also performed in north Melbourne in order to receive potentially interfering RF signals from the Melbourne Airport.

2.4 TEST OBJECTIVES

The test objectives were as follows:

- Become familiar with Wi-Fi technology
- Evaluate COTS Wi-Fi equipment for possible future use at KSC
- Evaluate Wi-Fi operation in an office/industrial environment
- Identify any fundamental shortcomings, such as security, that must be filled in commercial Wi-Fi communication technologies prior to integrating functions into an integrated future data

2.5 TEST SETUP

Various test configurations were used during the testing. Specific test configurations and dimensions are captured in the Test Result data sheets included in Appendix C. General descriptions are described below.

2.5.1 Key Test Components

Detailed descriptions of the test components and equipment are presented in Section 2.6. A brief description of the key Wi-Fi components is necessary to fully understand the test setup descriptions provided in the following sections.

Key Wi-Fi test components descriptions are as follows:

- Base Station – Router type interface from wired to wireless networks; 802.11b
- Laptop – Laptop computer with internal Wi-Fi (802.11b) transceiver and link monitoring software
- Access Point – Interface from wired to wireless network; less robust but faster than Base Station; 802.11g
- Cardbus Adapter – Card for use in Laptop to enable faster 802.11g communication

2.5.2 System Setup and Initialization

All systems evaluated were Commercial-off-the-shelf (COTS) components. The first two tests were to evaluate how complete and user-friendly the COTS systems were to initialize and install.

2.5.3 Antenna Position Test Setup

To evaluate the sensitivity of Base Station antenna position to the Wi-Fi link's performance, the Base Station and Laptop were spaced 25 feet apart and the antenna position varied. Laptop software was used to measure link SNR for each component. The Base Station's external antenna position was varied in 45-degree increments while the distance between the Base Station and the Laptop was kept constant at 25 feet (Figure 2-1). Testing was performed within the Advanced Network Development Lab.

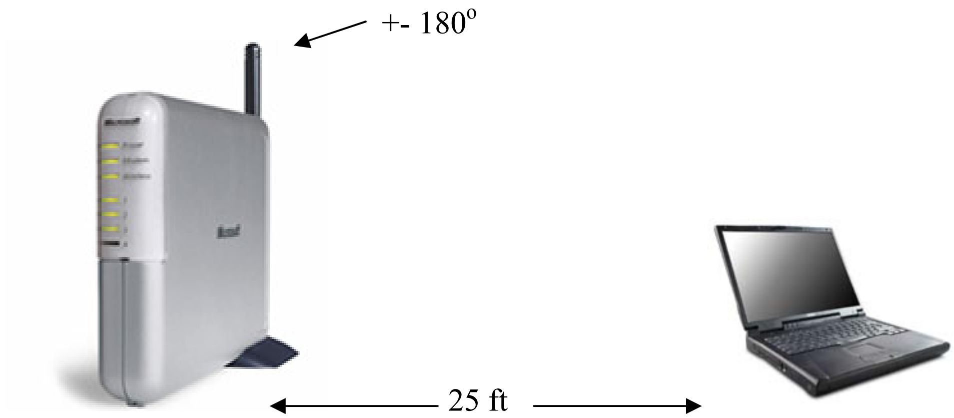

Figure 2-1 Antenna Position Test Setup

2.5.4 Communication Range Test Setup

A Base Station to Laptop link was established. Laptop software was used to measure SNR and other data. The distance between the Base Station and Laptop was varied from 10 feet to 300 feet using the EDL first floor hall and extending outside to the EDL East parking lot (Figure 2-2).

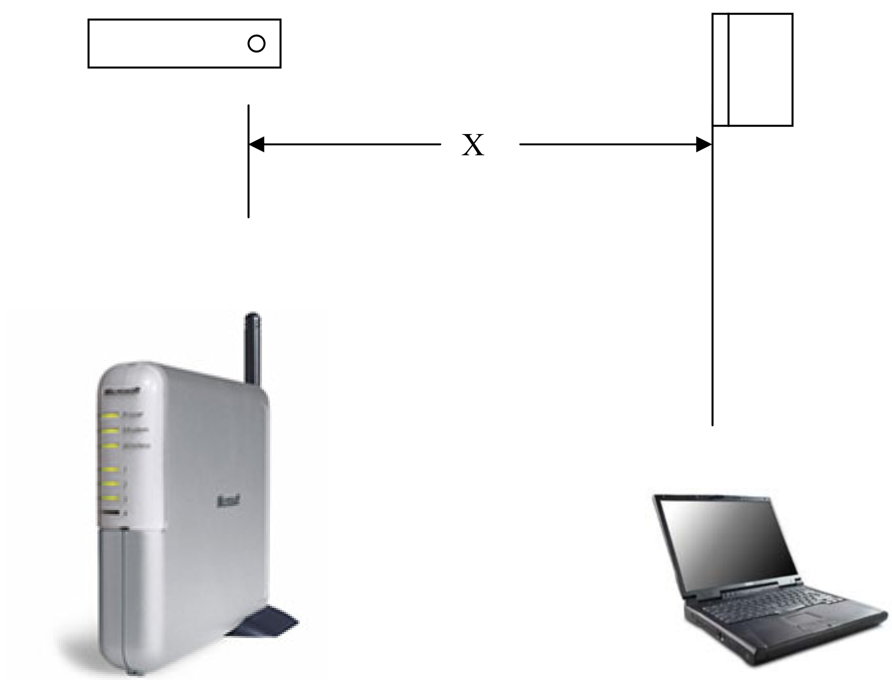

Figure 2-2 Communication RangeTest Setup

2.5.5 Attenuation Test Setup

A Base Station to Laptop link was established. Laptop access point software was used to measure SNR and other data. The distance between the Base Station and Laptop was kept constant at 25 feet while various attenuation barriers were varied between 2 and 23 feet from the Base Station (Figure 2-3). Testing was performed primarily within the Advanced Network Development Lab.

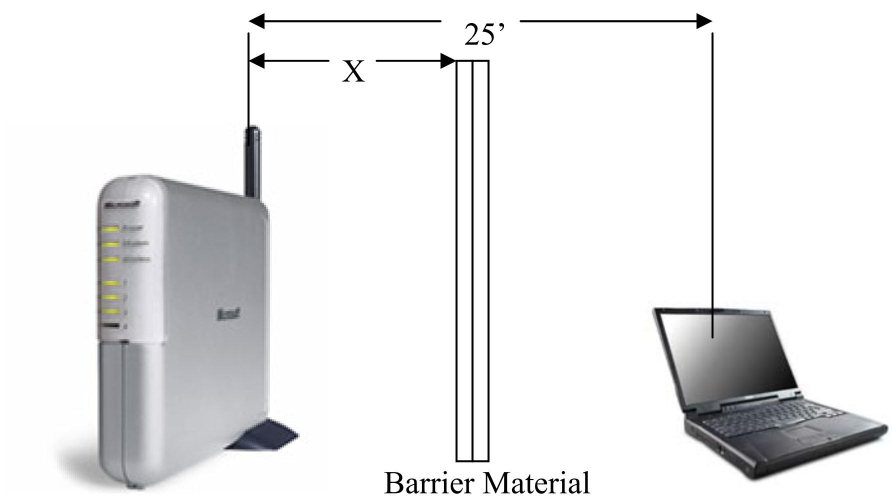

Figure 2-3 Attenuation Test Setup

2.5.6 Interference Test Setup

A Base Station to Laptop link was established. Laptop software was used to measure SNR and other data. The distance between the Base Station and Laptop was kept constant at 25 feet while various radiation sources were varied between 2 and 23 feet from the Base Station (Figure 2-4). Testing was performed within the Advanced Network Development Lab and at remote locations.

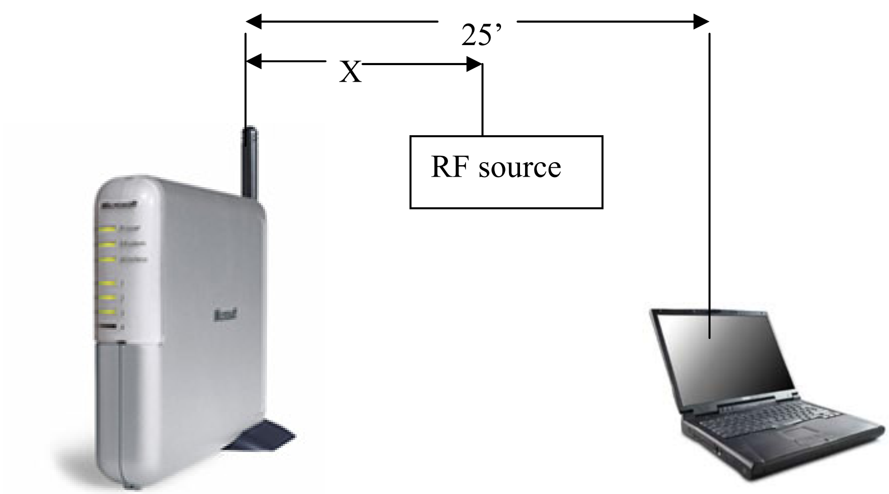

Figure 2-4 Interference Test Setup

2.5.7 Communication Range Comparison Test Setup

Links were established between one Laptop and the Microsoft Base Station (802.11b), and between a second Laptop and the D-Link Access Point (802.11g). The distance between the Base Station / Access Point and the Laptops was varied from 10 feet to 160 feet using the EDL first floor hallway. (Figure 2-5).

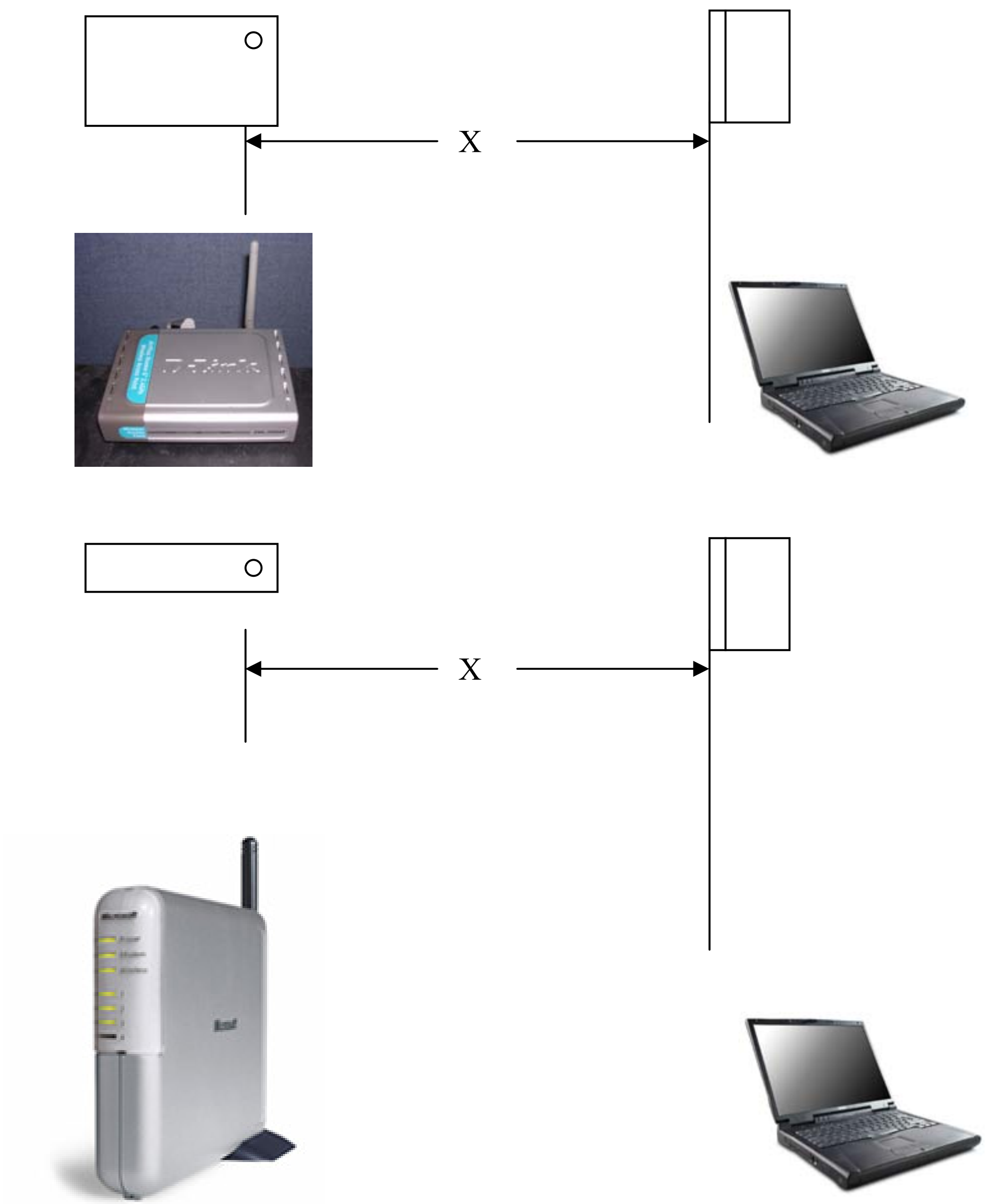

Figure 2-5 Communication Range Comparison Test Setup

2.6 TEST EQUIPMENT

Test equipment consisted primarily of the following items:

- Base Stations (2)
- Laptop computers (2)
- Spectrum analyzer
- Access Point
- Cardbus Adapter
- Assortment of barrier materials
- Assortment of interference equipment

2.6.1 Base Station (802.11b)

Two Base Stations (Figure 2-6) were procured early in the program. These were initialized and named EDL-lab1 and EDL-lab2. One was installed in EDL Room 124 (ANDL) and the second was installed in EDL Room 240.

Figure 2-6 Microsoft MN-500 Base Station

Specifications and installation parameters for the Base Stations are shown in the following tables.

Table 2-1 Base Station Specifications

Manufacturer	Microsoft
Model	MN-500
Standard	802.11b
Ports	Four 10/100 Mbps
Connector	RJ-45
Channels	1-11
Security	Off, 64-bit, 125-bit
Frequency Range	2.400 to 2.4835 GHz

Table 2-2 Base Station Installation Parameters

Name (SSID)	EDL-lab1	EDL-lab2
IP Address	128.217.107.200	128.217.107.201
Channel	6	7
Location Building	EDL	EDL
Room	122	240
MAC	00-50-F2-C7-21-6C	00-50-F2-C7-C5-6C
PW	ECT-01	ECT-01
Firewall	On	On
Encryption	64 Bit	64 Bit
WEP mode	Hex	Hex
Key	See User's Guide	See User's Guide

2.6.2 Laptop

Two Gateway laptop computers, as shown in the following figure, were procured to support the ECT project. These were later renamed BH and GB after the two individuals to whom they were assigned for testing. Each laptop computer has a built-in Wi-Fi transceiver and diagnostic software. The built-in diagnostic software proved to be the most effective way to quantify the Wi-Fi link quality.

Figure 2-7 Gateway 450 XL Laptop Computer

Specifications for the Laptops are shown in the following table.

Table 2-3 Laptop Computer Specifications

Manufacturer	Gateway
Model	DS 450 XL
Processor	Intel Pentium 4
Speed	2.0 GHz
Hard Drive	40 GB
RAM	512 MB
Connectors	USB, RJ-45, Phone
Wi-Fi Standard	802.11b (Internal)
Operating System	Windows XP V.2002

Table 2-4 Laptop Computer Installation Parameters

Name	BH	GB
IP Address	128.217.107.174	128.217.107.175
MAC	00-02-2D-6E-A2-F4	00-02-2D-6E-5B-7E

2.6.3 Spectrum Analyzer

A Wi-Fi spectrum analyzer, see following figure, was procured late in the Phase II program. It did not arrive until August 2003 and was therefore used only in a few tests.

Figure 2-8 Wi-Fi Spectrum Analyzer

Specifications for the Spectrum Analyzer are presented in the following table:

Table 2-5 Spectrum Analyzer Specifications

Manufacturer	Aerocomm
Name	ConnexRF
Model	SA3000
Frequency (center)	2.38 to 2.51 GHz
Span	7.29 MHz to 175.04 MHz
Sweep Time	100 mS to 300mS
Tuning	50 kHz
Measurement Range	-20 60 –90 dBm
Safe Input Level	+23 dBm
Accuracy (amplitude)	+/- 2 dBm
Scale Units	dBm
Interface	RS-232
Interface Rate	115,200 baud
Operating System	Windows XP V.2002

2.6.4 Access Point (802.11g)

An 802.11g D-Link Access Point, shown in the following figure, was procured in late July 2003 and used for comparison testing with the 802.11b Base Station described above.

Figure 2-9 D-Link Access Point (802.11g)

Table 2-6 D-Link Access Point Specifications

Manufacturer	D-Link
Name	AirPlus Xtreme G
Model	DWL-2000AP
Standards	802.11, 802.11b, 802.11g, 802.3, 802.3u
Operating Range - Indoors	328 ft (100 m)
Operating Range - Outdoors	1312 (400 m)
Freq Range	2.400 to 2.4835 GHz
Data Rates	54 Mbps, 48, 36,24,18,12,11,9,6,5.5, 2, 1 Mbps
Transmitted RF Power	15 dBm +/- 2 db
Security	802.1x, 64 or 128 WEP with TKIP, MIC, IV Expansion
Port	Ethernet RJ-45
Channels	1-11
Antenna	External (+1.0 dB gain)
Modulation	OFDM & CCK

Table 2-7 Access Point Installation Parameters

Name (SSID)	EDL-lab3
IP Address	128.217.107.202
Channel	8
Location Building	EDL
Room	240
MAC-ethernet	00-40-05-2a-90-eb
MAC-wireless	00-40-05-2a-9f-22
User Name	Admin
PW	ECT-03
Firewall	None
Encryption	128 Bit
WEP mode	Hex
Key	See installation guide

2.6.5 Cardbus Adapter (802.11g)

A total of three 802.11g Cardbus adapters, as shown in the following figure, were procured in late July and used with the new 802.11g Access Point. These cards, when inserted into the card slot of the two laptops, enabled them to communicate with the 802.11g Access Point at the higher data rate (54 Mbps).

Figure 2-10 D-Link Cardbus Adapter (802.11g)

Table 2-8 D-Link Cardbus Adapter Specifications

Manufacturer	D-Link
Name	AirPlus Xtreme G
Model	DWL-G650
Standards	802.11, 802.11b, 802.11g
Operating Range - Indoors	328 ft (100 m)
Operating Range - Outdoors	1312 (400 m)
Freq Range	2.400 to 2.462 GHz
Data Rates	54 Mbps, 48, 36, 24, 18, 12,11, 9,6,5.5, 2, 1 Mbps
Power	15 dBm +/- 2 db
Security	802.1x, 64 or 128 WEP with TKIP, MIC, IV Expansion
Bus Type	32-bit Cardbus
Channels	1-11
Antenna	Internal (1.0 dBm gain)
Modulation	OFDM

Table 2-9 D-Link Cardbus Adapter Parameters

Name (SSID)	None
IP Address	Per Laptop
Channel	Per Access Point
Location Building	Laptop
MAC	00-40-05-26-45-42
Utility Version	2.02
Driver Version	1.0.0.5
PW	NA
Firewall	None
Encryption	Per Access Point
WEP mode	Per Access Point
Key	NA

2.6.6 Attenuation Materials

An assortment of typical building and office materials were tested to determine their effect on the Wi-Fi signal. Materials included the following:

- Cubicle partition walls (particle board and carpet)
- Aluminum metal sheet (2 thicknesses)
- Steel sheet
- Cinder blocks
- Human

Pictures of these items are shown in the Test Results, Section 2.7.

2.6.7 Interference Components

An assortment of typical home and office components were tested to determine if they interfered with, or were interfered by, an adjacent Wi-Fi system.

Systems studied under these tests included the following:

- Ultra Wide Band (UWB) Transceiver
- Microwave Oven
- 2.4 GHz Cordless Phone
- Cell Phone
- Aircraft Transceiver in Nav Mode
- Aircraft Transceiver in Com Mode
- GPS Receiver
- Iridium Phone

Pictures and descriptions of these items are shown in the Test Results, Section 2.7.

2.7 TEST RESULTS

Seven series of tests were performed on the Wi-Fi equipment. The first three tests involved setting up the two Base Stations and obtaining a baseline. The other series investigated performance as a function of parameters such as antenna positions, range, attenuation, and interference. New baselines were obtained prior to each series of tests. A summary of all tests is presented in Table 2-10.

Table 2-10 Wi-Fi Test Summary

St	Test	Date	Description
c	1		Initialize EDL-1
c	2		Initialize EDL-2
c	3	3/27/03	Baseline @ 25 Ft
c	4.0	4/8/03	Summary - Wi-Fi Performance with Antenna Position
c	4.1	3/28/03	Wi-Fi Performance with Antenna Position: Back-12:00
c	4.2	3/28/03	Wi-Fi Performance with Antenna Position: Back-10:30
c	4.3	3/28/03	Wi-Fi Performance with Antenna Position: Back-9:00
c	4.4	3/28/03	Wi-Fi Performance with Antenna Position: Back-7:30
c	4.5	3/28/03	Wi-Fi Performance with Antenna Position: Back-6:00
c	4.6	3/28/03	Wi-Fi Performance with Antenna Position: Front-6:00
c	4.7	3/28/03	Wi-Fi Performance with Antenna Position: Front-4:30
c	4.8	3/28/03	Wi-Fi Performance with Antenna Position: Front-3:00
c	4.9	3/28/03	Wi-Fi Performance with Antenna Position: Front-1:30
c	4.10	3/28/03	Wi-Fi Performance with Antenna Position: Front-12:00
c	5.1	4/2/03	Wi-Fi Performance with Distance (EDL-lab1)
c	5.2	4/17/03	Wi-Fi Performance with Distance (EDL-lab2)
c	5.3	4/17/03	Wi-Fi Performance with Two Base Stations (EDL-lab1 & EDL-lab2)
c	6.1	4/11/03	Wi-Fi Performance with One Partition
c	6.2	4/11/03	Wi-Fi Performance with Two Partitions
c	6.3	4/8/03	Wi-Fi Performance with .125 Al Sheet
c	6.4	4/8/03	Wi-Fi Performance with .187 Al Sheet
c	6.5	4/8/03	Wi-Fi Performance with .063 Steel Sheet
c	6.6	4/17/03	Wi-Fi Performance with Cinder Blocks (3 h, 1 w, 1 t)
c	6.7	4/17/03	Wi-Fi Performance with Cinder Blocks (3 h, 1 w, 2 t)
c	6.8	4/17/03	Wi-Fi Performance with Cinder Blocks (3 h, 2 w, 1 t)
c	6.9	4/15/03	Wi-Fi Performance with Human Barrier
c	7.1	4/15/03	Wi-Fi Performance Adjacent To UWB
c	7.2	7/20/03	Wi-Fi Performance Adjacent To Microwave Oven
c	7.3	7/20/03	Wi-Fi Performance Adjacent To 2.4 GHz Cordless Phone
c	7.4	4/15/03	Wi-Fi Performance Adjacent To Cell Phone
c	7.5	7/8/03	Wi-Fi Performance Adjacent To Aircraft Nav Radio
c	7.6	7/10/03	Wi-Fi Performance Adjacent To Aircraft Com Radio
c	7.7	7/14/03	Wi-Fi Performance Adjacent To GPS Receiver
c	7.8	4/15/03	Wi-Fi Performance Adjacent To Iridium Phone
c	8.0	8/28/03	Wi-Fi Performance Comparison Between 802.11b and 802.11g

2.7.1 Test 1: Initialization of EDL-lab1

Test 1 was an evaluation of the setup of Base Station EDL-lab1 in Room 124 of the EDL. Factory installation instructions were followed with no problems. The equipment was initialized and a Laptop to Base Station link established with no significant problems. The initialization, test checklist, and results are included in Appendix C, Test 1.

2.7.2 Test 2: Initialization of EDL-lab2

Test 2 was an evaluation of the setup of Base Station EDL-lab2 in Room 240 of the EDL. Factory installation instructions were again followed with no problems. The equipment was initialized and a Laptop to Base Station link established with no significant problems. The initialization, test checklist, and results are included in Appendix C under Test 2.

2.7.3 Test 3: Baseline

Test 3 established a baseline for a link between Base Station EDL-lab1 and Laptop BH. The Base Station was placed on a box sitting on the floor of the Advanced Network Development Lab, as shown in Figure 2-11. The Laptop was on a similar size box placed 25 feet away in the same room. SNR data were recorded at 30-second intervals for 4.5 minutes. All other parameters were held constant. A plot of the SNR at each device versus time is shown in Figure 2-12. Actual data is presented in Appendix C. The Base Station SNR was nominally constant while the Laptop SNR showed significant variation with time. The standard deviations were 1.0 and 4.1 respectively. Surprisingly, the average SNR for both the Base Station and the Laptop was 4.34. Similar base runs were made before each major test series (#4 through #7).

← 25 Ft →

Figure 2-11 Base Station & Laptop Located 25 Ft Apart

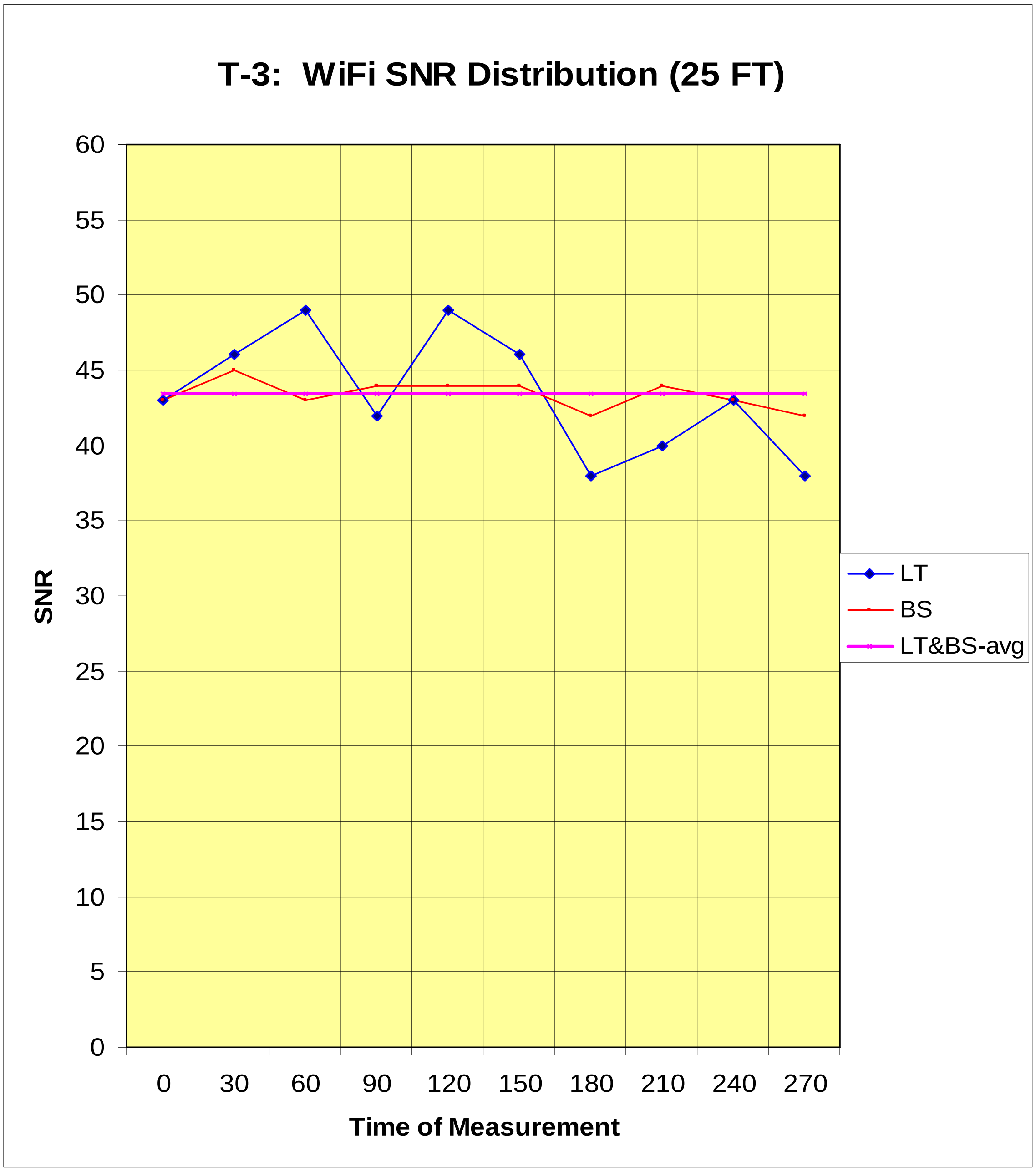

Figure 2-12 Test 3: Baseline of EDL-lab1

2.7.4 Test 4: Antenna Position

Test 4 investigated the effect of Base Station antenna position on the SNR of each component in a Wi-Fi link. Testing was conducted using a link between Base Station EDL-lab1 and Laptop BH. The Base Station and Laptop were placed 25 feet apart in the same configuration as Test 3. The Base Station antenna was set in a test position and SNR data were measured at 30-second intervals for 3 minutes. All other parameters were held constant. Figure 2-13 shows one test with the antenna at the 9 o'clock position (+90 degrees). Positive direction was CCW. These measurements were repeated for ten antenna positions. Test for positions from 12 O'clock to 6 O'clock required the unit to be turned around with its back facing the Laptop. A plot of the average SNR of each component versus time is shown in Figure 2-14. Peak average SNR values of 52 and 54 occurred at plus and minus 90 degrees or when the antenna was horizontal. Actual data for each of the ten tests are presented in Appendix C, Test 4. Test 4.0 is the summary of Tests 4.1 through 4.10.

Figure 2-13 Test 4.3: Antenna at 9 o'clock (+90 Degrees)

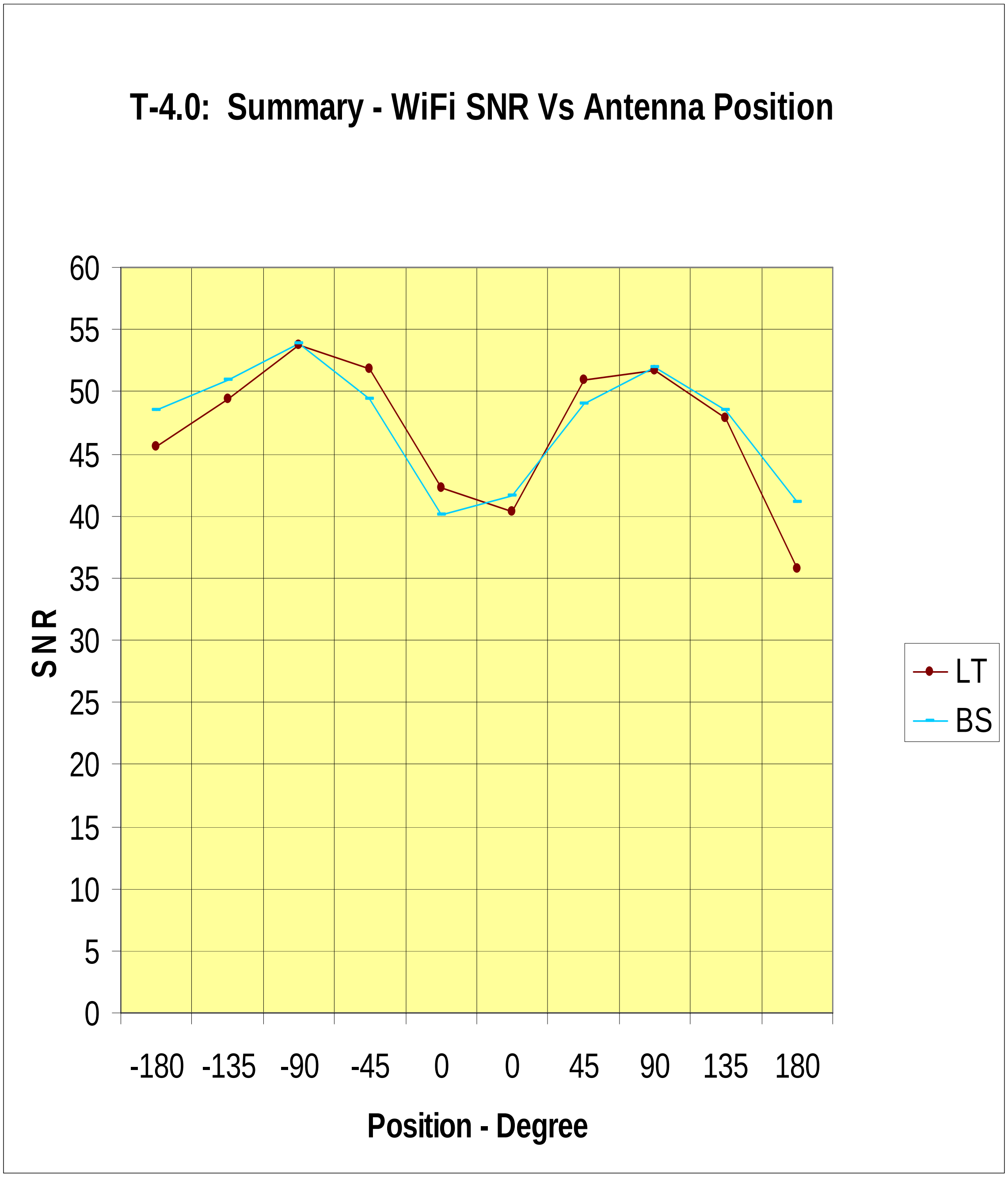

Figure 2-14 Test 4: Summary of SNR versus Antenna Position Tests

2.7.5 Test 5: Distance

Test Series 5 investigated Wi-Fi performance as the distance from the Base Station and the Laptop was increased. Distances were varied from 10 to 300 feet. The Base Station was placed on an empty non-metallic cardboard box sitting on the first floor hall (Figure 2-15). The Laptop was placed on a cart and moved at 10-foot intervals to various distances from the Base Station (see Figure 2-16). For distances beyond 160 feet, the Laptop and cart were moved outdoors into the EDL East parking lot. SNR and data rates were recorded at each position on 30-second intervals for 3 minutes. All other parameters were held constant. Due to the large variations, data at each location were averaged for representative values. Average SNR versus distance for Base Station EDL-lab1 are shown in Figure 2-17. The SNR drops quickly in the first 50 feet from 48 to 35 (Base Station). From 50 feet out to 300 feet, the decrease is more linear. Test 5.1 was for Base Station EDL-lab1. Test 5.2 was for Base Station EDL-lab2. Test 5.3 was a head to head comparison of EDL-lab and EDL-lab2 at two specific distances. Additional comparison data was also handled under Test 5.3.

Figure 2-15 Base Station in EDL Hall for Distance Testing

Figure 2-16 Laptop Collecting Data at 10 Ft to Base Station

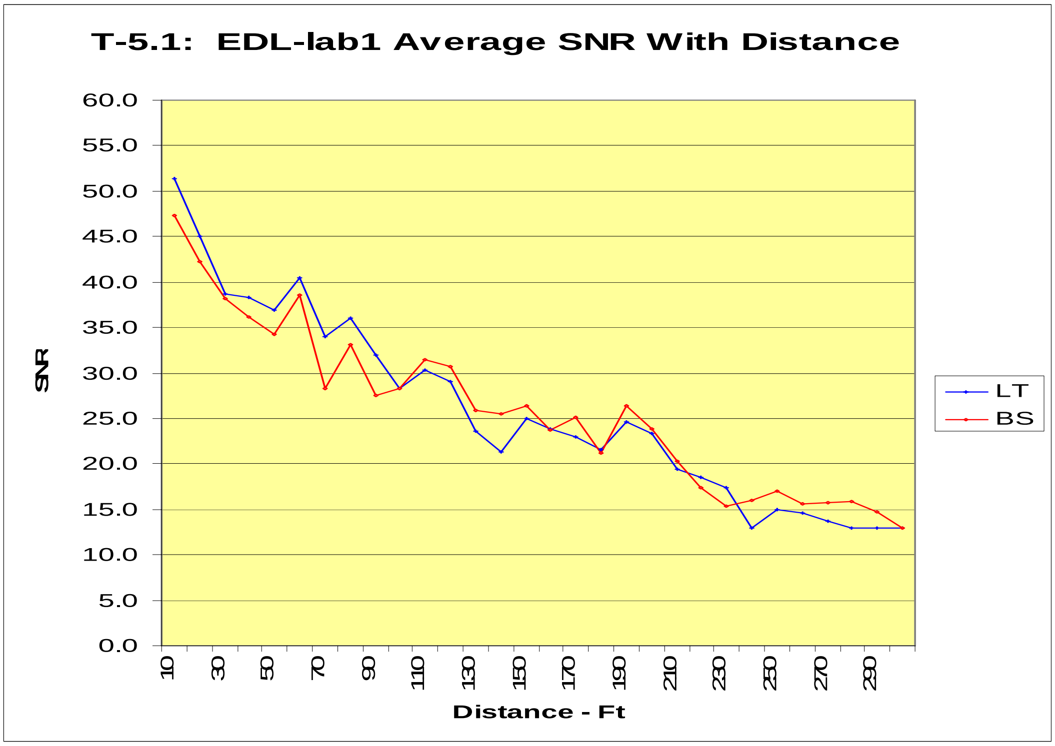

Figure 2-17 Test 5.1: EDL-lab1 Average SNR versus Distance

SNR data for EDL-lab2 are shown in Figures 2-18. EDL-lab2 displayed the large initial decrease in SNR for the first 70 feet. From 70 feet to 300 feet, EDL-lab2 also displayed an almost linear decrease.

