A HIGH-SPEED WIRELESS LAN

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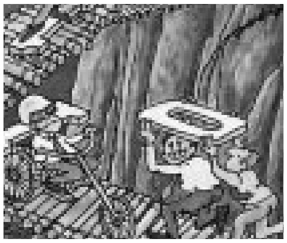

This millimeter-wave prototype transmits at a link speed of 54 Mbps to achieve reliable data transfer at 27 Mbps, using a robust coded multicarrier modulation scheme.

Wireless local area networks (WLANs) small enough for portable computing devices have transmission rates up to a few Mbps, the lower end of rates obtained in IEEE 802-compliant wired LANs. WLANs can provide a useful service when the application demands and number of users are low. Accommodating more users and multimedia traffic requires much higher performance, from several tens of Mbps to over 100 Mbps.

Achieving wireless access at these high rates is difficult. WLAN systems face technical problems similar to those encountered in outdoor wide-area radio-based systems, including the limited available bandwidth and fading noise due to multipath interference and blockage. The goal in WLAN system design is to transmit at the maximum information rate with an acceptable probability of error and minimum equipment complexity, power, and cost. Competing approaches use either infrared radiation or radio waves in the microwave or millimeter-wave bands.

The success of radio-based indoor WLAN systems depends on access to the radio spectrum. There is fierce competition for the small amount of unallocated spectrum in the microwave bands. Therefore, research on high-speed WLANs has focused on infrared and millimeter-wave carriers.[1] With a virtually unlimited and unregulated spectrum available, many researchers have proposed and developed infrared-carrier techniques for wireless indoor access to LANs.

So far, the most practical infrared techniques use diffuse infrared links; they have demonstrated raw link transmission rates up to 50 Mbps in cells a few meters in radius.[2] Nevertheless, we believe that the prospect of economically achieving reliable infrared transmission rates much above 10 Mbps for truly portable terminals in the next five years is poor. The obstacles are the high power requirements and the delay spread of the diffusely reflected (multipath) received signals. Overcoming these obstacles requires remarkable breakthroughs: either equalizers to accommodate the delay spread or adaptive directional links that limit the delay spread while maintaining an acceptable signal-to-noise ratio.

We have developed a radio solution at millimeter-wavelength frequencies, where the spectrum is sufficient to accommodate link speeds of hundreds of Mbps. Using a test bed with burst-mode transmission capability and an experimental 40-GHz radio, we have demonstrated a picocellular approach with a range of approximately 10 meters and link rates up to 185 Mbps. In addition, we have built a prototype modem with a raw link rate of 54 Mbps for use in a high-speed indoor WLAN demonstrator.

Key design decisions

The spectral band from 54 to 65 GHz is strongly absorbed by the atmosphere and so is unsuitable for long-distance communications. It *is* suitable for short-distance operation on the scale of a LAN. Propagation studies[3,4] have shown that propagation in this band is quasi-optical, with low penetration of walls and partial penetration of partitions. The signals also reflect well off many surfaces, providing coverage of areas without a direct line of sight to the transmitter. An unfortunate side effect is that signal reception occurs over multiple paths, resulting in destructive interference and significant intersymbol interference.

Use of this spectral band requires both a diversity scheme to overcome the destructive interference and a robust modulation and error correction coding scheme to overcome the effects of intersymbol interference. The latter becomes more difficult as the bit rate increases. With a typical indoor environment and a user data rate above 20 Mbps, achieving an effective data rate band-

