

# ***A mm-Wave High Speed Wireless LAN for Mobile Computing - Architecture and Prototype Modem/Codec Implementation***

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## **1 INTRODUCTION**

Current wireless LANs that are small enough for portable computing devices have transmission rates up to a few Mbit/s, at the lower end of that obtained in IEEE 802-compliant wired LANs. These LANs can provide a useful service when the application demands and number of users are kept low. Much higher performance, from several 10's of Mbit/s to over 100 Mbit/s, is needed to accommodate more users and multimedia traffic.

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

The success of radio-based indoor wireless LAN systems lies in access to the radio spectrum. This is fiercely competitive and alarmingly scarce in the microwave bands. For this reason, research on higher speed wireless LANs has focussed on infra-red and millimetre-wave carriers [Fernandes *et al.*, 1994]. With virtually unlimited and unregulated spectrum, many researchers have proposed and developed infra-red carrier techniques for wireless indoor access to local area networks.

To date the most practical infrared techniques use diffuse infrared links and have demonstrated raw link transmission rates up to 50 Mbit/s in cells a few metres in radius [Marsh & Kahn, 1995]. Nevertheless, we contend that the prospect of economically achieving reliable infrared transmission rates much above 10 Mbit/s for truly portable terminals in the next five years is poor because of the high power requirements and delay-spread of the received diffusely-reflected (multi-path) signals. Remarkable breakthroughs are needed either in the design of equalisers to accommodate the delay spread or in the development of adaptive directional links that limit the delay spread while maintaining acceptable signal-to-noise ratio.

This paper proposes a radio solution at millimetre wavelength frequencies where there

is sufficient spectrum to accommodate link speeds of hundreds-of-megabits-per-second. Using a test-bed with a burst-mode transmission capability and experimental 40 GHz radio, we have demonstrated a pico-cellular approach with a range of approximately 10 metres and link rates up to 185 Mbit/s. Additionally, we have built a prototype modem with a raw link rate of 54 Mbit/s for use in a demonstrator high-speed indoor WLAN. This paper presents the architecture of the proposed WLAN and the design and performance of the prototype modem.

Section 2 discusses key design decisions that follow from the choice of spectrum and propagation characteristics in the millimetre-wave band. Section 3 describes the overall WLAN system architecture. Section 4 describes the prototype modem implementation.

## **2 SPECTRUM, PROPAGATION AND KEY DESIGN DECISIONS**

The spectral band from 54 GHz to 65 GHz is strongly absorbed in the atmosphere and is unsuitable for long distance communications. It is suitable for short distance operation on the scale of a LAN. Our propagation studies [Bird *et al*, 1994] and others [eg ITU-R SG3, 1996; Smulders & Wagemans, 1992; Davies *et al*, 1991] 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 which do not have a direct line of sight to the transmitter. The unfortunate side effect of this is that signal reception occurs over multiple paths resulting in destructive interference and significant intersymbol interference.

Use of this spectral band requires 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. Given a typical indoor environment and a user data rate above 20 Mbit/s it is difficult to achieve a data rate bandwidth efficiency of 1 bit/s/Hz<sup>1</sup>. An example of this is the HIPERLAN (High Performance Radio LAN) system [ETSI, 1995] which achieves a data rate bandwidth efficiency of significantly less than 1 bit/s/Hz. HIPERLAN uses GMSK modulation with an equaliser and BCH (31,26) FEC coding. To achieve an efficiency of 2 bit/s/Hz would require a very complex receiver.

Our WLAN uses a coded multicarrier modulation scheme to overcome multipath interference [Skellern & Percival, 1994; Lee *et al.*, 1995; Skellern *et al.*, 1995]. This approach, which has been widely used in other transmission applications [eg Alard & Halbert, 1987; Bingham, 1990; Chow *et al.*, 1991; Sari *et al.*, 1995], is less complex to implement than solutions that use a single carrier plus equaliser. The reduced complexity provides the potential for lower power consumption than solutions using a single carrier. The HIPERLAN choice of a single carrier plus equalisation is an interesting one, apparently based on a concern about distortion products in the output power amplifier arising from the non-unity peak-to-average power ratio of the multicarrier signal. However, the probability of large peak excursions in the multicarrier

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<sup>1</sup>Note that the bandwidth efficiency can be quoted as higher, up to around 2 bit/s/Hz, if forward error correction bits are not discounted.

signal is low. Moreover, clipping of the signal does not substantially degrade the error performance.