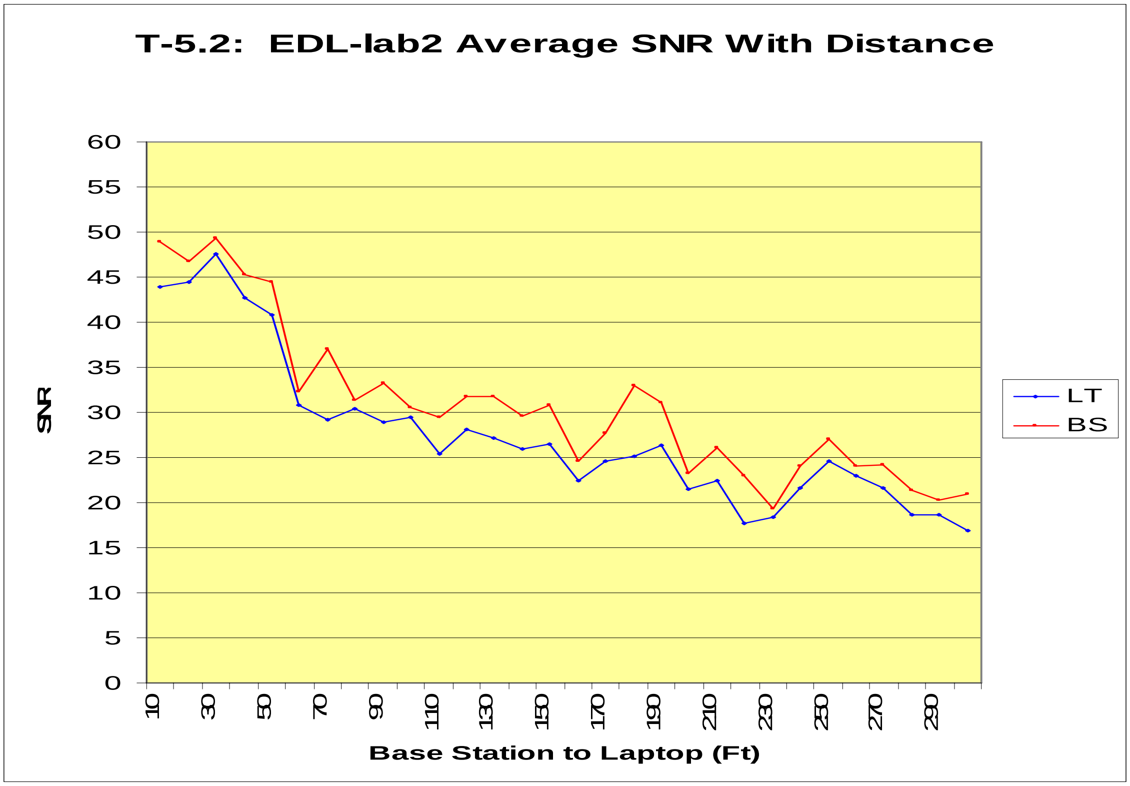

Figure 2-18 Test 5.2: EDL-lab2 Average SNR versus Distance

The SNR is only part of the story when link distances get large. As the link distance increases, there are more lost packets. When this happens, the link automatically decreases the data rate and resends the lost packets. The data rate starts at 11 Mbps, but then steps down to 5.5, 2, or 1 Mbps as required to keep the data link running. It is therefore of interest to see how the percentage of a particular data rates varies with distance. Data rates with EDL-lab1 are shown in Figure 2-19. Figure 2-20 is the same data presented in a bar chart format. Both figure show that 100% of transmissions are at the full 11 Mbps data rate up to a distance of 70 feet. From 70 feet to 100 feet, only 60 to 80% of the transmissions are at 11 Mbps. The other transmissions are mostly at 5.5 Mbps with a small amount occurring at 2 Mbps. At 140 feet, full 11 Mbps data rates become less frequent. Around 220 feet, almost all transmissions are at the low data rate of only 1 Mbps.

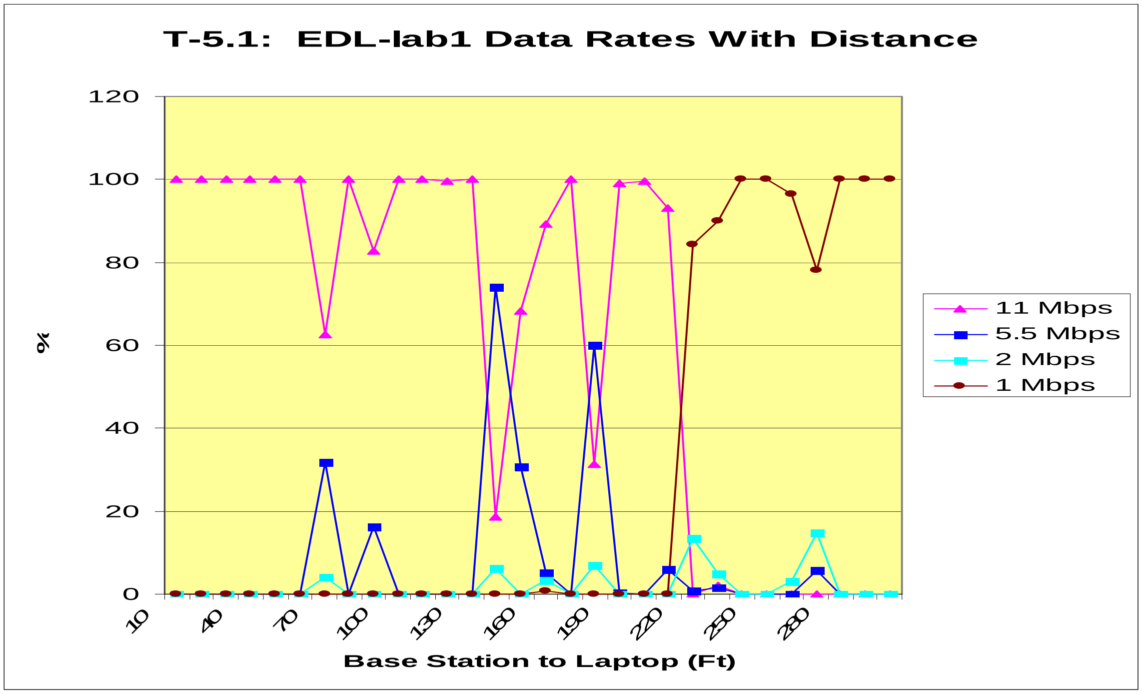

Figure 2-19 Test 5.1: EDL-lab1 Data Rates versus Distance

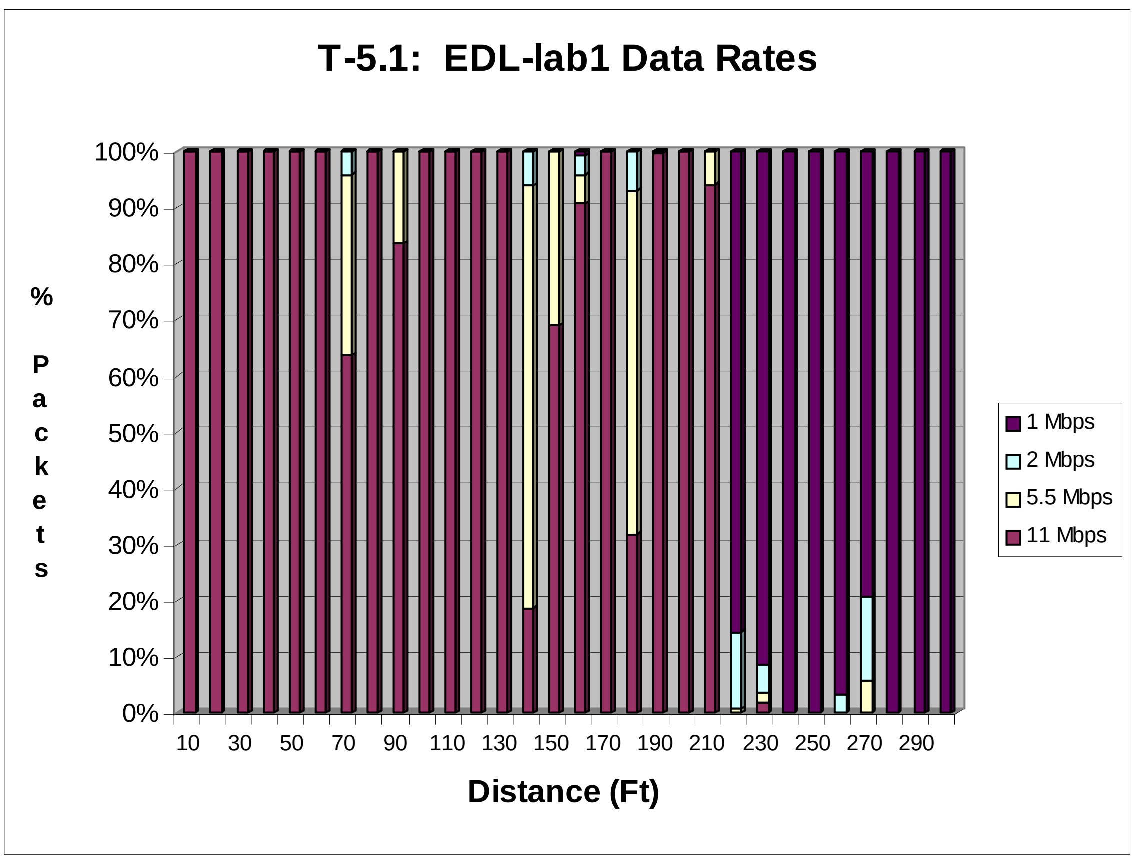

Figure 2-20 Test 5.1: EDL-lab1 Data Rates versus Distance (Bar Chart)

Data rate information for EDL-lab2 is shown in Figure 2-21. The same data in bar chart format is shown in Figure 2-22. EDL-lab2 displayed less variation in data rates. EDL-lab2 managed to maintain a full 11 Mbps data rate at distances to about 220 feet, except for some small decreases around 110 and 170 feet. The 1 Mbps data rate was never required in these tests.

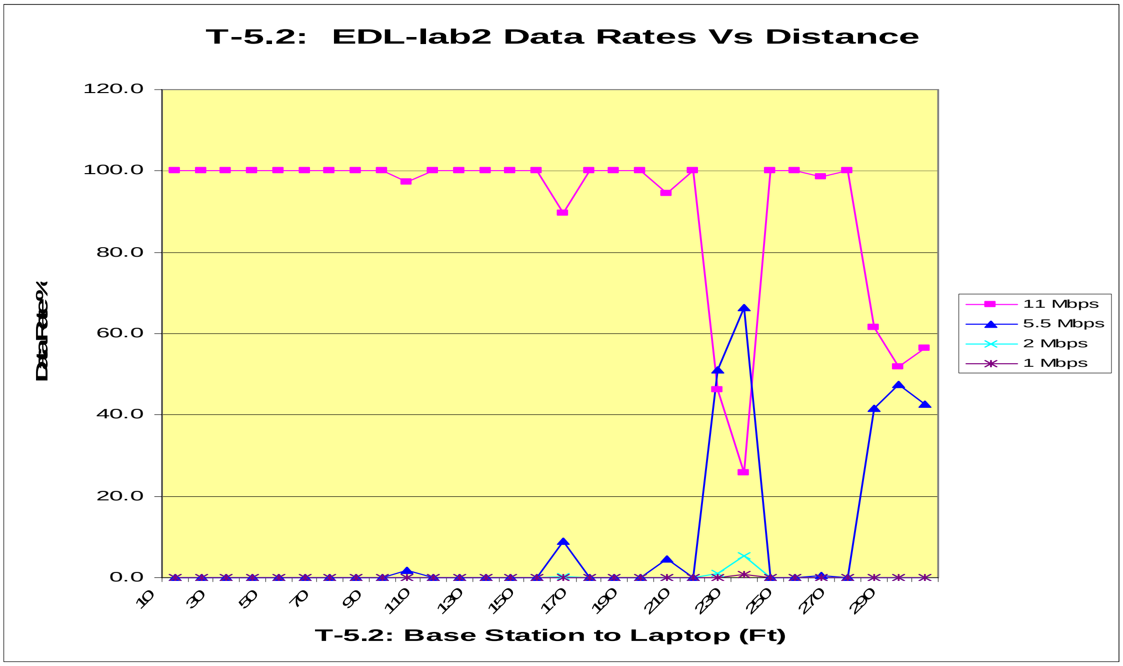

Figure 2-21 Test 5.2: EDL-lab2 Data Rates versus Distance

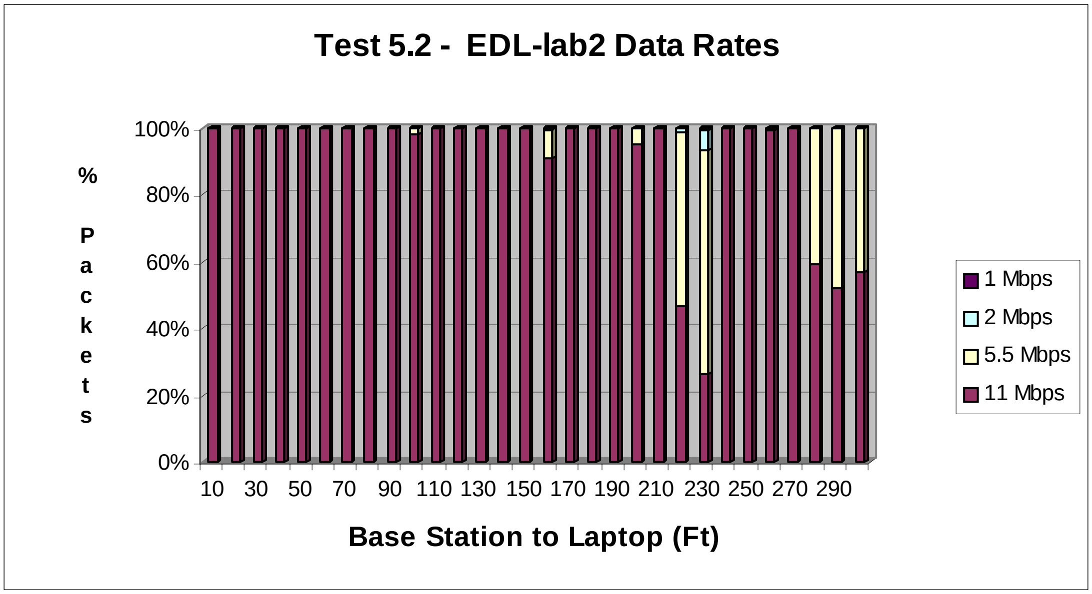

Figure 2-22 Test 5.2: EDL-lab2 Data Rates versus Distance (Bar Chart)

A comparison between EDL-lab1 and EDL-lab2 at 25 and 50 feet is shown in Figure 2-23. This data was taken at the same time on the same day. Although both Base Stations are identical Microsoft MN-500 models, Base Station EDL-lab2 tested slightly stronger (SNR) than EDL-lab1 at both 25 and 50 feet. Actual test data for all runs are included in Appendix C.

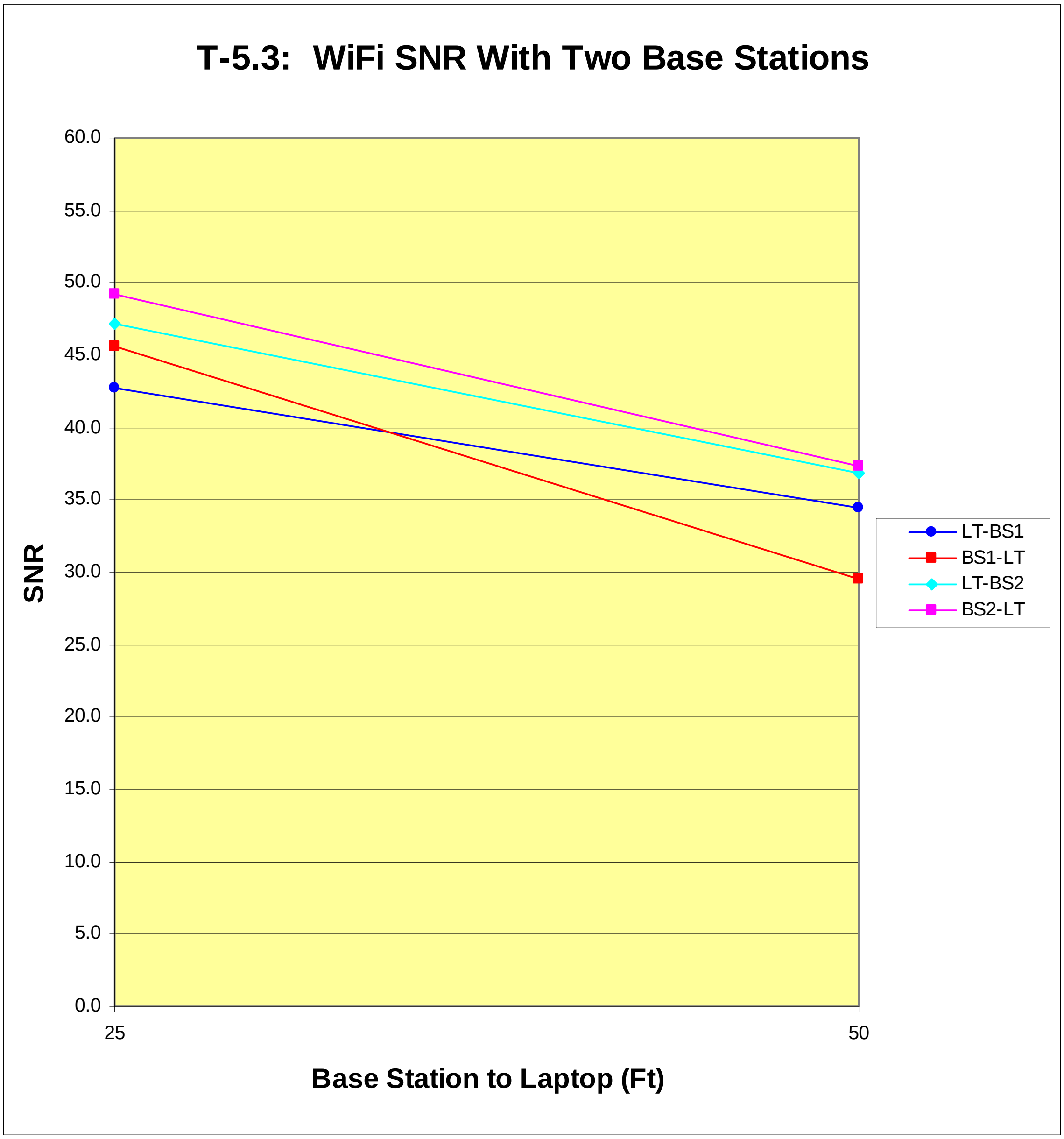

Figure 2-23 Test 5.3: Comparison of Both Base Stations at 25 and 50 Feet

A comparison of average SNR for EDL-lab1 and EDL-lab2 over the entire 300-ft range is presented in Figure 2-24. This figure is a comparison of data taken on separate days. It is evident that EDL-lab2 has a stronger SNR over most of the range. A comparison of average Data Rates with the two Base Stations over the full ranges is shown in Figure 2-25. This figure shows how EDL-lab1 weaker link caused the data rate to start decreasing at a much shorter distance than EDL-lab2.

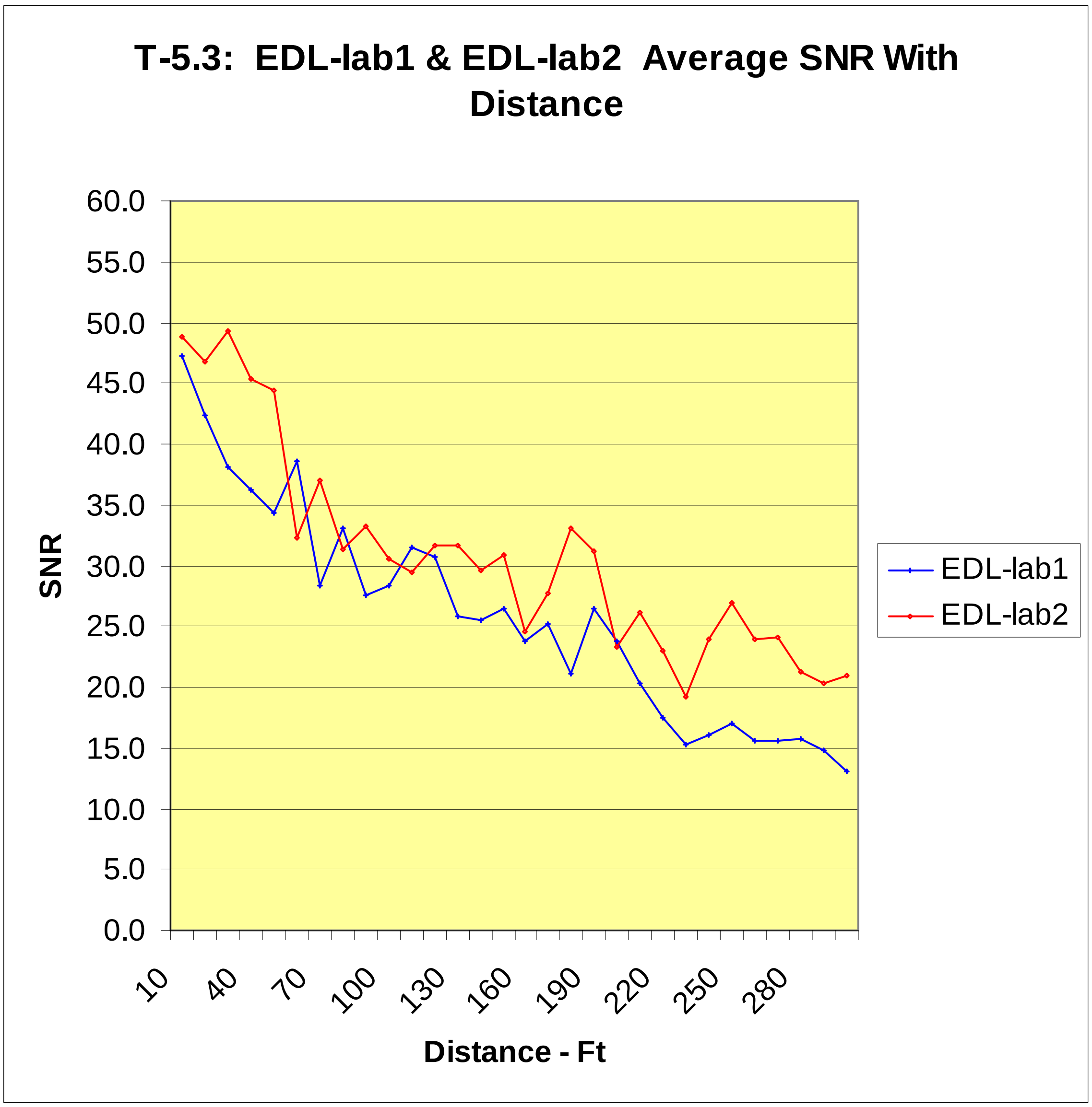

Figure 2-24 Comparison of EDL-lab1 and EDL-lab2 Average SNR with Distance

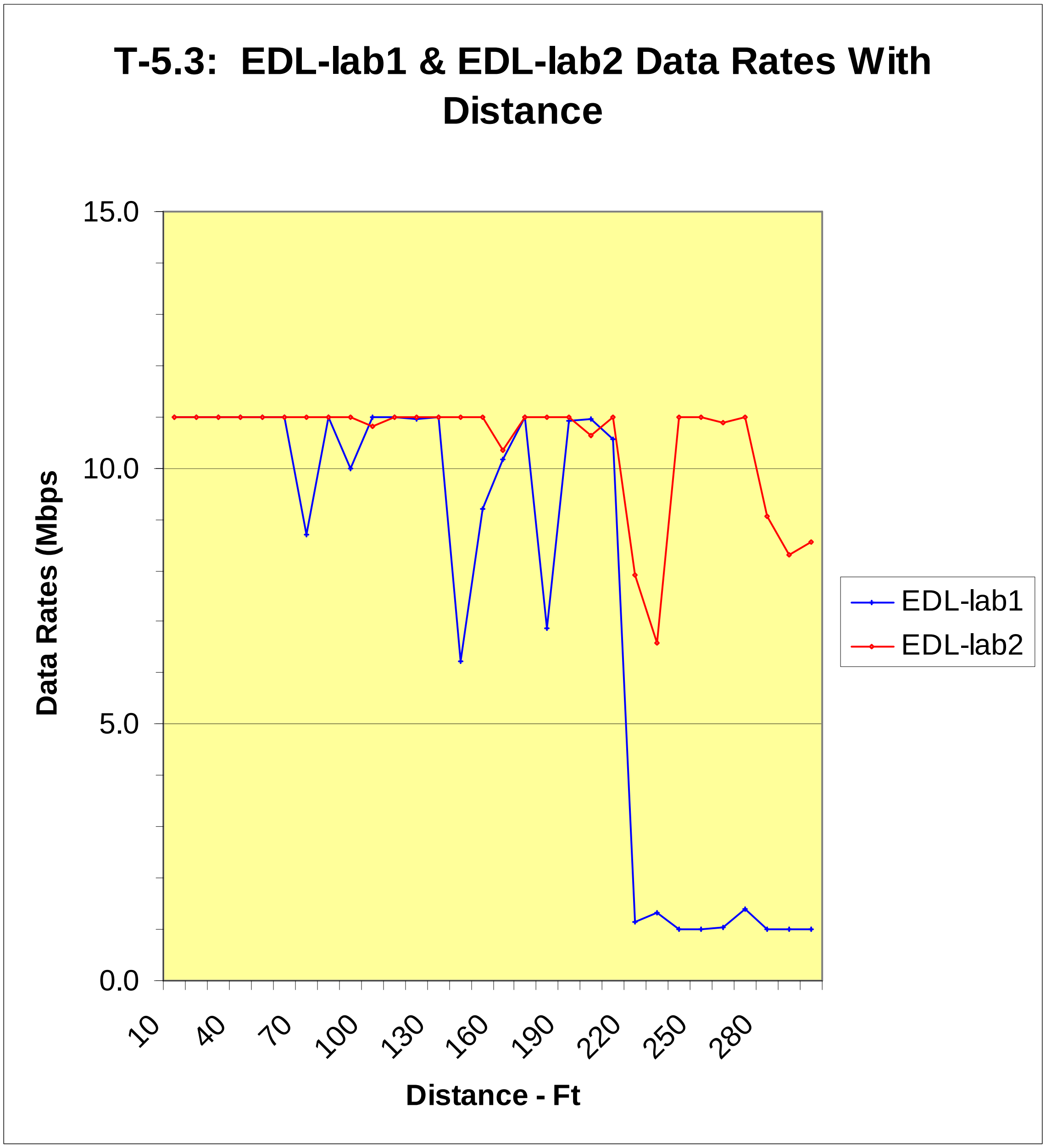

Figure 2-25 Comparison of EDL-lab1 & EDL-lab2 Avg Data Rates with Distance

2.7.6 Test 6: Attenuation with Barriers

Test 6 investigated Wi-Fi performance with typical barriers and materials that might adversely attenuate a Wi-Fi signal within an office environment. All tests were performed using EDL-lab1 and Laptop BH located 25 feet apart in a configuration as described in Test 3. Nine barrier samples were tested at controlled distances of 2 to 23 feet from the Base Station. Baseline data were recorded prior to the start of each test at 30-second intervals for 3 minutes. After recording the baseline, the barrier sample under test was placed at the 2-ft mark and data were recorded in 30-second intervals for 3 minutes. The barrier was then moved further from the Base Station and the test repeated. This was continued until the 23-ft measurements were complete. Test results showed positive and negative SNR changes within the ranges that were evaluated. The variations are attributed to multi-path and constructive/destructive interferences. Results are discussed separately below by barrier. Actual test data for all runs are included in Appendix C.

2.7.6.1 Single Partition

Test 6.1 investigated attenuation effects of a single partition typical of what might be found in an office. The test setup is shown in Figure 2-26. Test results are presented in Figure 2-27. Significant attenuation was observed when either the Base Station or Laptop are within 5 feet of a partition. At 10 feet from the Base Station or Laptop, the attenuation effects were negligible and the SNR was almost the same as the baseline.

Figure 2-26 Test 6.1: Configuration With 1 Partition @ 2-Ft

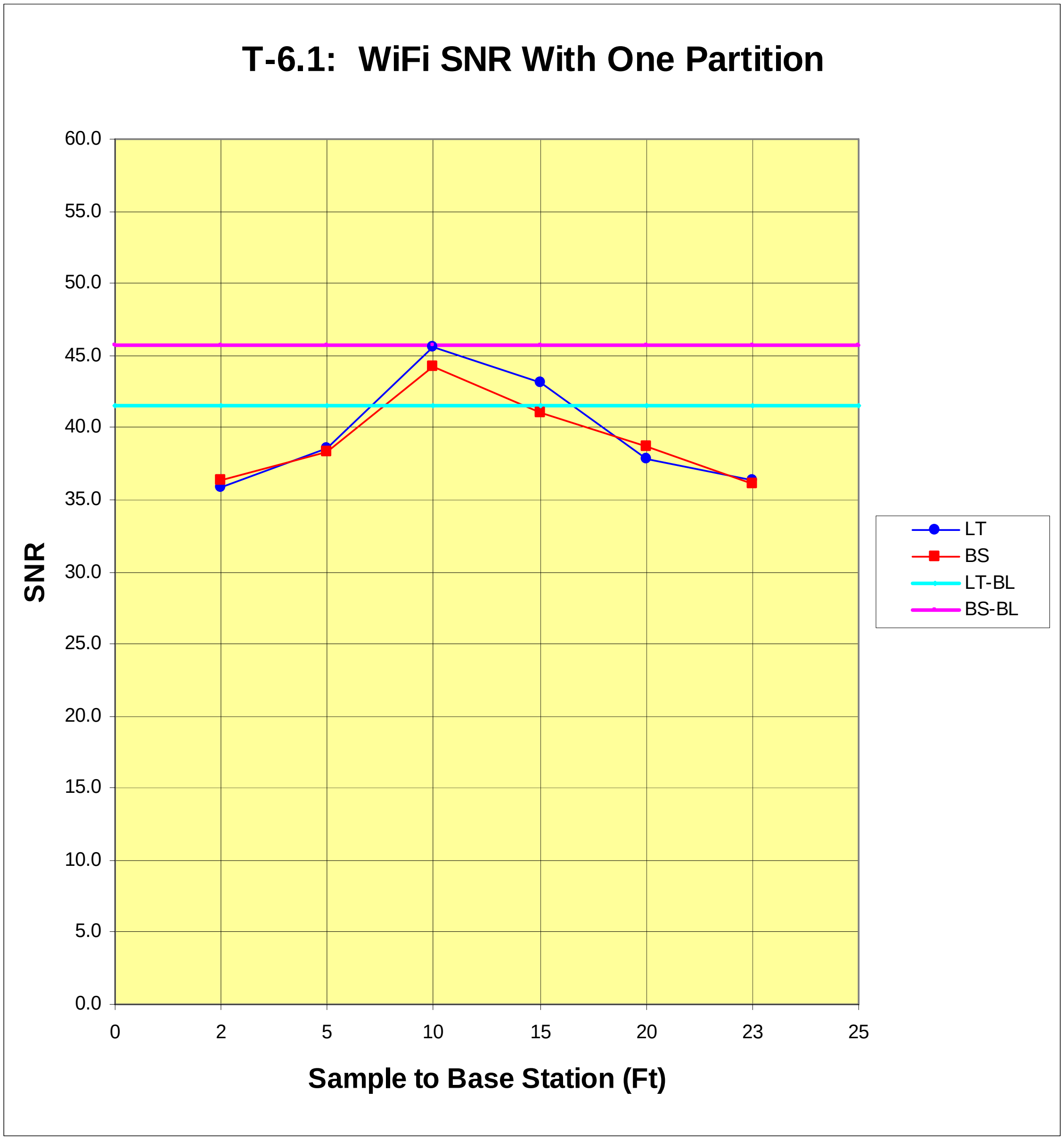

Figure 1-1
Figure 2-27 Test 6.1: SNR with One Partition

2.7.6.2 Double Partition

Test 6.2 was a repeat of Test 6.1 but with two partitions place together to represent a double thickness partition within the Wi-Fi link. The double partitions are shown in Figure 2-28. Results presented in the following-on figure show that attenuation near each component is about the same as with the single partition. Mid-point data did not show the same SNR improvement as was reflected in the single partition test (Test 6.1).

Figure 2-28 Test 6.2: Typical Barrier Made from Two Adjacent Partitions

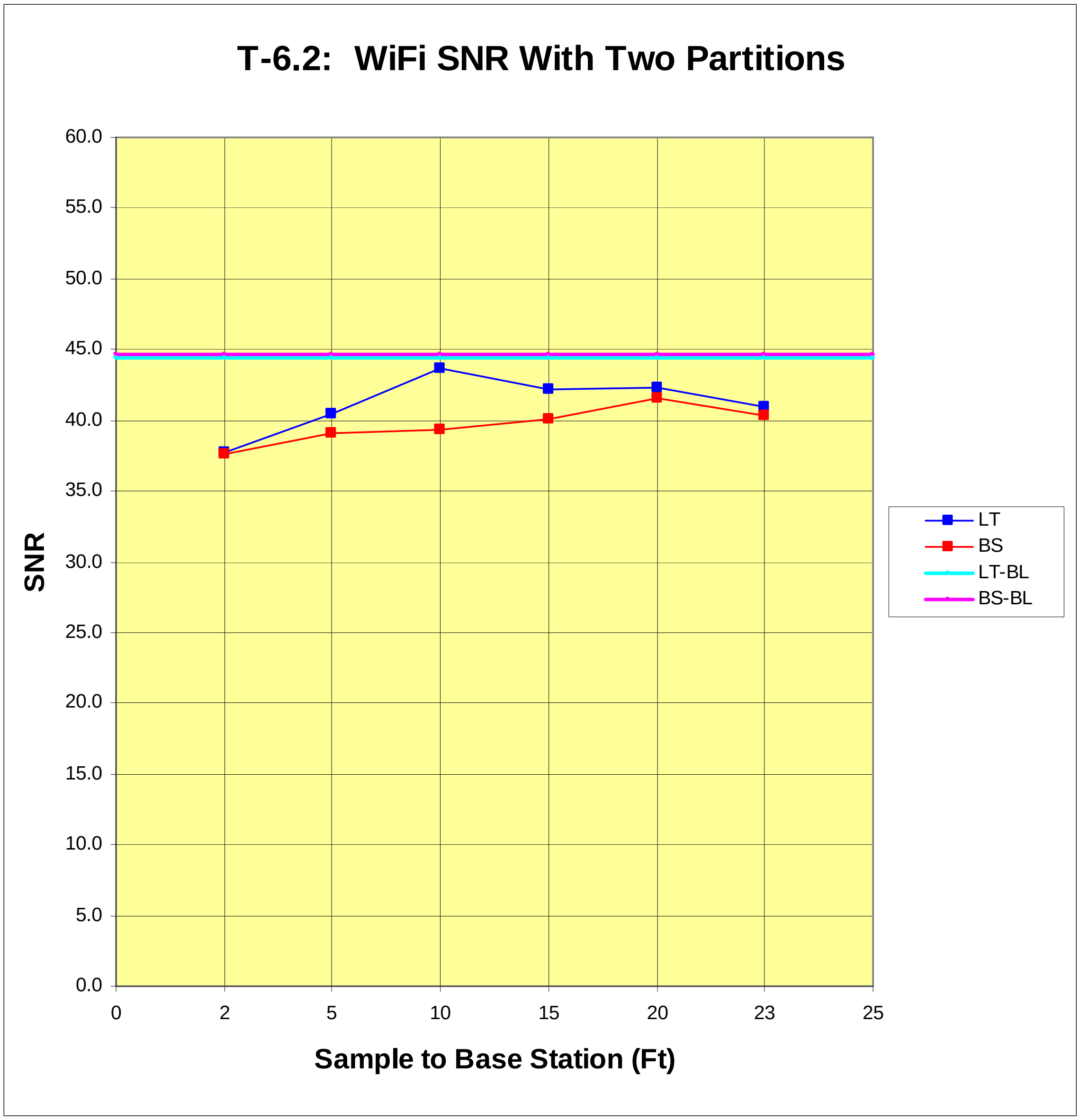

Figure 2-29 Test 6.2: SNR with Two Adjacent Partitions

2.7.6.3 Aluminum Sheet (0.125-inch)

Test 6.3 was conducted using a 0.125-inch aluminum sheet (See Figure 2-30). Results in the follow-on figure show that the SNR decreased 1 to 6 points over the distances evaluated.