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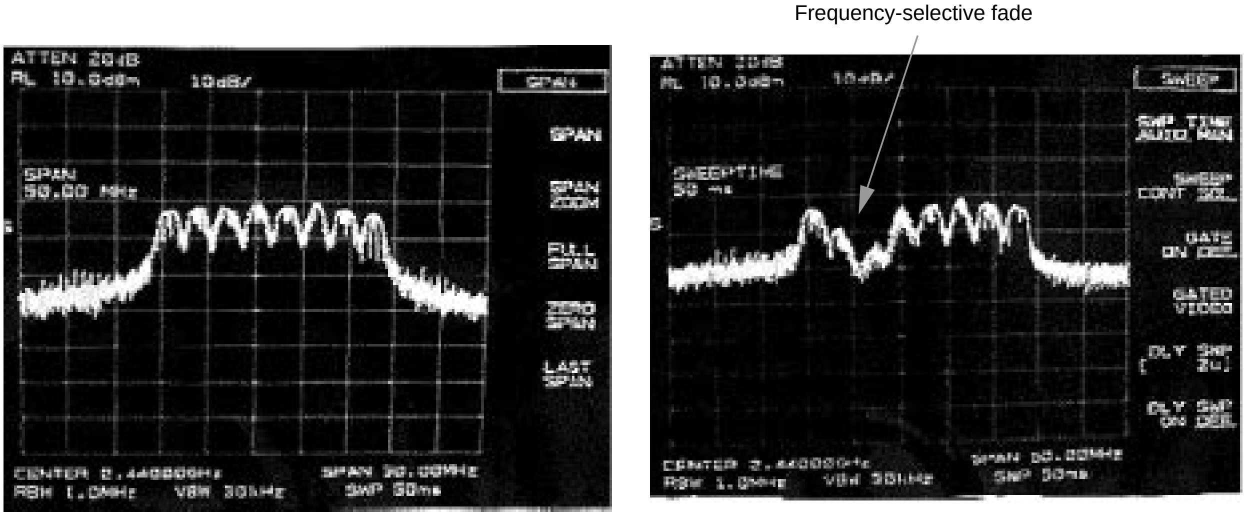

(a)

(b)

Figure 1. Measured multicarrier spectra at 40 GHz: without (a) and with (b) multipath interference.

width efficiency of 1 bps/Hz after error control decoding is difficult. An example is the HiperLAN (High-Performance Radio LAN) system,[5] which achieves a data rate bandwidth efficiency of significantly less than 1 bps/Hz. HiperLAN uses GMSK (Gaussian minimum shift keying) modulation with an equalizer and BCH (31,26) FEC (forward error correction) coding. Achieving an efficiency of 2 bps/Hz would require a very complex receiver.

Our WLAN uses a coded multicarrier modulation scheme to overcome multipath interference.[6,7] This approach, widely used in other transmission applications,[8,9] is less complex to implement for typical WLAN channels than solutions that use a single carrier plus equalizer. The reduced complexity provides the potential for lower power consumption. The HiperLAN developers apparently based their choice of a single carrier plus equalization on a concern that distortion products in the output RF (radio frequency) power amplifier would arise from the multicarrier signal's nonunity peak-to-average-power ratio. However, the probability of large peak excursions in the multicarrier signal is low. Moreover, our studies show that signal clipping does not substantially degrade the WLAN's performance.

A well-designed coded multicarrier modulation scheme, involving FFT (fast Fourier transform) processing, coding, and interleaving, protects well against multipath effects. The transform processing converts a time-invariant intersymbol interference channel to one that behaves effectively with no memory. Thus, a practical system requires no equalizer to combat intersymbol interference.

Figure 1 shows a measured eight-tone multicarrier modulation signal suffering a frequency-selective fade due to multipath interference on a 40-GHz link. The coding scheme used in our WLAN allows recovery of information lost in the faded tones.

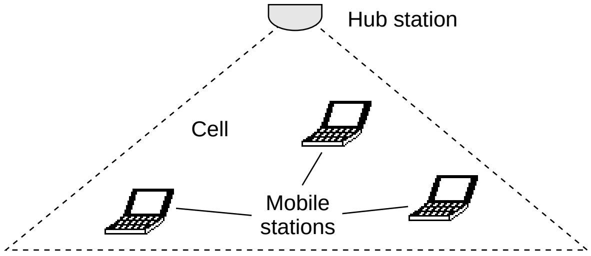

Figure 2. A WLAN radio cell.

Subtractive interference can cause broadband fading, which can result in an inability to obtain synchronization or in high error rates (around 10^{-1}). Correcting subtractive interference is difficult with any FEC scheme and requires some form of diversity. Antenna diversity in the form of spatial diversity or beam steering is preferable to frequency hopping at the high data rates of this application. One can achieve spatial diversity by placing the antennas a significant fraction of a wavelength apart, which is quite practical at millimeter wavelengths. Beam steering is also practical at these wavelengths.[3]

The US Federal Communications Commission has announced the allocation of the 59- to 64-GHz band for unlicensed short-range transmission. This band is ideally suited for high-speed WLANs.

