TEST BED FOR WIRELESS MULTIMEDIA NETWORKS

by

David L. Hu

Thesis

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A test bed for wireless multimedia networks is established in Broadband Communications Laboratory. The test bed is based on wireless LAN technology. Real-time applications, such as video conferencing, and Internet access have been experimented on the test bed. The observations and technical issues are presented and discussed. A survey of current indoor radio propagation models is introduced. The potential expansion of the project and research activities for the next phase of the project is proposed.
Table of Contents

Acknowledgments ............................................................................................. iii
Abstract ............................................................................................................. iv
List of Figures ................................................................................................... vi
List of Tables ................................................................................................... vii
Introduction ....................................................................................................... 1
Chapter 1. Technical and Design Issues ......................................................... 9
Chapter 2. Observations and Discussions ..................................................... 48
Chapter 3. Conclusions .................................................................................... 54
References ......................................................................................................... 56
Introduction

Multimedia communications are more effective and efficient method of information exchange and are becoming more and more desirable in our information age. In general, voice, animation, still and motion images can boost much higher information processing power of human brain in terms of speed and accuracy than the pure textual information. Limited by the technology, the early computer communications were plain text plus handful of printable symbols, which can be handled relatively well by the existing wired and narrow band wireless telecommunication and data communication networks. While multimedia communications and mobility are playing an increasing role in today’s society, wireless broadband communications are becoming the key to pave the road towards realizing ubiquitous multimedia communication in the future.

Several wireless broadband systems (WBS) may emerge for different users with various requirements on data rate ranging from 2 Mb/s to 155 Mb/s [1]. Terminals can be mobile or portable (static while communicating), and moving speed may be as fast as that of a train. Depending on the application, or required data rate, one or multiple channels may be allocated to a user, and bandwidth allocation can be either fixed or dynamic. Mobile terminals communicate with each other either through base stations/access points or through direct links, the latter is more likely in ad hoc networks.

There are two major approaches for the wireless broadband systems (WBS): wireless local area networks (WLAN), and mobile broadband systems (MBS) [1]. High
Performance Radio LAN (HIPERLAN) [2] and IEEE 802.11 [3] are the examples of today’s wireless local area networks. As a cellular system, the mobile broadband systems (MBS) intend to provide full mobility to broadband integrated services digital network (B-ISDN) users [1].

To study and support future research activities in the broadband wireless networks, a test bed has been built in the Broadband Communication Laboratory at the University of Texas at Dallas. The first phase of the project achieved the goal to setup a small scale multimedia wireless network in the EC building, so the behaviors of the multimedia traffic in a wireless environment can be observed and studied.

The test bed established in the Broadband Communication Laboratory adopted IEEE 802.11 wireless LAN (WLAN) approach. The basic system architecture is shown in Fig. 1. The Access Point which serves as a base station is connected to the campus local area network through Ethernet. A multimedia PC is linked to the campus local area network through Ethernet to simulate a fixed network node, and a multimedia laptop computer equipped with a wireless LAN adapter is used as the mobile station. To simplify the system design and make the system more realistic, all the components are off-shelf products, including radio system, test software and operating systems.

The wireless LANs (WLAN) are typically the extensions of the wired LAN backbone, which allow the mobile users to access the shared resources at relatively high speed. Wireless LAN (WLAN) uses radio frequency (RF) or infrared (IR) technology.
to provide mobile links. The base station (called Access Point in WLAN) is either attached
to wired LAN as a node or connected to a communication server. The messages in such
applications are usually short; on the order of a few hundred bytes, but the message
Figure 1 The Architecture of Wireless Multimedia Network Test Bed at University of Texas at Dallas
frequency can be very high, as much as hundreds per second [4]. The access point is the
gateway between the radio cell and wired LAN so that IP or IPX or other node
designations can be mapped one-for-one with user IDs on the user directory and
password [5]. As a gateway the access point is also responsible for converting signals
from wired networks to RF or IR format.. The data rate of current WLAN products is
in the range of 1 Mb/s ~ 20 Mb/s. Table 1 shows a comparison on the different WLAN
technologies. WLAN provides terminal roaming capability among the different base
stations (access points). If sufficient access points are deployed, the coverage of a
building or whole campus can be achieved. Within the coverage area, the mobile
terminals can roam at normal walking speed without losing connectivity and maintaining
relatively high data rate.

Currently, most of wireless LAN products are operating at ISM (Industrial,
Scientific, and Medical) unlicensed bands (2.4 GHz is more common because it is
standard both in the USA and Europe). Motorola’s Altair system operates at 18 GHz
or 24 GHz, which offers higher data rate and better propagation characteristics for in-
house cellular networks compared to ISM bands [6], however, site-specific FCC
licensing is required. Infrared (IR) systems offer higher data rate (10 Mb/s and up)
compared to RF systems, but the drawback is its line-of-sight (LOS) limitations, i.e. it
can not pass through solid objects (walls, people, furniture, etc.), and for out door
systems, the transmission is affected by weather, such as rain and fog etc.. The lack of
industry standards is the most significant obstacle to wide spread of WLANs.
<table>
<thead>
<tr>
<th>Technique (Mb/s)</th>
<th>DF/IR</th>
<th>DB/IR</th>
<th>RF</th>
<th>DSSS</th>
<th>FHSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Rate</td>
<td>1 ~ 4</td>
<td>10</td>
<td>5 ~ 10</td>
<td>2 ~ 20</td>
<td>1 ~ 3</td>
</tr>
<tr>
<td>Range (ft)</td>
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<td>80</td>
<td>40 ~ 130</td>
<td>100 ~ 800</td>
<td>100 ~ 300</td>
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<td>Wave Length or Frequency</td>
<td>λ = 800 ~ 900 nm</td>
<td>λ = 800 ~ 900 nm</td>
<td>18 GHz / ISM bands</td>
<td>ISM bands</td>
<td>ISM bands</td>
</tr>
<tr>
<td>Radiation Power</td>
<td></td>
<td></td>
<td>25 mW</td>
<td>&lt; 1 W</td>
<td>&lt; 1 W</td>
</tr>
<tr>
<td>Access Method</td>
<td>CSMA</td>
<td>Token Ring CSMA</td>
<td>Reservation ALOHA CSMA</td>
<td>CSMA</td>
<td>CSMA</td>
</tr>
</tbody>
</table>

Table 1 Comparison of Wireless LAN Technologies

Note:
IR - Infrared
RF - Radio Frequency
DSSS - Direct Sequence Spread Spectrum
FHSS - Frequency Hopping Spread Spectrum
Without accepted standards, WLAN adapters from different vendors will not necessarily offer the same interoperability as Ethernet adapters from different suppliers. The IEEE is addressing the need for a standard via its 802.11 working group and draft standard. However, the completion of the standard is still far away. The effect of a future transition to IEEE 802.11 compliance can be minimized by adopting technology that closely matches the draft. Few WLAN products are compatible with each other so far; to my best knowledge, only DEC’s RoamAbout Access Point can operate with WaveLAN adapters from AT&T and RangeLAN2 adapters from Proxim.

The radio modulation techniques used by RF based wireless LAN falls into two categories defined by IEEE 802.11 standard: Frequency Hopping Spread Spectrum (FH-SS) and Direct Sequence Spread Spectrum (DS-SS). In specifying both alternatives, members of the 802.11 working committee felt that DS-SS would offer higher performance when the applications require so, while FH-SS would provide a solution when the cost is the major issue [7]. Offering DS-SS and FH-SS in the physical layer is analogous to the choice of 10BaseT, 10Base5, and other physical layers in the Ethernet arena. The test results of nine commercial WLAN products (including RoamAbout) from PC Magazine indicate that each technique has its trade-offs: basically FH-SS systems have lower data throughput than DS-SS systems, but FH-SS systems are scaleable when multiple access points are added, less susceptible to interference, and
drains less battery power from the mobile stations [8]. We selected DS-SS systems out of data throughput consideration.