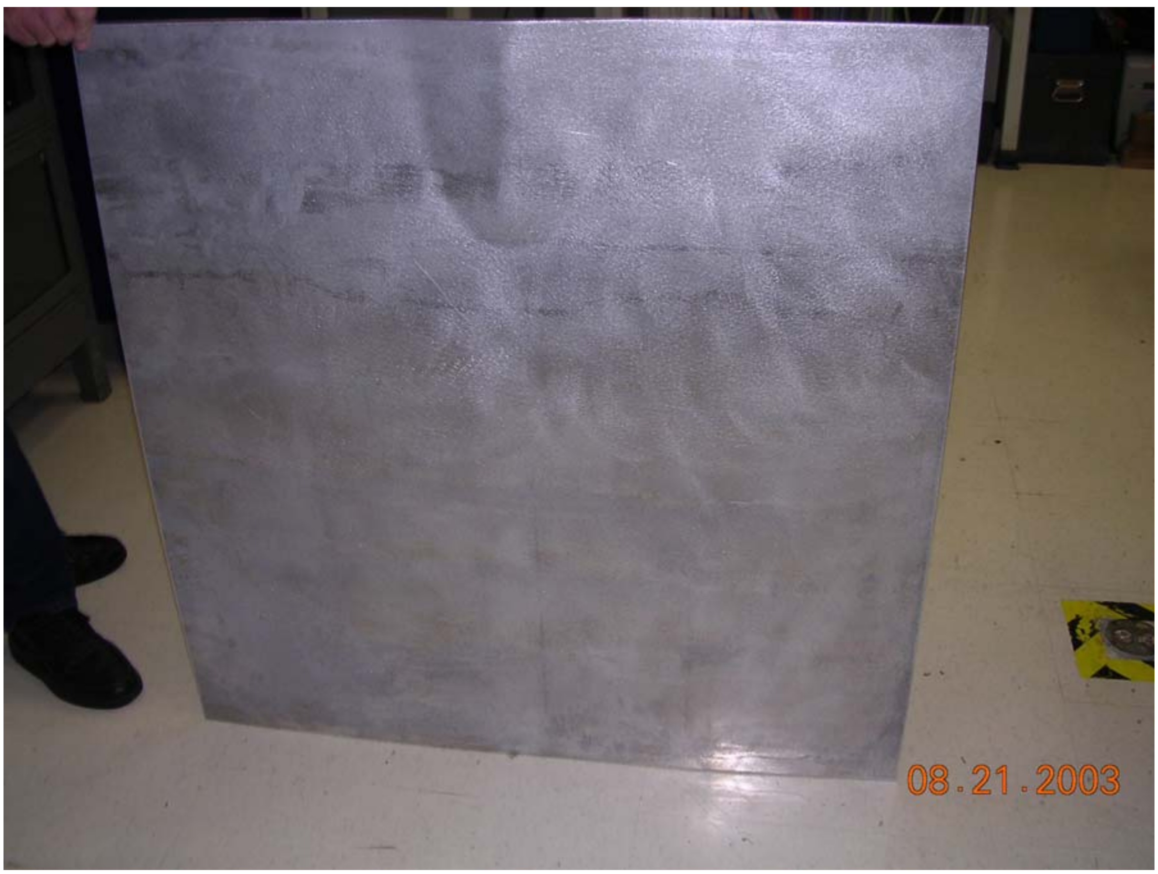

Figure 2-30 Test 6.3: 0.125-inch Aluminum Sheet

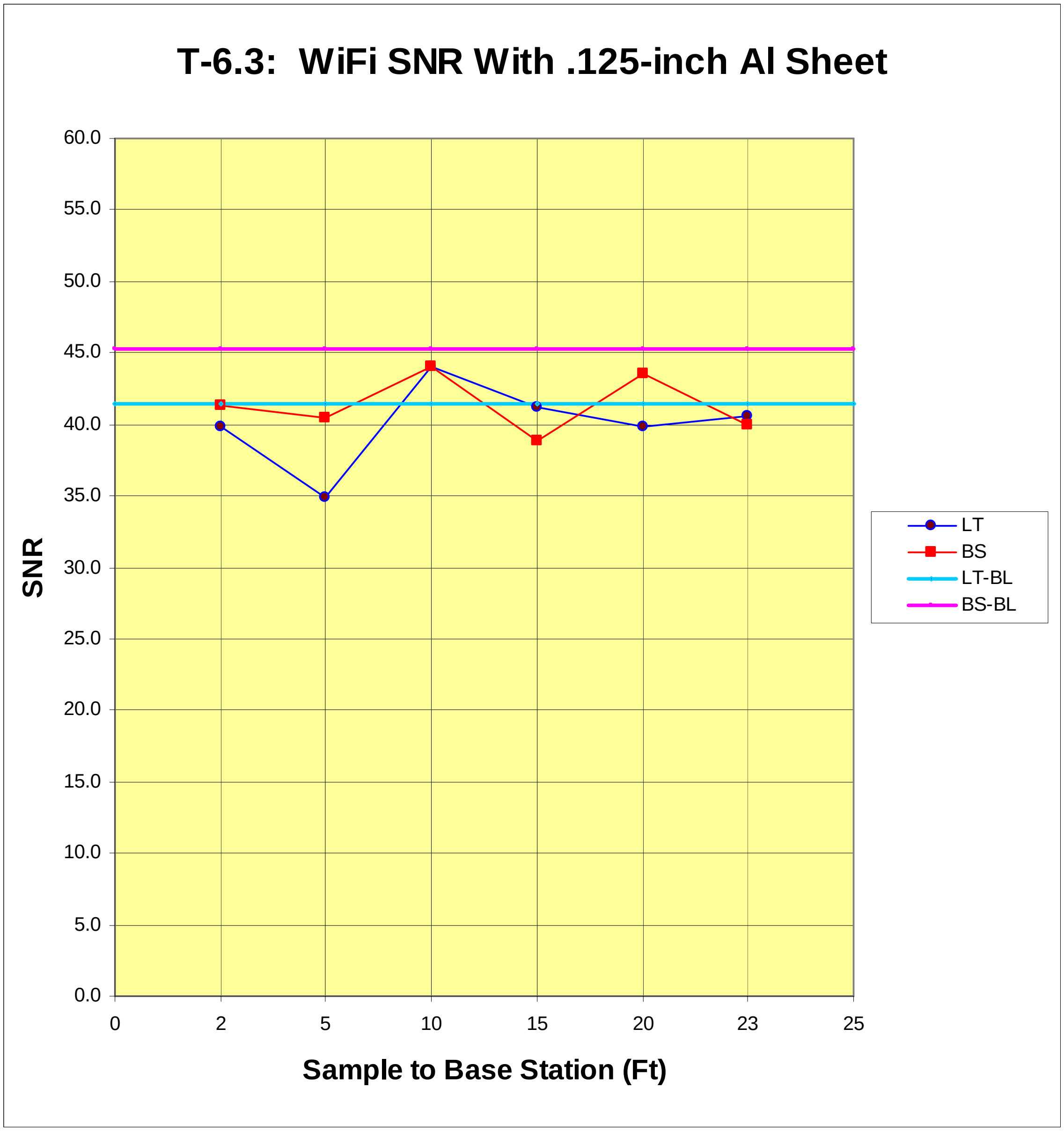

Figure 2-31 Test 6.3: SNR with 0.125-inch Aluminum Sheet

2.7.6.4 Aluminum Sheet (0.187-inch)

Test 6.4 was conducted using a 0.187-inch aluminum sheet. The test setup is shown in the following figure. Test results, in the follow-on figure, show less variation and slightly less attenuation than was seen in Test 6.3 with the thinner (0.125-inch) Aluminum sheet.

Figure 2-32 Test 6.4: Configuration with 0.187-Inch Thick Aluminum Sheet

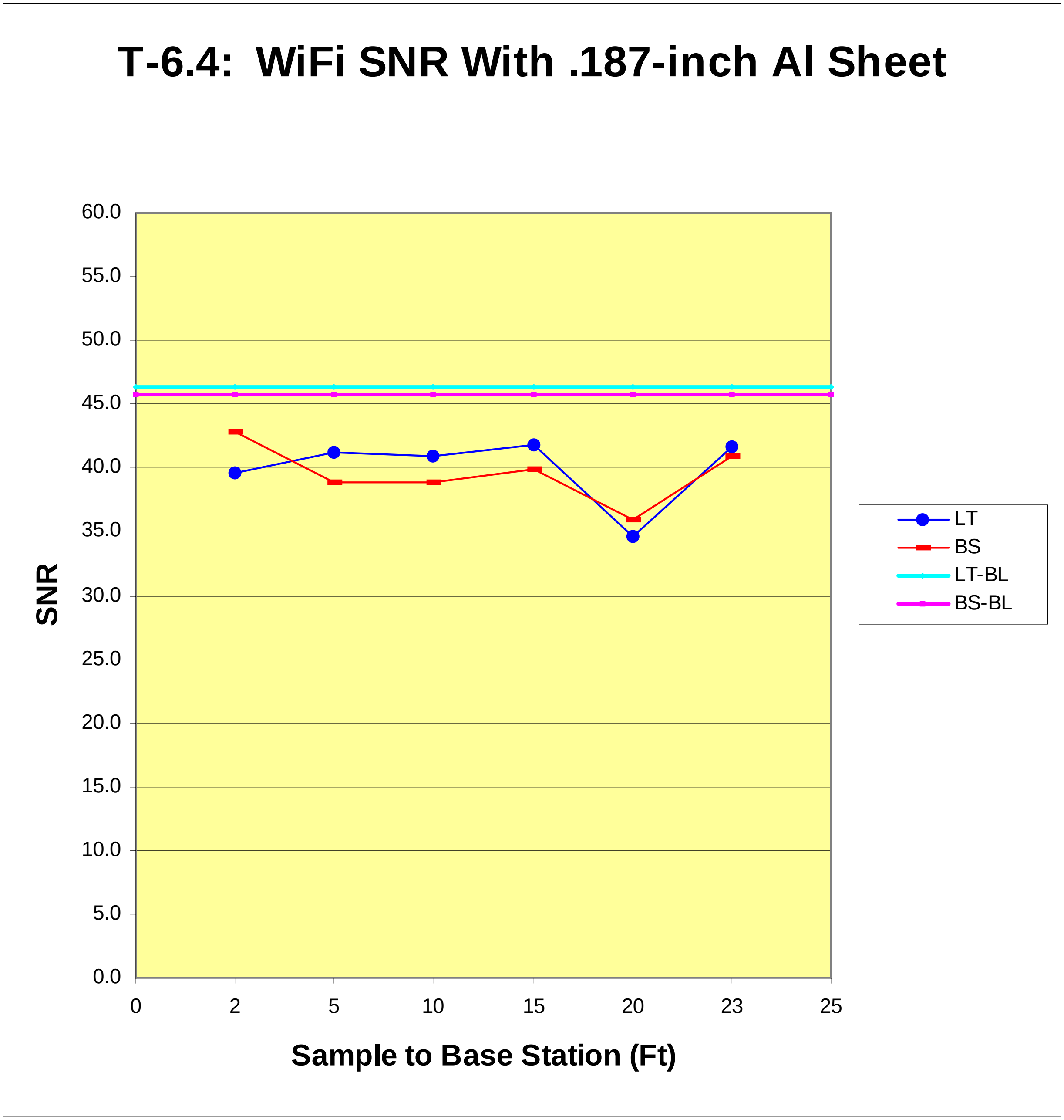

Figure 2-33 Test 6.4: SNR with 0.187-Inch Aluminum Sheet

2.7.6.5 Steel Panel (0.063-inch)

Test 6.5 was conducted using a 0.063-inch steel panel. The test item is shown in the following figure. Test results, in the follow-on figure, show that the SNR decreased by 0 to 8 points over the distances evaluated.

Figure 2-34 Test 6.5: 0.063-Inch Steel Panel

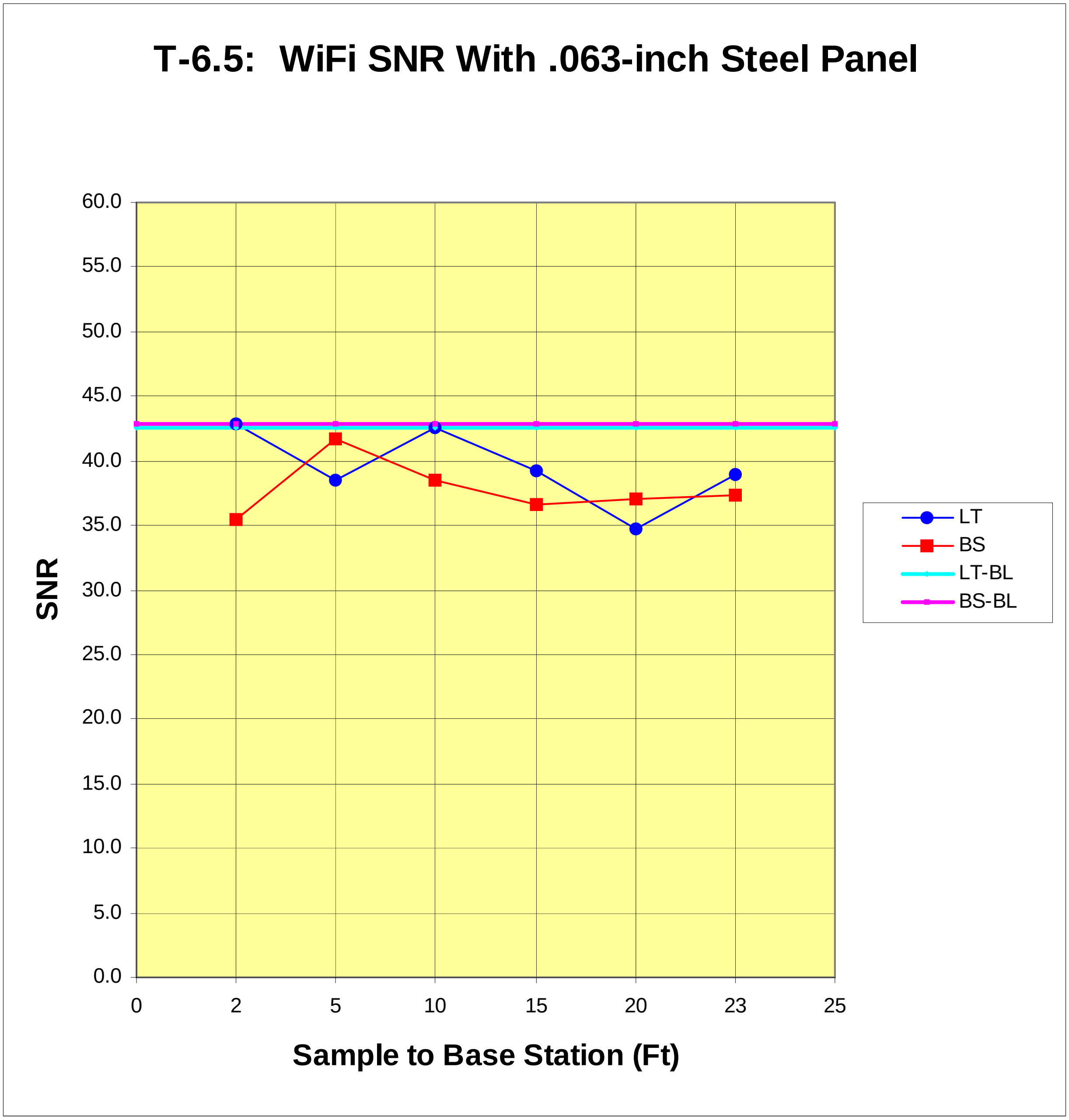

Figure 2-35 Test 6.5: SNR with .063-inch Steel Panel

2.7.6.6 Cinder Blocks (3h, 1w, 1t)

Test 6.6 was conducted using three cinder blocks in the configuration shown in the following figure. This test setup was 3 high, 1 wide, 1 thick (3h, 1w, 1t). Test results, in the follow-on figure, show the SNR drops 6 points over most of the range investigated. However, at the 2-ft and 20-ft locations, there was no SNR reduction. There was apparently multi-path signal enhancement occurring in these regions.

Figure 2-36 Test 6.6: Configuration with 3 Cinder blocks

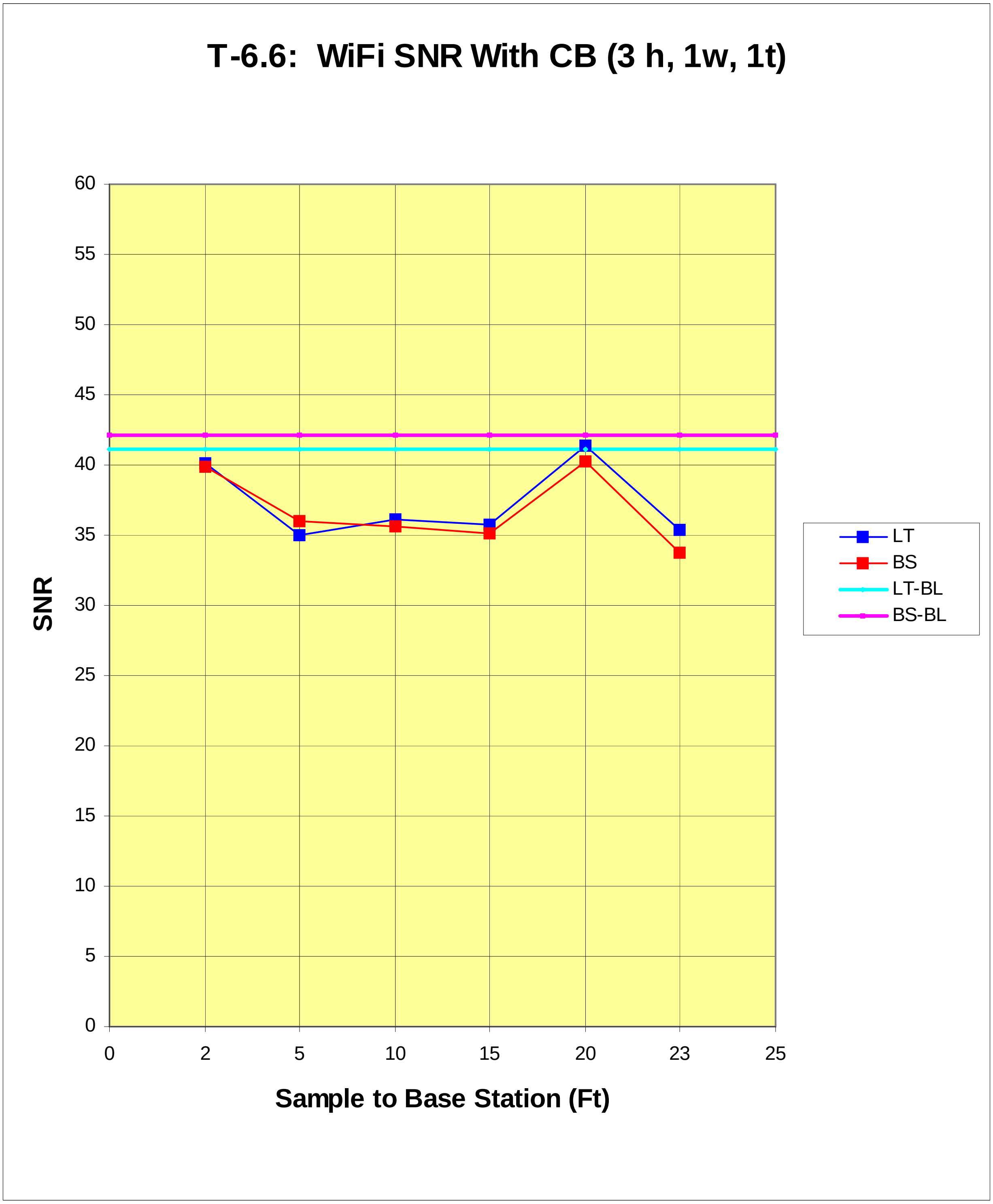

Figure 2-37 Test 6.6: SNR with Cinder Blocks (3h, 1w, 1t)

2.7.6.7 Cinder Blocks (3h, 1w, 2t)

Test 6.7 was conducted using 6 cinder blocks in the configuration shown in the following figure. This test setup was 3 high, 1 wide, 2 thick (3h, 1w, 2t). Test results, in the follow-on figure, show that attenuation decreased the SNR by 2 to 8 points over the range of interest.

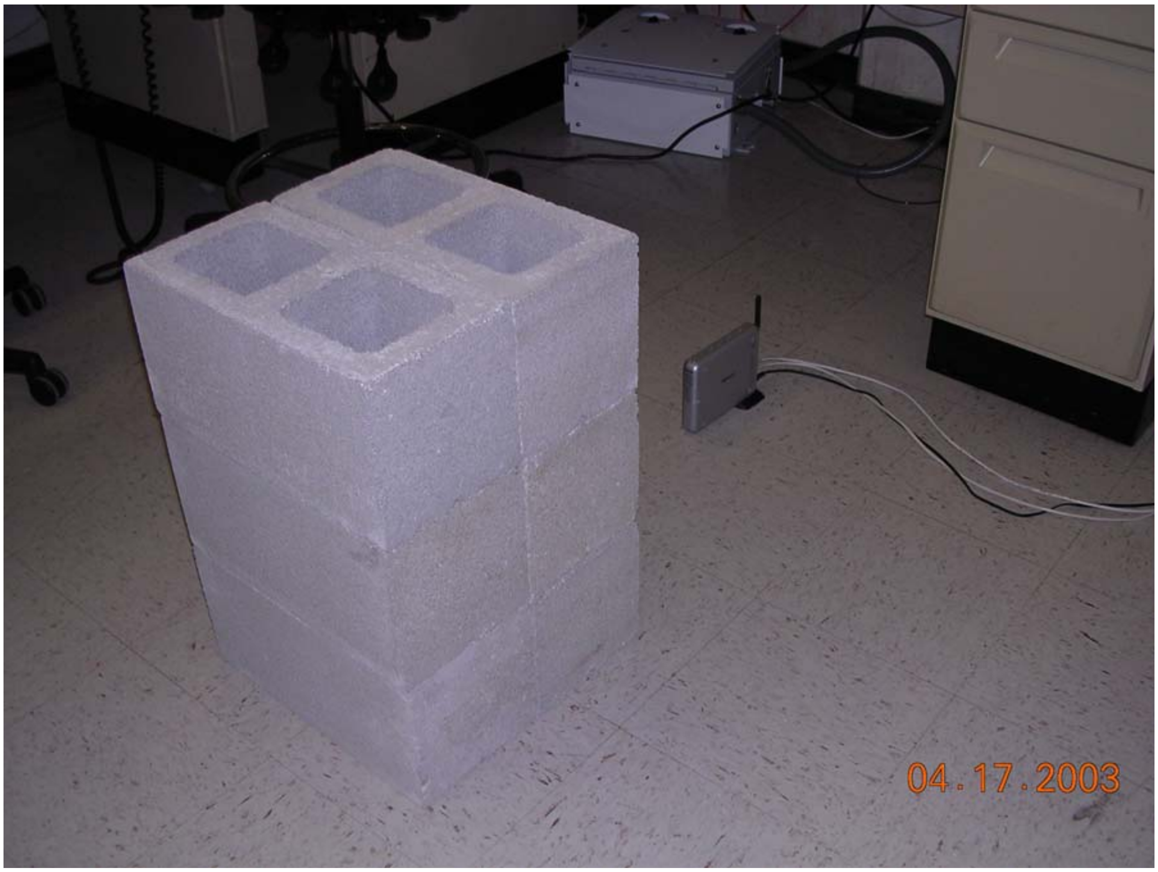

Figure 2-38 Test 6.7: Configuration with 6 Cinder Blocks (3h, 1w, 2t)

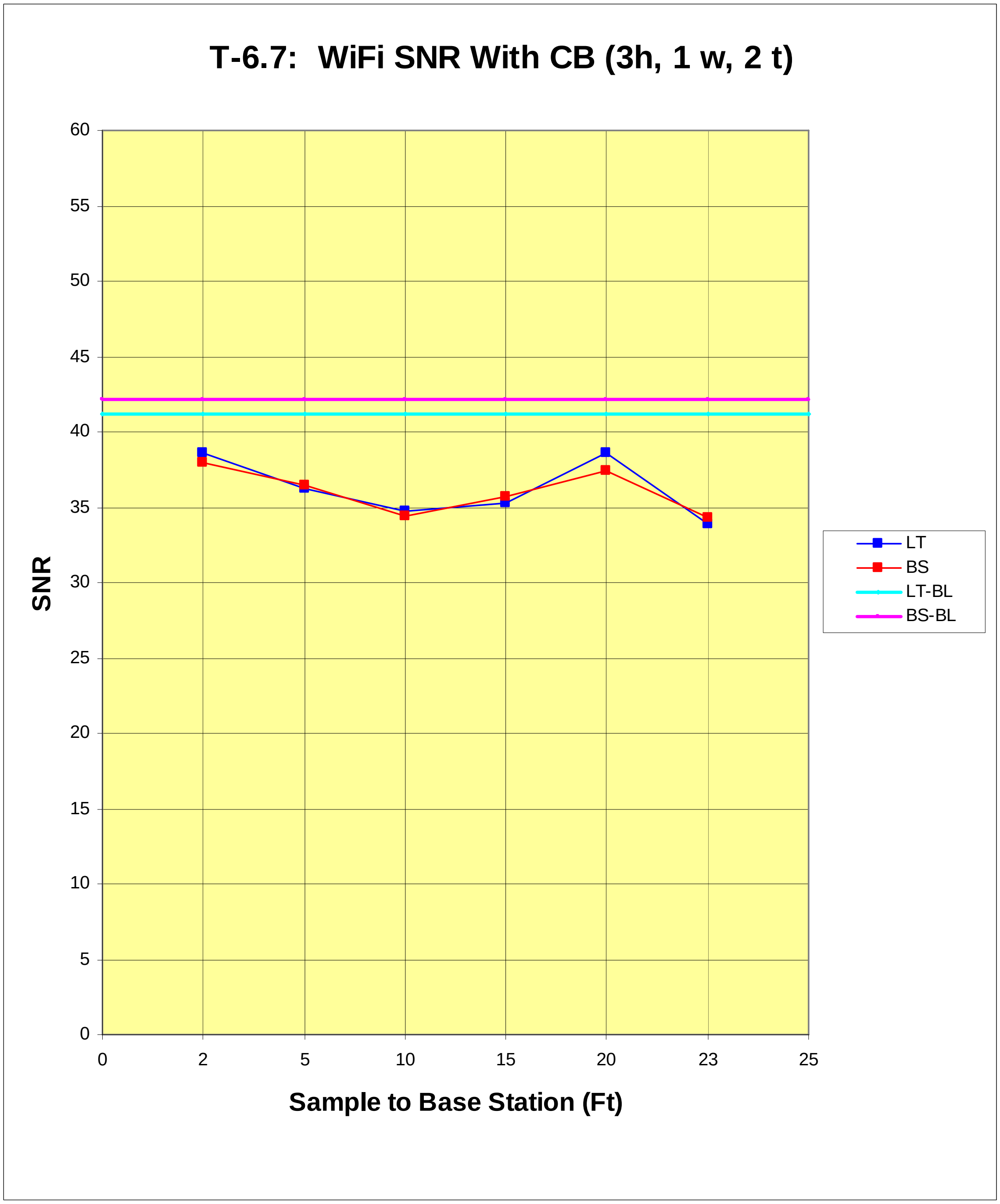

Figure 2-39 Test 6.7: SNR with Cinder Blocks (3h, 2w, 1t)

2.7.6.8 Cinder Blocks (3h, 2w, 1t)

Test 6.8 was conducted using 6 cinder blocks in the configuration shown in the following figure. This test setup was 3 high, 2 wide, 1 thick (3h, 1w, 1t). Test results, in the follow-on figure, show the SNR decreased 3 to 8 points over the range of interest except at 20 feet where it actually exceeded the baseline. Some form of constructive interference is suspected at this 20-ft mark.

Figure 2-40 Test 6.8: Configuration with 6 Cinder blocks (3h, 2w, 1t)

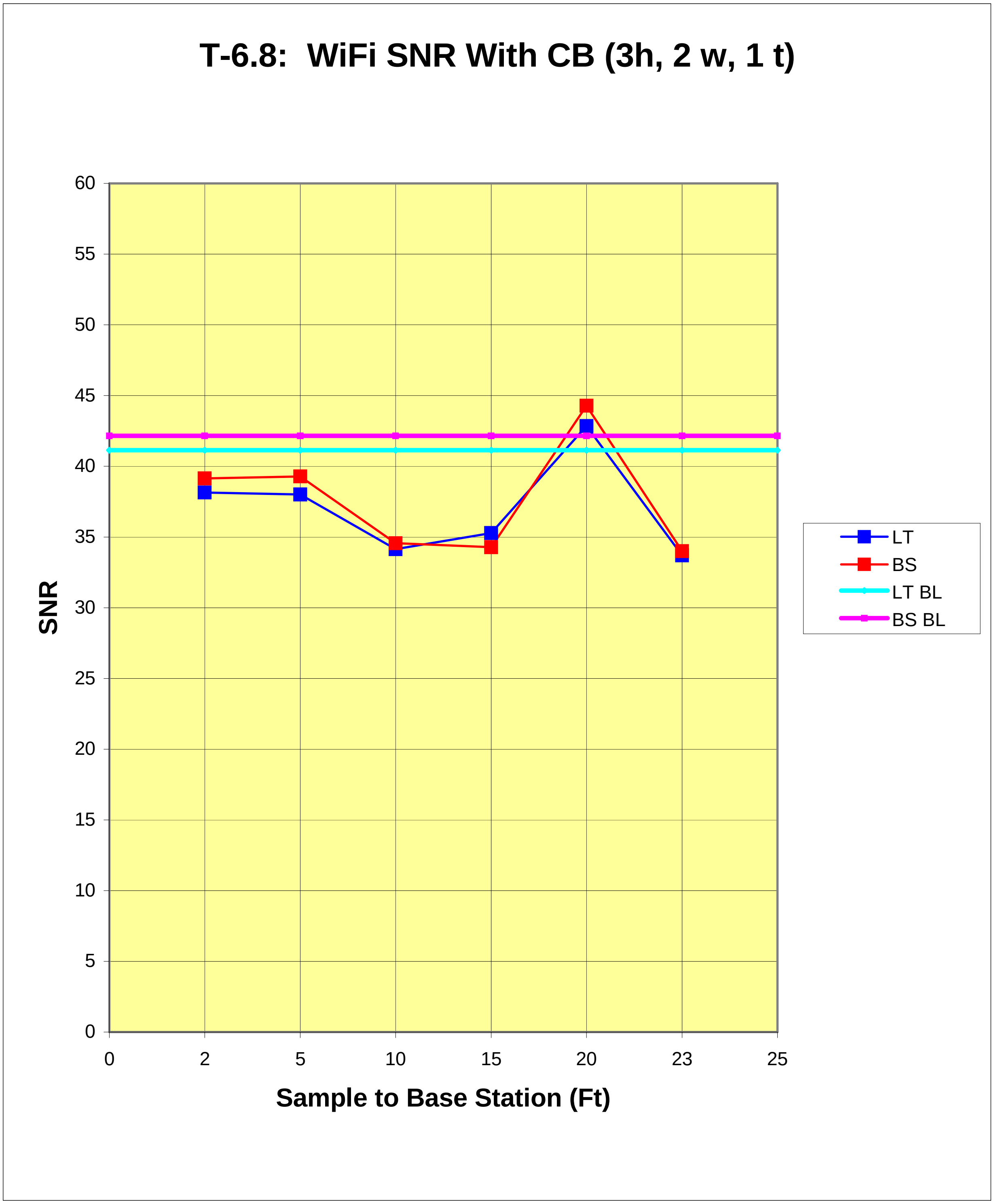

Figure 2-41 Test 6.8: SNR with Cinder Blocks (3h, 2w, 1t)

2.7.6.9 Human Body

Test 6.9 investigated the effect of someone walking through the link path. A volunteer was placed at selected points 2 to 23 feet from the Base Station. SNR and other data were recorded. The volunteer was 215 lbs, 6’2” tall. Results in the following figure show the Base Station SNR tracked very close to the baseline except when very close to the Laptop. SNR at the Laptop was down 2 to 4 points over the distances investigated.

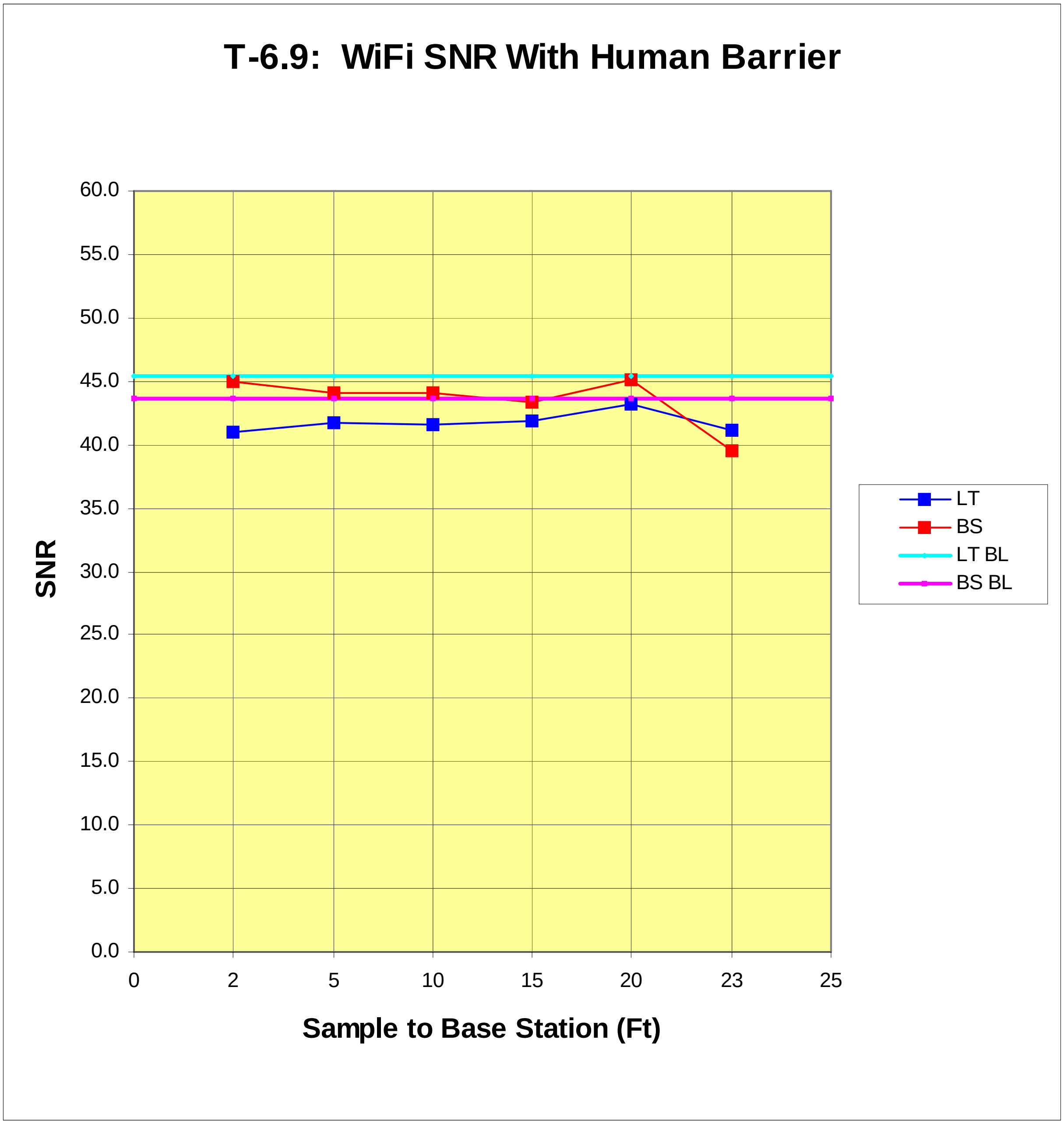

Figure 2-42 Test 6.9: SNR with 215 Lb, 6’2” Human Barrier

2.7.7 Test 7: Interference Effects

Eight items were investigated for possible interference with or from the 2.4 GHz Wi-Fi link. These are discussed in the following sections. Actual test data are included in Appendix C under Test 7. SNR values varied throughout the distances that were investigated (2 to 23 feet). Sometimes SNR values actually increased over baseline values. These wide variations are attributed to multi-path and constructive/destructive interferences.