WLAN system architecture

The implicit low range of operation at 60 GHz is advantageous for interference minimization and hence for distributed bandwidth use. It also suggests an architecture with numerous small hub stations providing access to a cabled infrastructure.

The WLAN's basic entity is a radio cell, illustrated in Figure 2, containing a hub station and mobile stations. A radio cell is a volume—about 20 meters in diameter for millimeter-wavelength carriers—within which reliable two-way communication is possible between the hub and mobile stations.

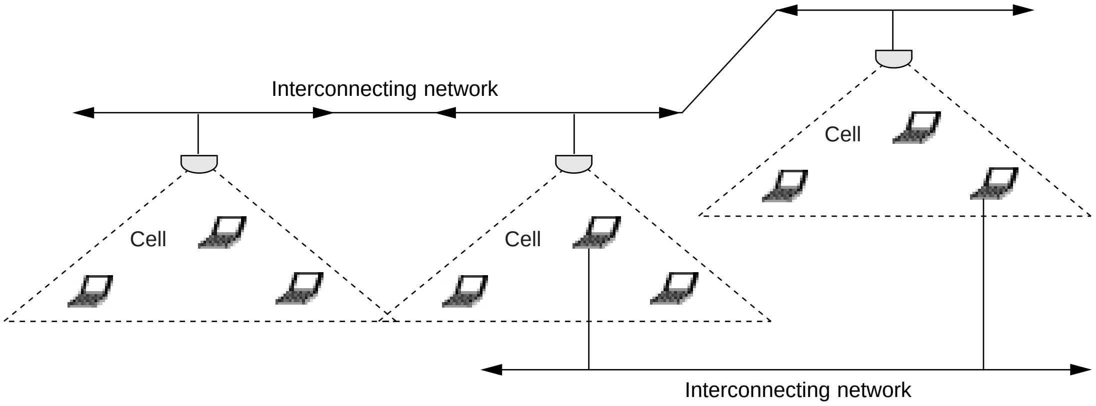

Figure 3. WLAN system.

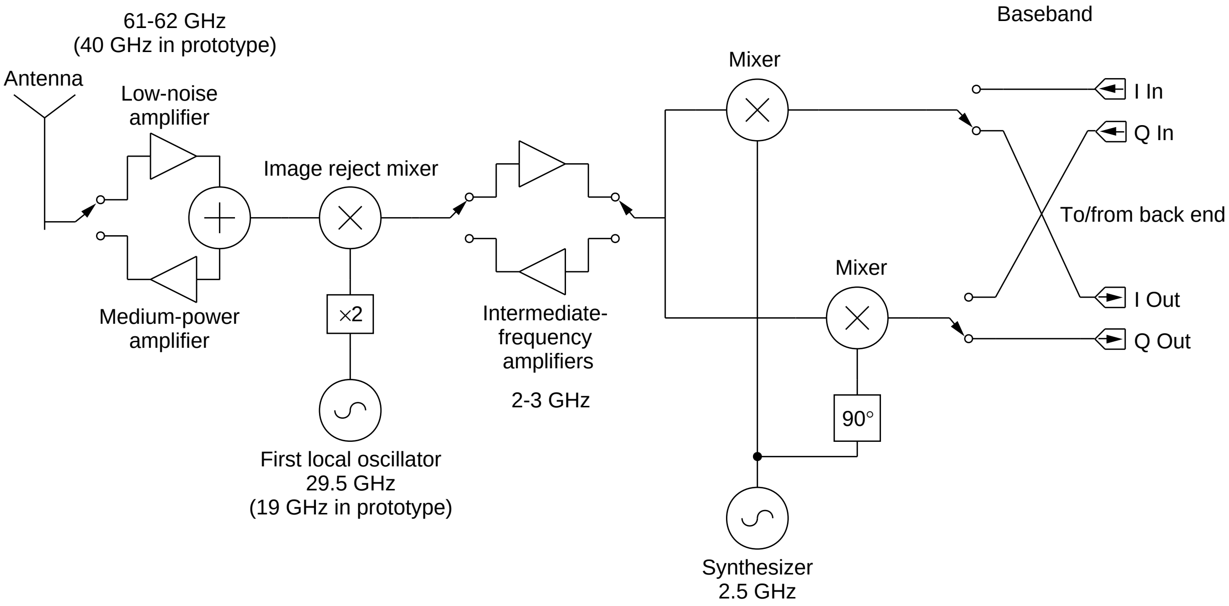

Figure 4. WLAN transceiver.