The bearer services which are qualified as broadband access are defined as hundreds of kb/s up to 2 Mb/s in the FPLMTS/IMT-2000 (Future Public Land Mobile Telecommunications System/International Mobile Telecommunication by the year 2000) for both fixed and mobile access [4]. Currently 2 Mb/s is the best throughput for most commercial available RF WLAN product operating in the ISM unlicensed bands. We have evaluated the performance of current available wireless LAN technologies and products, and chosen Digital Equipment Corp.’s RoamAbout Access Point and 2.4 GHz Direct Sequence Spread Spectrum (DS-SS) PCMCIA wireless LAN adapter as the wireless network part of the test bed. Table 2 shows the technical specifications of the RoamAbout PCMCIA adapters which operate at 915 MHz and 2.4 GHz.

To inject the real multimedia traffic into the test bed, a video conferencing system is setup to put the real-time traffic load on the network. An Internet video conferencing software system CUSeeMe™ from White Pine Software, Inc. is installed in both fixed PC node and mobile station to provide multimedia traffics. Other Internet applications such as Microsoft Internet Explorer, Telnet etc. are also experimented on the radio link. Performance is evaluated and problems are observed and discussed in this thesis.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>915 DS/PC Adapter</th>
<th>2400 DS/PC Adapter</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power Consumption</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sleep Mode</td>
<td>0.18 W</td>
<td>0.175 W</td>
</tr>
<tr>
<td>Receive Mode</td>
<td>1.48 W</td>
<td>1.575 W</td>
</tr>
<tr>
<td>Transmit Mode</td>
<td>3.00 W</td>
<td>1.825 W</td>
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<td><strong>R-F Specification</strong></td>
<td></td>
<td></td>
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<tr>
<td>Frequency</td>
<td>902 ~ 928 MHz</td>
<td>2400 ~ 2500 GHz</td>
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<tr>
<td>Modulation Technique</td>
<td>Spread-Spectrum DQPSK</td>
<td>Spread-Spectrum DQPSK</td>
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<tr>
<td>Output Power</td>
<td>250 mW</td>
<td>50 mW</td>
</tr>
<tr>
<td>FCC Regulations</td>
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<td>No site license required</td>
</tr>
<tr>
<td><strong>Data Communications</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data Rate</td>
<td>2 Mb/s</td>
<td>2 Mb/s</td>
</tr>
<tr>
<td>Media Access Protocol</td>
<td>Ethernet (CSMA/CA)</td>
<td>Ethernet (CSMA/CA)</td>
</tr>
<tr>
<td>Bit Error Rate</td>
<td>Better than $10^{-8}$</td>
<td>Better than $10^{-8}$</td>
</tr>
</tbody>
</table>

Table 2 Specifications of DEC’s RoamAbout 915/2400 DS/PC Adapter
1.1 Spread Spectrum Technology

Spread spectrum communication is a relatively mature technology with many highly developed disciplines, including modulation, coding, and synchronization methods. The distinguishing characteristic of spread spectrum systems is that the carrier signals used to transmit base band signals have much wider bandwidth than the underlying information bit rate of the systems. There are two basic methods to implement spread spectrum systems: direct-sequence spread-spectrum (DS-SS) and frequency-hopping spread-spectrum (FH-SS).

The major advantages of spread-spectrum transmission are as following [14]:

• Spread-spectrum signals can be overlaid on top of the radio bands where other systems are already operating, with minimal performance impact to or from the existing systems.

• The anti-multipath characteristics of spread-spectrum signaling and reception techniques are attractive in applications where multipath is likely to be extensive (achieving good performance in frequency-selective fading channels may require the use of a Rake receiver, which is in effect a matched filter for a multipath channel).

• The convenience of unlicensed spread-spectrum operation in ISM bands is attractive to both manufactures and users.
The basic principles of DS-SS and FH-SS are briefly discussed in the following sections.

1.1.1 The basic principle of DS-SS system

The information signal is spread at baseband, and the spread signal is modulated. The received signal is first demodulated to recover the spread signal, and it is de-spread to recover the original information signal. Fig. 2 illustrates a simple block diagram of a DS-SS system.

In Fig. 3 a square pulse with duration $T_b$ represents a baseband binary bit in the time domain, and its Fourier transform is a sinc pulse with zero crossings spaced by $1/T_b$. This binary bit is multiplied by a sequence of narrower pulses with time duration $T_c$ in the time domain and zero crossing spaced by $1/T_c$ to form spread-spectrum signal. The narrow pulses are referred to as *chips* [14], and their amplitudes are $\pm 1$. The *bandwidth expansion factor* is defined as $N = \frac{T_b}{T_c}$, the baud rate is $R_b = \frac{1}{T_b}$ and the chip rate of the system is $R_c = \frac{1}{T_c}$. Because the transmitted power is spread over a bandwidth $N$ times wider than the baseband symbol rate, the spectral height of the spread signal is $N$ times lower than it would be if the baseband signal was not spread. The chip sequence is coded to appear random, so it is referred to as *pseudorandom* (PN) sequences or codes [14]. Some performance details will be discussed in the next section 2.2. Figure 4
shows a diagram for a typical DS-SS transceiver operating in the ISM band. A microprocessor controls the operation of the transceiver. The transmitter enable signal TXENA controls the switch that determines whether the system in transmit
Figure 2 Simple Block Diagram of a DS-SS System
Figure 3  Spreading and Despreading in DS-SS System [14]
Figure 4  A Typical DS-SS Transceiver for Operation in the ISM Band [14]
(TX) or receive (RX) mode. TXD and RXD are the data and TXCHIPS and RXCHIPS are the chips for transmitting and receiving respectively. Other signals such as clock TXCLK and RXCLK are also essential for the operation.

1.1.2 The basic principle of FH-SS system

The FH-SS technique can be viewed as a two-layer modulation technique. The first layer can be any standard digital modulation technique, while the second layer is $M$-ary FSK. The digitally modulated signal makes a $PN$ selection of one of $M$ frequencies as its carrier frequency, i.e. the carrier frequency of the modulated baseband signal is hopped over a wide range of frequencies determined by a periodic $PN$ code [14]. The hopping of the carrier frequency produces a desired spreading of the transmitted signal spectrum. The changes in the carrier frequency do not affect the performance in additive noise, and the AWGN performance remains exactly the same as the performance of the digitally modulated system without frequency hopping [14].

In a FH-SS system the interval of the time spent at each hop frequency is referred as the *chip duration* [14]. However the chip duration in a FH-SS system is not determined by the inverse of the bandwidth because the system does not necessarily hop per symbol or bit, it can hop more than once during one bit period. If the chip duration is sorter than the bit duration, i.e. there are more than one hop per bit, the system is called fast-FH-SS system. If the chip duration is greater than the bit duration, i.e. there are more than one bits per chip, the system is called slow-FH-SS system. Fast frequency hopping is effective to compensate narrowband interference
and frequency-selective fading, and error-correction coding is more effective for fast 
FH-SS than slow FH-SS [14]. Fig. 5 shows the block diagram for a FH-SS system. 
Some performance issues are discussed in the following section.

1.2 Comparison of DS-SS and FH-SS

The two spread spectrum approaches: Frequency Hopping Spread Spectrum (FH-SS), 
and Direct Sequence Spread Spectrum (DS-SS) deployed in the wireless LAN are different. 