2.7.7.1 UWB

Test 7.1 investigated the effect of a UWB transceiver within the Wi-Fi link. The test setup is shown in the following figure. Test results are shown in the follow-on figure. Test and component details are provided in Appendix C. Test results show that the Base Station SNR changes very little until the UWB got close to the Laptop. At 10 feet from the Laptop, the Base Station SNR decreased 5 points but then rose back toward the baseline. The Laptop SNR showed a 3 to 5 point decrease over most of the distances of interest.

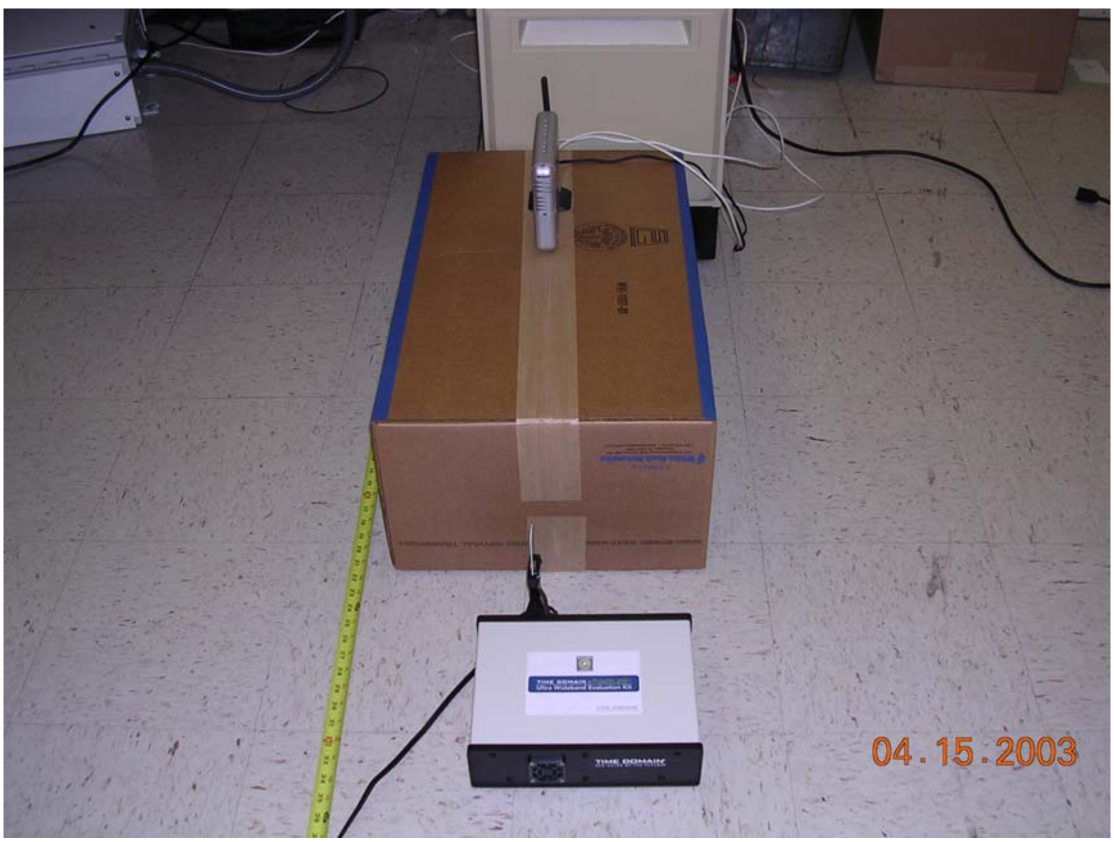

Figure 2-43 Test 7.1: Test Setup with UWB Transceiver within Wi-Fi Link

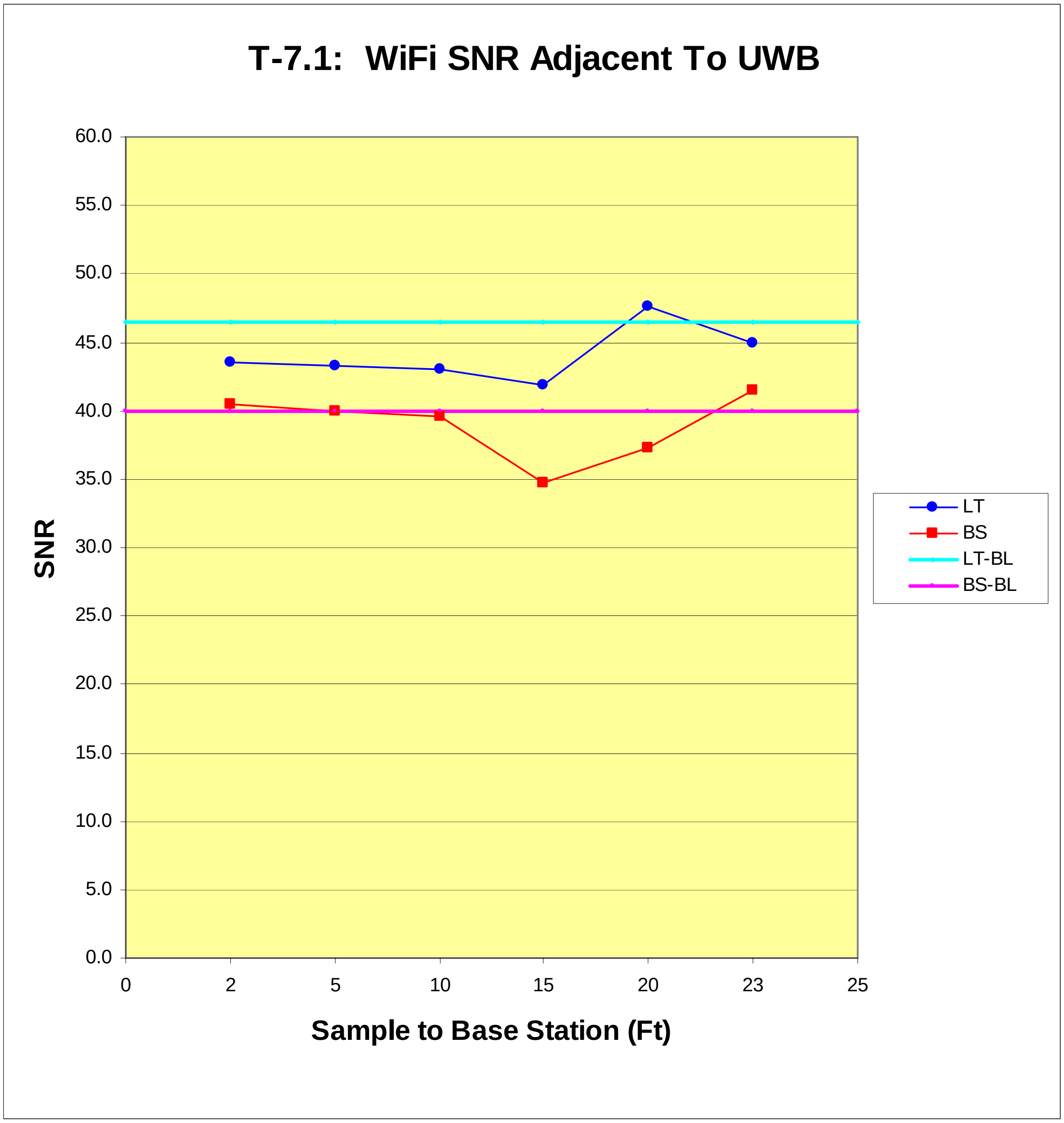

Figure 2-44 Test 7.1: SNR with UWB Transceiver within Wi-Fi Link

2.7.7.2 Microwave Oven

Test 7.2 investigated the effect of a Microwave Oven within the Wi-Fi link. The Magic Chef Model MCD990SC test component is shown in the following figure. This 900W microwave oven operates at 2.45 GHz, adjacent to the 2.4 GHz frequency band of the Wi-Fi components. Test results are shown in the follow-on figure. Test and component details are provided in Appendix C. Test results show the SNR decreasing 0 to 5 points over the range of interest.

Figure 2-45 Test 7.2: Magic Chef Microwave Oven Used for Tests

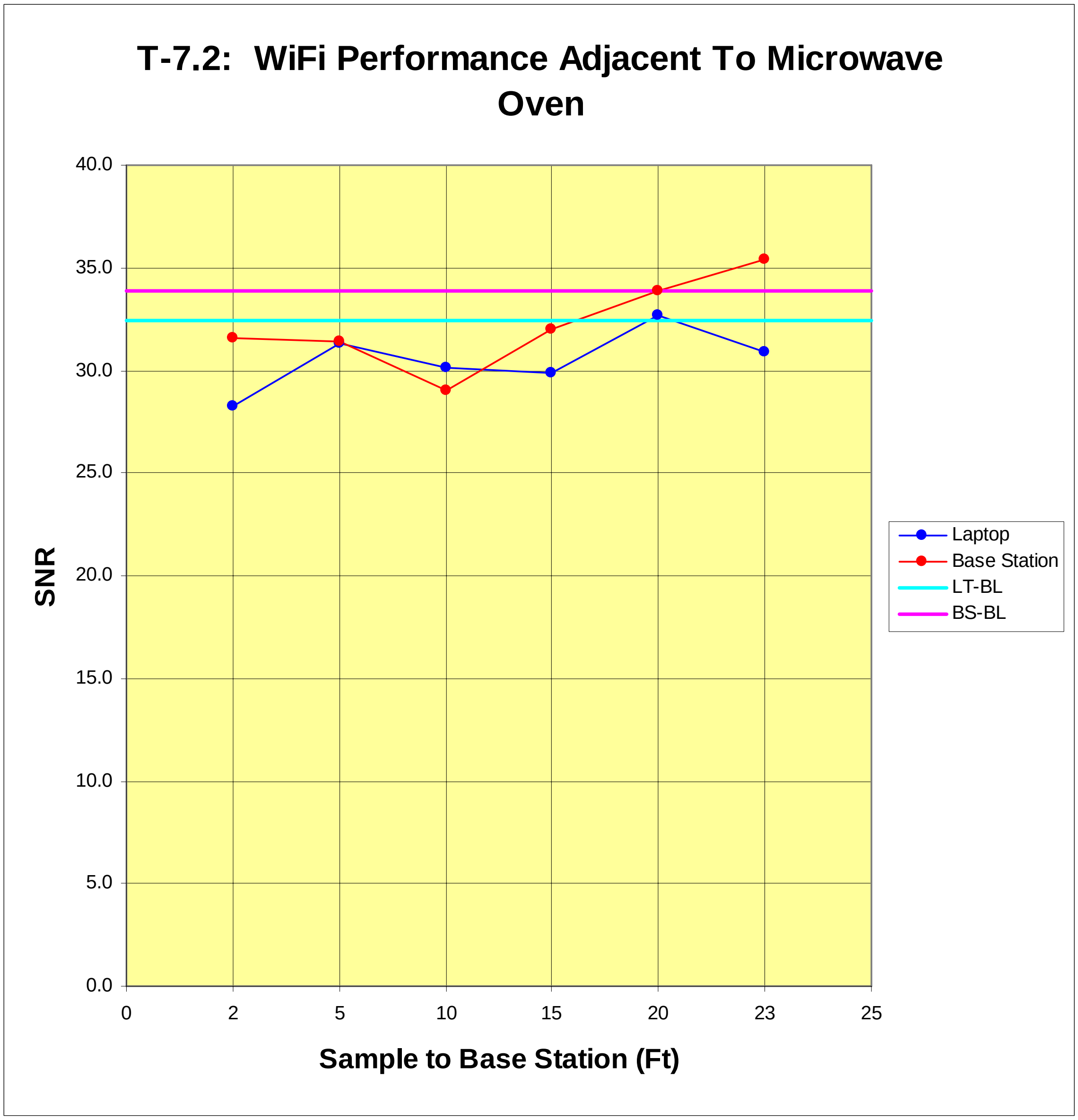

Figure 2-46 Test 7.2: SNR with Microwave Oven within Wi-Fi Link

2.7.7.3 2.4 GHz Cordless Phone

Test 7.3 investigated the effect of a 2.4 GHz cordless phone within the Wi-Fi link. The test item, a Panasonic 2.4 GHz, Digital Cordless Phone, Model KX-TG2237, is shown in the following figure. Test results are shown in the follow-on figure. Test and component details are provided in Appendix C. Test results show no significant effects to, or from, the cordless phone. SNR values varied from slightly above to slightly below the baseline values.

Figure 2-47 Test 7.3: Test Sample, Panasonic 2.4 GHz Digital Cordless Phone

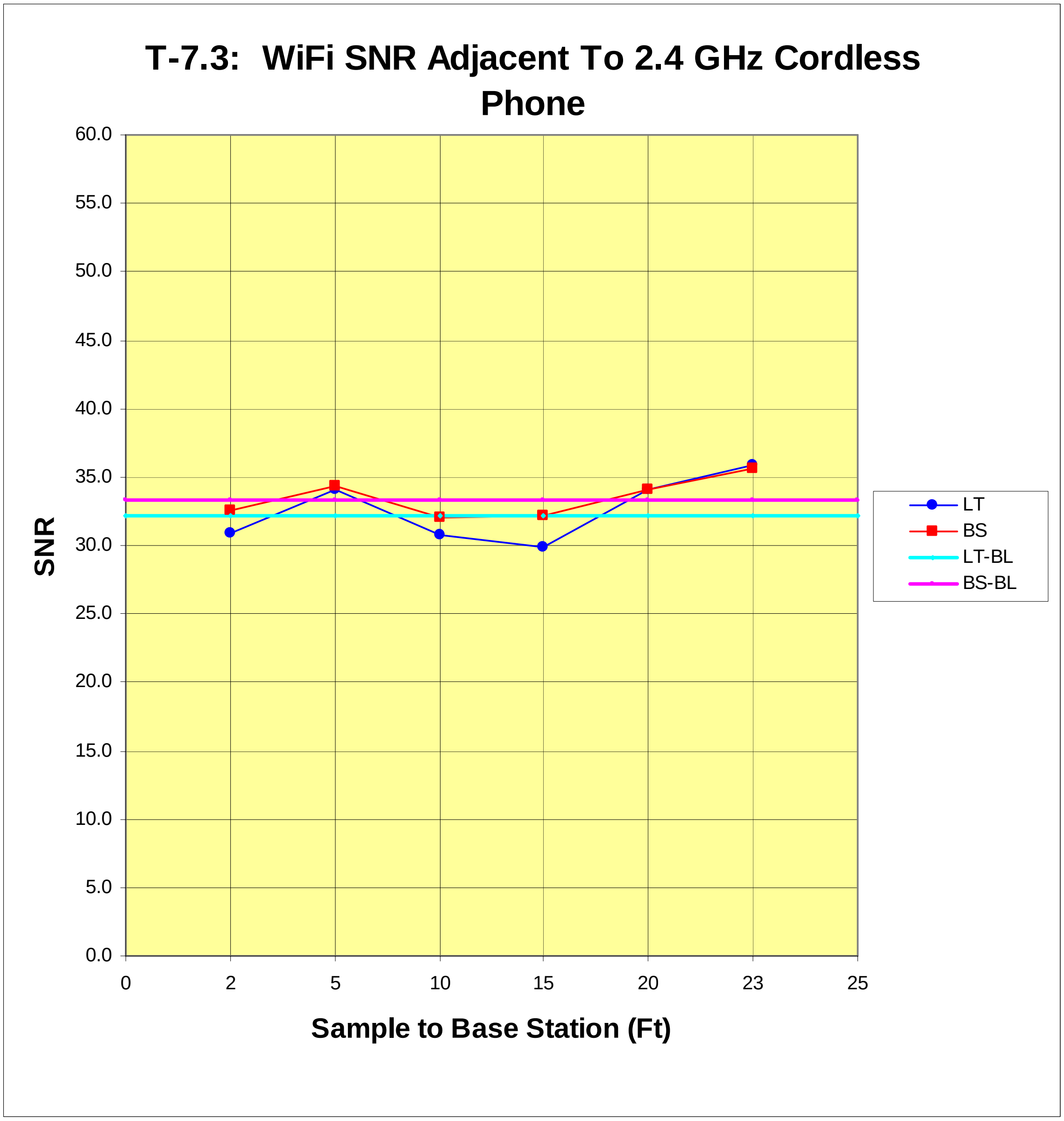

Figure 2-48 Test 7.3: SNR with 2.4 GHz Cordless Phone within Wi-Fi Link

2.7.7.4 Cell Phone

Test 7.4 investigated the effects of a cell phone within the Wi-Fi link. The test sample, shown in the next figure, was a Motorola StarTAC cell phone using CDMA modulation and subscribed to the Sprint network. The test setup is shown in the next figure. Test results are shown in the follow-on figure. Test and component details are provided in Appendix C. Test results show no significant effects to or from the cell phone. SNR values varied from 0 to 3 points below the baseline values over the range investigated.

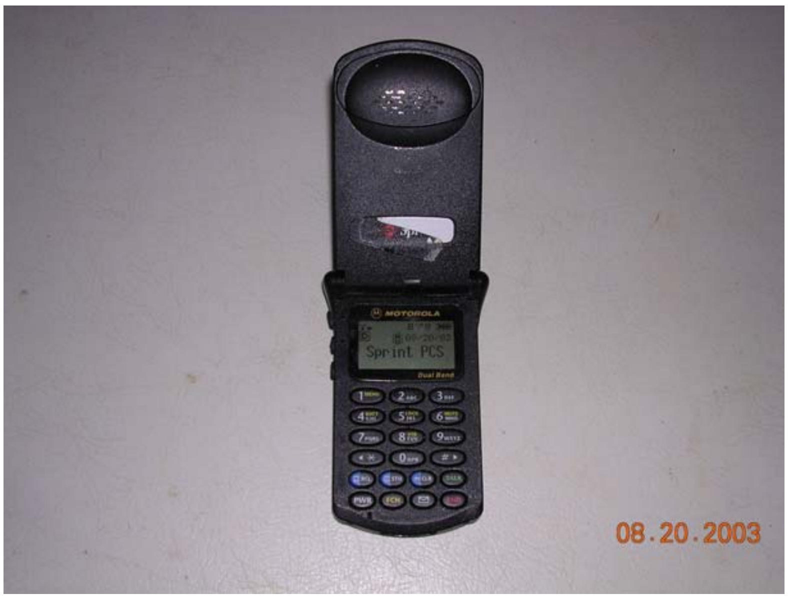

Figure 2-49 Test 7.4: Motorola StarTAC Cell Phone

Figure 2-50 Test 7.4: Setup with Cell Phone within Wi-Fi Link

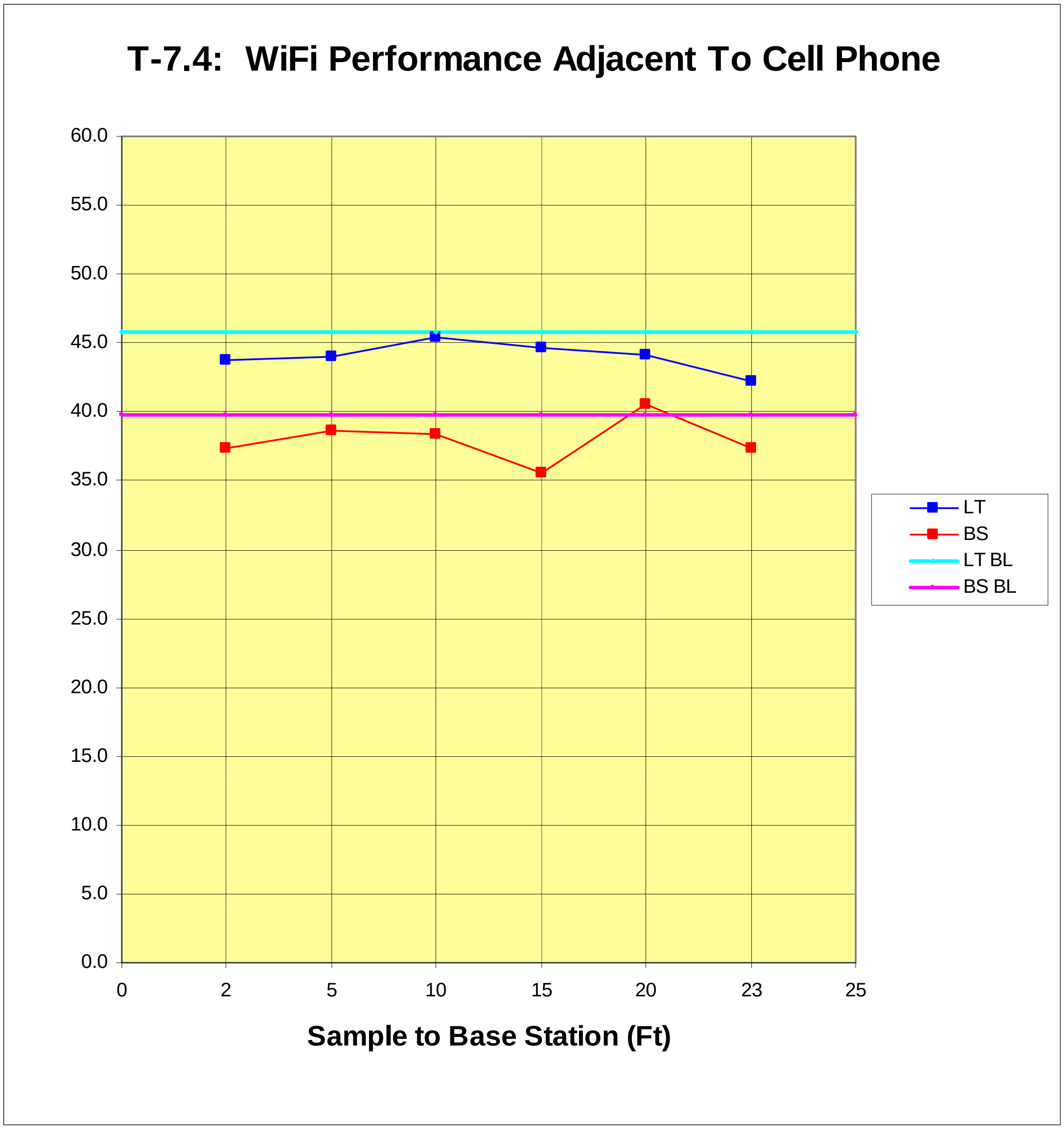

Figure 2-51 Test 7.4: SNR with Cell Phone within Wi-Fi Link

2.7.7.5 Aircraft Nav Radio

Test 7.5 investigated the effects of a hand-held aircraft transceiver operating in the Navigation mode while placed within the Wi-Fi link path. The test component is shown in the following figure. The handheld ICON IC-A22 transceiver was tuned to the Melbourne VOR (110.0 kHz). The testing was conducted in north Melbourne approximately 10 miles from the Melbourne VOR. Test results are shown in the follow-on figure. Test and component details are provided in Appendix C. Test results show the SNR values decreased 2 to 3 points over the range investigated. It was not possible to investigate the full range of distances due to the logistics of receiving a suitable signal. The Nav radial position data (323 bearing from the VOR) was also recorded during the test. No loss or significant variation of the VOR signal attributed to the Wi-Fi was found during the test.

Figure 2-52 Test 7.4: Aircraft Handheld Transceiver

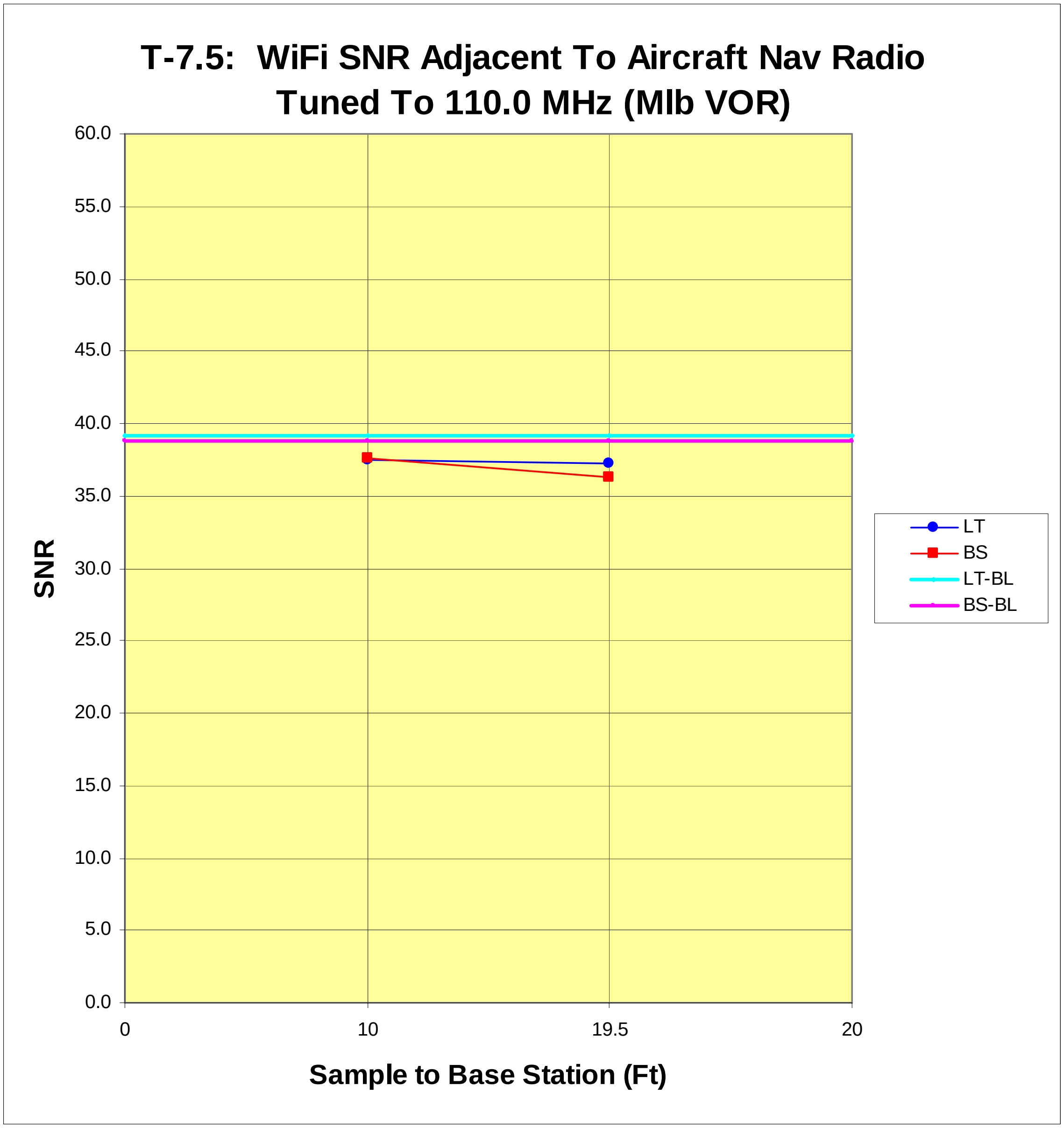

Figure 2-53 Test 7.5: SNR with Aircraft Nav Radio within Wi-Fi Link

2.7.7.6 Aircraft Com Radio

Test 7.6 repeated Test 7.5 with the Transceiver in the Communication mode. The test component is shown in the following figure. The handheld ICOM IC-A22 transceiver was tuned to the Melbourne Automatic Terminal Information System (ATIS) at 132.55 MHz. This continuous broadcast message was monitored for quality while SNR and other data were recorded. The test location was in north Melbourne approximately 10 miles from the ATIS transmitter. Test results are shown in the following figure. Additional test and component details are provided in Appendix C. Test results show no significant effects to, or from, the Com radio. No reduction in radio reception was noted during the test. All testing were in the receive mode only; no transmitting was attempted.

Figure 2-54 Test 7.6: Aircraft Handheld Transceiver in the Com Mode

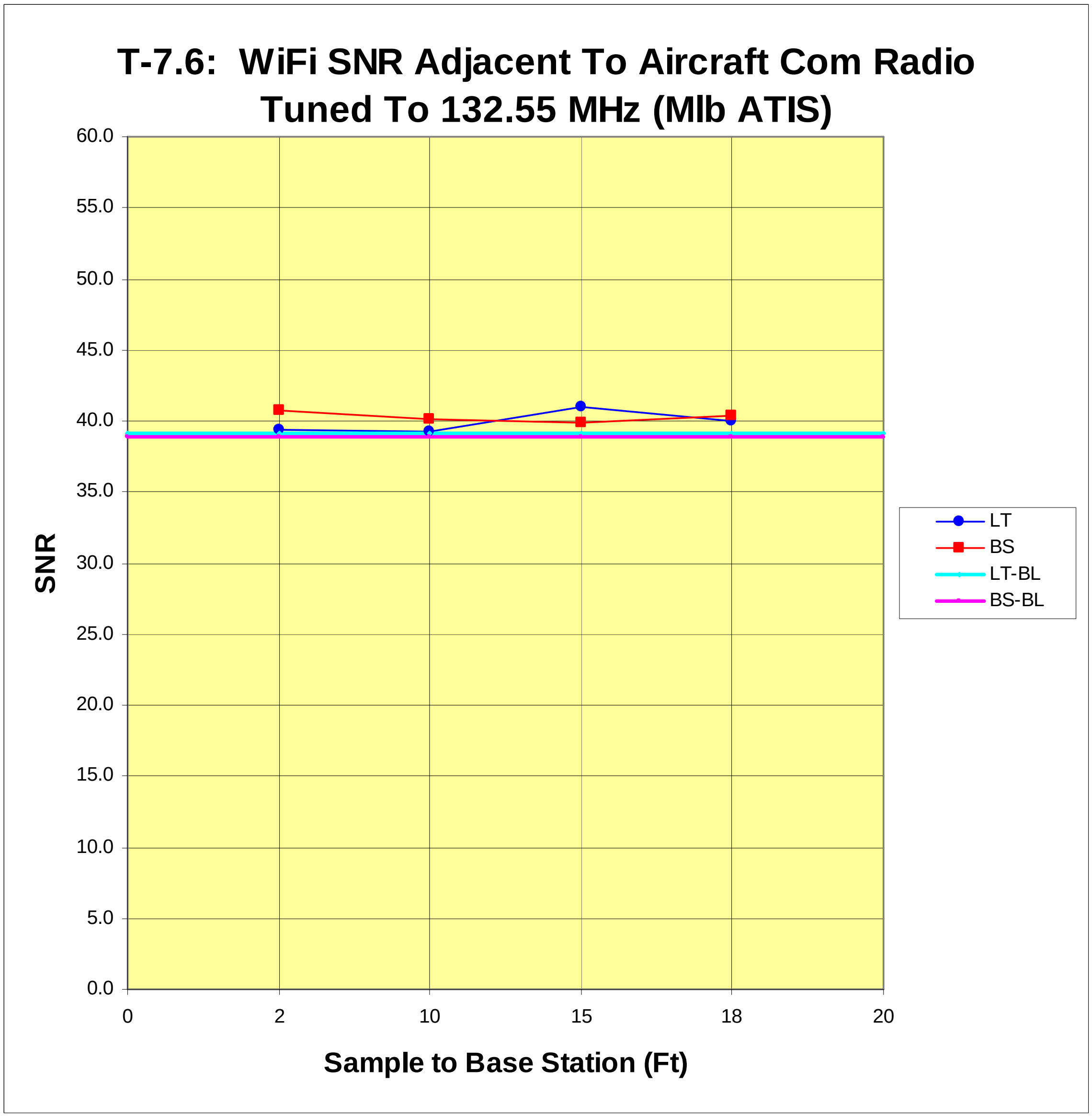

Figure 1-2

Figure 2-55 Test 7.6: SNR with Aircraft Com Radio within Wi-Fi Link

2.7.7.7 GPS

Test 7.7 investigated the effect of a handheld aircraft GPS operating within the Wi-Fi link path. The test component is shown in the following figure. The handheld LowRance AirMap GPS receiver was configured to display Lat/Long. The GPS position data was recorded along with SNR and other data. Test results are shown in the follow-on figure. Additional test and component details are provided in Appendix C. SNR values tracked very closely to the baseline values over the distances of interest. A 4-point dip occurred around 17 feet. This was attributed to multi-path or destructive interference. Lat/Lon values from the GPS varied as follows:

Lat: N28-09.172 to N28-09.176
Lon: W80-40.725 to W80-40.730

Figure 2-56 Test 7.7: Aircraft Handheld GPS

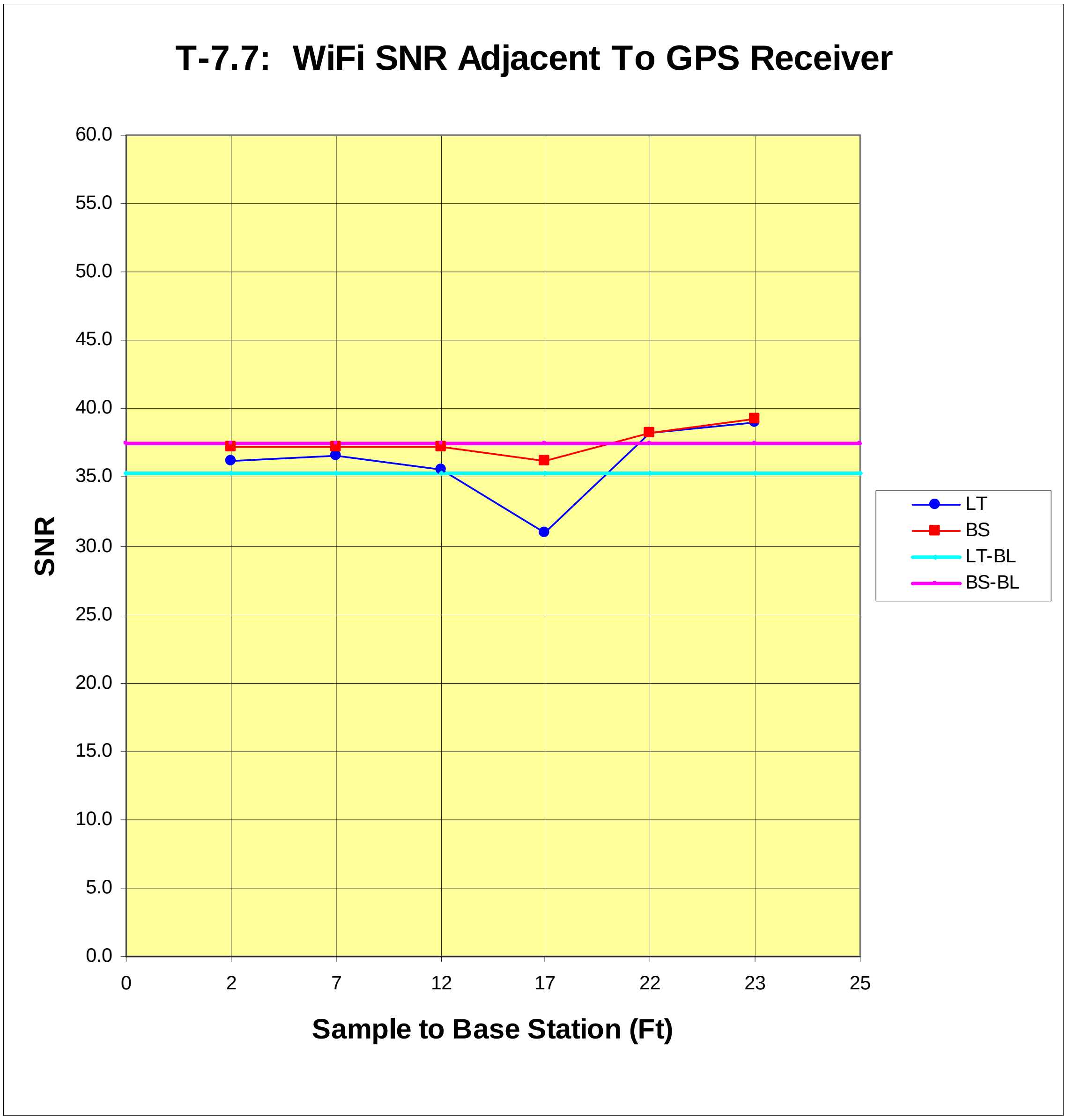

Figure 2-57 Test 7.7: SNR with Aircraft GPS within Wi-Fi Link

2.7.7.8 Iridium Phone

Test 7.8 investigated the effect of a hand-held Iridium satellite phone operating within the Wi-Fi link path. The test setup is shown in the following figure. The handheld Motorola Model MS1-10 was configured to establish a link with the satellite. The phone was then placed at selected locations and SNR and other data were recorded. Test results are shown in the follow-on figure. Test results are shown in the follow-on figure. Test and component details are provided in Appendix C. Base Station SNR was constant with the baseline out to 10 feet where a 5-point dip occurred and then recovered. Laptop SNR data showed a 3-point decrease out to again 10 feet where a 5-point dip occurred followed by a recovery. Test results show no significant effects to, or from, the satellite phone.