Figure 3 illustrates a WLAN system, which can consist of either a single radio cell or multiple, interconnected radio cells. Interconnection takes place via attachment of one or more of the hub and mobile stations in a cell to another network, which may be either wired or wireless.

The hub station is responsible for providing connectivity among all mobile stations, so we placed it to overcome the so-called hidden-terminal problem—the inability of mobile stations to directly contact each other because of blockages. The hub station acts as a relay for all communications within the cell. It also fairly manages access to the wireless medium for mobile stations within the radio cell and from the interconnecting network.

A spectrum channel plan and an appropriate dynamic channel allocation scheme can minimize interference between close hubs without coordination. A WLAN with 25 Mbps capacity per hub and with 10 channels available for dynamic channel allocation should occupy less than 10% of the available spectrum. Expansion to a system operating at 155 Mbps is feasible.

Station implementation

A WLAN station consists of three principal components:

- a physical layer consisting of a modem sublayer and a radio transmission sublayer called the transceiver,
- a medium-access control (MAC) sublayer, and
- a station management entity (SMT).

We refer to the modem sublayer, MAC, and SMT collectively as the WLAN back end. Mobile and hub stations differ in their antenna systems, MACs, and SMTs.

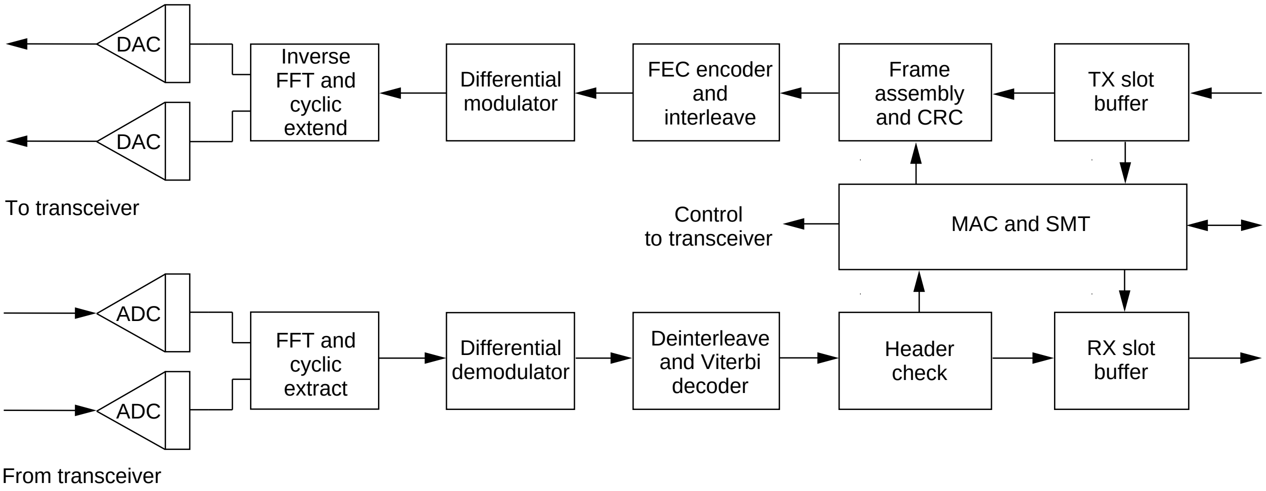

Figure 5. WLAN station back end.

Transceiver. Although the target carrier frequency is in the 59- to 64-GHz band, the prototype link uses a 40-GHz radio. Figure 4 shows the transceiver for a 61-GHz WLAN, similar to the 40-GHz transceiver used in the prototype. The transceiver front end operates in half-duplex mode. The front end consists of an antenna, a transmit/receive switch, a low-noise amplifier, a medium-power amplifier, and an image reject mixer.