FH-SS changes transmission frequency periodically. A frequency hopping signal may be 
regarded as a sequence of modulated data bursts with time-varying (pseudorandom) 
carrier frequencies. Hopping occurs over a frequency band that includes a number of 
channels. Each channel is defined as a spectral region with a central frequency in the 
hopset and a bandwidth large enough to include most of the power in a narrowband 
modulation burst (usually FSK) having the corresponding carrier frequency. The 
bandwidth of a channel used in the hopset is called the *instantaneous bandwidth* [9]. FH-SS systems send one or more data packets at one carrier frequency, hop to another 
frequency and send one or more data packets, and continue this sequence. The time the 
FH-SS radios stay on each frequency depends on a combination of individual 
implementation, governmental regulations, and adherence to the IEEE 802.11 draft 
standard [7]. The hopping pattern or sequence appears random, but it is actually a 
periodic sequence tracked by the pair of sender and receiver. FH-SS systems can be 
susceptible to noise during any one hop but during other hops around the wideband range,
the transmission is typically error-free [7]. The probability of error for the asynchronous

FH-SS is [9]:
Figure 5   Block Diagram of a FH-SS Modem [14]
Where $\frac{E_{b}}{N_{0}}$ is the signal energy per bit to noise power spectral density, $K$ is number of different transmitted signals, $N_b$ is the number of bits per hop, and $M$ is the number of possible hopping channels. We should be aware that the bit-error rate (BER) of a GFSK-based FH-SS system at 2 Mb/s makes transmission at rate somewhat unreliable. The IEEE 802.11 draft actually describe FH-SS WLANs operating at a standard speed of 1 Mb/s, with 2 Mb/s speed optional in optimal-quality conditions [7]. The IEEE 802.11 committee selected GFSK for use in FH-SS system because it simplifies the design of the RF transmitter [7]. The information is conveyed by the frequency of a FSK signal instead of the amplitude, therefore a low-cost, non-linear amplifier can be used to transmit such a constant-envelope signal without considering clipping of the signal peaks.

The Direct Sequence Spread Spectrum systems (DS-SS) spread the baseband data by directly multiplying the baseband data pules with a pseudonoise sequence that is generated by a pseudonoise generator. A single pulse of symbol of the $PN$ waveform is called a *chip* [9]. The received spread spectrum signal for a single user can be represented as [9]:

$$S_{ss}(t) = \sqrt{\frac{2E_{s}}{T_s}} m(t) p(t) \cos(2\pi f_{c} t + \theta)$$  \hspace{1cm} (1.2)
where $m(t)$ is data sequence, $p(t)$ is the PN spreading sequence, $f_c$ is the carrier frequency, and $\theta$ is the carrier phase angle at $t = 0$. The data waveform is a time sequence of rectangular pulses, each of which has an amplitude equal to +1 and -1. Each symbol in $m(t)$ represents a data symbol and has duration $T_s$. Each symbol in $p(t)$ represents a chip and has a duration of $T_c$. The transitions of the data symbols and chips coincide such that the ratio $T_s$ to $T_c$ is an integer [9]. The multiplication operation in a DS-SS transmitter increases the used bandwidth-modulation rate based on the length of the chip sequence.

At the receiving end, assuming that code has been synchronized, the received signals pass through the wideband filter and is multiplied by a local replica of the PN code sequence $p(t)$. If $p(t) = \pm 1$, then $p^2(t) = 1$, and the multiplication yields the despread signal given by

$$S_{\text{despread}}(t) = \sqrt{\frac{2E}{T_s}} m(t) \cos(2\pi f_c t + \theta)$$  \hspace{1cm} (1.3)

The corresponding demodulation can extract information $m(t)$. Fig. 6 (a) illustrates the received spectra of the desired signal and the interference, at the output of the receiver wideband filter. Assuming the bandwidth of the signal $m(t)\cos(2\pi f_c t + \theta)$ is $B$, and the spread bandwidth of $S_{ss}(t)$ is $W_{ss}$, the spreading due to $p(t)$ gives $W_{ss} \gg B$. Multiplication by the spreading waveform produces the spectra of Fig. 6 (b) at the demodulator input. The signal bandwidth is reduced to $B$, while the interference energy is spread over a bandwidth exceeding $W_{ss}$. The filtering action of the demodulator removes most of the
interference spectrum that does not overlap with the signal spectrum. Therefore, most of
the original interference energy is eliminated and does not affect the receiver performance.

An approximate measure of the interference rejection capability is given by the ratio \( \frac{W_{ss}}{B} \),
which is equal to the processing gain defined as [9]
(a) Wideband filter output

(b) Correlator output after despreading

Figure 6  Spectrum of desired received signal with interference [9]
Where $R_c$ is chip rate and $R_s$ is base band data rate. The higher the process gain of the system, the greater will be its ability to suppress in-band interference.

For DS-SS systems, the Gaussian approximation yields an expression for the average probability of bit error with $Q$ function [9]:

$$P_e = Q\left(\frac{1}{\sqrt{\frac{K-1}{3N} + \frac{N_0}{2E_b}}}\right)$$  \hspace{1cm} (1.5)

where $N$ is the number of chips per message symbol period $T$ such that $NT_c = T$ [9].

In the DS-SS systems, a spread signal can undergo as many as $N$ phase changes per symbol period where as a non-spread QPSK signal would undergo a maximum of one phase change per symbol period. The receiver correlates the received signal with $N$-chip sequence to obtain the original data sequence. Due to this redundancy in the transmitted information, the receiver can better identify the data sequence even if the received signal sequence contains errors.

The difference in performance, capacity, and price depends on the choice of DS-SS or FH-SS and the type of modulation scheme. The reliability and high data rate of DS-SS systems are best achieved by using a phase-varying modulation such QPSK or differential phase-shift keying (DQPSK). The FH-SS systems do not presume any specific modulation scheme, although the IEEE 802.11 draft prescribes the use of Gaussian
frequency-shift keying (GFSK). Most existing FH-SS implementations use some form of
frequency-shift keying (FSK) [7].

Compared to DS-SS systems, FH-SS systems require less receiver digital-signal-
processing (DSP) power in terms of rated million instructions per second (MIPS) than
DS-SS systems to recover the spread signals [7]. This implies the cost of FH-SS system
is lower than a DS-SS system. In a DS-SS system, because QPSK requires accurate
transmission of amplitude to maintain the spectral purity of the transmitted signal,
highly-linear power amplifier must be used to eliminate clipping of the signal peaks,
which will increase the cost of a DS-SS system. However, the cost of a linear amplifier
can be justified considering the performance. QPSK-based DS-SS system provides a
significant theoretical advantage over FSK-based FH-SS system in terms of peak data rate
and immunity to noise [7].

Besides the peak data rate, the aggregate throughput is also very important because the
peak data rate determines how well the network can handle the multimedia traffic for an
individual user, while the aggregate throughput determines how many users can
effectively connect to a WLAN through a single access point (AP). A DS-SS access point
offers substantially more aggregate throughput than a FH-SS access point [7]. The
latencies related to medium access and the errors that result in re-broadcasting of packets
are the biggest enemy for maximizing the aggregate throughput. The IEEE 802.11
standard will prescribe that both DS-SS and FH-SS systems use similar medium access
schemes. However, FH-SS systems inherently have longer latencies on each frequency
hop, and also suffer more frequent re-broadcasting of packets because the systems are fundamentally more susceptible to noise [7].

The IEEE 802.11 recommended packet size for FH-SS systems is 400 bytes, and 1,500 to 2,400 bytes for DS-SS systems [7]. Therefore a FH-SS system will have to break up almost all long data packets into 400-byte fragments. Since a transmission preamble and MAC header are needed for each fragment and a separate acknowledgment frame is necessary for each transmission, the overhead becomes significant when a long data packet is transmitted in a FH-SS system. As a matter of fact the DS-SS systems use radio waves more efficiently, which yields a 4 ~ 10% difference in performance [7].