Figure 2-58 Test 7.8: Test Setup with Iridium Phone within Wi-Fi Link Path

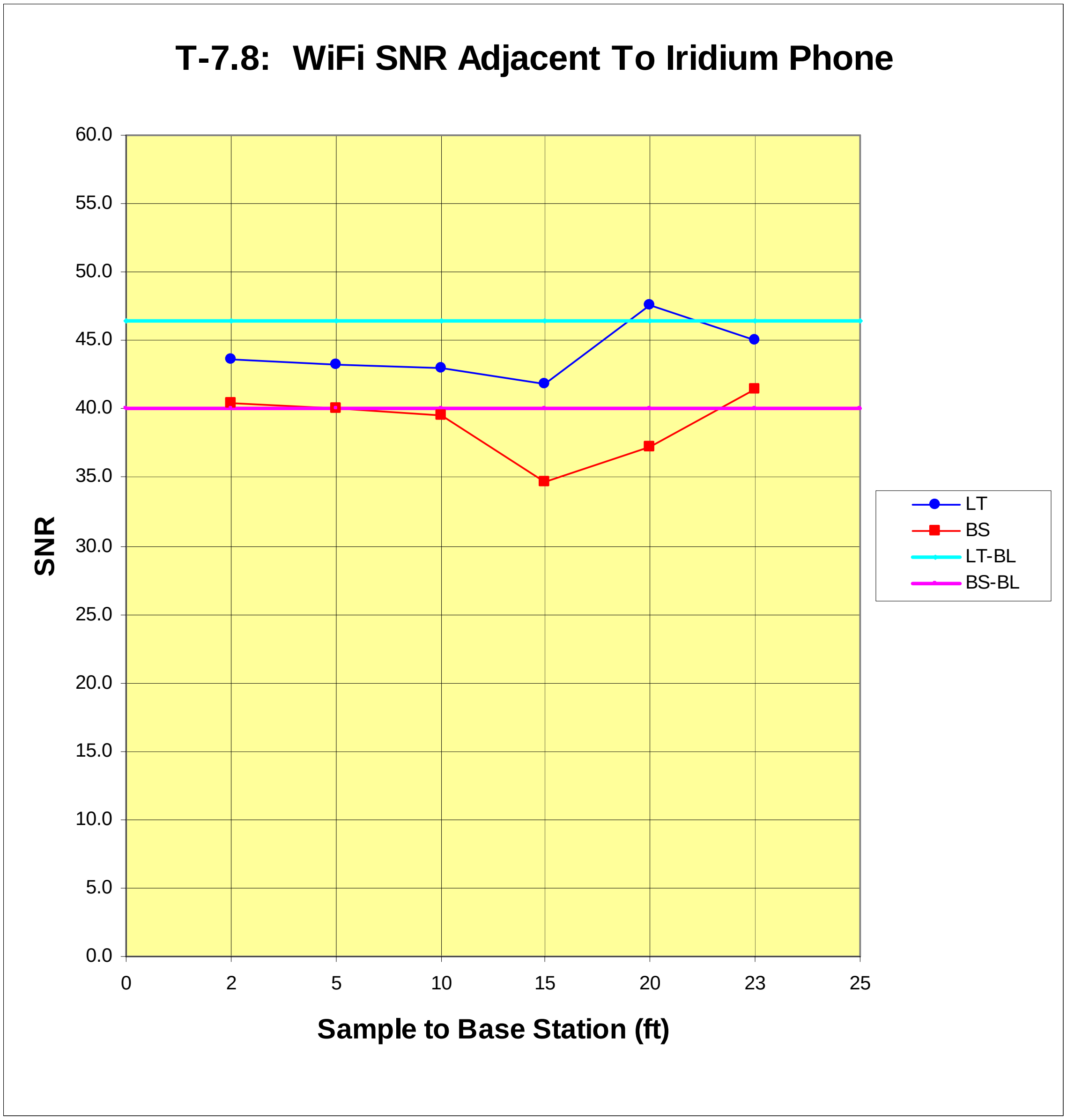

Figure 2-59 Test 7.8: SNR with Iridium Phone within Wi-Fi Link Path

2.7.8 Test 8: Comparison of 802.11b and 802.11g

Test 8.0 was a head-to-head comparison of the 802.11b (Microsoft Base Station) and the 802.11g (D-Link Access Point) systems.

The Base Station and Access Point were placed side by side on a 24-inch high box in the first floor hallway of the EDL (Figure 2-60). Communication links were established between the Base Station (EDL-lab1) and Laptop GB. A second communication link was established between the Access Point (EDL-lab3) and Laptop BH. The Laptops were placed side-by-side on a cart and rolled down the hallway to test locations placed every 10 ft. (Figure 2-61). Link SNR performance for the Base Station was calculated by internal software provided by the manufacturer. Data was recorded at 30-sec intervals for 3-minutes at each location out to 150 ft. An average was calculated for each position. SNR performance versus distance is shown in Figure 2-62 for the Laptop and Base Station out to 160 feet. Overlaid on this figure is the original EDL-lab1 data from Test 5.1 recorded on 4/2/03. There appears to be good overall agreement between the two measurements. This helps validate the assumption that the close proximity of the two units would not cause significant interference.

The Access Point is not shown on this figure since SNR data was not available. The D-Link Utility software provides data rates; however it only provides qualitative indicators of Quality and Performance. Calls to the manufacturer for assistance in correlating these numeric indicators with quantitative performance information were unsuccessful. It is believed that the D-Link numeric indicators are not in any way calibrated, and are meant solely for qualitative use.

Figure 2-60 Base Station (802.11b) and Access Point (802.11g) in EDL Hallway

Figure 2-61 Comparison Testing of Base Station & Access Point @ 10-Ft

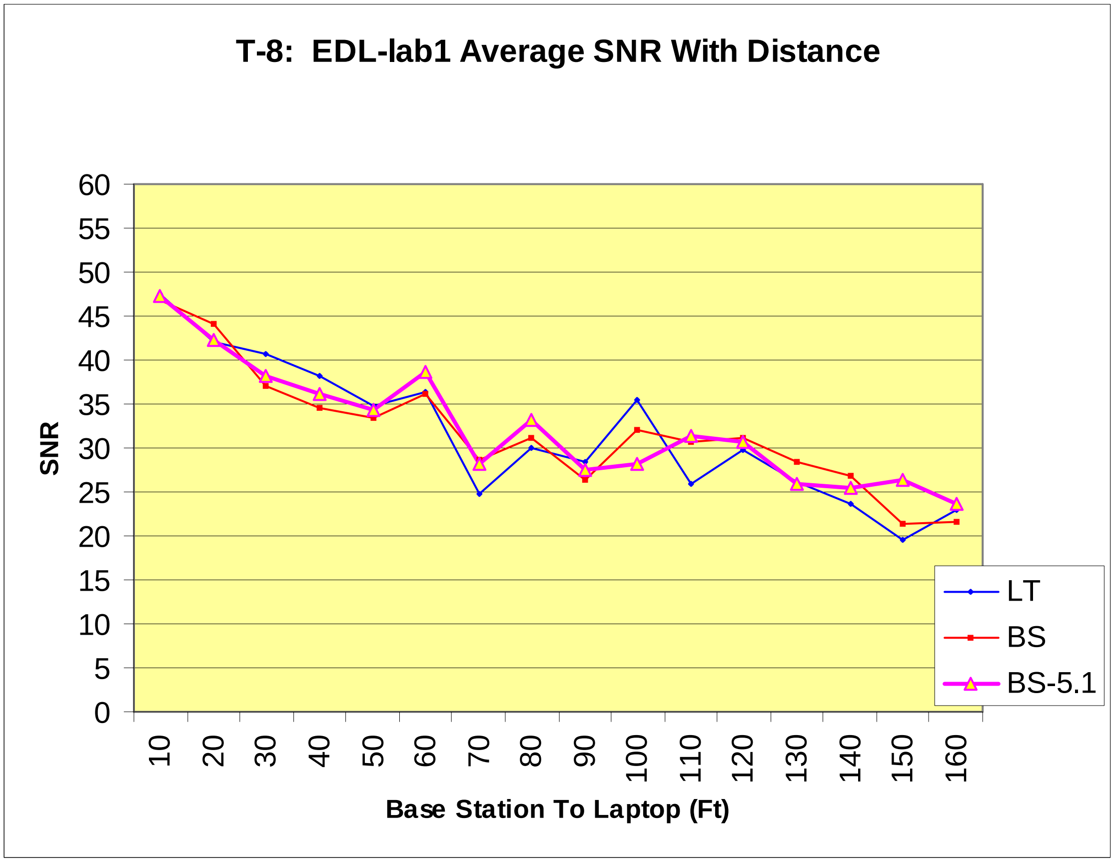

Figure 2-62 Comparison of SNR for EDL-lab1 and Laptop

It was possible to compare data rates directly versus distance for the 802.11b Microsoft Base Station and the 802.11g D-Link Access Point. That average data rates as a function of distance are presented in the following figure. Although the 802.11g Access Point quickly stepped down from its maximum data rate (54 Mbps), it still significantly outperformed the 802.11b system over the entire 160-ft distance investigated.

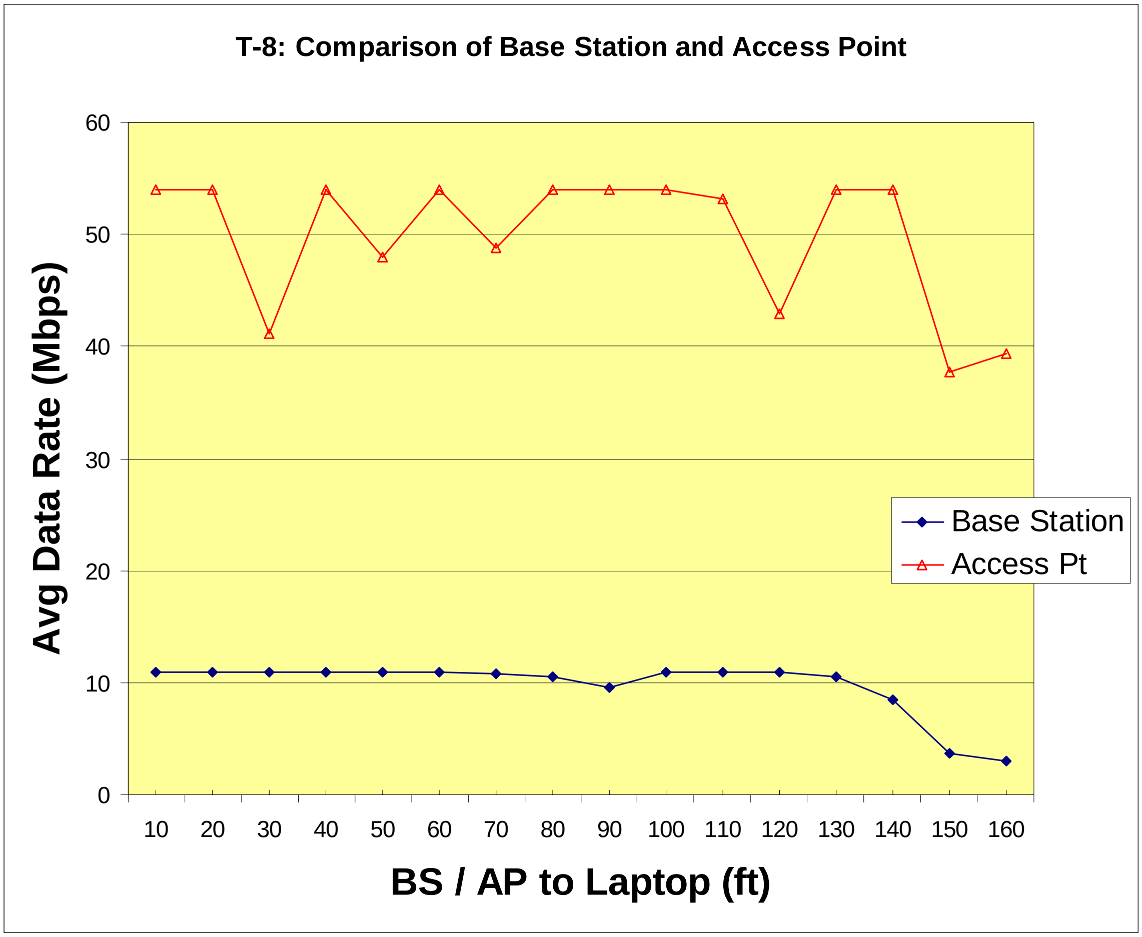

Figure 2-63 Comparison of Data Rates vs. Distance for 802.11b & 802.11g Systems

2.8 REVIEW OF ADVERTISED PERFORMANCE

Wi-Fi testing was conducted to meet the objectives outlined in Section 2.4. Hardware qualification or acceptance was not an objective. However, test data did produce results that can be easily compared to advertised performance values. A short comparison is provided below:

Microsoft MN-500 Wireless Base station

Max users	200	not tested due to lack of
Coverage area	1000 ft^2	equipment
	Range (ft)	
(Open environment)		
11 Mbps	900	not tested since not typical of
5.5 Mbps	1300	office environment
2 or 1 Mbps	1500	
(Closed environment)		
11 Mbps	160	60 to 200
5.5 Mbps	200	210+
2 or 1 Mbps	300	300+

The Microsoft MN-500 meets its advertised key performance parameters.

2.9 WI-FI SECURITY ISSUES

The Achilles heel of Wi-Fi is security. Anyone up to 300 feet away can eavesdrop on Wi-Fi wireless transmissions if they have the proper tools, skills, time, and intent to hack into the transmissions. If they have adequate time to intercept up to 10 million packets, they can break the WEP (Wired Equivalent Privacy) key. Such tools are readily available on the Internet (Air Snort, NetStumbler, etc).

In many installations, hacking is not even necessary because the access points are installed with all security features disabled, just as they are shipped from the factory. No doubt, although some of these non-secured installations are due to overlooked installation steps, many are purposely configured this way to enable anyone within the transmission range to have free access to the Internet through an open Wi-Fi LAN. In some areas, this open configuration is openly promoted and used by "War Chalkers" to enable the public free access to the Internet. ("War Chalking" was discussed in the Phase I RISM report.). Although not tested in the courts, this open access configuration could result in significant liability exposure for companies with such installations if such systems were used for damaging others systems through introducing worms or viruses into the Internet.

The WEP key approach, initially thought to be relatively secure, has instead turned out to provide little or no security against a determined hacker with adequate transmission exposure time. However, WEP protection does appear to provide significant protection for home or small business applications that have little data on their computers worth the time and effort to access. WEP is usually just enough of a nuisance that an unmotivated hacker will just move on to an easier target of opportunity. In short, WEP only keeps honest people honest.

Newer protocols, like Protected Access[7], are being developed and some are currently being marketed in COTS equipment. The 802.1x protocol is also being promoted as a method of securing Wi-Fi better[8]. This technique attempts to verify the user, not just the equipment. The 802.1x protocol itself is not a single authentication method; rather it utilizes Extensible Authentication Protocol (EAP) as its authentication framework.

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[7] http://www.newswireless.net/articles/021123-secure.html
[8] http://www.summitwireless.net/security/wep/wep_vs_bluesocket.htm

2.10 WI-FI SUMMARY AND RECOMMENDATIONS

Wi-Fi experience gained during ECT (Phase 2) has shown that Wi-Fi is a valuable, inexpensive resource for providing mobility while solving the so-called first mile / last mile communication problem. The Wi-Fi industry has matured to a commercial, commodity-based product point, where market share is largely determined just by whoever has the most cost attractive equipment. No doubt, considerable marketplace vendor consolidation will occur over the next year, as profit margins are forced to become smaller and smaller, and economies of scale force vendors to become evermore larger yet fewer in number. As a result, the freedom and portability afforded with Wi-Fi will soon become ubiquitous in the modern Computer/LAN/Internet environment. During the ECT Phase 2 study, the experience level and commercial acceptance of Wi-Fi improved so fast that Wi-Fi access became always available during out-of-town conferences and meetings, thereby permitting easy Internet access and continuation of normal office computer activities (e.g., e-mail, PowerPoint presentation editing, timecard entries over the Internet, etc.)

Although security is still a concern, Wi-Fi in its present configuration using WEP encryption could probably be implemented in certain areas of an access controlled environment like KSC. Where a more secure level is required, equipment has been developed by Harris Corporation and other DOD suppliers that could easily provide additional levels of protection. The Wi-Fi industry is internally working the security issue.

Due to the maturity of the Wi-Fi industry and its ongoing internal development of better security protocols, additional Phase 3 work on Wi-Fi is not needed. However, during Phase 3, industry developments should be monitored. In addition, the experience level with Wi-Fi will continue to grow through daily use of newly introduced Wi-Fi equipment.

3.0 ULTRA WIDEBAND (UWB)

3.1 INTRODUCTION

Ultra Wideband (UWB) wireless technology is the prime candidate for becoming the next step in the continuing evolution of wireless technology. It is potentially well suited for use wherever high-speed data rates (to at least several hundred Mb/s) are desired over ranges up to several hundred meters, especially in locations prone to fading due to multi-path propagation. The fundamental reason UWB wireless can provide performance improvements over existing wireless technologies is that it uses short duration pulses known as *monocycles* to propagate signals over physical distances instead of the sinusoidal carriers used by traditional legacy systems.[9]

Two major UWB wireless technology application areas exist today, addressing communications and radar needs, respectively. This report largely focuses on just UWB communication applications since UWB radar applications will likely not see widespread use within the communication network portions of future Spaceports and Range.[10]

Irregardless of whether the application is communication or radar, nearly all of today's UWB systems derive from the pulse-based techniques first used in earlier radar systems. This is also true irrespective if UWB spectral occupancy is implemented all in one band, or over 5 to 15 sub-bands. In either case, the modulation waveforms currently used in UWB communication systems today have not changed significantly from their first use over 30 years ago in radar systems. As a result of their radar-system heritage, UWB wireless systems still retain many traditional radar capabilities, even when intended solely for communication purposes.

This characteristic capability of UWB communication system technology is expressed by stating that UWB systems are *position-aware;* that is, receiving UWB modulated signals fundamentally requires an inherent, automatic assessment of all the relative distances among all the transmitters and receivers within a UWB wireless network. Coupling communications features simultaneously with position-aware features enables wireless systems based on UWB concepts to provide capabilities that were previously never before possible in traditional wireless communication systems.

In spite of occupying very large bandwidths, UWB is often very benign to existing wireless systems and services. This is fortunate, because the use of ultra wide bandwidths has inherent advantages relative to occupying narrower bandwidths. Specifically, the correlation bandwidth of dense urban and dense structure propagation channels is typically less than 10 MHz over the FCC-authorized UWB frequencies that extend from 3.1 GHz to 10.6 GHz. The use of extremely short-duration bursts, that achieves ultra wideband occupancy over much greater than the correlation bandwidth of

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[9] Moe Z. Win and Robert A. Scholtz, "Ultra-wide Bandwidth Time-Hopping Spread-Spectrum Impulse Radio for Wireless Multiple-Access Communications", IEEE Trans. Comm. Vol. 48, No. 4, April 2000.
[10] UWB radar functions will still likely play a critical role in enhancing *security* around future Spaceports and Ranges; they just will not play any significant role within the *communication networks*.

the channel, completely mitigates the effects of destructive interference (i.e., fading) due to multi-path propagation.[11] Because of this inherent advantage, a high fidelity UWB replacement for FM tactical radios could completely avoid nearly all the fading commonly heard, for example, when operating in dense urban downtown areas and within many office buildings with conventional wireless gear. This is a key advantage for tactical radios based on UWB technology.

In addition to the fade resistance advantages already discussed, UWB also largely renders data compression technology obsolete. The requirement to pack more and more bits into a *limited* bandwidth is largely eliminated with UWB technology since the occupied bandwidth can be selected to be arbitrarily wide with UWB technology, at least up to a regulatory limited bandwidth of 7.5 GHz, or so. By avoiding a need to achieve higher spectral efficiencies, UWB systems avoid the need for data compression and de-compression chip-sets, and inherently eliminate the power consumption/dc power that would otherwise be required to power such chips. UWB also has additional economic advantages. UWB transmitters and receivers do not require all of the oscillators, mixers, filters, and numerous other expensive radio frequency (RF) components required in conventional wireless gear. The end result is that UWB equipment often requires lower-cost components totaling only around ten percent of the cost of the components historically required to implement conventional wireless gear. Likewise, UWB gear can use batteries that are only 10% to 25% of the cost, size, and weight of batteries required for existing wireless battery-powered equipment for a given operating time due to improved power efficiencies of the short-duration transmitted signals, elimination of power-hungry data compression chip-sets, and the elimination of other power-consuming functional blocks.

Because of these numerous economic and performance advantages, UWB radios have clear advantages over existing wireless gear. UWB radios can provide:

- Voice and data communication with selectable degrees of security
- Indoor, through-the-wall, and perimeter security radar functions
- Precise ranging capability to determine the precise distances between objects with real-time tracking to within an inch
- Elimination of data compression requirements to fit data into pre-set narrow bands
- Nearly complete immunity to multi-path propagation, such as encountered in dense, urban areas, simultaneously increasing data throughput as well as avoiding low signal levels due to destructive interference (fading) of received multi-path signals

[11] Correlation bandwidth refers to the bandwidth over which a spectral null is typically correlated and all frequencies fade simultaneously. It is the bandwidth over which a fade exists in, for example, an urban channel. Any signal within this bandwidth is simultaneously lost during fading events, and the fade is said to be ‘correlated’ over this range of frequencies.

With these diverse capabilities, UWB technology can enhance numerous Spaceport and Range disciplines including:

- Wideband operation during a launch event, in spite of considerable multi-path reflections caused by aluminum-based particles in exhausts
- Real-time tracking of high cost assets, with high precision
- Reliable, high-speed, secure wireless voice, data and video transmissions inside buildings
- Personal radar for security system functions for perimeter control
- Radar functions, with through-the-wall sensing to penetrate materials such as brick and concrete to provide more defined images than conventional radar for security sweeps of buildings and cargo areas of tractor trailers

SBIR investigations of UWB technology have also been conducted in coordination with Johnson Space Center to enable in-helmet video transmission in next generation spacesuits.

In short, UWB represents a major shift in terms of implementation capabilities. Further, because of battery life extensions, it is possible to tailor the battery-life to reduce the cost of existing batteries through eliminating materials. With all the benefits, as well as the cost reductions possible, UWB technology is truly a disruptive technology worthy of consideration for use on future Spaceports and Ranges.

3.2 UWB REGULATORY OVERVIEW

Current UWB applications typically use one of two fundamental types of modulations: Time-Hopping (TH) Pulse Position Modulation (PPM) or Bi-phase Pulse Modulation. By current FCC Part 15 rules adopted February 14, 2002, a total of 7500 MHz of unlicensed spectrum is available for UWB communication over 3.1 to 10.6 GHz.[12] The present UWB communication rules specify neither the exact modulation nor waveform shapes that must be used; instead, only the maximum effective isotropic radiated power (EIRP) levels (-41.3 dBm/MHz), the maximum permitted frequency spectrum allocation (3.1 GHz to 10.6 GHz, for emissions above a maximum spectral mask limit of 10 dB down from the peak radiated emission of the complete system, including the antenna), and additional usage specifications (indoors, ac power only) are established. This *laissez faire* approach sets the minimum characteristics necessary to encourage the peaceful co-existence of UWB transmissions among more established narrowband transmissions, while still permitting UWB innovation to continue largely unhindered.[13]

[12] See: 47 CFR Ch. I, Part 15, Subpart F Ultra-Wideband Operation, (10-1-02 Edition). Available from: http://www.gpoaccess.gov/fr/index.html (Retrieved 21 August 2003.)
[13] Unfortunately, as of early August 2003, this inexactness has led to rogue proposals for implementing the IEEE 802.15.3a standard for which not all are truly UWB transmissions. Instead, in order to occupy the necessary bandwidth to be classified legally as UWB, some proposals, using more narrow-band modulation schemes, have merely included pilot tones to occupy enough bandwidth to achieve classification

Because of this legislated freedom, there are at present two approaches used for occupying the allocated 7,500 MHz of unlicensed spectrum. So-called *old UWB* equipment occupies as much of the 7500 MHz bandwidth simultaneously as the electronics and antenna can actually accommodate. In practice, typical bandwidths still span only 2,000 MHz to 4,000 MHz out of the total 7,500 MHz that is permitted when implementing UWB communications using commonly available (and low cost) semiconductor processes.

Reconciliation of the limitations of affordable semiconductor process implementations of UWB communication ICs (integrated circuits), with only a partially filled one-band spectral occupancy, has led to newer proposals, set forth during 2003 at IEEE 802.15.3a standards Task Group 3A (TG3a) meetings to improve UWB spectral efficiency. These proposals recognize the inability of current generation low-cost hardware to occupy 7500 MHz of bandwidth simultaneously by instead dividing this UWB spectrum into multiple sub-bands. This sub-banded approach is now being called *new UWB* by several vendors.[14] Various numbers of sub-bands are proposed for meeting the proposed 802.15.3a specifications, ranging from 5 sub-bands up to 15 sub-bands.[15]

Regardless of the exact number of sub-bands ultimately selected, there are many advantages to sub-banding the allocated UWB spectrum. The semiconductor processes that can supply less-expensive solutions, usable only over the lower sub-bands (e.g., CMOS or SiGe), can still be used. Then, as semiconductor-processing technology improves and/or processing costs drop for higher performance processes, the higher sub-bands can subsequently be occupied. Likewise, specific sub-bands that may cause interference in particular locations can simply be turned OFF in *new UWB*. For example, spectrum in and around 5.5 GHz, falling in sub-band 2 of *new UWB*, is also used by recently introduced IEEE 802.11a standard wireless Ethernet (Wi-Fi) hardware that runs at 54 Mb/s. For locations where this 5.5 GHz spectrum is occupied by Wi-Fi hardware, the newer sub-banded UWB approach would elegantly allow simply avoiding sub-band 2, thereby improving the peaceful coexistence of UWB among narrowband wireless legacy systems. An additional advantage would be the possibility of running multiple (i.e., perhaps up to 4 or 5, or possibly even up to 14 or 15) *piconets* in the same local area through utilizing a different UWB sub-band for each *piconet*.

Among the major companies, there is still not consensus on how best to provide IEEE 802.15.3a implementations that utilize the Part 15 allocated bandwidth, whether through sub-banding, or through using but one band. In late July 2003, fifteen of the major UWB companies combined their approaches and merged the Intel-led multi-band approach with the Texas Instruments' led multi-band approach through settling on one common multi-

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(technically) as UWB transmissions and which accomplish little else, adding no performance enhancements.

[14] No doubt a different moniker will arise shortly in place of *new UWB*, as even newer UWB advances occur.

[15] As of the writing of this report (August 2003), no resolution of the number of sub-bands ranging from 1 to 5 to 15 has occurred.

band approach and establishing the Multiband-OFDM (Orthogonal Frequency Division Multiplexing) Alliance (MBOA). The major members of the MBOA include Texas Instruments (TI), Staccato (formerly Discrete Time), General Atomics, Time-Domain, Intel, Panasonic, Mitsubishi, Philips, and Samsung. Still proposing a single-band approach, at odds with the approach proposed by the MBOA, are XtremeSpectrum, Motorola, STMicroelectronics, Communications Research Lab, the University of Minnesota, and ParthusCeva. At least two of the single-band proponents, XtremeSpectrum and STMicroelectronics, are proposing CDMA (Code Division Multiple Access) in addition to Bi-Phase Pulse modulation.[16]

A series of meetings were held by the FCC in early August 2003 to collect information on the two opposing camp's viewpoints in an attempt to reach consensus on the best implementation to endorse for occupying the 7500 MHz of allocated Part 15 UWB bandwidth. At the present time (i.e., late August 2003 through early September 2003), no final decision has been made by the FCC as to which proposal to endorse.[17] Until a formal decision is made, reaching an industry-wide consensus for standardizing UWB communication links for WPAN/WLAN applications similar to Wi-Fi will likely not occur. Because of this, most UWB chipset developments have been placed on hold, awaiting a final FCC decision.

3.3 UWB TECHNOLOGY OVERVIEW

UWB communication systems use very low power (Part 15 levels are 5 mW or less), unlicensed, very short duration (< 2 ns, typically 10 to 1000 ps) UWB pulses at repetition rates from 10 to 40 MHz. Centered at a typical center frequency of 2 GHz, first-generation UWB typical system occupied 1.4 GHz. To avoid interfering with GPS signals and other low-power signals below 2 GHz, newer UWB systems, in compliance with current Part 15 UWB requirements, now occupy 3.1 to 10.6 GHz, either in one band, or within several sub-bands.

Because the pulses are pseudo-randomly (PN) shifted in time, transmitted signals resemble white noise to narrowband, conventional receivers. Because of their wideband, low-power characteristic, UWB systems typically co-exist with existing narrowband communication systems, without causing significant interference. Likewise, because of their high processing gains of 30 dB or better due to occupying wide bandwidths, noise rejection performance of UWB systems is superior to that seen in narrowband systems. Since the short duration pulses provide excellent multi-path immunity, the pronounced fades seen within buildings, or around a launch pad, with conventional narrowband systems are avoided. The use of short pulses enhances communication reliability of wireless LANs and other systems using UWB technology. In addition, because of the

[16] Outside Plant Magazine, August 7, 2003, http://www.ospmag.com/op_enl/inside_scoop.htm, retrieved 25 August 2003.
[17] Patrick Mannion and Robert Keenan, *"Samsung taps Staccato for wireless personal nets,"* Electronic Engineering Times, August 18, 2003.

precise timing inherent from the time-modulated characteristics, precise position location functions are inherently features of UWB.

For a given range, limited mostly by peak powers, UWB systems provide an especially attractive solution for portable, battery-powered applications. Because they employ pulses, the average power is extremely low (5 mW, or less), whereas the range associated with the systems is more like that seen for transmitter powers of 30 dB or so higher, as associated with their peak transmitter powers. In other words, a 5 mW average power signal is equal to 6.98 dBm; a peak power of 30 dB higher is equal to 36.98 dBm, or, in terms of Watts, 5 Watts. So, for the battery drain associated with a 5 mW transmitter, the effective range for a UWB system is more like that of a 5 Watt transmitter. This equates to a lessened load on batteries, and longer battery life for a fixed size battery.

Put another way, whereas a tactical radio might have 90 minutes of talk time on a typical battery, if UWB technology were used instead, talk time, *ceteris paribus*, would approach tens up to hundreds of hours for the same battery charge. Alternately, for a given talk-time, the size of the phone and the cost of the tactical radio could be greatly reduced. Whereas battery technology is mature, and greatly increased battery capacity is not feasible with known battery chemistries, UWB modulation could provide the equivalent effect of a disruptive technological breakthrough in battery technology for implementing a new generation of body-worn, battery-powered communications gear.

3.4 UWB DESCRIPTION

The history of UWB dates to the earliest days of radio, and to even before radio was called radio, back to when radio was first called *wireless*.[18] Recent advances in digital processing have made it possible to re-think the fundamental trades long used for implementing radios, allowing improvements over the trades when analog circuits were the sole means by which to fashion communication system building blocks. With a fresh re-thinking of communication system implementations arising with UWB technology, it becomes possible to gain significant advantages over previous communication systems implementations, while simultaneously reducing implementation complexity, physical volume, and power consumption.

How is this re-thinking of implementation details, long established by practice, possible? It is possible because UWB communication is simply traditional radio or wireless technology with a different choice of ranked importance of the variables than what has traditionally been chosen. Specifically, UWB communication systems trade pulse shortness, thereby gaining high peak powers, in exchange for two other variables:

1.) *Bandwidth* (which is increased in UWB due to the short duration of the pulses), and
2.) *Signal to noise ratios* of individual pulses (which are decreased in UWB, thereby requiring correlation to combine coherent pulse energies coherently, while gaining an advantage over noise powers that only can combine non-coherently, being uncorrelated.)

Some refer to UWB communication as *impulse radio*. Others see it as simply being traditional radar modulation used for communication purposes. Both viewpoints are technically correct.

With a re-thinking of the rules that have governed radio design for so long, UWB technology enables new communication systems to be created with higher performance levels than have ever before been possible.

[18] Terrence W. Barrett, *History of UltraWideBand (UWB) Radar & Communications: Pioneers and Innovators*, Progress in Electromagnetics Symposium 2000 (PIERS2000), Cambridge, MA, July 2003. See: http://www.ntia.doc.gov/osmhome/uwbtestplan/barret_history_(piersw-figs).pdf (Retrieved 19 August 2003.)

3.4.1 UWB Vendor Survey

To understand the range of possibilities inherent with UWB technology, it is worthwhile to explore first the applications being investigated today, prior to tabulating current UWB work by vendor. These possibilities include:

> **Fade-free Tactical Radios:** High-bandwidth tactical radios, providing video and voice, with position-aware features for tracking position in real-time while also providing communication data links.
>
> **Localizers:** Devices for enabling the real-time tracking location of high-value items to within centimeters on assembly area floors independent of GPS signals that typically are unable to penetrate buildings.
>
> **Cable-HDTV Upgrades:** Both wireless and wired possibilities exist for UWB technology. For example, shown under Pulse~link is a wired UWB application, enabling the emergence of HDTV overlaid onto existing cable-TV service while eliminating the obsolescence of existing cable-TV equipment.
>
> **Perimeter radars:** Protection of high-value items through detecting intrusion of people or small robotic instruments.
>
> **Long Battery-life Portable Wireless Apparatus:** The efficiency of UWB transmitters can increase the effectiveness of existing battery technology.
>
> **UWB Chipsets:** Fabless semiconductor designers are at work, designing the core chipsets needed by all UWB product designers.

Clearly, this set of possibilities will grow as UWB technology matures, and more possibilities are envisioned. Today, UWB technology is still in its infancy.

In addition to the vendors tabulated in Table 1.2.1, considerable original work has also been done at national laboratories and universities around the United States (e.g., LLNL (Lawrence Livermore National Laboratory), University of Southern California, Clemson University, etc.). Original work has also been done at foreign facilities, especially in the Soviet Union/Russian Federation, Singapore, and China. Despite the international development of UWB technology, this report primarily focuses on just work and products that have either been performed or sold within the United States within the private sector. This is because UWB is a dual-use communication technology, and only companies with a significant presence in the United States will likely support the creation of future Spaceport and Range communication networks. Only these companies have been tabulated in Table 1.2.1, which lists the major UWB vendors active in the UWB market within the US over the last few years.

Table 3-1 UWB Vendors & Technical Approaches (Summer 2003)

Company	Location	Modulation	Products	Status
Aether Wire & Location, Inc. www.aetherwire.com/	Sunnyvale, CA	Pairs of positive and negative TH-PPM pulses called *doublets*	Pager-sized localizers & comm. devices.	**Founded 1991, conducted two years of self-funded R&D. First round of private financing in 1993. Developed first chips in 1.2 micron double-poly CMOS with Orbit Semiconductor in July 1994. $1.8M DARPA grant in 1998. First UWB patent in 1998. Puts spectral nulls where needed (e.g., GPS bands) without filtering through adjusting the spacing between positive and negative pulses. Typically, Aether Wire UWB systems are non-coherent at RF frequencies.**
Alereon, Inc.	Austin, TX	Multi-Band TH-PPM	UWB chips	Founded by former Time-Domain Corporation executives; company was first announced August 25, 2003. (Not to be confused with AMD's 1999 K7 microprocessor chip that was also named Alereon.) Has taken over development of the 802.15.3a chipset from Time Domain Corporation known as PulsON 300 or P300.
Cellonics http://www.cellonics.com/index.htm	Singapore	Direct PPM UWB through non-linear upconversion without any VCO or mixer required.	Pulse-based Neural Nets. Non-linear UWB processing cells are based on biological analogies.	Founded Jan 1, 2000. First round VC financing May 2000. Holds US patent awarded on first basis (no prior art.) Very inexpensive UWB transmitters available now (Aug 2003). Simplified carrier-rate decoding modules are also available.