In systems using isotropic radiating antennas, a ceiling-mounted hub antenna receives a large variation in power from a mobile station moving from the center of a cell toward the edge. To partially avoid this problem, our WLAN hub antenna uses a shaped beam. The shaping increases the antenna's gain for shallow viewing angles. To completely eliminate this angle-related power variation, we would use hub and mobile antennas whose combined pattern is a co-secant squared function of angle. In our system, however, the beam shaping removes about half the potential variation, and the automatic gain control system handles the remainder. The mobile stations use a planar antenna.[3]

The bidirectional image reject mixer provides both up and down conversion. The first local oscillator is set at 59 GHz. The medium-power amplifier's output power is 10 mW. The first transmit/receive switch, the low-noise and medium-power amplifiers, and the mixer are HEMT MMICs (high-electron-mobility-transistor monolithic microwave ICs).[10]

The intermediate-frequency stage includes transmit/receive switches and a bandpass filter (not shown) to provide out-of-band rejection. The intermediate-frequency stage uses I,Q (in-phase and quadrature-phase) up and down conversion with a quadrature local oscillator.

WLAN station back end. Figure 5 shows a schematic diagram of a WLAN station back end. The back end accepts fixed-length protocol data units across the MAC-layer interface connecting the WLAN system to its host computer. We programmed a protocol-data-unit length of 218 bytes, which conveniently holds four ATM cells plus a link protocol header. In choosing this length, we had in mind the significant overhead of about 100 bits needed for synchronization and frequency tracking, as well as some 10 μs for switching between transmit and receive modes. The latter involves switching of the low-noise and medium-power amplifiers and other RF circuitry. The data efficiency of this protocol-data-unit length is approximately 85%. It is also short enough that Doppler effects are negligible for stations moving at speeds up to several meters per second.

The MAC adds its header to the protocol data unit and passes the resulting slot across a Utopia-like interface[11] to the physical layer, which calculates a cyclic redundancy check word and adds it to the end of the slot.

To encode the data stream, the station uses a rate 1/2, memory 6 trellis coder, whose output is interleaved and modulated as a block-differentially-encoded QPSK (quadrature phase shift keying) signal. The DQPSK (differential QPSK) symbols are assembled into frames suitable for generating multicarrier modulation. In the prototype, 12 of the 16 carriers are modulated. We avoided the carrier at zero frequency because of its high noise level resulting from receiver imperfections, including converter offsets and RF carrier breakthrough. We avoided three other carriers at the edges of the channel to accommodate channel filters. The use of only 12 carriers is a conservative choice. A 45-MHz, 16-point inverse FFT circuit transforms the frame, resulting in a serial complex number stream. After four-sample cyclic extension, 8-bit digital-to-analog converters convert these complex numbers to analog signals and pass them to the transceiver.

Figure 6 (next page) shows the measured spectrum of the transmitted signal, with the 12 modulated carriers, six on each side of the unmodulated zero-frequency carrier. The link bit rate is 54 Mbps (45 MHz × 2 bits/symbol × 12/20).

On the receive side, the input is a quadrature pair of baseband signals digitized by 8-bit analog-to-digital converters. After cyclic extraction to complement the transmit cyclic extension process, an FFT circuit separates the multicarrier signals. Synchronization circuits (not shown in Figure 5) obtain frequency, symbol, and frame sync. Information-carrying tones

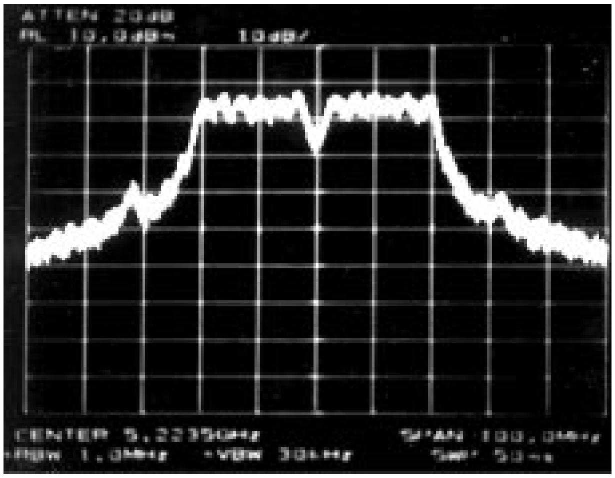

Figure 6. Measured spectrum of the WLAN transmitted signal, showing 12 modulated carriers.