A well-designed coded multicarrier modulation scheme, involving FFT processing, coding and interleaving, provides good protection against multipath effects. The transform processing converts a time-invariant intersymbol interference (ISI) channel to one that behaves effectively with no memory. Thus, no equaliser is needed to combat ISI in a practical system.

Figure 1 shows a measured 8-tone multi-carrier 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.

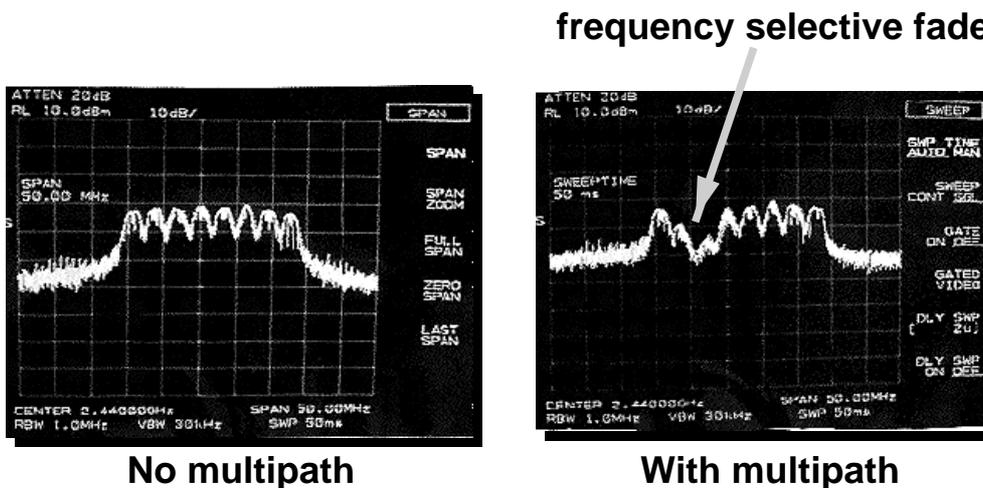


Figure 1 Measured multicarrier spectra at 40 GHz

Subtractive interference can cause broadband fading, which can result in an inability to obtain synchronisation or high error rates (around  $10^{-1}$ ). This is very hard to correct with any FEC scheme and some form of diversity is required. Antenna diversity in the form of spatial diversity or beam steering is preferred over frequency hopping at the high data rates of interest in this work. Spatial diversity can be achieved by placing the antennas a significant fraction of a wavelength apart, which is quite practical at millimetre wavelengths. Beam steering is also practical at these wavelengths [Bird *et al* , 1994].

The USA Federal Communications Commission has notified the allocation of the 59-64 GHz band for unlicensed short range transmission [FCC, 1995]. This band is ideally suited for high speed wireless LANs. Other countries are also actively opening the bands around 60 GHz for unlicensed use [e.g. Takimoto, 1995; Meinel, 1995a].

### 3 WLAN SYSTEM ARCHITECTURE

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

The basic entity of the WLAN is a radio cell, illustrated in Figure 2, containing a hub station and mobile stations. A radio cell is a volume, up to about 20m in diameter for millimetre wavelength carriers, within which it is possible to establish reliable two-way communication between the hub station and mobile stations.