Company	Location	Modulation	Products	Status
Discrete Time Communications	San Diego, CA	Unknown	Fabless CMOS ICs for UWB	First ICs were planned Q1 2004; Staccato Communications acquired Discrete Time Communications
Fantasma	San Diego, CA	Unknown	None	$11.6M first round VC funding in January 2000. Unable to raise 2nd round VC funding; assets purchased by Pulse~link in May 2001. Some senior staff joined Discrete Time Communications.
Farr Research, Inc. www.farr-research.com	Albuquerque, NM	Products to support all times of UWB modulation	UWB antennas, passive UWB components, time-domain antenna ranges, TEM sensors, Electronic Warfare (EW) antennas for using Marx Generators (400 kV pulses)	Numerous UWB antennas and antenna-related products spanning 150 MHz to 20 GHz are available. A catalog of products is available. Major products include collapsible and solid Impulse Radiating Antennas (IRAs), and calibrated TEM (Transverse Electro-Magnetic) wave sensors. UWB antennas for fixed, parachuted, space, and terrestrial uses are available. Much research is conducted with the U.S. Army Space & Missile Defense Command and with Phillips Laboratory, Kirtland AFB, NM.
Furaxa	Orinda, CA	Various UWB modulations through generating UWB pulses with programmable amplitude, position, & duration	Pulser Sampler ICs based on Libove Gates	Libove Gate architecture provides 4+ GHz repetition rate vs. only 250 MHz in earlier Gilbert Cell or Schottky Bridge + step recovery diode (SRD) pulser sampler architectures. Programmable UWB feature permits changing modulation details to meet evolving or new FCC rule changes ‘on the fly.’

Company	Location	Modulation	Products	Status
General Atomics	San Diego, CA	Multi-band OFDM (Spectral Keying^{tm})	480 Mb/s IAW IEEE 802.15.3a	**Founded in 1955. Photonics division is assigned responsibility for developing UWB. Teamed with Philips, to use Philips QuBIC semiconductor processes based on their own Spectral Keying^{tm} technology.**
General Electric http://www.crd.ge.com/	US, India, China	Various UWB modulations	Delay-hopped transmitted reference UWB comm.	GE Global Research has 2,000 researchers working in three research labs in the US, India, and China.
Harris Corporation (Government Communications Systems)	Palm Bay, FL	Bi-Phase Pulse	UWB defense products	Teamed with XSI, and uses their chipsets in producing UWB products for defense applications.
Intel (Intel Architecture Labs, (IAL))	Hillsboro, OR	2-PAM with high PRF	LAN/PAN applications. Presumably will ultimately support IEEE 802.15.3a.	Focused on MAC, and data transport issues at present, placing less emphasis on PHY layer than seen with many other UWB companies. Likely to depend on just acquiring a start-up to acquire a complete PHY layer capability once UWB standards mature and stabilize. Potential candidates would be Staccato or perhaps XSI. See: www.intel.com/technology/itj/q22001/articles/art_4.htm
I-tech	Slovenia	Unknown	Tx/Rx	Products available now.

Company	Location	Modulation	Products	Status
Motorola (Semiconductor Products Sector)	Austin, TX	Bi-Phase Pulse	UWB consumer electronics & computing market products (e.g., WPANs IAW IEEE 802.15.3a) *(planned)*	Teamed with XtremeSpectrum on March 10, 2003 to produce UWB consumer products using XSI's UWB Trinity^{tm} chipsets.
Multispectral Solutions, Inc. (MSSI)	Germantown, MD	FDM-TDMA UWB	Defense (Military) in comm., radar, geo-positioning areas (various). Tactical (1-2 km) as well as strategic (>100 km) UWB systems.	Founded 1988. Has developed UWB handheld transceivers, UWB radar altimeter, UWB sources, and UWB intrusion detectors. Has won over 60 UWB contract awards. Wireless LPI LPD intercoms/headsets (WICS) transitioned to production in July 2003. Typically, MSSI's UWB systems are non-coherent at RF frequencies.

Company	Location	Modulation	Products	Status
ParthusCeva, Inc.	San Jose, CA. Dublin, Ireland (Parthus) for RF technology + Santa Clara, CA (Ceva) for DSP cores	DS-spread pulse signaling from 3.85 to 7.7 GHz with bi-orthogonal M-ary symbols constructed using ternary Golay-Hadamard sequences, in combination with Reed-Solomon and convolutional error-control coding	**55 to 980 Mb/s (proposed)**	**Parthus Technologies PLC merged with Ceva, Inc. on September 26, 2002 upon a shareholder vote to merge the two operations. (Ceva, Inc. was formerly a subsidiary of US firm DSP Group, Inc.)** **ParthusCeva, Inc. ownership: DSP Group (fabless semiconductor company) owns 50.1%; Parthus owns 49.9%.**
Royal Philips Electronics	Amsterdam, the Netherlands	Multi-band OFDM	**Up to 480 Mb/s UWB chipsets IAW IEEE 802.15.3a**	Based on Philips' QUBiC semiconductor processes (e.g., QuBIC3 is a low-cost 0.5 micron 70 GHz f_{max} silicon BiCMOS process). Using license of General Atomics' spectral keying technology (i.e., multi-band OFDM UWB).
Pulse~link	San Diego, CA	MPEG DVD transport over UWB over wireline	UWB at 400 Mb/s up to 10 meters, 7 Mb/s up to 100 meters, both over wireline.	Founded June 2000 in Panama City, FL. Moved to San Diego, CA with purchase of Fantasma's assets. First to demonstrate UWB over wired media. Intends to be *the* HDTV CATV upgrade provider by 2005. Developing a very large UWB patent portfolio.
Pulsicom	Israel	Unknown	Unknown	Intel Forum, Oct 11, 2001

Company	Location	Modulation	Products	Status
Samsung Electronics Co., Ltd.	Korea	Multi-band OFDM	480 Mb/s UWB consumer, mobile, & computing PAN products IAW IEEE 802.15.3a	Partnered with Staccato to use Staccato's ICs. (Press release 12 August 2003)
Skycross, Inc. www.skycross.com/	Melbourne, FL	Products to support all times of UWB modulation	UWB Antennas	Has several designs for meeting UWB needs. Early products achieved operating bandwidths over just 3.1 to 6.0 GHz, as a sub-set of the current 3.1 to 10.6 GHz Part 15 regulations. Skycross holds a significant meanderline antenna patent portfolio (much of which is from BAE) that can achieve extended UWB-sized bandwidths while keeping physical antenna volumes small.
Staccato Communications	San Diego, CA	Multi-band OFDM	CMOS UWB ICs.	A fabless producer of UWB ICs. Formerly was Discrete Time Communications.
STMicroelectronics	Multiple locations; multiple countries	Position & polarity modulation with convolutional or turbo error-control coding, occupying 3 to 7 GHz	62.5 to 500 Mbps UWB ICs (proposed)	40,000 employees in 27 countries. Company was formed in June 1987 as a result of a merger between SGS Microelettronica of Italy and Thomson Semiconducteurs of France. Invested $977.9M (15.4% of revenues) in R&D in 2001.

Company	Location	Modulation	Products	Status
Texas Instruments	Dallas, TX	Multi-band 128-tone OFDM using 528-MHz bands and QPSK for the tone modulation	55 to 480 Mbps (proposed)	Patents currently exist for this PHY approach; some licensing workarounds will be needed if this proposed modulation is selected as the 802.15.3a standard.
Time-Domain Corporation (TDC)	Huntsville, AL	TH-PPM (positive pulses, only)	UWB Chipsets, Radarvision[tm] Through-wall radar, Eval Kits.	Shipping Evaluation Kits, Radarvision[tm] units. Typically, TDC UWB systems are coherent at RF frequencies, providing performance advantages.
Taiyo Yuden (TRDA)	Tokyo, Japan; USA: Chicago, San Jose, San Marcos, Dallas, & Raleigh	Bi-phase Pulse	UWB modules (planned)	**TRDA is the USA-based research and development arm of Taiyo Yuden. Teamed with XSI to produce UWB modules.**
WisAir www.wisair.com/	Tel-Aviv, Israel	Multi-band variable rate PHY for IEEE 802.15.3a	20 to 125 Mb/s UBLink[tm] chipsets and antennas. Evaluation toolkit (available June 1, 2003	**UBLink[tm] chips support 1-15 sub-bands selectable out of 30. WisAir successfully demonstrated transport of multiple HDTV streams using UWB on June 20, 2003 in Tokyo, Japan.**

Company	Location	Modulation	Products	Status
XtremeSpectrum Incorporated (XSI) www.xtremespectrum.com/	Vienna, VA; bay area, CA	Bi-Phase Pulse	UWB Chipsets (Trinity^{tm})	**Founded 1998, and produced many of the early UWB chipsets used for defense applications. Trinity chipset launched June 2002. Evaluation Kit & UWB chips were due out July 2003, but slipped.** **XSI is teamed with Harris Corporation for defense applications. XSI teamed with TRDA/Taiyo Yuden on January 9, 2003 to produce UWB modules. XSI teamed with Motorola March 10, 2003 to produce UWB products.**

3.5 BASIC UWB THEORY

The following introduces UWB theory starting with the simplest monocycle representation that incorporates all the fundamentals necessary for understanding basic UWB communication principles. Then, additional levels of detail are added as necessary for building on these principles for introducing more esoteric UWB concepts. The general approach chosen is to start with the representation of a monocycle seen at the output of a receive antenna, and to base all the correlation calculations on this most commonly used representation of a received monocycle. As UWB theory is expanded, different correlation templates are derived.

The preliminary introduction, in turn, is followed by a discussion of higher levels of complexity in the monocycle waveform itself, through examining the monocycle waveform (1) as it is produced as a Gaussian current pulse, (2) as it is transmitted from the transmitter antenna, (3) as it is received through the receive antenna, and (4) as it becomes a current pulse that is processed by the receiver. Understanding this time-domain complexity leads to the recognition of a *theory of relativity* as applied to monocycles. Namely, an observed monocycle changes its time-domain shape depending upon where the particular UWB monocycle is observed in a UWB system.[19]

Comparisons of monocycles with other solitary waves (solitons, wavelets) are also introduced where necessary for comparing and contrasting the spectral characteristics of these waves with monocycles.

Likewise a new technology application is developed for detecting UWB transmissions without requiring any *a priori* knowledge of the parameters of the UWB monocycles to be detected. This new technology application is based on wavelets, and provides a new, powerful method for detecting otherwise difficult-to-detect, illicit, or otherwise covert, UWB transmitters, such as used for electronic bugging purposes.

3.5.1 Simplified Monocycle Introduction

Traditional wireless radio transmissions have utilized sinusoidal waveforms since the 1920's for a variety of reasons. Perhaps the most compelling reason has been that sinusoidal waveforms are very amenable to mathematical modeling. Another reason is that, because of this ease of analysis, sinusoidal waveforms also make the analytical task easier for reducing occupied communication system bandwidths to near the minimum Nyquist-limit bandwidths required for such transmissions, thereby increasing spectral occupancy efficiency and permitting more transmitters to occupy the airwaves without causing one another harmful interference. When components are barely capable of achieving minimum bandwidths, there is some merit in this approach.

[19] Since this report is primarily focused on communications systems, UWB theory is not developed in this report beyond that which is required for understanding UWB communication principles. Further theoretical investigations, into UWB ground penetration and through-wall radar monocycle principles, remain topics for future research.

What happens, though, if traditional design trades are re-ranked by a new set of priorities? Unlike traditional wireless signals, UWB transmissions do not attempt to reduce their occupied bandwidth. Instead, UWB transmissions work to increase their occupied bandwidths to values much greater than the required minimums. This trade is intentionally made for improving communication link performance while permitting lower average transmitter power levels. UWB communication therefore permits, and even requires, re-selection of design trade choices that have been long been traditional.

The basic UWB waveform is an approximation of a Gaussian pulse. Specifically, UWB radio systems use Time-Hopping (TH) nanosecond (or shorter) duration Pulse Position Modulated (PPM) pulses known as monocycles to propagate signals over physical distances instead of the sinusoidal carriers used by most radio systems. A typical time-domain representation of a UWB monocycle waveform pulse is shown in Figure 3-1 as a received monocycle, and is simply a first-order approximation to an ideal Gaussian pulse waveform. This particular representation of a waveform assumes no channel distortions, and represents an observation of an idealized UWB monocycle, *p(t)*, observed approximately six inches from an appropriately ultra-wideband transmitting antenna, at the output of a second ultra-wideband receiving antenna, from which it is observed as a received current pulse.[20] There is undershooting on both the leading and trailing edge of this waveform. This particular UWB waveform is based in large part on a typical empirically-selected normalizing monocycle width value, $\tau_n = 0.4472$, selected for a best fit to a particular waveform monocycle by Ramirez-Mireles and Scholtz.[21]

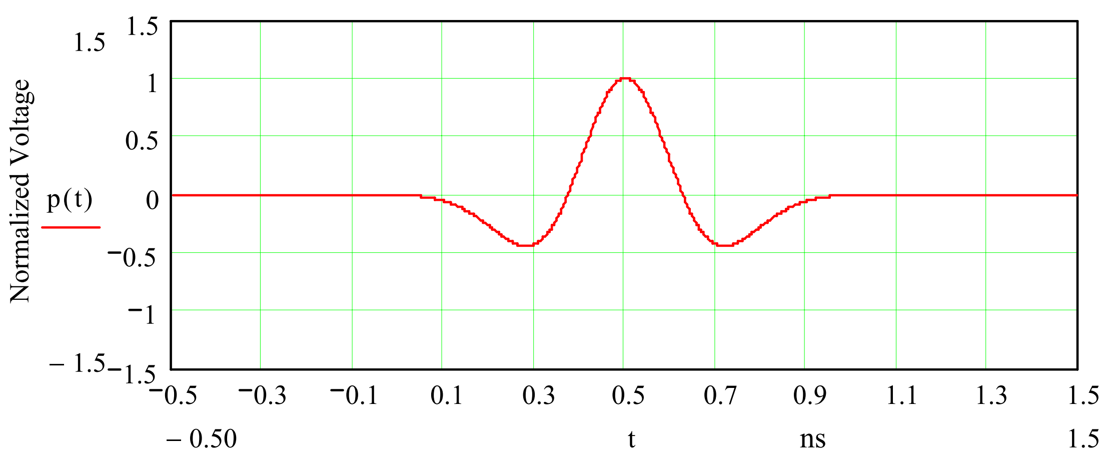

Figure 3-1 A Single TH-PPM Monocycle Pulse

[20] There is an additional level of subtle complexity that will be introduced later in this paper, in which it will be shown that the monocycle waveform discussed here is *not* preserved throughout the UWB system. Rather, the shape, and hence the spectral characteristics, of monocycles differ depending upon where the monocycles are observed.

[21] Fernando Ramirez-Mireles and Robert A. Scholtz, "System Performance Analysis of Impulse Radio Modulation", IEEE Proceedings RAWCON Conference, August 1998. http://ultra.usc.edu/New_Site/publications.html (University of Southern California Ultra Lab).

Mathematically, this monocycle time function shape can be expressed as the following:[22]

$$p(t) := \left[1 - 4\cdot\pi\cdot\left(\frac{t - \tau d}{\tau n}\right)^2\right]\exp\left[-2\pi\cdot\left(\frac{t - \tau d}{\tau n}\right)^2\right]$$

Monocycles provide practical and implementable waveforms that greatly improve data rate versus power consumption trades compared to traditional sinusoidal radio waveforms. For short (fixed) communication distances, monocycles enable communication at very high data rates at very low power consumption. Likewise, monocycles support the determination of relative location information among a network of receivers and transmitters. Monocycle waveforms also can be used to enable precise inspection and geo-location functionality for Ground Penetration radar systems.

Monocycles first arose in non-ground penetration radar applications. One of the first uses was for target discrimination in cluttered environments (e.g., searching for aircraft over ocean expanses, or searching for vehicles embedded within foliage). There were also other early uses for monocycles for achieving aircraft identification through taking time domain responses of radar reflections.[23] The significant fundamental theories for monocycles were derived almost entirely within the context of military radar systems.

In the simplest, earliest radar systems, *individual* monocycles or pulses always had to exceed a threshold for detection; in current radar systems and in even the simplest UWB systems, the sum totals of collections of pulses must always exceed a noise threshold, although individual pulses often are often well below noise thresholds.[24] Monocycles hence support achieving processing gain, similar to that achieved in spread spectrum communication systems. This is true regardless of whether monocycles are used within radar systems or within UWB communication systems. This characteristic also often allows the successful use of lower power levels than would otherwise be possible.

Unlike in fixed radar installations, UWB communication applications are ill suited for use in radio links having significant Doppler shifts. The reason is that determining time references becomes very difficult for deciding bit decisions ‘on the fly’ between ZEROs and ONEs in a continuous running UWB communication link, with closing or separating physical distances changing at high rates. (This will be shown later, while discussing the correlation detection process for demodulating digital data.) This deficiency could be addressed, through the incorporation of more elaborate decoding techniques, but at the expense of worsened complexity in the UWB receiver circuitry. This would negate a key

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[22] Fernando Ramirez-Mireles and Robert A. Scholtz, "System Performance Analysis of Impulse Radio Modulation", IEEE Proceedings RAWCON Conference, August 1998. http://ultra.usc.edu/New_Site/publications.html (University of Southern California Ultra Lab).

[23] C. E. Baum and E. G. Farr, Impulse Radiating Antennas, H. L. Bertoni (eds.), pp. 139-147 in *Ultra-Wideband, Short-Pulse Electromagnetics*, New York, Plenum, 1993.

[24] Mischa Schwartz, *Information Transmission Modulation and Noise, A Unified Approach to Communication Systems,* McGraw-Hill, New York, NY, 1959, p. 409.

advantage of UWB communication systems in the typical communication application, namely, simplicity. In a high Doppler environment, the normal simplicity advantage of UWB radios would be largely lost due to increases in decoding complexity.

3.5.2 Detection of UWB Monocycles

Because correlation is most often used for demodulation of monocycles, there are mathematical properties that monocycle waveforms must absolutely meet in order for convergence and proper detector correlation processor operation to occur in a UWB receiver.[25] Specifically, it is necessary that the function of the UWB monocycle integrated over all time (i.e., its area) be finite, and additionally equal to zero, in order for the correlation integral to converge. Namely, the monocycle waveform requirement is that:

$$A1 := \int_{-\infty}^{\infty} p(t)\,dt$$

must be numerically equal to, and must evaluate to, zero, which it does for the selected *p(t)* function given previously.

Although coherent detection processing is most commonly used in UWB receivers to provide the highest levels of performance, non-coherent processing (at RF) is sometimes also used to lower the recurring costs of UWB hardware for applications where cost matters more than performance.[26] The advantage of coherent detection processing is that an individual UWB monocycle modeled as p(t) can be coherently detected, even when many signals comprise a broadband noise floor that buries the desired monocycle signal in a cacophony of interference. Non-coherent processing, on the other hand, requires higher signal levels, and/or a lessened interference environment for the successful detection of non-coherent monocycles.

[25] Robert A. Scholtz, P. Vijay Kumar, and Carlos J. Corrada-Bravo, "Signal Design for Ultra-wideband Radio", Sequences and Their Applications (SETA '01), Bergen, Norway, May 13-17, 2001. (Work sponsored by Office of Naval Research under grant N00014-96-1-1192 (subcontract of the Univ. of Puerto Rico), and by the National Science Foundation under grant ANI-9730556.)

[26] Not all vendors chose coherent processing in designing their UWB receivers. Among the major vendors, only Time-Domain has always used coherent RF processing. Others, such as Aether Wire and Multispectral Solutions, typically have not used coherent RF processing. The new 802.15.3a standard being developed will likely require coherent RF processing. Coherent processing provides the highest functionality and is the most extensible. Non-coherent processing achieves the lowest cost, at the penalty of meeting only lower performance, with severely limited functionality and extensibility. See: Paul Withington, *"Ultra-Wide Band Radio, A New Frontier"*, Singapore IDA UWB *Programme* Framework, 25 February 2003.

Continuing with the highest performance, coherent processing method, consider one normalized signal correlation function, *γp(t)*, given by Ramirez-Mireles and Scholtz that can be used to detect the previously defined p(t):[27]

$$\gamma p(t) := \left[1 - 4\cdot\pi\cdot\left(\frac{t}{\tau n}\right)^2 + \frac{4\cdot\pi^2}{3}\left(\frac{t}{\tau n}\right)^4\right]\exp\left[-\pi\cdot\left(\frac{t}{\tau n}\right)^2\right]$$

Graphically, this normalized UWB signal correlation template function resembles the monocycle it detects, although there are slight differences in the shape of the template from the monocycle.

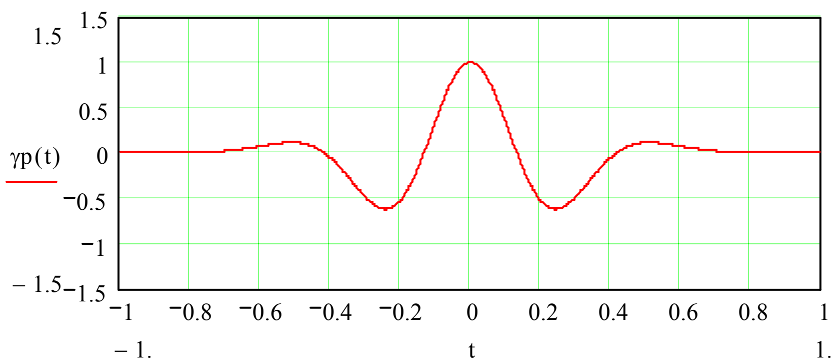

Figure 3-2 A TH-PPM Monocycle Correlation Template Function

Similar to the requirement that exists on the UWB monocycle waveform itself for convergence of the detection process, it is also necessary that the integrated value over all time of the UWB signal correlation template function (i.e., its area) likewise be both finite and equal to zero. Namely, it is necessary that:

$$A2 := \int_{-\infty}^{\infty} \gamma p(t)\, dt$$

when evaluated numerically, be equal to zero, which is true for this UWB signal correlation template function.

3.5.3 Advanced Introduction to Monocycles

Classic electromagnetics theory historically has always been applied to designing antennas while tacitly assuming steady-state responses. The reason for making this simplifying assumption is that it greatly simplifies the application of Maxwell's Equations for designing antennas and simultaneously permits using simplified Electromagnetics

[27] Fernando Ramirez-Mireles and Robert A. Scholtz, "System Performance Analysis of Impulse Radio Modulation", IEEE Proceedings RAWCON Conference, August 1998.

Theory, thereby avoiding the discontinuous anomalies that exist during the startup of the waveform (i.e., antenna capacitance charging effects.)

For UWB antennas, there is no shortcut that can be used to avoid the discontinuous events at the start of the pulse waveform, for this is all there is. Steady-state electrical conditions are never reached in UWB antennas. (Although, arguably, steady-state heating effects for high-power transmissions are reached, on an average basis.) The need to include complete, un-simplified Maxwell's Equations in designs is further exacerbated by the need for designing ultra wide bandwidth antennas to be compatible with transmitter output amplifiers, to guarantee unconditional stability in power amplifier output circuits. (Fortunately, there are analysis suites of modeling tools available that can do the time-domain analysis with Maxwell's Equations without assuming any steady-state approximations, e.g., commercial 3D Electromagnetic Simulation products such as IE3D, and, to a lesser extent, HFSS.)[28,29]

The main issue, of course, is that, during the initial rush of UWB monocycle current into an antenna, the antenna acts as an open-circuit and must be charged. The effect, however, is that the current in the antenna structure is phase-shifted by 90 degrees, which means that the UWB monocycle current pulse input into the structure has its derivative taken. Then, upon the Electromagnetic Wave impinging on a receiving antenna, the same derivative operation occurs again. The received signal is therefore the scaled first derivative of the Electric Field resulting from the original UWB current pulse, and is the scaled second derivative of the original UWB current pulse. Although this summarizes what happens, a more concise mathematical explanation is in order. From basic antenna theory, the electric field radiated from the antenna (i.e., the E-field, E(t)) is proportional to the derivative of the magnetic potential, A(t). That is:[30]

$$E(t) = k1 \cdot \left(\frac{d}{dt} A(t) \right)$$

However, the magnetic potential is proportional to the current flow in the antenna structure:

$$A(t) = k2 \cdot i(t)$$

The E-field radiated from an antenna is therefore proportional to the first derivative of the current flow into the antenna. For sinusoidal currents, the taking of the derivative of the sinusoidal current becomes a co-sinusoidal current, or, equivalently, a phase-shifted sinusoidal current. The derivative process is therefore generally ignored for continuous wave signals, being equivalent to simply a shift in the apparent position of the original transmitter antenna position.

[28] IE3D is available from Zeeland Software, Inc., http://www.zeland.com/

[29] HFSS is available from Ansoft Corporation, http://www.ansoft.com/products/hf/hfss/index.cfm

[30] Michael Chia, *"UWB Radio for wireless communications - I2R's perspectives,"* Ultra Wideband (UWB) Programme, Singapore Suntec Convention Center, Singapore, 25 February 2003 (an IDA UWB Seminar).

For non-sinusoidal pulses, however, such as are used for UWB transmissions, the derivative taking process becomes entirely different, causing the waveform to change its shape fundamentally. A transmitted monocycle hence will appear different, depending on where the monocycle is observed, and how it is observed, unlike a sinusoidal waveform.

Gaussian current pulses and signal pulses partially preserve their shapes when their derivatives are taken, at least for perfectly shaped Gaussian pulses. For truncated Gaussian approximations, however, such as occur in actual UWB radio implementations, the perfect shapes are not completely preserved when their derivatives are taken. Likewise, the computed power spectrums are not the same for the different derivatives, either, further exacerbating issues such as meeting FCC spectral masks imposed on UWB transmissions. Furthermore, true Gaussian pulses technically exhibit an infinite pulse-width. The trick that is most commonly used to overcome the infinite pulsewidth issue is to define UWB monocycles and Gaussian pulses as having a defined, although finite, pulsewidth that contains, say, 99.99% of the energy of the theoretical Gaussian pulse.

Unlike the series approximation to a Gaussian pulse used previously, a non-series, closed-form approximation to a Gaussian pulse can be written more compactly as follows:[31]

$$\text{p\_gp1}(t) := \frac{A}{\sqrt{2\cdot\pi}\cdot\sigma}\cdot\exp\left(\frac{-t^2}{2\cdot\sigma^2}\right)$$

This Gaussian pulse will be considered to be the UWB monocycle current pulse into the transmit antenna. The electromagnetic field from the transmitter antenna is then related to the scaled first derivative of this current pulse, that is, to:

$$\frac{d}{dt}\left(\frac{A}{\sqrt{2\cdot\pi}\cdot\sigma}\cdot\exp\left(\frac{-t^2}{2\cdot\sigma^2}\right)\right)$$

[31] Hongsan Sheng, Philip Orlik, Alexander M. Haimovich, Leonard J. Cimini Jr., Jinyun Zhang, *"On the Spectral and Power Requirements for Ultra-Wideband Transmission,"* IEEE International Conference on Communications, Anchorage, AK, May 2003.

Evaluating this:

$$\frac{d}{dt}\left(\frac{A}{\sqrt{2\cdot\pi}\cdot\sigma}\cdot\exp\left(\frac{-t^2}{2\cdot\sigma^2}\right)\right) \to \frac{-1}{2}\cdot A\cdot\frac{2^{\frac{1}{2}}}{\pi^{\frac{1}{2}}\cdot\sigma^3}\cdot t\cdot\exp\left(\frac{-1}{2}\cdot\frac{t^2}{\sigma^2}\right)$$

Hence,

$$p\_gp2(t) := \frac{-1}{2}\cdot A\cdot\frac{2^{\frac{1}{2}}}{\pi^{\frac{1}{2}}\cdot\sigma^3}\cdot t\cdot\exp\left(\frac{-1}{2}\cdot\frac{t^2}{\sigma^2}\right)$$

This Gaussian pulse, p_gp2(t) is what arrives at the receiver antenna as the E-field.

However, the Gaussian current pulse at the output of the receiver antenna is a scaled version of the ***derivative of this pulse***; that is:

$$\frac{d}{dt}\left(\frac{-1}{2}\cdot A\cdot\frac{2^{\frac{1}{2}}}{\pi^{\frac{1}{2}}\cdot\sigma^3}\cdot t\cdot\exp\left(\frac{-1}{2}\cdot\frac{t^2}{\sigma^2}\right)\right) \to \frac{-1}{2}\cdot A\cdot\frac{2^{\frac{1}{2}}}{\pi^{\frac{1}{2}}\cdot\sigma^3}\cdot\exp\left(\frac{-1}{2}\cdot\frac{t^2}{\sigma^2}\right) + \frac{1}{2}\cdot A\cdot\frac{2^{\frac{1}{2}}}{\pi^{\frac{1}{2}}\cdot\sigma^5}\cdot t^2\cdot\exp\left(\frac{-1}{2}\cdot\frac{t^2}{\sigma^2}\right)$$

Hence,

$$p\_gp3(t) := \frac{-1}{2}\cdot A\cdot\frac{2^{\frac{1}{2}}}{\pi^{\frac{1}{2}}\cdot\sigma^3}\cdot\exp\left(\frac{-1}{2}\cdot\frac{t^2}{\sigma^2}\right) + \frac{1}{2}\cdot A\cdot\frac{2^{\frac{1}{2}}}{\pi^{\frac{1}{2}}\cdot\sigma^5}\cdot t^2\cdot\exp\left(\frac{-1}{2}\cdot\frac{t^2}{\sigma^2}\right)$$

To clarify this further, depending on where one observes the UWB monocycle, one may see any of the following waveform shapes, scaled, of course, depending on actual circuit gains, path losses/distances, and actual signal levels:

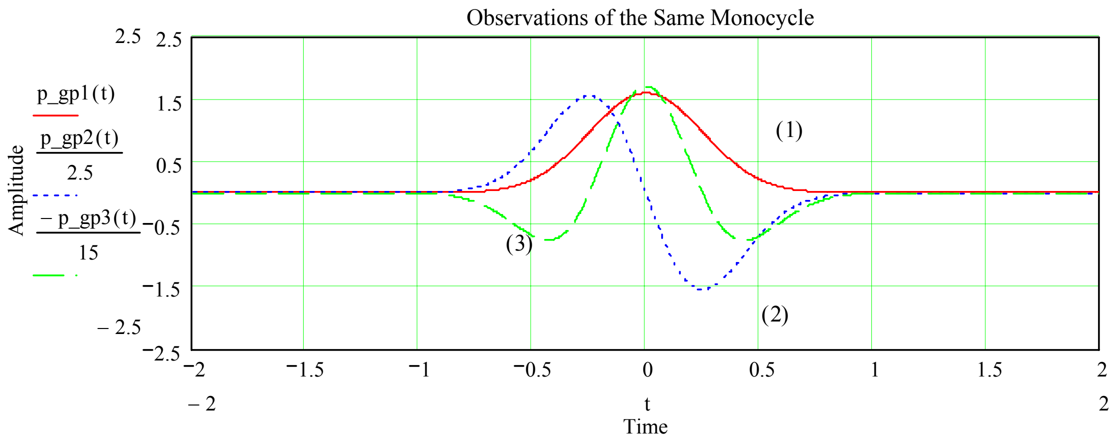

Figure 3-3 Observing the Same Monocycle at Different Locations

All of these waveforms are observations of the same monocycle, observed at different locations within the UWB communication system. It is important to realize that all of these scaled waveforms are the same UWB monocycle observed as either (1) a current pulse into the transmitter antenna, (2) as an electromagnetic field traveling from the transmitter antenna to the receiver antenna, and (3) as a current pulse out of the receiver antenna. Depending on one's observation point, all of these waveforms are simply a different scaled representation of the *same* UWB monocycle. This can be thought of analogously, as a *Theory of UWB Monocycle Relativity*.

An alternative treatment is simply to call these waveforms by different names, i.e., the Gaussian Pulse, the Pulse Doublet (for the first derivative), the Pulse Triplet (for the received current pulse out of the receive antenna, and, if another derivative is taken (the 3rd derivative) as the Pulse Quadlet.[32] (As a mnemonic to remembering these terms, just count the "bumps" on the signal waveform to determine whether to call the monocycle representation a pulse, a doublet, a triplet, or a quadlet.)

All in all, this is rather confusing for many traditional radio designers and antenna designers for, in the steady state, there *is* a derivative being taken, but the waveforms remain invariant, and are only shifted in time. Still, once it is understood that derivatives are taken of UWB Monocycles when passing through antennas, and their time-domain waveform shapes change because of this, the world of UWB Monocycles instantly becomes much clearer.

Unfortunately, however, the power spectra are not the same for all these different observations taken of the same pulse waveform at different points in a UWB

[32] Mark A. Barnes, Soumya K. Nag, Herbert U. Fluher, "*Method of Envelope Detection and Image Generation*," United States Patent US 6,552,677, dated April 22, 2003.

communication system. The information content remains the same, of course, but the shape of the pulse changes and the bandwidth occupied by the pulse also changes depending on where one observes the UWB monocycle. From a purely physical point of view, this is difficult to understand. However, if one accepts that there can be localized cancellation of amplitudes in three-dimensional space, much as is seen along a mismatched transmission line where a Voltage Standing Wave Ratio exists where there are nulls in the amplitude at specific physical points along a transmission line, this concept becomes easier to accept. It complicates the issue of just what the power spectrum is of a UWB monocycle-based communication system, however. There may be more than just one power spectrum for a given monocycle that must be considered in terms of interference potential. The factor that ultimately must determine which power spectrum to consider is the point of susceptibility in the susceptible wireless apparatus that may experience interference from the UWB power spectrum.

In general, it is possible to use UWB monocycles based on higher-order derivatives to tailor the power spectral density of transmissions to meet arbitrary spectral masks, such as imposed by the FCC in February 2003 for UWB transmissions.[33] The verification of whether a particular spectral mask is met, however, is an issue still subject to much debate, because different observers of a UWB waveform will see different power spectrums DEPENDING ON WHERE THEIR OBSERVATION POINT IS. This '*Relativity*' is a first for radio systems spectrum management.

Much remains before all UWB open issues can be resolved. Ultimately, however, the need to reuse frequency spectrum, and to use frequency spectrum more efficiently, will force the resolution of these details, for the idea of spectral reuse inherent with UWB communications systems holds too great a promise to ignore resolving these details.

3.5.4 Open Theoretical Issues with UWB Communication Systems

Despite the time-synchronization "hand waving" assumed thus far to analyze fundamental aspects of UWB radios, the myriad difficulties surrounding time-synchronization should not be underestimated. The fundamental problems in UWB radio design today can largely be grouped into just one area involving time-synchronization problems, and the associated multiple access issues. The two issues are closely related, as it can be extremely difficult to differentiate between individual monocycles from an assortment of UWB transmitters unless receiver complexity is greatly increased over what is required for implementing a single UWB link.

A common technique used in spread spectrum link designs is a fixed preamble consisting of a training sequence to enable quick recognition of a particular signal, thereby speeding acquisition. With a TH-PPM signal, this could be implemented with a known relative timing Time-Hop sequence of monocycles prepended onto the start of each major transmission (say a packet) that were transmitted using UWB modulation techniques. It

[33] Hongsan Sheng, Philip Orlik, Alexander M. Haimovich, Leonard J. Cimini Jr., Jinyun Zhang, *"On the Spectral and Power Requirements for Ultra-Wideband Transmission,"* IEEE International Conference on Communications, Anchorage, AK, May 2003.

would be somewhat the equivalent of a time-domain preamble in place of a frequency domain preamble.

Using a preamble simplifies the correct recognition of a particular signal once monocycle detection occurs, but with low-power UWB monocycle transmissions, monocycle detection often occurs only when timing is acquired. Use of a preamble does not mitigate the basic timing uncertainty problem inherent in UWB receiver designs necessary to enable detection in the first place. It only simplifies recognition of signals from a particular transmitter. As noted by Scholtz, et al, [34] "a one nanosecond time-resolution used in a system with an initial timing uncertainty equivalent to a spreading code period of one millisecond means that the receiver must compute 10^6 correlations. This acquisition problem is easily a few orders of magnitude more difficult than exists for narrowband systems with the same initial uncertainty..."

For expediency in acquiring UWB signals, therefore, the key to success is achieving an efficient parallel correlator architecture to search all the correlator bins quickly and accurately, rather than in a serial fashion, is to acquire timing fast. The acquisition problem for UWB transmissions likely poses the largest difficulty in terms of its impact on receiver complexity, power consumption, and physical size of receiver hardware relative to that required with traditional narrowband communication systems. Once timing is acquired, a monocycle pulse train stream can be detected and processed with a complexity and power consumption much less than the hardware required with a typical narrowband system. The fundamental problem is just to obtain proper timing in the first place.

For communication links involving high vehicle velocities with corresponding high rates of distance separation or distance closing, in which Doppler effects becomes prevalent, the timing problem only becomes worse. Spectral frequencies are shifted, pulse phases can change, and timing uncertainties only increase. Doppler effects simply increase the required receiver complexities to even higher levels.

For environments in which multiple UWB signals coexist, the difficulty in distinguishing specific monocycles as to their origin appears intractable without first incorporating higher system level concepts, such as those used in Galois Field computations for determining codeword orthogonality and Hamming distances in Error Correction Coding and spread spectrum spectral orthogonality areas. Of course, for UWB signals, the concepts must be extended to the time-domain, instead of to the codeword polynomial and Walsh function domains, respectively, for the Error Correction Coding and spread spectrum problems.