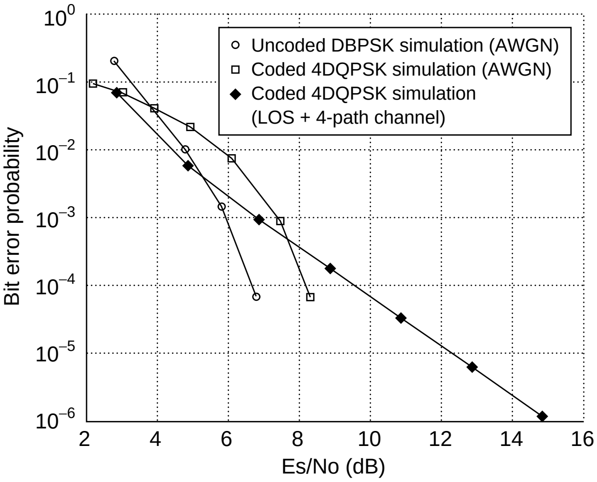

Figure 7. Bit error probability curves for uncoded differential binary PSK and coded DQPSK AWGN channels and for a coded channel with a line-of-sight (LOS) signal plus four multipaths. Es/No is the ratio of energy per symbol to noise power spectral density.

feed into a soft-decision differential demodulator before deinterleaving and soft-decision Viterbi decoding of the data. The decoded bits are formatted into a slot, checked for errors, and processed by the MAC and SMT entities.

We implemented the modem mainly with Xilinx programmable-logic parts including a custom FFT design and a commercial Viterbi decoder. The FFT and the Viterbi decoder limit the system's maximum clock speed to 45 MHz. We would expect much higher speed from a back-end custom-chip implementation, the design of which is entirely feasible.

The MAC builds on the physical layer's half-duplex operation. The MAC protocol's basic operation is as follows:

- Cell bandwidth is quantized into fixed-length slots.
- Each mobile station "owns" a fraction (one or more slots) of the total radio cell bandwidth, which it obtains upon registering with the hub station, and is guaranteed necessary access to that bandwidth at all times.
- Mobile stations can access any unused slots, which may or may not be the slots they own; the hub station has the responsibility of marking slots to indicate their potential use.
- MAC traffic for a mobile station always appears as an exchange: a transmit-slot-to-hub/receive-slot-from-hub pair.
- Mobile stations must synchronize their transmissions to hub timing.

A heavily loaded cell operates in a TDM-like (time division multiplex) mode, with each mobile station using its owned slots. In a lightly loaded cell, the MAC protocol provides a service that allows any station to access a substantial portion of the cell bandwidth. The transition between this mode and the TDM-like mode is smooth and seamless.

The SMT handles a variety of standard management functions as well as the registration process and power-down modes.

Link performance. Figure 7 shows the simulated error probability performance of a prototype link for one uncoded and two coded channels. The steep waterfall curves are for an AWGN (additive white Gaussian noise) channel. The other curve is for a representative hostile indoor channel consisting of a line-of-sight signal plus four multipath signals. This multipath channel's root mean square delay spread is 7 ns, and the maximum delay is 26 ns.

The range of channel characteristics in a practical indoor environment is great, and the best overall WLAN performance indicator is an acceptable BER (bit error ratio) throughout a radio cell. Figure 8 diagrams measurements taken for each of four beam directions at station sites in an open-plan office environment at Macquarie University for a link rate of 50 Mbps. The room's eye-level partitions define 32 work corners (open cubicles), a lab measurement area, and a meeting area. The room contains numerous metal filing cabinets, wooden bookshelves and desks, overhead metal light fittings, and several 0.5-meter square structural support columns. In the laboratory space and on the left side wall are many metal racks, cupboards, and shelves. At the bottom of the diagram is an exterior wall with 1.7-meter-high windows approximately 1 meter from the floor and occupying approximately 75% of the wall. We placed the hub station at a height of 2.7 meters.

The diagram shows four beams at each measurement site. Dark-shaded beams represent directions in which the measured BER was less than 10^{-5}. This is a satisfactory error level for computer network operation because it allows higher layer protocols to readily recover from resulting packet errors. Note that coverage even close to the hub requires the use of some form of diversity. The system performed satisfactorily everywhere within a 10-meter radius of the hub, apart from a small region at the room's main entrance between the laboratory space and offices at the top of the figure.