The last issue in this section is the capacity. When a single access point is considered, the capacity comparison between FH-SS and DS-SS systems is straightforward, but multiple access points will complicate the matter significantly. In both FH-SS and DS-SS implementations, multiple access points can be co-located in the same area to boost aggregate throughput. Theoretical calculations reveal the fact that degradation occurs as more access points are co-located since the number of collisions increase and such collisions require regular re-transmission by the access points no matter in FH-SS or DS-SS system [7]. Such calculation indicates that when using 1 Mb/s FH-SS access points, aggregate bandwidth (taking latencies and packet overhead into account) never exceeds 4 Mb/s regardless how many access points are used, and for reaching 3.7 Mb/s aggregate throughput, more than 10 FH-SS access points are needed, while only 3 DS-SS access points can offer 4 Mb/s aggregate throughput [7].
A detailed examination indicates that DS-SS system scale significantly better than FH-SS systems, and DS-SS access points can be packed more closely together because QPSK-based DS-SS systems is more robust relative to co-channel interference than GFSK-based FH-SS systems. When defining a difference in signal capture with respect of power level, the IEEE 802.11 draft specification has set the DS-SS defer level for valid transmissions 15 dB above the FH-SS defer level. This defer threshold advantage allows two DS-SS cells using the same channel to be packed 4 ~ 8 times as densely as two FH-SS cells that use the same hop sequence [7].

Lucent Technologies, based on experience in modulation algorithms and radio design, claims that DS-SS system has the potential to make a jump to 10 Mb/s in data rate, which is translated to that 3 co-located access points could offer an aggregate throughput of 30 Mb/s [7].

Based on the above reasoning, we decided to adopt DS-SS system to build the test bed.

1.3 The Multiple Access Control (MAC) Protocol in the Wireless LAN

The IEEE 802.11 working group has agreed in principle to adopt Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) as the basic MAC protocol for wireless LANs [10]. The MAC protocol has a strong impact on the performance of WLAN systems. Within WLAN, two types of network architectures exist, the distributed network with peer-to-peer communication between nodes and centralized network where all radio packets from source nodes will be concentrated to a base station (access point), then forwarded to the destination nodes. The former is a case of ad-hoc network where
the links are temporary and the number of user is typically small. The latter is the case of most WLAN applications including the test bed in our laboratory.

Real time applications where the channels are allocated on demand and asynchronous data services are supported using different protocols. However no matter what kind of protocols are used, they are built on the top of a simple access protocol - Distributed Foundation Wireless MAC (DFWMAC) [10]. The DFWMAC adopts CSMA/CA, which grants each participating station equal right to transmit. In a CSMA network, the nodes listen to the channel before transmission attempt, if the channel is busy, the transmission is deferred, otherwise a packet is transmitted. After a packet is transmitted, the channel is probed for any collision since two or more nodes might be transmitting simultaneously. This collision detecting capability is implemented in the Ethernet but rather difficult to implement in the wireless channels because in the wired LANs, the collision can be detected by monitoring if the signal level in the medium exceeds a certain threshold [11], while the large dynamic range of the radio medium makes bandwidth efficient collision detection technically very difficult.

For radio channel, a collision avoidance scheme CA is adopted where at the end of a deferral period and after sensing the channel to be busy, all deferral stations will select a random backoff period before sensing the channel again. This deferral period includes the time when the channel is sensed busy until the end of current transmission plus an inter frame space (IFS) period. The different values of IFS can be used for different classes of traffic which have different priorities to access the channel. When the channel is
determined free, a node can seize the channel and transmit the packets, otherwise the above algorithm is executed recursively. The random backoff period is a function of a random number generated, the contention window parameter in slot time intervals and slot time [10]. The contention window starts with a initial minimum value and increases exponentially after every transmission attempt up to a maximum value. The slot time is the total propagation delay and medium busy detect response time [10]. Some simulation model indicates that the choice of inter frame space (ISF) has significant impact on this collision avoidance algorithm [10].

1.4 Spectrum and Process Gain

In 1985, the U.S. Federal Communications Commission (FCC) allocated the Industrial Scientific Medical (ISM) 2.4 GHz band for wireless LAN use. Actually under FCC’s part 15 rules and regulations, three bands are available for unlicensed use: 902 ~ 928 MHz, 2400 ~ 2483.5 MHz, and 5125 ~ 5850 MHz [12]. Since 2.4 GHz is standard both in the U.S.A and Europe, we chose DEC’s RoamAbout 2400 DS/PC WLAN family which is operating in the 2.4 GHz band (the actual operating frequency is set at 2.4220 GHz) [13]. In the ISM bands, a minimum processing gain of 10 dB is required (definition of process gain is given by equation 2.4), so various techniques have been developed to allow large processing gains (greater than 25 dB) with minimum receiver code-acquisition times [12]. However, the larger the processing gain of spread spectrum system, the higher the cost and spectral needs the system will require. Without spread spectrum modulation in the indoor unequalized channel, data rate on the order of only 300 kb/s can
be supported [12]. The trade-off must be taken into account between process gain, data rate, robust performance, costs and regulations.

1.5 Indoor Propagation Characteristics and survey on the propagation models

The frequencies in the range of a few gigahertz (e.g. 2.4 GHz) is very attractive for broadband wireless communications. At these frequencies a transmitter with power less than 1 W can provide coverage for several floors within a building, and if used outdoors it can cover distance of the order of a few miles. Furthermore, at these frequencies the size of an efficient antenna can be on the order of an inch, and antenna separations as small as several inches can provide un-correlated received signals for achieving diversity in the received signals.

In the indoor environment the multipath is caused by reflection from the walls, ceiling, floor, and objects within an office. Because the distances in an office environment are usually shorter, the delays between arriving paths are smaller compared to the outdoor environment, the multipath spread is generally smaller. For broadband transmission such as spread-spectrum systems, the multipath characteristics of the channel and received power are the important parameters for system design and implementation.

In order to assess the performance capabilities of various wireless systems, the time dispersion - multipath delay spread is defined. In the practice, the root mean square (rms) delay spread $\tau_{\text{rms}}$ is used [9].

$$\tau_{\text{rms}} = \sqrt{\tau^2 - (\tau')^2} \quad (1.6)$$
where $\tau_k$ is the delay of the $k$th signal and
These delays are measured relative to the first detectable signal arriving at the receiver at \( \tau_0 = 0 \). Equation (2.7) and (2.8) do not rely on the absolute power level of \( P(\tau) \), but only the relative amplitudes of the multipath components within \( P(\tau) \) [9].

The simplest measure of multipath delay spread is the overall span of path delays (i.e. earliest arrival to latest arrival) which is sometimes referred to as the excess delay spread. One must be aware that the excess delay spread is not necessarily the best indicator of how any given system would perform on the channel because different channels with the same excess delay spread can exhibit different profiles of signal intensity over the delay span, and intensity-delay profiles will have greater or lesser impact on the performance of any given system [14].

Wireless LAN are designed for use in office and buildings. The indoor office areas typically consist of large spaces partitioned into cubicles. In each cubical there are several metallic objects such as bookshelves and desks. The frame of the building is usually constructed with metallic studs and sometimes concrete frames, while the insulation and the exterior walls can be similar to residential construction. The ceilings and floors
usually have significant amounts of metal and concrete, presenting a strong barrier to radio wave penetration from one floor to another. This physical operating environment has its unique influence on the characteristics of wireless channels, e.g. the layout of the building, the construction materials, and the building type.

Most of the wideband indoor radio propagation studies in various buildings report maximum $rms$ multipath delay spreads of around 100 nsec, the excess delay spread is usually on the order of several hundred nanoseconds, typically on the order of several microseconds without distant reflectors, and around 100 $\mu$sec with distant reflectors [14].

Indoor radio propagation is dominated by the same mechanisms as outdoor: reflection, diffraction, and scattering. However, conditions are much more variable. For instance, signal levels vary greatly depending on whether interior doors are open or closed inside a building. Where antennas are mounted also has the impacts on large-scale propagation. Antennas mounted at desk level in a partitioned office receive vastly different signals than those mounted on the ceiling. Furthermore, the small propagation distances make it more difficult to insure far-field radiation for all receiver locations and types of antennas [9]. In general, indoor channels may be classified either as line-of-sight (LOS) or obstructed (OBS), with varying degrees of clutter [9]. Some of the key models which have recently emerged are briefly discussed below.

- Partition Losses (same floor)
Partitions in the buildings vary widely in their physical and electrical characteristics, thus it is virtually impossible to develop a general model for specific indoor configurations. Nevertheless, researchers have developed extensive data bases of losses for a great number of partitions, as shown in Table 3 [9].