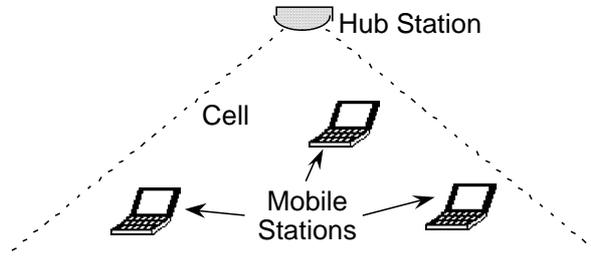


Figure 2: A radio cell

A WLAN system, illustrated in Figure 3, consists of either a single radio cell or multiple interconnected radio cells. Interconnection is via attachment of any 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 has the responsibility of providing connectivity between all mobile stations and is placed to overcome the so-called 'hidden terminal problem' - not all mobile stations may be able 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 the mobile stations within the radio cell and from the backbone.

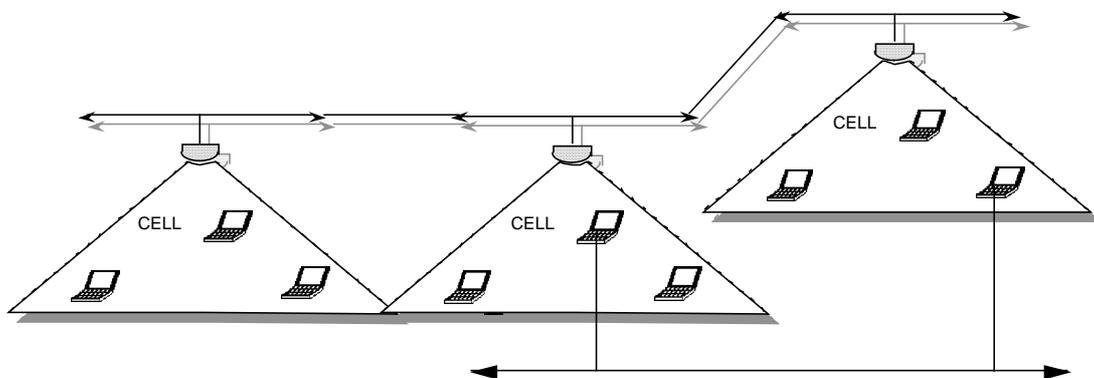


Figure 3: A wireless LAN system

Interference between nearby hubs can be minimised without coordination by adoption of a spectrum channel plan and the use of an appropriate dynamic channel allocation (DCA) scheme by the hub stations. A WLAN with 25 Mbit/s capacity per hub and with ten channels available for DCA would occupy around 250 MHz or 5% of the available spectrum. Expansion to a system operating at 155 Mbit/s is feasible.

#### 4 STATION IMPLEMENTATION

A WLAN station has four principal components:

- a Physical layer (PHY) consisting of:
  - a Transmission sub-layer - the 'RF section'
  - a Modem sub-layer
- a Medium Access Control (MAC) sub-layer
- Station Management (SMT)

The modem sub-layer, MAC sub-layer and SMT together will be referred to as the WLAN backend. The differences between the mobile station and the hub station are their antenna systems, the MAC and SMT.

#### **4.1 RF-section**

While the target carrier frequency is in the 59-64 GHz band, the prototype link uses a 40 GHz radio. An RF-section for a 61 GHz WLAN, similar to the 40 GHz transceiver front-end used in the prototype, is illustrated in Figure 4. The transceiver 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 a mixer.

Figure 4 WLAN RF section

For isotropic radiating antennas, there is a large variation in power received from a mobile station at a ceiling-mounted hub antenna as the mobile moves from the centre of a cell towards the edge. The WLAN hub antenna uses a shaped beam to partially compensate for this power variation. The shaping increases the gain of the antenna for shallow look angles. To completely eliminate this angle-related power variation, the combined pattern of the hub antenna and mobile antenna should be a cosec squared function of angle. However, in our system about half the potential variation is removed by the beam shaping and the remainder is handled by the AGC (automatic gain control) system. The mobile stations use a planar antenna [Bird *et al*, 1994].

The first mixer is a bi-directional image reject mixer that provides both up and down conversion. The first local oscillator is at 59 GHz. The MPA output power is 10 mW. The first transmit/receive switch, LNA, MPA and mixer are HEMT MMICs [Archer, 1992; Batchelor *et al.*, 1993].