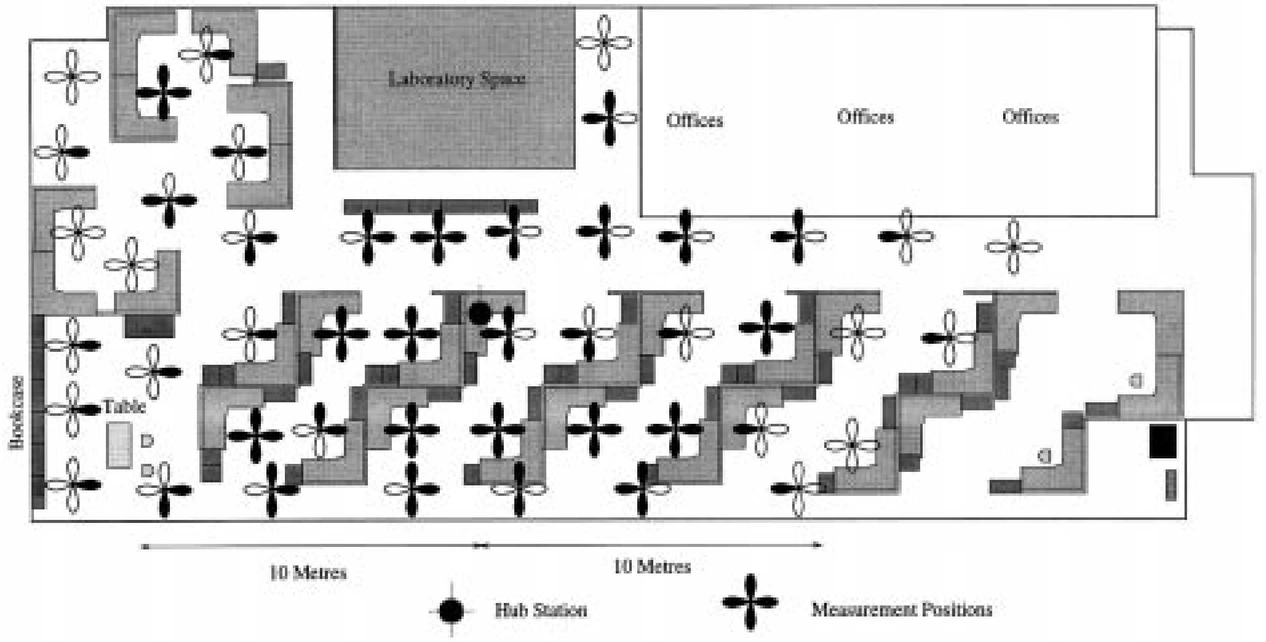

Figure 8. BER measurements of 40-GHz-link WLAN in Room E6A256 at Macquarie University. Shaded clover patterns indicate beam directions for which the BER is less than 10^{-5}.

OUR PROTOTYPE WLAN transmits at a link speed of 54 Mbps to achieve reliable data transfer at 27 Mbps (after decoding) by means of a robust coded multicarrier modulation scheme. The system demonstrates the feasibility of untethered indoor multimedia communications. However, the cost of millimeter-wave radio systems is currently too high for consumer use. Estimates indicate that cost-effective solutions could exist within five years.[6,12] For shorter term solutions, we must consider lower frequencies. The prototype modem described here is suitable for lower frequency carriers, but spectrum availability to date has concentrated our efforts on millimeter-wave carriers.

Recent regulatory changes may open the way for lower frequency multimedia WLANs. In April 1996, the US FCC proposed an allocation of up to 350 MHz of spectrum for unlicensed operation of high-speed data links. Known as the NII/Supernet band (National Information Infrastructure/Shared Unlicensed Personal Radio Network), this band overlaps the 5.2-GHz HiperLAN and the 5.7-GHz ISM (Instrumentation, Scientific and Medical) bands, which are allocated for similar use in many countries. The cost of 5-GHz radio systems is dropping and should reach acceptable levels in the next two to three years. We have recently built a 5-GHz transceiver for use with our modem sublayer.

Acknowledgments

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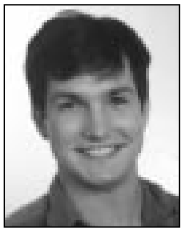

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