• Partition Losses between Floors

The losses between floors of a building are determined by the external dimensions and materials of the building, as well as the type of construction used to build the floors and the external surroundings [9]. Even the number of windows in a building and the presence of tinting (which attenuates radio energy) can impact the loss between floors.

• Log-distance Path Loss Model

Indoor path loss has been shown by many researchers to obey the distance power law in equation:

\[ PL(dB) = PL(d_0) + 10n \log\left(\frac{d}{d_0}\right) + X_\sigma \]

(1.9)

where the value \( n \) is determined by the surroundings and building type, and \( X_\sigma \) represents a normal random variable in dB having a standard deviation of \( \sigma \) dB.

Table 4 provides typical \( n \) values for various buildings [9].

• Ericsson Multiple Breakpoint Model

This model was obtained by measurements in a multiple floor building [9]. The model has four breakpoints and considers both an upper and lower bound on the path loss.
The model also assumes that there is 30 dB attenuation at $d_0 = 1m$, which can be shown to be accurate for $f = 900$ MHz and unity gain antennas [9]. Rather than assuming a log-normal shadowing component, the Ericsson model provides a
<table>
<thead>
<tr>
<th>Material Type</th>
<th>Loss (dB)</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>All metal</td>
<td>26</td>
<td>815 MHz</td>
</tr>
<tr>
<td>Aluminum siding</td>
<td>20.4</td>
<td>815 MHz</td>
</tr>
<tr>
<td>Foil insulation</td>
<td>3.9</td>
<td>815 MHz</td>
</tr>
<tr>
<td>Concrete block wall</td>
<td>13</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Loss from one floor</td>
<td>20~30</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Loss from one floor and one wall</td>
<td>40~50</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Fade observed when transmitter turned a right angle corner in a corridor</td>
<td>10~15</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Light textile inventory</td>
<td>3~5</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Chain-like fenced in area 20 ft high containing tools, inventory, and people</td>
<td>5~12</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Metal blanket - 12 sq ft</td>
<td>4~7</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Metallic hoppers which hold scrap metal for recycling - 10 sq ft</td>
<td>3~6</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Small metal pole - 6” diameter</td>
<td>3</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Metal pulley system used to hoist metal inventory - 4 sq ft</td>
<td>6</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Light machinery &lt; 10 sq ft</td>
<td>1~4</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>General machinery - 10~20 sq ft</td>
<td>5~10</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Heavy machinery &gt; 20 sq ft</td>
<td>10~12</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Metal catwalk/stairs</td>
<td>5</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Light textile</td>
<td>3~5</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Heavy textile inventory</td>
<td>8~11</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Area where workers inspect metal finished products for defects</td>
<td>3~12</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Metallic inventory</td>
<td>4~7</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Large 1-beam - 16~20”</td>
<td>8~10</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Metallic inventory racks - 8 sq ft</td>
<td>4~9</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Empty cardboard inventory boxes</td>
<td>3~6</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Concrete block wall</td>
<td>13~20</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Ceiling duct</td>
<td>1~8</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>2.5 m storage rack with small metal parts (loosely packed)</td>
<td>4~6</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>4 m metal box storage</td>
<td>10~12</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>5 m storage rack with paper products (loosely packed)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>packed</td>
<td>2~4</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Material Type</td>
<td>Loss (dB)</td>
<td>Frequency</td>
</tr>
<tr>
<td>------------------------------------------------------------------------------</td>
<td>-----------</td>
<td>-----------------</td>
</tr>
<tr>
<td>5 m storage rack with large paper products (tightly packed)</td>
<td>6</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>5 m storage rack with large metal parts (tightly packed)</td>
<td>20</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Typical N/C machine</td>
<td>8~10</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Semi-automated assembly line</td>
<td>5~7</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>0.6 m square reinforced concrete pillar</td>
<td>12~14</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Stainless steel piping for cook-cool process</td>
<td>15</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Concrete wall</td>
<td>8~15</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Concrete floor</td>
<td>10</td>
<td>1300 MHz</td>
</tr>
<tr>
<td>Commercial absorber</td>
<td>38</td>
<td>9.6 GHz</td>
</tr>
<tr>
<td>Commercial absorber</td>
<td>51</td>
<td>28.8 GHz</td>
</tr>
<tr>
<td>Commercial absorber</td>
<td>59</td>
<td>57.6 GHz</td>
</tr>
<tr>
<td>Sheetrock (3/8 in) - 2 sheets</td>
<td>2</td>
<td>9.6 GHz</td>
</tr>
<tr>
<td>Sheetrock (3/8 in) - 2 sheets</td>
<td>2</td>
<td>28.8 GHz</td>
</tr>
<tr>
<td>Sheetrock (3/8 in) - 2 sheets</td>
<td>5</td>
<td>57.6 GHz</td>
</tr>
<tr>
<td>Dry plywood (3/4 in) - 1 sheet</td>
<td>1</td>
<td>9.6 GHz</td>
</tr>
<tr>
<td>Dry plywood (3/4 in) - 1 sheet</td>
<td>4</td>
<td>28.8 GHz</td>
</tr>
<tr>
<td>Dry plywood (3/4 in) - 2 sheets</td>
<td>8</td>
<td>57.6 GHz</td>
</tr>
<tr>
<td>Dry plywood (3/4 in) - 2 sheets</td>
<td>4</td>
<td>9.6 GHz</td>
</tr>
<tr>
<td>Dry plywood (3/4 in) - 2 sheets</td>
<td>6</td>
<td>28.8 GHz</td>
</tr>
<tr>
<td>Dry plywood (3/4 in) - 2 sheets</td>
<td>14</td>
<td>57.6 GHz</td>
</tr>
<tr>
<td>Wet plywood (3/4 in) - 1 sheet</td>
<td>19</td>
<td>9.6 GHz</td>
</tr>
<tr>
<td>Wet plywood (3/4 in) - 1 sheet</td>
<td>32</td>
<td>28.8 GHz</td>
</tr>
<tr>
<td>Wet plywood (3/4 in) - 1 sheet</td>
<td>59</td>
<td>57.6 GHz</td>
</tr>
<tr>
<td>Wet plywood (3/4 in) - 2 sheet</td>
<td>39</td>
<td>9.6 GHz</td>
</tr>
<tr>
<td>Wet plywood (3/4 in) - 2 sheet</td>
<td>46</td>
<td>28.8 GHz</td>
</tr>
<tr>
<td>Wet plywood (3/4 in) - 2 sheet</td>
<td>57</td>
<td>57.6 GHz</td>
</tr>
<tr>
<td>Aluminum (1/8 in) - 1 sheet</td>
<td>47</td>
<td>9.6 GHz</td>
</tr>
<tr>
<td>Aluminum (1/8 in) - 1 sheet</td>
<td>46</td>
<td>28.8 GHz</td>
</tr>
<tr>
<td>Aluminum (1/8 in) - 1 sheet</td>
<td>53</td>
<td>57.6 GHz</td>
</tr>
</tbody>
</table>

Table 3 Average Signal Loss Measurements Reported by Various Researchers for Radio Paths Obstructed by Common Building Material [9]
deterministic limit on the range of path loss at a particular distance. Fig. 9 shows a plot of in-building path loss based on Ericsson model as a function of distance.

• **Attenuation Factor Model**

Attenuation factor model takes the effect of building type and variations caused by obstacles into account to predict path loss [9]. This model provides flexibility and was shown to reduce the standard deviation between measured and predicted path loss to be around 4 dB, as compared to 13 dB when only a log-distance model was used in two different buildings. The attenuation factor model is given by

\[
PL(d)[dB] = PL(d_o) + 10n_{MF} \log\left(\frac{d}{d_o}\right) + FAF[dB] \tag{1.10}
\]

where \(n_{MF}\) represents the exponent value for the “same floor” measurement. If an accurate estimate for \(n\) exists on the same floor, the path loss on a different floor can be predicted by adding an appropriate value of \(FAF\).