[34] Robert A. Scholtz, P. Vijay Kumar, and Carlos J. Corrada-Bravo, "Signal Design for Ultra-wideband Radio", Sequences and Their Applications (SETA '01), Bergen, Norway, May 13-17, 2001. (Work sponsored by Office of Naval Research under grant N00014-96-1-1192 (subcontract of the Univ. of Puerto Rico), and by the National Science Foundation under grant ANI-9730556.)

Much work remains to make UWB communication techniques practical in specialized environments, especially where multiple UWB transmitters exist and where either receivers or transmitters are moving at high rates of speed relative to each other.

3.6 EVALUATION KIT (EVK)

Taking advantage of one of the first commercial products available, an early pair of Evaluation Kit (EVK) TM-UWB radios was purchased and received early in January 2003 from Time-Domain Corporation, of Huntsville, AL. This EVK, consisting of a pair of UWB transmitter/receiver radios with Ethernet link interfaces, along with controlling software for use on a laptop, was the UWB exemplar tested on this project. Working with Time-Domain Corporation, two software/firmware upgrades were received, resolving the shortcomings discovered during testing. The testing results of this EVK provide the bulk of the content of the UWB laboratory-testing results, discussed at length later in this report.

XtremeSpectrum Incorporated (XSI) of Vienna, VA, was also approached regarding the availability of their Bi-phase Pulse Modulation evaluation kit, consisting of a four-chip (now three-chip, e.g., *Trinity*[tm]) chipset providing 100 Mb/s data rates and consuming less than 200 mW that was to be priced at only $19.95 in quantities of 100,000.[35] Unfortunately, XSI's Evaluation Kit, originally scheduled for availability by July 2003, slipped its availability date, and was not available in time for testing on this project.

3.7 TEST RESULTS

Complete test results are contained in Volume 2 of this final report, in the UWB test procedure section, which contains both the procedure and testing results. Volume 3 of this final report contains a detailed look at the in-depth theoretical details of UWB Radio.

3.7.1 Test Result Summary

UWB experience gained during ECT (Phase 2) has shown that UWB is a valuable, potentially inexpensive resource for providing mobility while solving the first mile / last mile communication problem over very short distances up to a few tens of meters at very high data rates. The UWB industry has not yet matured to the point where there is a widespread selection of cost attractive equipment, or even standardized modulation formats. Nonetheless, the freedom and portability afforded with UWB, especially for battery powered wireless gear, will undoubtedly soon become commonplace in the modern Computer/LAN/Internet environment. During the ECT Phase 2 study, UWB Radio went from being just a theoretical concept to actual Evaluation Kits available for the early testing of fundamental UWB limits. Standardization through the IEEE is expected within the next few months. Commercial products are expected within the year.

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[35] Yoshida, Junko. *Startup bets chip set on ultrawideband home nets.* Electronic Engineering Times, June 24, 2002, p. 4.

4.0 FREE SPACE OPTICS (FSO)

4.1 BACKGROUND

Free Space Optics (FSO) was the third of the three First Mile/Last Mile broadband wireless access systems identified in the RISM Phase I report. Optical communication systems provide the highest available carrier frequencies and thus the fastest data rates possible today. FSO is designed to be a lower cost alternative to conventional fiber-optic cable-based communication links[36]. FSO is especially attractive within a metropolitan environment where the costs for trenching, cable installation, and street repairs can run from $200K to easily over $1M per mile, depending on the urban location.

FSO is a maturing technology that offers significant enhancements over most wireless technologies, including higher data rate, and the complete avoidance of any spectrum licensure costs. Its primary competition today is from existing fixed fiber installations. Today, 65% of FSO sales are international[37]. This has occurred due to the extensive USA fiber infrastructure that was installed in the 1990's slowing its expansion within the USA.

Although FSO offers the potential of maximum wireless performance, the limited opportunities within the US and an international recession have combined to reshuffle the FSO industry. Table 4-1 lists the key international FSO players that exist today. Notably absent from this list is AirFiber which just 12 months ago was the industry's leader.

Table 4-1 FSO Industry Participants

Alcatel SA	Maxima Corp.
Cablefree Solutions Ltd.	Mostcom Ltd.
Canon Inc.	MRV Communications Inc.
Communication By Light GmbH (CBL)	Omnilux Inc.
Corning Cable Systems	PAV Data Systems Ltd.
Dominion Lasercom Inc.	Plaintree Systems Inc.
fSona Communications Corp.	Sceptre Communicaitons Ltd.
iRLan Ltd.	Silcon Manufactueing Technology Inc.
LaserBit Communication Corp.	Sunflower Technologies Ltd.
LightPointe Communications Inc.	Terabeam Corp.
LSA Photonics	

FSO links are based on infrared lasers and optical detectors. Over short distances, they are capable of providing very high data rates. Standard rates of OC-3 (155 Mb/s), OC-12 (622 Mb/s), and OC-48 (2.5 Gb/s) are all available off the shelf today.

[36] http://www.airfiber.com/products/index.htm
[37] Web Seminar, "Free Space Optics Access For Future", 8/22/03, LightPointe

The primary limitations on using FSO involve weather over distance. Thick fog can attenuate the laser signals and restrict the usefulness of a FSO link. Distance is not normally a concern when FSO is used as a "First Mile" technology; however, distance does magnify weather effects.

FSO testing under the ECT project was conducted around the AirFiber 5800 Optical Transceiver Units (OTU). The AirFiber 5800 system was selected after an evaluation of FSO COTS equipment and manufacturers. The AirFiber system was selected based on the following items:

- Cost
- Engineering & Factory Support
- Market Share
- Technical and Performance Features
    - Auto Track
    - Internal Camera
    - Dual Speed

Unfortunately, on 2/26/03, shortly after ECT received its pair of 5800 OTUs, AirFiber Corporation went out of business. In September 2003, AirFiber's Web site[38] was still up with no mention of the company closure. No one is answering the phones.

The lack of factory support for technical questions and warranty issues had some impact on ECT FSO testing. Minor system lockups consumed large amounts of time before being resolved. Later, azimuth adjustment became inoperative in one unit. Later, this same unit experienced a temporary elevation lockup. These items combined to impact the time available for testing and resulted in tests of distances greater than 1100 feet having to be deleted. Most of the other original test goals were achieved.

Fortunately, as part of the ECT purchase of equipment, AirFiber had provided factory training for three KSC engineers in San Diego on 1/21/03. This training became especially valuable later when minor operating problems surfaced, especially after AirFiber had closed its doors.

[38] airfiber.com

4.2 BASIC FSO THEORY

Free Space Optical (FSO) communication, as discussed at length in the previous Phase I RISM report, dates to pre-history. Extensive FSO networks were established in the 19^{th} Century throughout France and North Africa, based around semaphore systems. Later, during the latter part of the 19^{th} century, FSO telephone communication was developed.

The modern FSO age commenced with the invention of the laser slightly more than 40 years ago. With this light source, the possibility of coherent light in place of the earlier non-coherent light enabled the use of monochromic light of but a single wavelength. This further enabled the ability to select specific wavelengths by which to design FSO systems, to achieve the goals of lessening atmospheric attenuation, providing operation through rain, and achieving eye-safety through the selection of appropriate wavelengths for the laser light selected.

Fundamentally, modern FSO systems typically employ NRZ (non-Return to Zero) modulation of laser light. Modulation gear within the transmitters for FSO systems based on this principal specifically work much like a high-speed dimmer switch on a car's headlights. Digital data is either encoded as either a high intensity beam or as a low intensity beam, depending on the extinction ratio present in the ON to OFF states engendered by the modulating device.

Within the receiver, a photodetector provides the optical to electrical (OE) conversion. Depending on the range over which communication is desired, both Positive-Intrinsic-Negative (PIN) diodes and APDs (Avalanche Photodetector Diodes) are used. PIN diodes provide less sensitivity, but require only minimal voltage bias to make them operational. APDs provide the maximum in sensitivity, but require voltages often exceeding 100 Volts dc to achieve their maximum sensitivity. This, in turn, increases the need for properly coating circuit cards for FSO apparatus intended for use outdoors, through conformal coating the cards, in order to avoid accidentally shorting out the high dc bias during high humidity conditions.

At the output of the photodetector is a Trans-Impedance Amplifier (TIA). Its purpose is to provide the necessary gain by which to generate a voltage from the current produced by the photodetector diode when exposed to light. Beyond this lie the framing and other packetizing electronics, needed to provide the proper data interfaces for the subsequent parts of the communication system. For fiber optic extensions, it is necessary to have clock and data recovery circuitry, by which clocks are derived from incident light pulses coming into the FSO system via fiber optic cable, to provide proper timing interfaces.

For the AirFiber system tested on this project, a Smartbits OC-12 fiber optic interface operating at 622 Mb/s was the data interface into, and out of, the two OTUs.

4.3 TEST DESCRIPTION

FSO testing was conducted in and around the Engineering Development Laboratory (EDL) at KSC. Testing involved setting up the equipment and monitoring/testing the laser communication link. The initial draft FSO Test Plan is included in Appendix I. The draft FSO Test Procedures are included in Appendix J.

4.4 TEST OBJECTIVES

The test objectives were as follows:

- Evaluate COTS FSO equipment for possible future use at KSC
- Identify any fundamental shortcomings that must be filled in commercial FSO communication technologies prior to integrating this technology into future range architectures.

4.5 TEST SETUP

Various test configurations involving different locations were used during the testing. The initial Test Procedures are included in Appendix J. Actual testing varied from the initial Plan as opportunities became available. Specific test configurations are described in the following sections. Detailed test data sheets are included in Appendix K. General descriptions are described below.

Testing was performed at various locations base on the distances under test. A summary of test locations and distances is included in Table 4-2.

Table 4-2 FSO Test Locations

No.	Location	One Way Distance (ft)	Loop Back
1	EDL ANDL[39]	28	Y/N
2	EDL Roof	300	Y
3	EDL East Parking Lot	113	Y
4	EDL to SSPF Parking Lots	1066	Y

[39] EDL Advanced Network Development Lab, Rm 124

4.5.1 EDL ANDL Setup

Initial testing and checkout were performed in the Advanced Network Development Lab (ANDL), Room 124 in the EDL. Factory personnel successfully installed both OTUs in the ANDL on 1/15/03. Each of the two AirFiber 5800 was programmed with a un ique name (Tower #1 & Tower #2). Tower #1 was placed on top of an existing workbench (Figure 4-1) while Tower #2 was place 30 feet away on top of a cabinet (Figure 4-2). A safety rope was attached to an overhead beam to prevent Tower #2 from falling if disturbed. The two locations were selected to avoid laser beam interruption during normal lab operations.

Figure 4-1 Tower #1 in the EDL ANDL on the North Bench

Figure 4-2 Tower #2 in the EDL ANDL on the South Cabinet

The fiberglass screen mesh was placed over each OTU's window per factory recommendations to provide additional beam attenuation and improved signal acquisition at the short distances involved with the indoors lab test. Even without these screens, no damage to the receiver circuits from the Class 1M eye-safe lasers could have occurred at the close distances used within the lab.

The Advanced Network Development Lab was chosen since it was a secure area and contained a SmartBits test unit that could be used as a source of data packets. Data was sent by multi-mode fiber (MMF) from the SmartBits into one of the OTUs. This unit then sent data via an FSO link to the second OTU that then returned data to the SmartBits by a second multi-mode fiber. The SmartBits then compared sent and received data for generation of measured bit error rate results. Later lab tests used a loop back fiber at Tower 1 with external fiber input/output functions occurring at Tower 2.

4.5.2 EDL Roof Test Setup

The second series of FSO tests were performed on the roof of the EDL. The roof link was established on 5/9/03. The AirFiber OTUs were purchased with parapet mounts. In addition, the factory agreed to supply another pair of freestanding mounts. One of the parapet mounts was installed on the SW corner of the EDL (Figure 4-3). Tower #1 mounted on top of this support, using the attachment ring visible in the picture.

Figure 4-3 OTU Parapet Mount on EDL Roof For Tower #1

Unfortunately, the West side of the EDL is the only side with a parapet. This necessitated Tower#2, located 300 feet away near the SW corner of the EDL roof, being placed on a freestanding mount. The freestanding mount utilizes a base ring, upright and water-filled segmented base. This base (Figure 4-4) provides a large footprint that spreads the load and supports the OTU in high winds. A metal base ring and aluminum upright attach to the base segments (Figure 4-5). These were reused during the trailer-testing phase described in the next section. The box structure in Figure 4-4 was already present on the roof and was used to support the power box for Tower #2.

Figure 4-4 FSO Roof Top Water-Filled Support Segments for Tower #2

Figure 4-5 Mounting Ring and Upright Used to Support the OTU

The mating female bracket is shown in Figure 4-6 attached to the bottom of the OTU. This enables the OTU to be quickly installed by slipping the female bracket down over the upright support. Radial setscrews were provided but were not generally used except during extended roof testing.

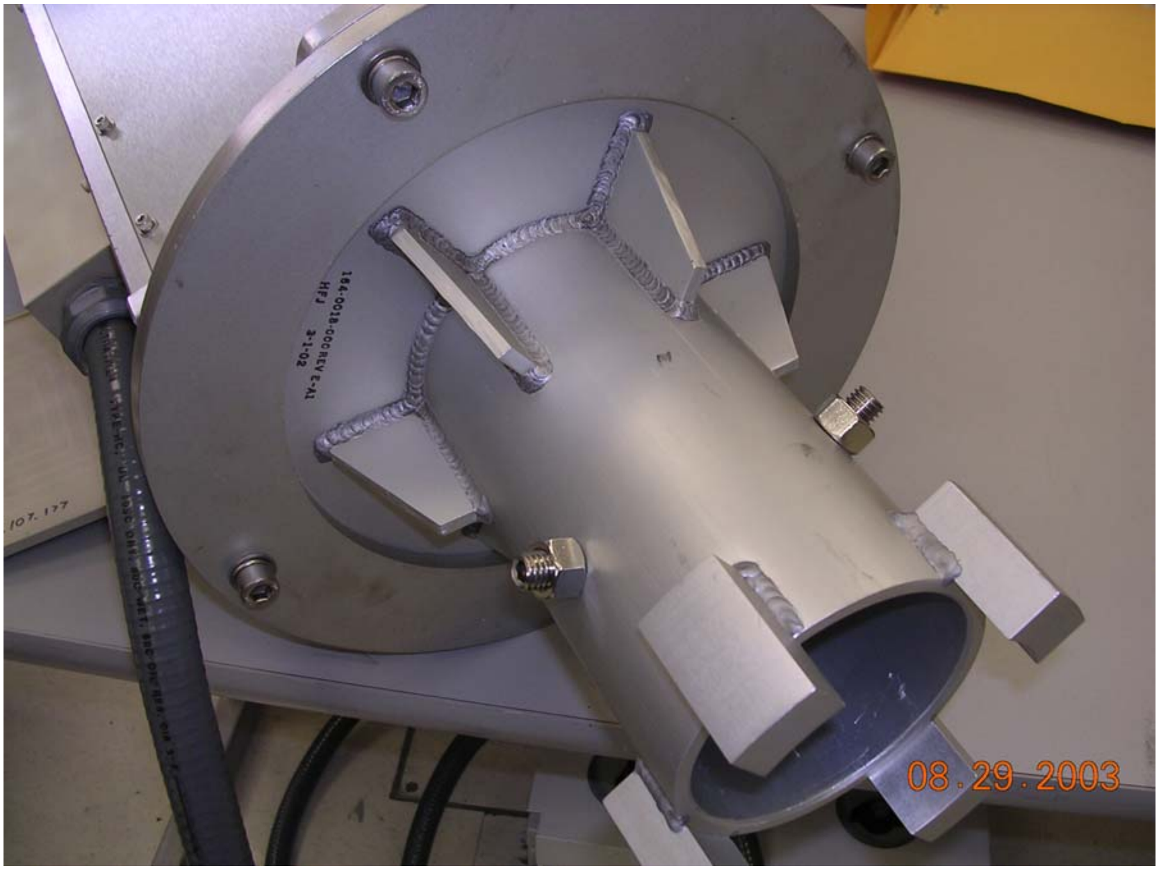

Figure 4-6 OTU Adapter for Mounting OTU to Upright

Roof top power for each OTU was provided by extension cords plugged into two separate air handler rooms that were reasonably close to each position. The orange cable in Figure 4-4 running toward the top center is the power cable. The green cable running off to the left center is a ground cable tied to the roof lightning protection cables.

Fiber and Ethernet cables were run overhead from the ANDL on the first floor, across the hall, out through a window, up to the roof and over to Tower #2. The orange cable running to the right in Figure 4-4 is the multimode duplex fiber. Running with it is a black Ethernet cable.

The fiber was used to send and receive data packets. The SmartBits, located within the Advanced Network Development Lab on the first floor, was the source of the optical payload. The duplex fiber connected the SmartBits to Tower #2 on the roof. Tower #2 used FSO to send the payload over to Tower #1. There a short fiber jumper was used as a loop back from the output port to the input port. Tower 1 then used FSO to return the payload to Tower #2 where it was routed via the duplex fiber back to the SmartBits on the first floor. A 1000 M roll of duplex, multimode duplex fiber was purchased for ECT testing. During roof top testing, the optical signals traveled full length of this roll.

The Ethernet cable was used to communicate with the OTU's management port. During most tests, the rooftop FSO link was fully monitored from the first floor ANDL. This enabled collecting data during rainstorms without having anyone physically on the roof.

Roof top access, though, was required during initialization. A short USB cable was used to connect the on-board camera and alignment software with the AirFiber CamLAP software residing on a Laptop computer. Once initialized and the link established, the USB cable was then removed and the weatherproof enclosure door was closed, in preparation for inclement weather testing.

4.5.3 EDL East Parking Lot Test Setup

The third series of FSO tests were performed on the back parking lot of the EDL. To facilitate moving, spacing and positioning the units, each OTU was mounted on a trailer. A pair of existing antenna trailers (Figure 4-7), remaining from another project, were modified to support ECT FSO testing. The factory base rings and uprights provided with the freestanding mounts were bolted to the trailer floor plates to provide a quick mount (Figure 4-5). The antennas shown stored horizontally across the top of the trailers were not used in these tests.

Figure 4-7 OTU Mounted on an Existing Antenna Trailer

Setup, initializing and monitoring were performed using a Laptop computer. Packet testing was performed using a SmartBits test unit. A 50-ft fiber and an Ethernet cable of similar length were fabricated specifically for these tests. A short fiber jumper was used on the distant OTU to loop back the payload, thus allowing control and monitoring from only one end of the link. For the East parking lot test, the trailers were placed 113 feet apart (Figure 4-8). This distance was selected based on available parking space.

Figure 4-8 Trailer Mounted OTUs in East EDL Parking Lot (113-Ft Range)

Power was provided by a pair of small generators (See Figure 4-9).

Figure 4-9 Portable Generator Used for Power During Remote Testing

4.5.4 EDL to SSPF Parking Lots Test Setup

The fourth series of FSO tests used one trailer parked on the North side of the EDL and the second trailer parked in the SE corner of the SSPF parking lot. This configuration provided a one-way distance of 1066 feet. The fiber loop back jumper was again used in the distant OTU so that the FSO signals traveled twice this distance, or 2132 feet. The OTUs, mounts, power, and test equipment were all the same as during the EDL parking lot tests.

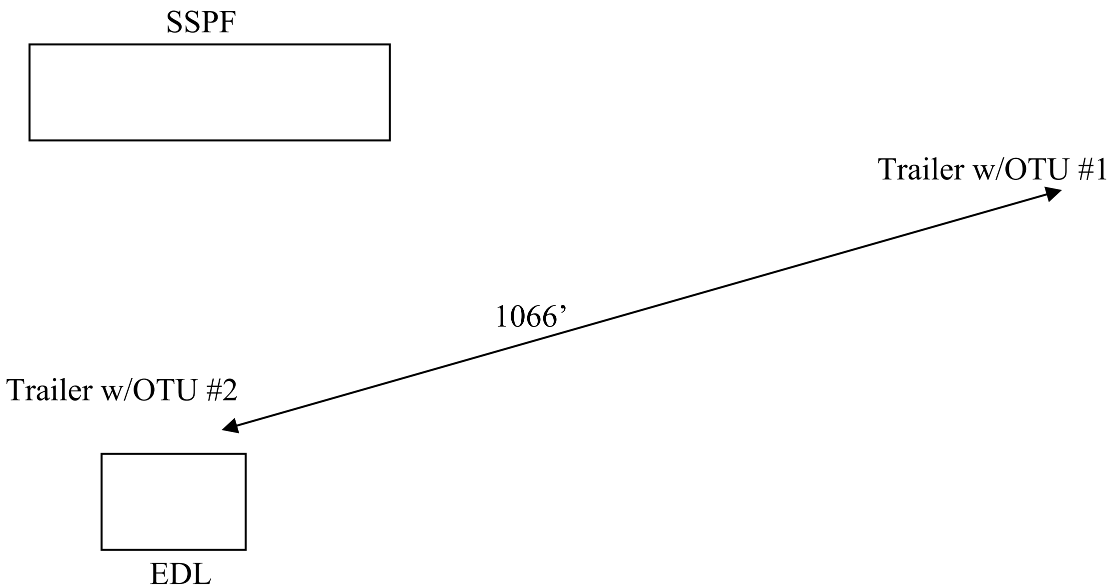

Figure 4-10 EDL to SSPF Parking Lots Test Setup

4.6 TEST EQUIPMENT AND SOFTWARE

Key FSO hardware test components are as follows:

- AirFiber 5800 - Optical Transceiver Unit (OTU)
- Laptop – Laptop computer for interfacing with the OTU
- SmartBits – Data packet source for measuring Throughput and Packet Loss

In addition to hardware, four software packages were instrumental in testing and data acquisition. These software packages are as follows:

- CamLAP
- AirFiber 5800 Operating System
- AirFiber Craft Interface Shell
- SmartApplications

4.6.1 AirFiber 5800

The AirFiber 5800 OTU shown in the following figures was the primary component under test. The units were supplied with protective outer fiberglass shrouds not shown in Figure 4-11. The shrouds were removed for convenience during testing.

Figure 4-11 Front of AirFiber 5800 OTU with Shroud Removed

Figure 4-11 Rear of 5800 OTU Showing Terminal Interface Board

Specifications for the two purchased AirFiber 5800s are tabulated in the following table[40]:

Table 4-3 AirFiber 5800 Specifications

Manufacturer		AirFiber
Model		5800-0622-MM
Data rates		OC-3 (155 Mbps) & OC-12 (622 Mbps)
Distance	Min	30 ft
	Max	1 mile tested
El Limit		+/- 20 deg
Az limit		+/- 5 deg
Motor steps		660 steps/deg
Tx wave length		785 nm
Interfaces	Payload In/Out	SC
	Management	RJ-45, RS-232, SC
	Camera	USB
BER		10^{-12}
Max Operating Temp		170 F
Max Operating wind		120 mph
Laser Safety		Class 1M
Cost		$23,724/pair w/training

[40] http://www.airfiber.com/products/AirFiber5800.pdf

A full description of the AirFiber 5800 is provided in "700-0162-000, AirFiber 5800 System Description". (This document and others remain available on the AirFiber Web site (airfiber.com), at least as of September 30th, 2003.)

The 5800 OTUs purchased by ECT for evaluation had an optional dual data rate capability. They could operate at either OC-3 or OC-12. All testing was performed at OC-12 data rates.

The AirFiber 5800 is a protocol independent, free space optical (FSO) system, which enables very quick deployment of optical bandwidth. The OTUs take any user supplied optical payload as input, package this data into a super frame, attach housekeeping & monitoring data, deliver the super frame to the peer OTU, strip off the payload from the super frame, and deliver the exact user's payload to the output port.

The OTUs were shipped with a fixed IP address. These were changed during setup to be compatible with the ANDL equipment, routers and the Laptop computers. The addresses are as shown in the following table.

Table 4-4 FSO IP Addresses

OTU	IP Address
Tower 1	128.217.107.176
Tower 2	128.217.107.177
Factory Setting	10.0.0.1

Each OTU has a separate power box as shown in the following figure. This weatherproof enclosure contains a regulated power supply that converts 110 VAC to 48 VDC. A large flexible conduit connects the power enclosure to the OTU. Since the terminal board within the OTU is not robust, the connects/disconnects were minimized by keeping the OTU and power enclosure attached when ever possible.

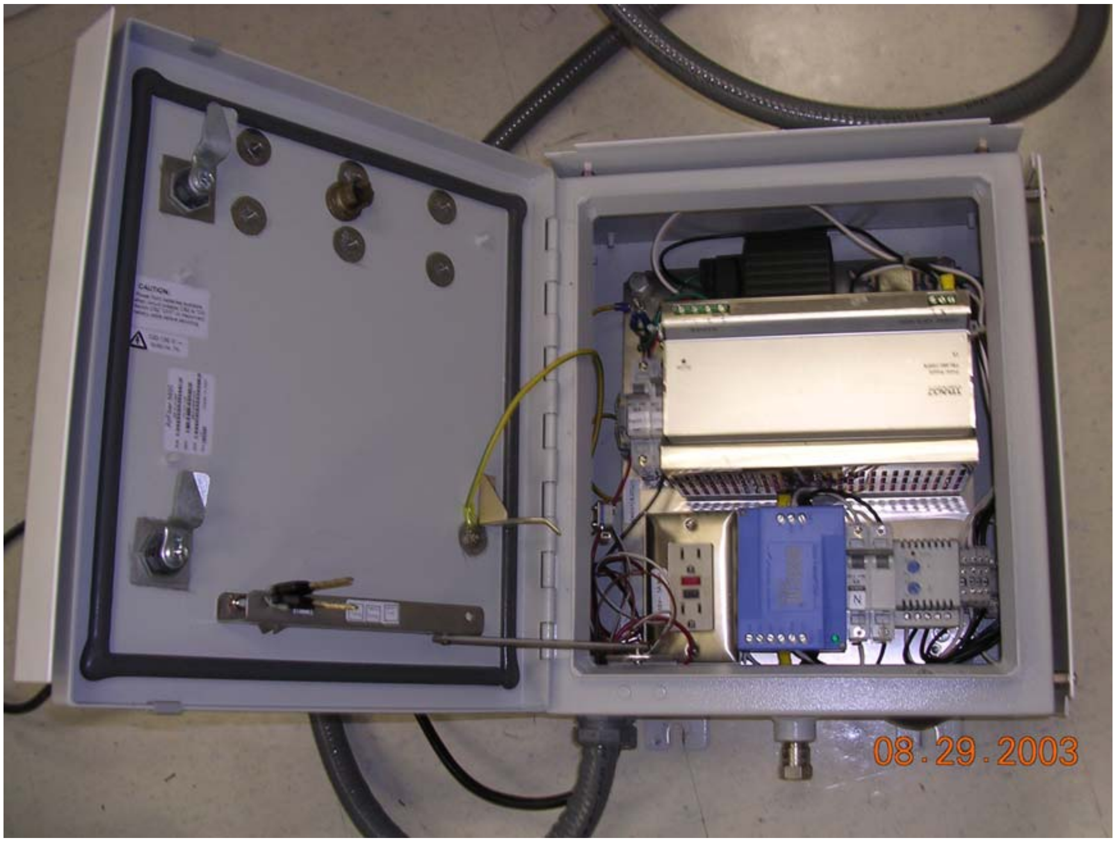

Figure 4-13 Remote Power Supply Enclosure

The AirFiber 5800 OTUs have narrow beams with auto-tracking capability. Once the units are closely aligned, software drives stepper motors that tilt movable mirrors to optimize the link between the two peer OTUs. Each OTU also has a built-in USB camera to assist in initial alignment. Cross hairs are super-imposed over real-time images, to facilitate initial aiming to expedite closing the optical link.

4.6.2 Laptop

A pair of Gateway laptop computers, as shown in the following figure, was procured to support the ECT project. These were later renamed BH and GB after the initials of the two individuals to whom they were assigned. Each laptop computer was configured with a local IP address that was compatible with the OTUs. Each computer was also loaded with AirFiber software that enabled either unit to be used to initialize, control, and monitor the OTUs. The software is discussed in a later section.

Figure 4-14 Gateway 450 XL Laptop Computer

Specifications for the Laptops are shown in the following table.

Table 4-5 Laptop Computer Specifications

Manufacturer	Gateway
Model	DS 450 XL
Processor	Intel Pentium 4
Speed	2.0 GHz
Hard Drive	40 GB
RAM	512 MB
Connectors	USB, RJ-45, Phone
Wi-Fi Standard	802.11b (Internal)
Operating System	Windows XP V.2002

Table 4-6 Laptop Computer Installation Parameters

Name	BH	GB
IP Address	128.217.107.174	128.217.107.175
MAC	00-02-2D-6E-A2-F4	00-02-2D-6E-5B-7E

4.6.3 SmartBits

An existing SmartBits test unit, shown in Figure 4-14, was used to exercise the OTUs. The SmartBits created varying size data packets that were sent through the FSO communication link at OC-12 data rates. The SmartBits compared the data sent with the data received and produced a report on Throughput and Packet Loss.

The SmartBits are populated with test drivers that produce data streams of different protocols. For ECT testing, Cards 17 and 19 shown in Figure 4-15 were used. These cards are for ATM at OC-12. Card 17 was usually the transmitter and Card 19 was the receiver. A jumper, shown in Figure 4-15, was used from the receive port in Card 17 to the transmit port of Card 19.

The SmartBits was initially rack mounted in the ANDL. During lab and EDL roof testing, a duplex multimode fiber was routed from the input and output ports of the roof top 5800 OTU to the SmartBits. For testing in the parking lots, the SmartBits was removed from the rack and powered by the portable generator.

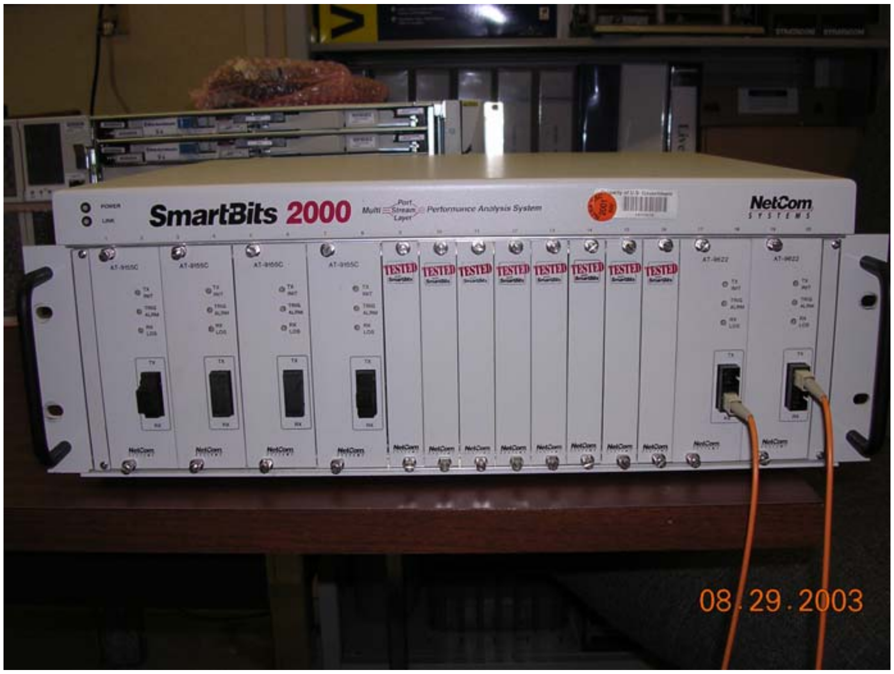

Figure 4-15 SmartBits Test Unit

Figure 4-16 SmartBits ATM Cards 17 & 19

4.6.4 CamLAP Software

CamLAP (**Cam**era **L**ink **A**ccess **P**rogram) software (Figure 4-17) was provided by AirFiber and was used to align the OTUs and to initialize the communication link. The software resides on a Laptop that is connected to the OTU through both an Ethernet cable (RF-45) and a short USB cable. CamLAP displays the real time video image from the camera inside the OTU. The image shown in Figure 4-17 is looking out toward the peer OTU. During initialization, the image is overlaid with the set of cross hairs shown. The operator uses the arrows on the right side to center the cross hairs on the peer OTU. Once the unit is approximately centered, the operator commands the OTU to establish a link and the auto-tracking feature engages. Auto tracking drives both OTUs until their beams are in optimal alignment. The CamLAP Operating Manual[41] is built into the software; however, a copy is usually available on the AirFiber Web site[42]. Additional details are provided in the FSO Notes included in Appendix L.

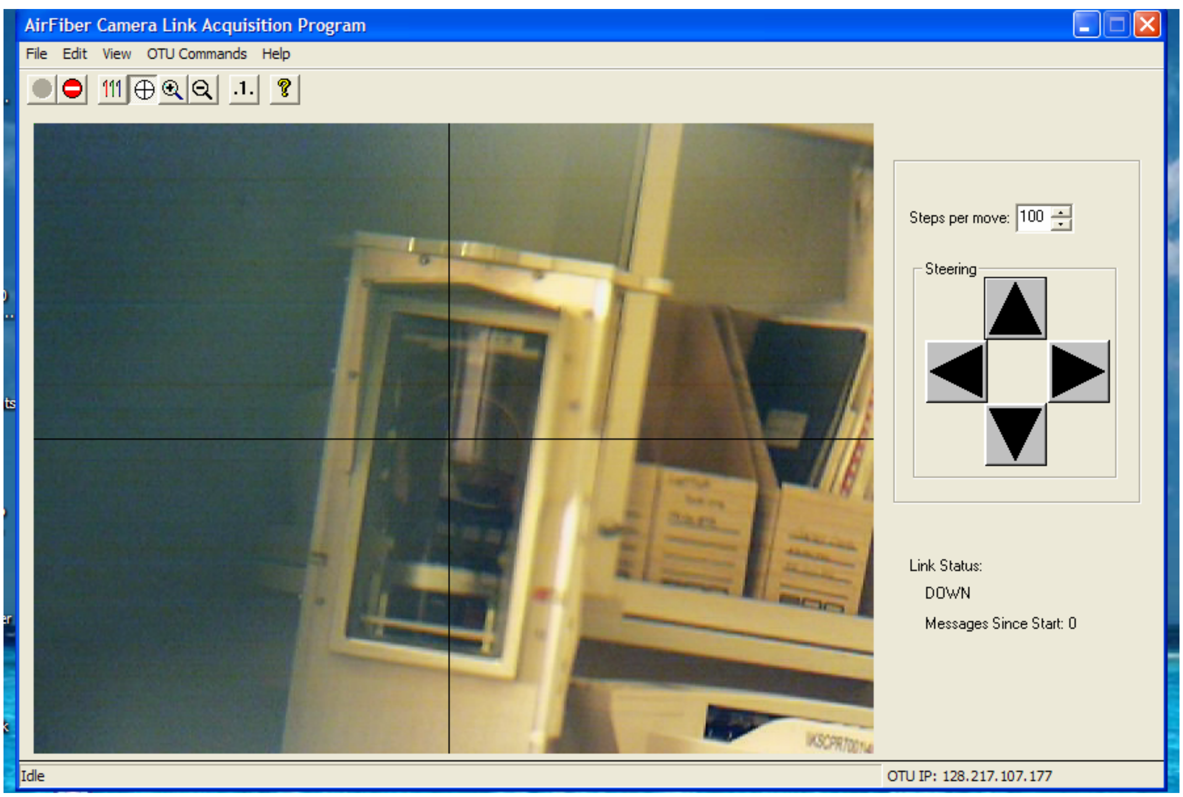

Figure 4-17 CamLAP Software Main Page

[41] 700-0163-000, AirFiber 5800, Camera Link Acquisition Program, User Guide
[42] www.airfiber.com

4.6.5 AirFiber 5800 Management System

The main Operating System for the AirFiber 5800 is stored within the OTU memory. It is accessed using a network browser such as Internet Explorer. Directions are provided in the reference manual[43] available on the Web and in the FSO notes in Appendix L. The Operating system enables the user to monitor and control certain functions of the 5800 OTU. CamLAP calls this Operating System to execute many of its aligning and initializing operations.

The main page of the Operating System (Element Management System) is shown in Figure 4-18. This page shows the OTU's name, IP address, link status, commission status and other valuable information. When the link is up, the center lens will show a green light.