In multiple floor buildings, equation (2.10) can be modified such that [9]

\[
PL(d)[dB] = PL(d_o) + 10n_{MF} \log\left(\frac{d}{d_o}\right) + d\alpha + FAF[dB] \tag{1.11}
\]

where \(\alpha\) is the attenuation constant for the channel with units of dB per meter (dB/m). Table 5 provides typical values of \(\alpha\) as a function of frequency [9].

• **Ray Tracing and Site Specific Modeling**
Recently the computational and visualization capabilities of computers have increased rapidly. New techniques and methods for predicting radio signal coverage involve the use of Site Specific (SISP) propagation models and graphical information system
Figure 9  Ericsson In-Building Path Loss Model [9]
<table>
<thead>
<tr>
<th>Building</th>
<th>Frequency (MHz)</th>
<th>$n$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retail Stores</td>
<td>914</td>
<td>2.2</td>
<td>8.7</td>
</tr>
<tr>
<td>Grocery Stores</td>
<td>914</td>
<td>1.8</td>
<td>5.2</td>
</tr>
<tr>
<td>Office, hard partition</td>
<td>1500</td>
<td>3.0</td>
<td>7.0</td>
</tr>
<tr>
<td>Office, soft partition</td>
<td>900</td>
<td>2.4</td>
<td>9.6</td>
</tr>
<tr>
<td>Office, soft partition</td>
<td>1900</td>
<td>2.6</td>
<td>14.1</td>
</tr>
</tbody>
</table>

**Factory LOS**

<table>
<thead>
<tr>
<th>Location</th>
<th>Frequency (MHz)</th>
<th>$n$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Textile/Chemical</td>
<td>1300</td>
<td>2.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Textile/Chemical</td>
<td>4000</td>
<td>2.1</td>
<td>7.0</td>
</tr>
<tr>
<td>Paper/Cereals</td>
<td>1300</td>
<td>1.8</td>
<td>6.0</td>
</tr>
<tr>
<td>Metalworking</td>
<td>1300</td>
<td>1.6</td>
<td>5.8</td>
</tr>
</tbody>
</table>

**Suburban Home**

<table>
<thead>
<tr>
<th>Location</th>
<th>Frequency (MHz)</th>
<th>$n$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor Street</td>
<td>900</td>
<td>3.0</td>
<td>7.0</td>
</tr>
</tbody>
</table>

**Factor OBS**

<table>
<thead>
<tr>
<th>Location</th>
<th>Frequency (MHz)</th>
<th>$n$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Textile/Chemical</td>
<td>4000</td>
<td>2.1</td>
<td>9.7</td>
</tr>
<tr>
<td>Metalworking</td>
<td>1300</td>
<td>3.3</td>
<td>6.8</td>
</tr>
</tbody>
</table>

Table 4  Path Loss Exponent and Standard Deviation Measured in Different Buildings [9]

<table>
<thead>
<tr>
<th>Location</th>
<th>Frequency</th>
<th>Attenuation $\alpha$ (dB/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building 1:  4-story</td>
<td>850 MHz</td>
<td>0.62</td>
</tr>
<tr>
<td></td>
<td>1.7 GHz</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>4.0 GHz</td>
<td>0.47</td>
</tr>
<tr>
<td>Building 2:  2-story</td>
<td>850 MHz</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>1.7 GHz</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>4.0 GHz</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Table 5  Free Space Plus Linear Path Attenuation Model [9]
GIS) database [9]. SISP models support ray tracing as a means of deterministically modeling any indoor or outdoor propagation environment. By using building databases, which may be drawn or digitized utilizing standard graphical software packages, wireless system designers can include accurate representations of building and terrain features. As building databases become prevalent, wireless systems will be developed utilizing computer aided design (CAD) tools that provide deterministic, rather than statistical, prediction models for path loss in a wide range of operating environments [9].

1.6 Design Considerations in Wireless LANs

It is important for system designers to understand some basic design issues in the design of WLANs when integrating the systems. The design issues in wireless LANs will have significant impact on the performance of the system. The system designers should also be aware of federal regulations for the wireless systems. The discussions on the design issues will be divided into several subsections as following.

- Physical Media

There are two types of physical media for the wireless LANs - Radio Frequency (RF) and Infrared (IR). Generally RF system has better coverage but lower data rate than IR system. The discussion on IR system is beyond the scope of this thesis. The radio medium is affected by noise sources and variety of radio propagation effects as discussed in the previous section 2.5. The radio medium must follow
spectrum usage regulations of the Federal Communication Commission (FCC) in the United States (and similar organizations in other countries) and contend with the unpredictable quality of radio links. These characteristics of the radio medium place a unique set of requirements on the MAC protocol compared to the wired LAN systems.

Today wireless LAN products are available in all three ISM bands at 902 ~ 908 MHz, 2.400 ~ 2.485 GHz, and 5.725 ~ 5.850 GHz. No licenses are required to operate in these bands, but transmitted power is limited to 1 W [18].

Section 2.5 has discussed indoor propagation characteristics, basically the power of a radio signal decrease with distance $d$ according to $d^{-\beta}$ where the roll-off exponent $\beta$ can vary significantly. In the indoor environment, roll-off exponents have been observed to vary from approximately 2 (free-space) along hallways and corridors to nearly 6 over highly cluttered paths [18]. Besides the deterministic power roll-off law, the random short-term variations in signal power due to multipath fading must be taken into consideration as discussed in section 2.5. Energy from a transmitted radio signal will typically travel along several different scattering paths that are of different lengths, components of the original signal will be received at different times. These types of delays can produce transmission errors due to intersymbol interference (ISI).

- Multiple Access Control (MAC) protocols
The wireless channel is shared by multiple users no matter how it is channelized (FDMA, TDMA or CDMA). The MAC protocols coordinate the channel access on a demand basis among the users. The MAC protocols of most wireless LANs are based either on random access techniques or reservation techniques or a combination of the two techniques [18].

The two most common types of random access protocols are slotted ALOHA and Carrier Sense Multiple Access (CSMA) protocols [18]. We are not going to discuss slotted ALOHA protocol since our test bed uses CSMA protocol. The CSMA protocols can be divided into three categories: 1) non-persistent, 2) 1-persistent, and 3) $p$-persistent protocols [11]. In a 1-persistent protocol, once the channel is sensed idle by a station, the transmission takes place with probability one whereas in a $p$-persistent protocol, the channel is sensed idle by a station, the transmission takes place with probability $p$ or transmission is deferred one unit of time with probability $(1-p)$. The IEEE 802.3 protocol (Ethernet MAC protocol), uses 1-persistent CSMA protocol with collision detection (i.e. CSMA/CD) [11]. With wireless systems, a form of $p$-persistent CSMA protocol is needed because it is impossible to detect collision reliably in the wireless medium. The $p$-persistent protocol is backed by a random back-off algorithm which reduces the collision probability between multiple stations accessing the medium at the point where a collision would most likely occur, just after the medium become free following a busy period [16]. This kind of
protocols provide collision avoidance (CSMA/CA). Specially, in the CSMA/CA
protocol proposed by IEEE 802.11 committee, a uniformly distributed back-off time
is used whenever the channel is sensed to idle after some station has completed its
transmission. The range of the uniform distribution is increased when collision occurs
as is done in the Ethernet protocol. In the proposed 802.11 CSMA/CA protocol an
explicit acknowledgment message is sent by the receiving station. Thus, a collision or
some other error is implied when the transmitting station does not receive an
acknowledgment [18].