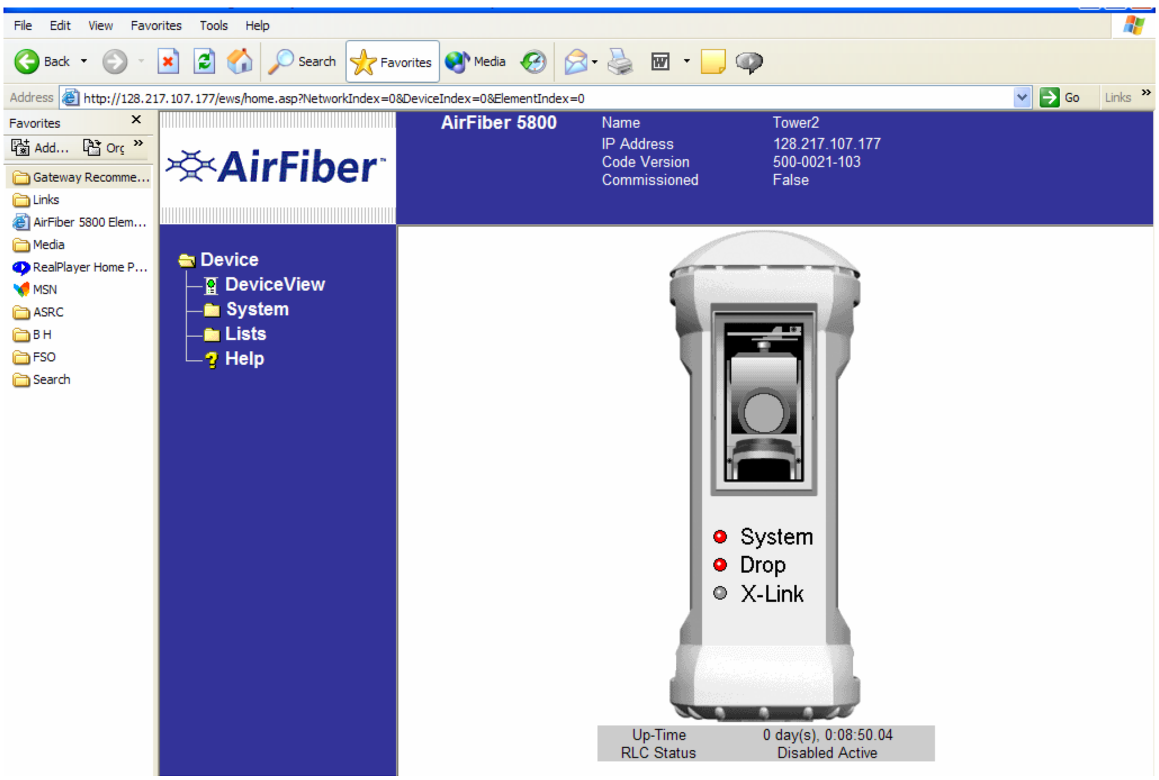

Figure 4-18 Operating System Main Page

After the two OTUs are aligned, the user must call up the Operating System and set the Commissioned flag to true. This flag identifies if the system has been previously aligned and operating. Once aligned and the Commissioned flag is set to true, the units will automatically

[43] 700-0155-000, AirFiber 5800, Element Management System, User Guide

recover from a power outage or link interruption. The Commission Flag is changes in one of the sub-layers as shown in Figure 4-19.

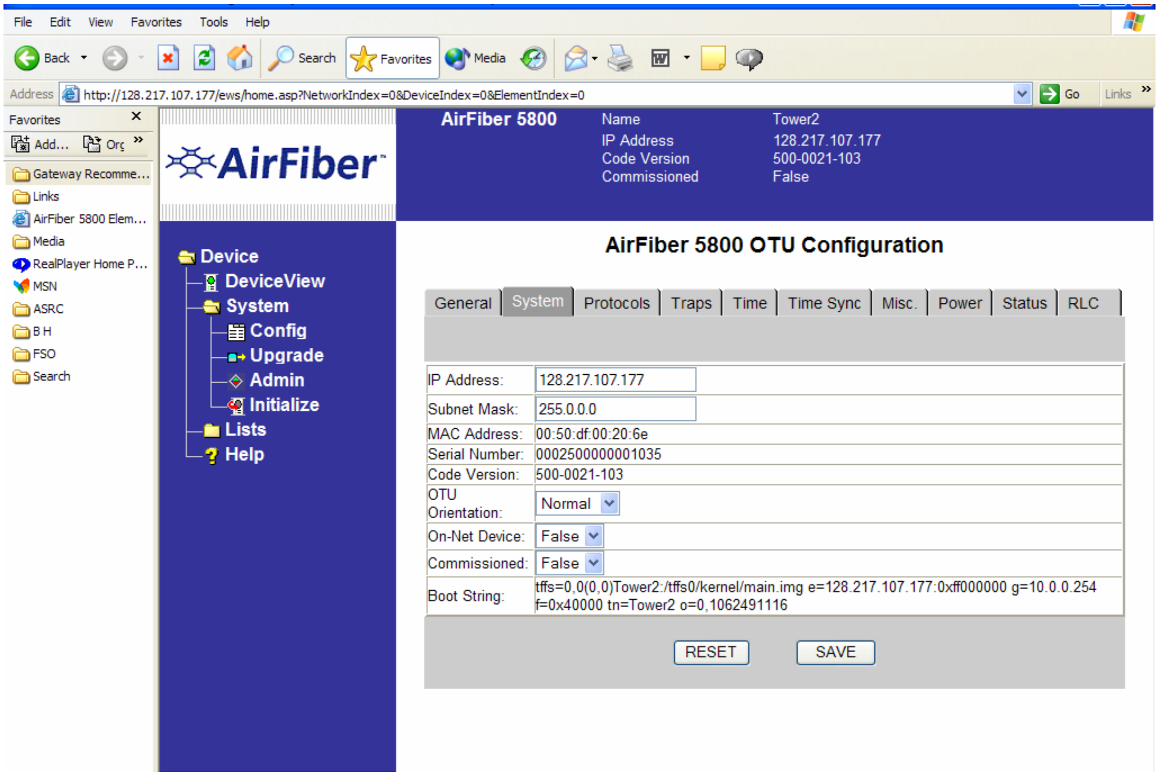

Figure 4-19 Operating System Lower Level for Setting Commissioned Flag

The Operating System also allows the user to command up to six internal signal loops that loop back the payload for hardware testing. This feature was not used during ECT testing since a fiber jumper was easier and more reliable.

4.6.6 AirFiber Craft Interface Shell

The AirFiber 5800s may also be monitored through a Craft Interface Shell. The internal VxWorks software may be accessed through a Laptop HyperTerminal using the RS-232, the RJ-45 Ethernet, or the SC fiber interface. The RJ-45 Ethernet was most often used for testing. The Craft Interface Shell was used to obtain test data on laser output strength and receiver input signal strengths. This is discussed more in the test output section.

The Craft Interface main page with the initial data retrieval command is shown in Figure 4-20. The "ttdump 1,1" command enabled the extraction of the laser power (TxP) and receiver power (RxP). These are all shown as zero in Figure 4-20 since the link was not established.

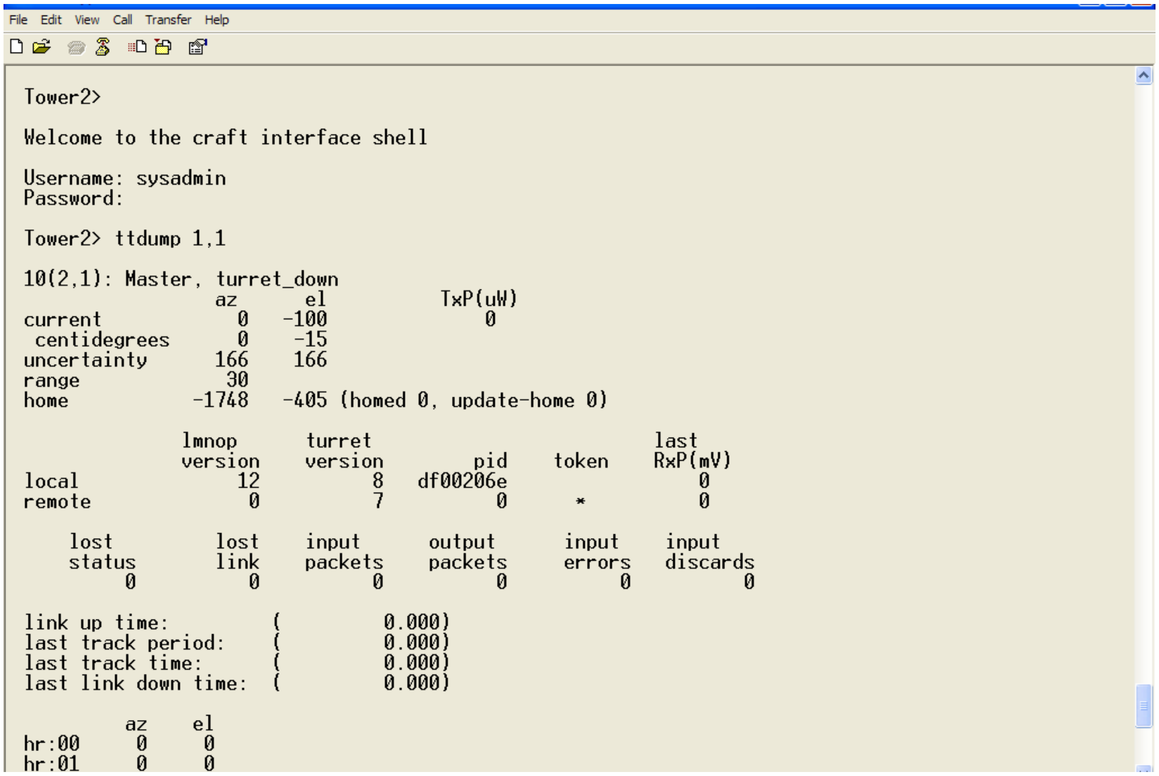

Figure 4-20 Craft Interface Main Page & Output

The ECT OTUs had the following Craft Interface properties:

- SkyeFyre version 500-0021-103 3
- Model 5800-0622-MM-RLC
- VxWorks version 5.3.1 (Wind version 2.5)
- Created on Sept 13, 2002, 12:35:11
- Boot line: tffs=0,0(0,0)Tower2:/tffso/kernel/main.img e=10.0.0.2:0xff000000 g=10.0.0.254 tn

4.6.7 SmartApplications

SmartApplications is the operating system software for the SmartBits. This software enables the user to setup the communication links (Cards 17 to 19 for these tests) and to control the specifics of each tests. The software User Manual[44] and hardware-operating manual[45] are is normally available within the ANDL.

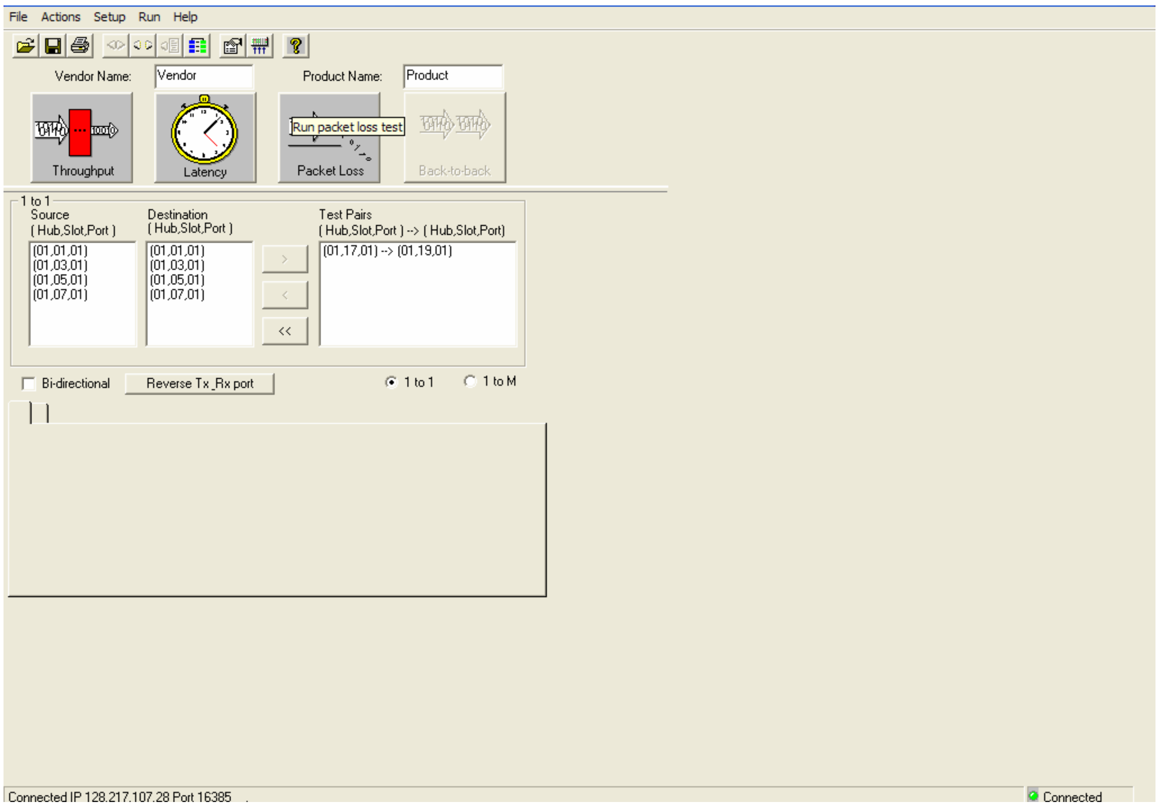

Figure 4-21 Smart Applications Main Page with Card 17 to Card 19 Test Setup

Figure 4-21 shows a test setup for Card 17 to input data to the OTU with Card 19 receiving the return data. The three types of tests available, Throughput, Latency, and Packet Loss, are also shown in this figure. Only Throughput and Packet Loss tests were run on the FSO equipment. The Latency tests are not applicable to FSO laser hardware testing.

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[44] Smart applications for Ethernet, Token Ring, ATM; User Guide; Net Com systems; 3/21/98
[45] SmartBits – Advanced Multiport Performance Tester / Simulator / Analyzer; SMB-2000; Getting Started

4.7 TEST RESULTS

FSO testing was composed of four test locations with two types of tests at each location. The four locations and the general test objectives at each are summarized in the following table.

Table 4-7 Summary Of Test Locations & Objectives

Location	Test Objectives
EDL ANDL	Setup, Initialization, Checkout, Familiarization, Baseline
EDL Roof	Initialization, Checkout, Weather performance, & Long Term performance
EDL East Parking Lot	Remote location initialization, checkout, & performance
EDL to SSPF Parking Lots	Intermediate distance initialization & performance

The two types of tests at each location are summarized in the following table.

Table 4-8 Summary of Test Types and Data Measurements

Test Type	Data Measurements
Craft Interface Software	Transmit & Receive Signal strengths
SmartBits	Throughput and Packet Loss

4.7.1 Results Summary

FSO testing was conducted from January 2003 through August 2003. During most of that period, the AirFiber 5800 operated without any significant link problems. In August 2003, one of the units did experience some manual drive problems. The units were still usable during most of this period.

While the FSO links were up and being monitored, no throughput degradation or packet losses were ever observed. The link remained up even during heavy Florida thunderstorms. No fog testing opportunities occurred.

Laser transmitter power data and receiver reception power levels indicate that the link always had reserve margin for the weather and distances investigated.

4.7.2 Craft Interface Testing

At each test location, the Craft Interface software was used to monitor internal transmit and receive power levels. These power levels provide an indication of the link strength between the two peer OTUs. A summary of this data is provided in the following table.

Table 4-9 Craft Interface Test Data

Date	Time	Az	El	Output TxP uW	Range Ft	Local RxP mV	Remote RxP mV	T °F	Loc	Wx	Local Input Twr	Loop Back	Comments
1/15/03	900	-	-	2000	28	-	-	75	ANDL	Indoors	1	N	Factory install
4/3/03	1000	-	-	2000	28	-	2546	75	ANDL	Indoors	2	Y	
4/3/03	1030	-	-	2000	28	2838	2457	75	ANDL	Indoors	2	Y	
4/3/03	1035	-	-	2000	28	2800	-	75	ANDL	Indoors	2	Y	
4/3/03	1036	-	-	2000	28	2800	2571	75	ANDL	Indoors	2	Y	
4/3/03	1037	-	-	2000	28	2741	2572	75	ANDL	Indoors	2	Y	
4/3/03	1038	-	-	2000	28	2767	2559	75	ANDL	Indoors	2	Y	
4/3/03	1039	-	-	2000	28	2950	2556	75	ANDL	Indoors	2	Y	
4/3/03	1040	-	-	2000	28	2641	2556	75	ANDL	Indoors	2	Y	
4/3/03	1041	-	-	2000	28	2647	2556	75	ANDL	Indoors	2	Y	
4/3/03	1042	-	-	2000	28	2732	2556	75	ANDL	Indoors	2	Y	
4/3/03	1043	-	-	2000	28	2680	2565	75	ANDL	Indoors	2	Y	
4/3/03	1044	-	-	2000	28	2687	2574	75	ANDL	Indoors	2	Y	
4/3/03	1103	-	-	2500	28	-	-	75	ANDL	Indoors	2	Y	2 screens on tower 1
4/3/03	1030	-	-	2500	28	-	-	75	ANDL	Indoors	2	Y	2 screens on tower 1
4/3/03	1035	-	-	-	28	2408	2093	75	ANDL	Indoors	2	Y	2 screens on tower 1
4/3/03	1036	-	-	-	28	2390	2093	75	ANDL	Indoors	2	Y	2 screens on tower 1
4/3/03	1037	-	-	2500	28	2275	2093	75	ANDL	Indoors	2	Y	2 screens on tower 1
4/3/03	1038	-	-	2500	28	-	2093	75	ANDL	Indoors	2	Y	2 screens on tower 1
4/3/03	1039	-	-	2500	28	2381	2093	75	ANDL	Indoors	2	Y	2 screens on tower 1
5/9/03	900	-	-	-	300	-	-	80	ANDL	Clear	2	Y	Roof Link established
5/12/03	830	1622	-1402	2000	300	4399	3867	80	Roof	Clear	2	Y	EDL roof
5/21/03	900	1622	-1419	2000	300	4390	3808	80	Roof	Clear	2	Y	
5/29/03	1600	1614	-1410	2000	300	4452	3956	90	Roof	Clear	2	Y	
5/30/03	1340	1613	-1410	2000	300	4461	3860	90	Roof	Cloudy	2	Y	
6/2/03	1400	1615	-1408	2000	300	3892	3783	90	Roof	Cloudy	2	Y	
6/4/03	1310	1619	-1412	2000	300	4447	3860	90	Roof	Cloudy	2	Y	
6/5/03	1056	1620	-1407	2000	300	4438	3851	85	Roof	Cloudy	2	Y	
6/9/03	1338	1617	-1423	2000	300	3856	3112	85	Roof	Rain	2	Y	
6/9/03	1343	1617	-1423	2000	300	4026	2898	85	Roof	Rain	2	Y	
6/9/03	1345	1617	-1423	2000	300	3922	2772	85	Roof	Rain	2	Y	
6/9/03	1347	1617	-1400	2000	300	2936	2253	80	Roof	Hv rain	2	Y	
6/9/03	1350	1620	-1406	2000	300	2936	3159	80	Roof	Hv rain	2	Y	
6/9/03	1352	1620	-1414	2000	300	3849	3486	80	Roof	Lt rain	2	Y	
6/9/03	1355	1620	-1414	2000	300	4208	3594	80	Roof	Lt rain	2	Y	
6/9/03	1359	1620	-1414	2000	300	4003	3463	80	Roof	Lt rain	2	Y	
6/9/03	1400	1620	-1414	2000	300	4003	3417	80	Roof	Lt rain	2	Y	
6/9/03	1402	1620	-1414	2000	300	3746	3134	80	Roof	Med rain	2	Y	
6/9/03	1404	1620	-1414	2000	300	3505	3189	80	Roof	Med rain	2	Y	
6/9/03	1406	1620	-1414	2000	300	3403	3189	80	Roof	Med rain	2	Y	
6/9/03	1407	1620	-1414	2000	300	4015	2845	80	Roof	Lt rain	2	Y	
6/9/03	1411	1622	-1411	2000	300	4073	3368	80	Roof	Lt rain	2	Y	
6/10/03	711	1622	-1415	2000	300	4305	3582	75	Roof	Lt fog	2	Y	
6/10/03	715	1620	-1406	2000	300	4379	3676	75	Roof	Lt fog	2	Y	
6/10/03	721	1622	-1415	2000	300	4351	3644	75	Roof	Lt fog	2	Y	

Table 4-9 Craft Interface Test Data (Continued)

Date	Time	Az	El	Output TxP uW	Range Ft	Local RxP mV	Remote RxP mV	T °F	Loc	Wx	Local Input Twr	Loop Back	Comments
6/11/03	1352	1620	-1404	2000	300	4508	3863	90	Roof	Clear	2	Y	
6/12/03	1308	1619	-1402	2000	300	4485	3640	90	Roof	Clear	2	Y	
6/12/03	1312	1619	-1402	2000	300	4527	3649	90	Roof	Clear	2	Y	
6/12/03	1316	1618	-1406	2000	300	4520	3923	90	Roof	Clear	2	Y	
6/13/03	1335	1619	-1405	2000	300	4532	3916	85	Roof	Clear	2	Y	
6/13/03	1336	1619	-1405	2000	300	4535	3859	85	Roof	Clear	2	Y	
6/13/03	1340	1619	-1416	2000	300	4532	3785	85	Roof	Clear	2	Y	
6/16/03	1002	1612	-1408	2000	300	3923	3867	75	Roof	Clear	2	Y	
6/17/03	1233	1621	-1401	2000	300	4532	3869	85	Roof	Cloudy	2	Y	
6/17/03	1234	1621	-1401	2000	300	4536	3851	85	Roof	Cloudy	2	Y	
6/17/03	1235	1621	-1401	2000	300	4534	3847	85	Roof	Cloudy	2	Y	
6/18/03	717	1618	-1411	2000	300	4437	3743	75	Roof	Clear	2	Y	
6/18/03	721	1618	-1411	2000	300	4494	3783	75	Roof	Clear	2	Y	
6/20/03	1453	1622	-1409	2000	300	4036	2790	85	Roof	Lt rain	2	Y	
6/20/03	1455	1622	-1411	2000	300	4036	2960	85	Roof	Lt rain	2	Y	
6/20/03	1456	1618	-1412	2000	300	4036	2488	85	Roof	Lt rain	2	Y	
6/20/03	1457	1618	-1419	2000	300	3567	2839	85	Roof	Lt rain	2	Y	
6/20/03	1459	1618	-1419	2000	300	3302	2651	85	Roof	Lt rain	2	Y	
6/23/03	1427	1620	-1414	2000	300	4544	3886	80	Roof	Clear	2	Y	
6/23/03	1428	1620	-1414	2000	300	4544	3870	80	Roof	Clear	2	Y	
6/24/03	818	1619	-1405	2000	300	4546	3807	80	Roof	Clear	2	Y	
6/24/03	823	1619	-1406	2000	300	4544	3822	80	Roof	Clear	2	Y	
6/24/03	825	1619	-1406	2000	300	4546	3812	80	Roof	Clear	2	Y	
6/27/03	711	1616	-1418	2000	300	4040	3887	75	Roof	Clear	2	Y	
6/27/03	712	1616	-1414	2000	300	4546	3862	75	Roof	Clear	2	Y	
6/27/03	718	1616	-1414	2000	300	4543	3854	75	Roof	Clear	2	Y	
6/27/03	720	1616	-1416	2000	300	4543	3829	75	Roof	Clear	2	Y	
6/27/03	723	1616	-1416	2000	300	4546	3840	75	Roof	Clear	2	Y	
6/27/03	726	1616	-1416	2000	300	4546	3819	75	Roof	Clear	2	Y	
6/27/03	1346	1615	-1407	2000	300	4546	3947	80	Roof	P cloudy	2	Y	
6/27/03	1350	1616	-1410	2000	300	4546	3711	80	Roof	P cloudy	2	Y	
6/30/03	946	1615	-1397	2000	300	4546	3862	85	Roof	clear	2	Y	
6/30/03	948	1615	-1402	2000	300	4544	3784	85	Roof	clear	2	Y	
6/30/03	951	1616	-1402	2000	300	4194	3791	85	Roof	clear	2	Y	
7/2/03	1425	1615	-1411	2000	300	4506	3873	90	Roof	Clear	2	Y	
7/2/03	1427	1615	-1411	2000	300	4546	3873	90	Roof	Clear	2	Y	
7/2/03	1429	1615	-1411	2000	300	4546	3853	90	Roof	Clear	2	Y	
7/3/03	717	1616	-1417	2000	300	4546	3750	75	Roof	Clear	2	Y	
7/3/03	721	1616	-1417	2000	300	4366	3753	75	Roof	Clear	2	Y	
7/15/03	1400	1609	-1422	2000	300	4540	3793	80	Roof	Lt rain	2	Y	
7/15/03	1402	1609	-1422	2000	300	4546	3702	80	Roof	Lt rain	2	Y	
7/15/03	1408	1608	-1423	2000	300	3815	3055	80	Roof	Med rain	2	Y	
7/15/03	1409	1608	-1423	2000	300	4001	2935	80	Roof	Med rain	2	Y	
7/15/03	1414	1608	-1423	2000	300	3729	3195	80	Roof	Med rain	2	Y	
7/15/03	1421	1608	-1423	2000	300	4322	3283	80	Roof	Med rain	2	Y	
7/15/03	1426	1610	-1419	2000	300	4475	3550	80	Roof	Lt rain	2	Y	
7/17/03	1452	1618	-1411	2000	300	4494	3783	85	Roof	Clear	2	Y	
7/17/03	1453	1611	-1415	2000	300	4315	3764	85	Roof	Clear	2	Y	
7/17/03	1453	1611	-1415	2000	300	4278	3764	85	Roof	Clear	2	Y	
7/21/03	1515	1605	-1416	2000	300	4546	3839	90	Roof	Clear	2	Y	
7/21/03	1517	1605	-1413	2000	300	4546	3839	90	Roof	Clear	2	Y	
7/21/03	1518	1608	-1416	2000	300	4546	3711	90	Roof	Clear	2	Y	
7/21/03	1520	1605	-1416	2000	300	4546	3853	90	Roof	Clear	2	Y	
7/22/03	1510	1609	-1404	2000	300	4546	3835	85	Roof	Lt rain	2	Y	
7/22/03	1512	1610	-1416	2000	300	4546	3773	85	Roof	Lt rain	2	Y	
7/22/03	1514	1610	-1416	2000	300	4546	3781	85	Roof	Lt rain	2	Y	
7/22/03	1515	1610	-1416	2000	300	4546	3813	85	Roof	Lt rain	2	Y	
7/22/03	1516	1610	-1416	2000	300	4546	3802	85	Roof	Lt rain	2	Y	
7/22/03	1524	1610	-1416	2000	300	4546	3631	85	Roof	P cloudy	2	Y	
7/22/03	1525	1610	-1423	2000	300	4546	3554	85	Roof	P cloudy	2	Y	

Table 4-9 Craft Interface Test Data (Continued)

Date	Time	Az	El	Output TxP uW	Range Ft	Local RxP mV	Remote RxP mV	T °F	Loc	Wx	Local Input Twr	Loop Back	Comments
7/31/03	928	-1427	-423	2000	113	4546	3655	85	E Lot	Clear	2	Y	EDL E. parking lot
7/31/03	929	-1404	-423	2000	113	4546	3434	85	E Lot	Clear	2	Y	
7/31/03	931	-1414	-404	2000	113	4546	3347	85	E Lot	Clear	2	Y	
7/31/03	947	-279	-862	2000	113	3781	4546	85	E Lot	Clear	1	Y	
7/31/03	948	-268	-863	2000	113	3781	4546	85	E Lot	Clear	1	Y	
7/31/03	950	-268	-876	2000	113	3781	4546	85	E Lot	Clear	1	Y	
7/31/03	952	-268	-862	2000	113	3635	4546	85	E Lot	Clear	1	Y	
7/31/03	1327	-1361	-390	2000	113	4546	3813	85	E Lot	Clear	2	Y	
7/31/03	1329	-1361	-390	2000	113	4546	3822	85	E Lot	Clear	2	Y	
7/31/03	1330	-1361	-390	2000	113	4546	3761	85	E Lot	Clear	2	Y	
8/4/03	1555	-276	-875	2000	113	3536	4546	85	E Lot	Clear	2	Y	
8/4/03	1556	-276	-874	2000	113	3649	3935	85	E Lot	Clear	2	Y	
8/4/03	1556	-276	-874	2000	113	3665	3935	85	E Lot	Clear	2	Y	
8/4/03	1557	-276	-874	2000	113	3668	3935	85	E Lot	Clear	2	Y	
8/4/03	1602	-1371	-418	2000	113	4543	3630	85	E Lot	Clear	1	Y	Switch input
8/4/03	1603	-1371	-418	2000	113	4544	3668	85	E Lot	Clear	1	Y	
8/4/03	1606	-1371	-418	2000	113	4546	3638	85	E Lot	Clear	1	Y	
8/6/03	646	-1472	-146	9000	1066	4533	3935	75	SSPF	Clear	2	Y	EDL N lot to SSPF
8/6/03	648	-1472	-423	9000	1066	4533	-	75	SSPF	Clear	2	Y	113 ft
8/6/03	657	-1472	-423	9000	1066	4533	-	75	SSPF	Clear	2	Y	
8/6/03	706	-1512	-419	2000	1066	-	-	75	SSPF	Clear	2	Y	
8/6/03	712	-1512	-419	2000	1066	3567	2593	75	SSPF	Clear	2	Y	
8/6/03	722	-2203	-363	2000	1066	2531	3642	80	SSPF	Clear	1	Y	Switch input
8/6/03	735	-2203	-363	2000	1066	2115	3159	80	SSPF	Clear	1	Y	

The AirFiber 5800 is designed to respond to an increase or decrease in the ambient attenuation due to fog or rain. By dynamically controlling the laser output, the link is maintained through variations in the weather while also ensuring maximum laser life[46]. AirFiber stated that transmit power levels could range from 2000 to 10,000 µW, or even up to 12,000 µW with a hot laser. During ECT testing, power levels were normally at 2000 µW, except during one brief testing period at the 1066-ft distance when a couple of 9000 µW values were recorded. These values lowered to 2000 µW after 5-minutes. Values of 2500 µW were seen during ANDL tests when artificial attenuation was added by using double masks (screens) over the two OTU lenses.

[46] 700-0162-000, AirFiber System Description, P.3-5

Receiver power levels indicate the amount of air attenuation that is occurring over the link. Recorded values ranged from the mid 4000 mV to low 2000 mV. The lowest observed values were as follows:

Table 4-10 Lowest Measured Receiver Power Levels

Rx uV	Test Configuration
2093	ANDL with double lens filters
2115	SSPF lot with intermediate distance
2253	EDL Roof during heavy rain

4.7.3 SmartBits Testing

SmartBits testing was performed at all four locations. Test profiles included Throughput and Packet loss. Throughput tests included the following frame sizes and packet rates.

Table 4-11 SmartBits Throughput Test Parameters

Frame Size	Pks/Sec
64	706415
128	470943
256	235471
512	128439
768	83107
1024	64219
1518	44150

Packet loss tests used the same frame sizes and always resulted in zero packet losses.
A summary of all SmartBit tests is provided in the following table. Most data files are included in Appendix K.

Table 4-12 Summary Of SmartBits Testing

Date	Throughput		Packet Loss		Loc	Loop	Comments
	Results	File	Results	File		Back	
4/3/03	100%	Lost	0	Lost	ANDL	Y	Files lost when lab computer was changed
4/3/03	100%	Lost	0	Lost	ANDL	Y	2 screens masks on Twr 1
4/3/03	100%	Lost	0	Lost	ANDL	Y	1000 M of fiber, 2 masks Twr 1
5/9/03	100%	-	0	T-050903-pl.xls	roof	Y	
5/19/03	100%	-	0	T-051905-pl.xls	roof	Y	
6/2/03	100%	-	0	T-060203-pl.xls	roof	Y	
6/27/03	100%	-	0	T-062703-pl.xls	roof	Y	
6/4/03	100%	-	0	T-060403-pl.xls	roof	Y	
6/5/03	100%	T-060503-tp.xls	0	T-060503-pl.xls	roof	Y	
6/27/03	100%	T-062703-tp.xls	0	T-062703-pl.xls	roof	Y	
7/15/03	100%	T-071503-tp.xls	0	T-071503-pl.xls	roof	Y	
7/22/03	100%	T-072203-tp.xls	0	T-072203-pl.xls	roof	Y	
7/31/03	100%	T-073103-tp.xls	0	T-073103-pl.xls	E lot	Y	East EDL parking lot, 113 ft
8/6/03	100%	T-080603-tp.xls	0	T-080603-pl.xls	SSPF	Y	N EDL lot to SSPF lot, 1066 ft

4.8 FSO SECURITY CONCERNS

Security for FSO links is usually achieved by controlling access to the equipment. The FSO beam is relatively narrow and thus the field of view is usually limited to items in the immediate vicinity of the receiving OTU. Any attempts to redirect the beam would normally be immediately obvious due to the loss of signal and the breaking of the communication link. Security of the connecting fiber is likewise assured by either access control or existing fiber security methods.

4.9 FSO SUMMARY AND RECOMMENDATIONS

FSO testing was considered very successful. One of the major achievements was overcoming the learning curve and becoming familiar with FSO operations. Unfortunately, this learning curve was with the AirFiber 5800s, i.e., units that are no longer available due to the business closure of AirFiber. Experience with these units has shown that FSO links can be very reliable in a KSC type weather environment. Although no significant fog days were observed during the testing, heavy Florida afternoon thunderstorms did not significantly impact the FSO performance over the 300-ft roof top distance.

Although some mechanical problems were encountered, these could have been the results of the frequent moving and relocating the OTUs experienced during testing. Normally, OTUs would remain stationary throughout most of their service life.

While ECT Phase 2 provided a good experience foundation on which to expand FSO development on the range, the AirFiber 5800s are no longer being produced. Meanwhile during the past year, many FSO industry products are moving away from AirFiber's narrow beam, auto-tracking architecture to multi-beam, non-tracking configurations. ECT follow-on activities should investigate these new lower-cost and presumably higher reliability architectures through procurement and operation of additional test links. Where possible, side-by-side comparisons between the two architectures should be performed to determine which is best suited for the Range environment.

5.0 ECT SUMMARY RECOMMENDATIONS FOR CONTINUED RESEARCH

The following tasks are recommended for continued research in the next fiscal year:

1.) Conduct an industry survey on wide-beam optical FSO systems, and procure a fixed, non-tracking, wide-beam optical FSO system with redundant optical beams to overcome the limitations noted in year one with blockages of single beam systems, such as can occur for bird blockages.
2.) FSO Testing:
    a. Update previously generated test procedures, adapting and expanding these procedures to account for the multiple parallel optical beams, to permit testing the FSO system exemplars for Bit Error Rate, and throughput rates versus weather-induced degradations (e.g., fog, rain, etc.).
    b. Test the performance limits of this FSO hardware within the unique environment of KSC, with data path links over both water and over land, comparing the applicability of this technology to KSC's needs versus the first generation auto-tracking, narrow-beam, FSO system procured and tested on ECT during FY03.
3.) UWB Analysis:
    a. Analyze new, multi-band UWB hardware for applicability on the Range, with particular emphasis on piconet sub-division capability within LANs, recurring costs of hardware, and life-cycle operational costs.
    b. Analyze position-aware capabilities of UWB communication technology, with particular emphasis on determining positional accuracy limitations (e.g., accuracy in centimeters, ability to provide relative and absolute positional information.)
4.) UWB Testing:
    a. Update previously generated test procedures, adapting and expanding these procedures for testing the UWB evaluation kit for position aware functionality.
    b. Test position-aware capabilities of UWB communication technology using the UWB evaluation kit (EVK) procured during FY03, following the position aware enhanced test procedures developed from previously generated test procedures.
    c. Review current UWB and FSO products and theoretical developments through attending two major optical communication conferences and one joint NASA-USAF Advanced Range and Spaceport Technology Conference.

These activities are needed to achieve the 24/7, always-on, highly-mobile vision of an interconnected communication for use on the Range employing First Mile / Last Mile extensions to the existing Range communication infrastructure.

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The Emerging Communication Technology (ECT) project investigated three First Mile communication technologies in support of NASA's Second Generation Reusable Launch Vehicle (2nd Gen RLV), Orbital Space Plane, Advanced Range Technology Working Group (ARTWG) and the Advanced Spaceport Technology Working Group (ASTWG). These First Mile technologies have the purpose of interconnecting mobile users with existing Range Communication infrastructures.

ECT was a continuation of the Range Information System Management (RISM) task started in 2002. RISM identified the three advance communication technologies investigated under ECT. These were Wireless Ethernet (Wi-Fi), Free Space Optics (FSO), and Ultra Wideband (UWB). Due to the report's size, it has been broken into three volumes: 1) Main Report 2) Appendices 3) UWB

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