IEEE 802.11 protocols support both random and scheduling access techniques
operating simultaneously, called Distributed Coordination Function (DCF) and Point
Coordination Function (PCF) respectively [19]. The DCF is the fundamental access method used to support asynchronous data
transfer on a best effort basis. The DCF sits directly on top of the physical layer and
supports contention-based services [19]. The DCF is based on the CSMA/CA
protocol. In the IEEE 802.11, carrier sensing is performed at both the air-interface
(physical carrier sensing), and the MAC sub-layer ( virtual carrier sensing) [19].
Physical carrier sensing detects the presence of other IEEE 802.11 WLAN users by
detecting activities in the channel via relative signal strength from other sources.
Virtual carrier sensing is used by a source station to inform all other stations of how
long the channel will be occupied for the successful transmission of a MAC protocol
data unit (MPDU) [19]. An MPDU is a complete data unit that is passed from the MAC sub-layer to the physical layer. The source station sets the duration field in the MAC header of data frames, and Request to Send (RTS) and Clear to Send (CTS) control frames. The duration field indicates the amount of time (in microseconds) [19] after the end of the present frame that the channel will be utilized to complete the successful transmission of the data or management frame. The stations detecting a duration field in a MSDU, adjust their Network Allocation Vector (NAV) which indicates the amount of time that must elapse until the current transmission session is completed and the channel can be sampled again for idle status [19]. The channel is marked busy if either physical or virtual carrier sensing mechanism indicates the channel is busy.

The PCF is an optional capability, which is connection-oriented, and provides contention-free (CF) frame transfer [19]. The PCF relies on a point coordinator (PC) to perform polling. PCF enables polled stations to transmit without contending for the channel. Thus PCF is able to offer a time-bounded service for real-time sources, as long as the maximum length of the polling list can be controlled [16].

The PCF is required to coexist with DCF and logically sits on top of the DCF. The contention-free period (CFP) repetition internal is used to determine the frequency with which the PCF occurs. Within a repetition interval, a portion of the time is
allocated to contention free traffic, and the remainder is provided for contention-based traffic [19].

- **Network Topologies**

  We are only interested in the cellular topology since most wireless LANs available today have the cellular topology for access to wired media although the non-cellular topology offers potentially greater efficiency, the complexity and dynamic nature of the required control make it an unattractive topology at the present time [18]. In the cellular topology, mobile stations get access to the wired network infrastructure via base stations (access points in wireless LAN). The access points are attached to the wired network with a fixed connection, usually wired, like our test bed, the access point is connected to the campus Ethernet via 10BaseT cable. The purpose of the base station is to coordinate access of the multiple mobile stations in its cell, i.e., the range of its direct communication. A key feature of the cellular topology is that at one time, a mobile station is talking to only one base station. The coordinating functions of the base station can include scheduling of high-priority communications, providing guarantees for real-time traffic, and controlling access to the wired infrastructure [18]. Once a while, due to the movement of mobile station or changes in radio propagation conditions, a base station can hand off the mobile station to another base station. In a packet-switched network, handoff can be achieved when the cells are not overlapped by storing packets in the base station or some other nodes in the wired network until
the mobile station roams into the cell which is controlled by the corresponding base station.

- Networking Issues

Wireless LANs connected to the wired backbone infrastructure raise many inter-networking design issues. Modern networks is comprised of many heterogeneous sub-networks (Ethernet, Token-Ring, wired WANs) interconnected by a variety of communications devices (bridges, routers and gateways) running multiple network protocols (SNA/APPN, TCP/IP, Novell Netware, Netboid, Appletalk) and algorithms that support connections with static end points [18] as shown in Fig. 10. Mobile users desire location independent network access and seamless connectivity as they move from one location to another and inter-operability across various network interfaces and protocols. This requirement will impact all layers of the network protocol stacks.
Figure 10  A Typical Heterogeneous Network Environment
One characteristic of the wireless links is a dynamically varying bit error rate (BER). Typically the average BER in the wireless environment is higher than wired networks. Standard data link control (DLC) protocols such as HDLC, LAPB, SDLC, and IEEE 802.2 LLC are designed and optimized to operate over wired media with static BER. These protocols are inefficient when the BER is high and continuously changing [18]. For the wireless networks, more reliable operation of the data link layer protocols requires new strategies and algorithms. A good and reliable wireless data link layer protocol may use hybrid strategies drawn from Forward Error Correction (FEC), automatic repeat request protocols (ARQ), adaptive adjustment of link layer protocol parameters, and sophisticated acknowledgment algorithms [18]. On the other hand the speed mismatch between wireless sub-net and wired network requires some form of flow control to avoid congestion, which could have a significant impact on the performance of the data link layer that runs from the base station between the wired and wireless loops to the mobile station, particularly if the base station is functioning just as a bridge (layer 2 switching) as opposed to a router (layer 3 switching).

In layer 2 switching the base stations are responsible for the packet filtering and forwarding as well as format conversion between the MAC frame of the wireless LAN and the wired LAN. The base station needs to have a dynamically updated database containing the relationship between mobile station MAC address and the
Layer 2 switching is relatively fast because the packet handling is limited to processing of layer 2 header functions. The major problem of layer 2 switching is that different mobility solutions are required for different LAN types [18]. For instance, to connect to an Ethernet, the base station must operate as a transparent bridge and perform Ethernet protocols. To connect to a token ring LAN, the base station must operate as a source routing bridge as viewed by the wired network segment. Layer 2 mobility has the limitation that it will only work over network segments that belong to the same routing domain, i.e., wired and wireless LAN sub-nets interconnected only by bridges, in another word, layer 2 switching cannot maintain connectivity if a mobile station crosses a router or a general purpose packet switch node [18]. Several market available wireless LAN systems are in layer 2 switching category, such as the Telxon/Telesystems ARLAN, AT&T/NCR WaveLAN, Proxim RangeLan, and the IBM Infrared and Radio Wireless LANs [18]. The DEC RoamAbout used by our test bed also falls in this category.

The layer 3 switching is more intelligent than layer 2 switching. The base station performs a router function. Most of existing network layer protocols were
designed to route packets to fixed stations with fixed addresses and are not suited for mobility. Therefore enhancements are required to layer 3 protocols to meet the mobility requirements. The solution should be LAN media independent, i.e., if the solution only assumes that below the layer 3 (network layer) is an IEEE standards compliant LLC, then the same solution should be able to work with Ethernet, Token ring, and any local area network environment that is compliant with IEEE 802.2 [18]. It is hoped that the layer 3 solution can scale well to large networks and can work with wide area networks as well. The drawbacks are that relatively complex processing is required for layer 3 packet handling and routing functions and different solutions are needed for the different network protocol types. This issue could be very sticky, especially if the network environment is comprised of several distinctive network protocols, and even the issue of mobility in a multi-protocol network environment is not yet well understood [18]. Several solutions have been proposed to handle the mobile routing problem for the Internet’s TCP/IP protocol [18]. These solutions are referred to as “mobile-IP” protocols and they are currently under evaluation by the Internet Engineering Task Force (IETF) committee for standardization, which has put out a draft [18]. In the mobile-IP solution, each mobile station is given a unique, permanent, IP home address that is used by other nodes to communicate with the mobile station. As the mobile roams through the network, the routing directory that manages its home address is notified of the mobile’s current temporary location, usually the
address of its current base station. Packets sent to the mobile station’s address are automatically forwarded to the current location. The mobile stations can cache the forwarding information and use a direct return path without going through the home location [18].

2.7 Security Issues

The transmission of data via “open” radio links seems quite risky for privacy in communication, so it is a serious design issue for wireless LAN systems. DEC’s RoamAbout WLAN family has three levels of security:

- Network Identification (NWID): Each data packet has a NWID code that identifies its WLAN system. Only data with the proper NWID is accepted by the system for upper-level software transport. This also optimizes the bandwidth-sharing facility of the CSMA/CA protocol [12].

- Spread-Spectrum Modulation: The pseudorandom nature of the spread-spectrum modulation makes eavesdropping technically very difficult.

- National Bureau of Standard: Data Encryption Standard (NBS-DES) - An optional DES encryption capability is implemented in RoamAbout, which provides a third, and very high level of security.
Chapter 2. Observations and Discussions

The first phase of the experiments on the test bed are to obtain the first hand observations on the multimedia traffic in a wireless environment. Video conferencing and Internet access were experimented. The test bed is integrated based on wireless LAN technology with raw data rate of 2 Mb/s. Theoretically with compression the bandwidth is sufficient for “video phone” kind of motion video (Fig. 11 shows the bandwidth needed for various video sources [15]). The video used in the test system has a size of $160 \times 120$ and is color with frame rate less than 8 frames/second; the maximum frame rate is 15 frames/second as claimed by the camera manufacture could not be reached by us. We observed that the quality of video is associated with the T-R (Transmitter-Receiver) distance in the real system. In the close distance (the same room, for instance), the quality of the video is almost the same as that in the wired Ethernet subjectively, but when the mobile station roams away from the base station, the image refreshing sometimes has problems such as broken image because the data throughput is not enough to deliver the information needed for decompressing. The audio quality is generally poor because of the packet switching nature of the network. Significant delay and broken speech were observed even for a single fixed node to mobile node video conferencing session. Lacking of full-duplex sound cards in the test nodes may have worsen the problem, but so far transmitting high quality real-time voice through packet switched network such as Internet is still a challenge for the software developers.
The Internet access through Microsoft Explorer is very satisfactory, and subjectively no noticeable delay was observed on the mobile station. We did not feel
Figure 11   Today's Video Compression Capabilities  [15]

HDTV: High-Definition Television
NTSC: National Television Standards Committee
B-ISDN: Broadband ISDN
MPEG: Moving Picture Experts Group
any difference when accessing UTD academic computer center via telnet between regular workstation and our mobile station through wireless link.

When the mobile station moves at pedestrian speed we did not experience any connectivity and service quality degrading subjectively in Internet access, telnet sessions, the frame rate of video dropped but not significantly.

The radio links are fairly reliable within the base station coverage, when roaming out the coverage the signal was lost, but the communication resumed as long as the mobile station comes back into the cell. In the first phase of the project, only one base station is installed, however, with multiple base stations (access points in wireless LAN terms) and proper cell planing and system design, the full coverage of a whole building or campus can be achieved. The mobile stations can roam between the cells without losing connectivity.

The IEEE 802.11 standard uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) as the basic channel access protocol. Although CSMA/CA can provide sufficient resolution for the multiple access contention, the simulation done in [16] suggests that the Superframe structure employed by CSMA/CA protocol performs poorly for both the voice and data transmission in terms of the number of possible voice conversations and the maximum payload size, i.e. the maximum achievable throughput. The observation on the voice transmission from our test bed seems to support this prediction. However, the performance measurement on text file transfer showed CSMA/CA protocol has the efficiency as high as 85% [17].
The investigation on the performance of the IEEE 802.11 Wireless LAN using both DCF and PCF discovered [19]:

- The efficiency delivered by the DCF is reasonably high if the average MSDU length is longer than 500 bytes, fragmentation threshold is set to 500 ~ 1000 bytes, and the medium is relatively clean (BER is better than $10^{-6}$).

- Real-time services such as packet voice can be transported by the PCF (the experiment on our test bed proved this). However, packet voice systems must employ an echo cancellor since the end-to-end delay cannot be bounded under 25 ms.

- Compromised performance for both data and voice traffic is achieved when the voice payload length is between 100 ~ 200 bytes long.

- When a voice station does not have any data to receive and transmit during a poll, the station should be dropped from the polling list immediately so that the remaining bandwidth can be allocated to other stations.

The above conclusions may help us to have some guide lines to analyze voice transmission over IEEE 802.11 wireless LANs in the future projects.

To minimize the voice packetization delay the length of voice payload must be constrained to some level, while the large header overhead is not desired at the mean time. This is a conflicting goal. Re-transmissions of the voice frames are not necessary since
this kind of traffic is delay sensitive. Quality of service (QoS) for voice typically limit maximum delay to 25 ms without echo canceling, and 500 ms with echo canceling [19].

The coverage of the wireless LANs in a particular environment can be affected by short-term fading, multipath reception and the near far effect. We observed that when the mobile station moves to the different directions from the access point, the system experienced different signal reception quality and coverage, depending on the building layout and constructions along that direction. Generally in the open hall, the mobile station receives better signal quality at the same distance or better coverage at same signal level, while the at the laboratory, denser office partitions severely affected the signal quality and coverage, which matches theoretical predications.

The electromagnetic interference originating from equipment which operates in the same frequency band as the wireless LAN can have impact on the system operation, particularly for the spread-spectrum radio LANs operating in ISM band. In the ISM band industrial, scientific and medical devices which radiate electromagnetic power for other purposes other than telecommunications are used unrestrictedly. Consequently these devices may generate a fair amount of radiation.

The best-known and most wide-spread of such devices are microwave ovens. Interference from microwave ovens is very severe because of its bursty energy radiation and broad frequency spectrum.
Through the first phase of the test bed project, we realized that most off-shelf application software systems (e.g. Enhanced CUSeeMe™ from White Pine Software, Inc. for desk top video conferencing and standard windows applications) will work on top of the test bed transparently without knowing the lower layers. However those application may not be optimized for the underlying wireless transmission medium and protocols. One example is that longer delay in the wireless transmission worsen the speech quality that is below the par of near-toll quality even in the fixed network, which makes the application useless under some circumstances. From the research point of view, commercial packages are usually black boxes for users, meaning we cannot obtain detailed technical information regarding the design, implementation and source codes and consequently it is hard to design and conduct quantitative analysis. We hope the information and experience obtained from the first phase of this project will help us to design, integrate and build a better test bed in the next phase with which we can conduct protocol research, quantitative performance evaluation, and propagation analysis.

The first phase of the project proved that based on the current wireless technology it is feasible to build a campus wireless access network with acceptable quality of service for most standard applications though providing voice and video services with high QoS needs more work and innovation.
Chapter 3. Conclusions

We built a test bed for wireless multimedia network in the EC building at the University of Texas at Dallas. The first phase of the project has one cell on the first floor in the EC building. The coverage of this single-cell single-base station (access point) configuration is about 80 ~ 100 feet in radius because the building construction attenuate the signals significantly. However, with multiple overlapped cells (multiple access points) we can scale up the system to cover the whole EC building, even the whole campus.

The Internet access, standard network applications (e.g. telnet), and video conferencing were experimented and evaluated subjectively to observe the multimedia traffics and data transmission in a wireless environment. The quality of service of these applications is acceptable for the small group of users. For large scale and heavy load evaluation it is not feasible to use real devices because of the cost, but the simulation solution is considered for the next phase of the project.

The problems were observed and discussed. Generally the goal for the first phase of the project, i.e., build a real wireless multimedia network as the test bed for the future research activity is achieved. The information and experience obtained from the first phase of the project are valuable to provide guide lines for the next phase of the project.

The approach that integrating test bed by using off-self hardware and software components is tested in the project, and it proved both time and cost saving. But the drawback of this approach is that the components manufactures are not willing to release
the detailed information of the product, which makes some research very difficult since we cannot modify any part of the product. In-house developed hardware and software components are still needed to build up a controllable test bed. Because of the complexity of the test bed, it would be much more cost efficient if we can affiliate with hardware and software manufacturers to create some interfaces so that our in-house developed modules which are specific for some research purposes or measurement can communicate with those black boxes to utilize their functions and capabilities in order to avoid developing everything from scratch.
References


VITA

David L. Hu, the son of Xung-Hong Hu and Wei-Fang Ou, was born in Shanghai, P.R. China. He entered the Electrical Engineering Department at Baotou GongTie Institute of Technology, China in August, 1980. He received his Bachelor of Science degree with a major in electrical engineering in 1984. He worked with several companies including SIEMENS AG and Ericsson Inc. in the field of system design and software development. He began his education in the United States as a graduate student in the Graduate Business School, University of Dallas, and received his M.B.A in April, 1993. He entered the Erik Jonsson School of Engineering and Computer Science, University of Texas at Dallas as a part-time graduate student majoring in Digital Systems in May, 1995.