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

#### 4.2 WLAN Station Backend

A schematic diagram of a WLAN station backend is shown in Figure 5.

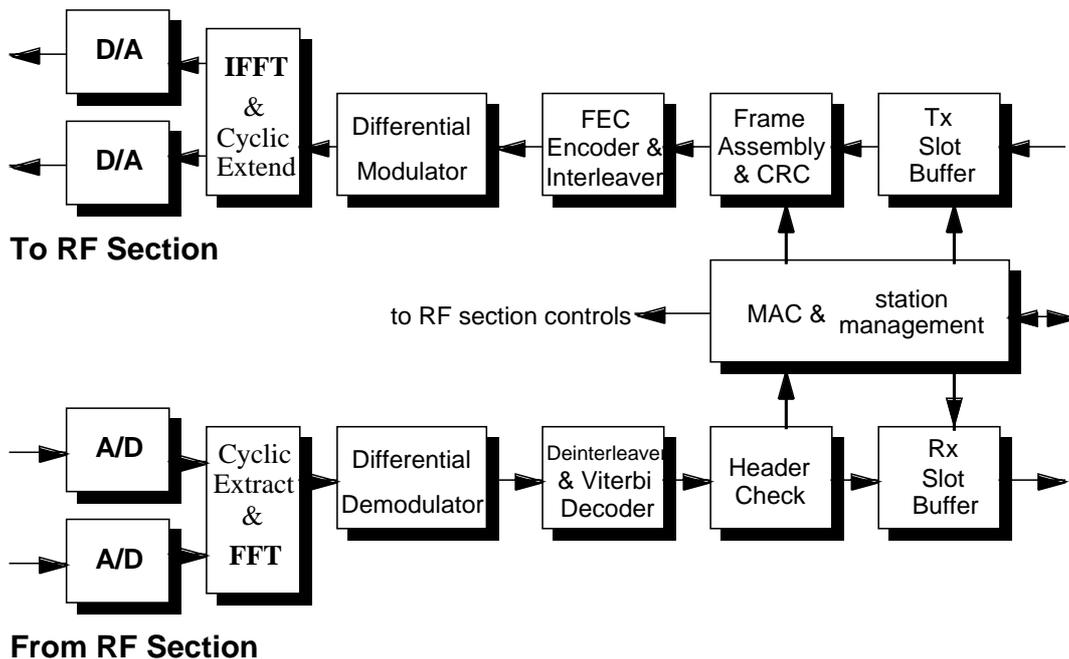


Figure 5 Station backend

The backend accepts protocol data units (PDU) of length 218 bytes across the MAC-layer interface connecting the WLAN system to its host computer. This PDU size conveniently holds four ATM cells plus link protocol header and is chosen recognising the significant overhead of around 100 bits needed for synchronisation and frequency tracking, as well as some 10  $\mu$ sec for switching between transmit and receive. The latter involves switching of low noise, medium power amplifiers and other RF circuitry. The data efficiency of this choice is approximately 85%. The PDU size is also short enough that Doppler effects for stations moving up to several m/s are negligible.

The MAC adds its header to the PDU, and passes the resulting slot across a UTOPIA-like interface [ATM Forum, 1994] to the PHY layer where a cyclic redundancy check word is calculated and added to the end of the slot.

The data stream is encoded by a rate 1/2, memory 6, trellis coder whose output is interleaved and modulated as a block-differentially encoded QPSK signal. The DQPSK

symbols are assembled into frames suitable for generating multi-carrier modulation. Only 12 of the 16 carriers are modulated in the prototype. The carrier at zero frequency is avoided because of its high noise level resulting from receiver imperfections, including converter offsets and RF carrier breakthrough. Three further carriers at the edges of the channel are avoided to accommodate channel filters. The use of only 12 carriers is a very conservative choice. The frame is then transformed by a 45 MHz, 16-point fast Fourier transform circuit, resulting in a serial complex number stream. After 4-sample cyclic extension, these complex numbers are converted to analog signals by 8-bit digital-to-analog converters and passed to the RF section.

The measured spectrum of the transmitted signal, shown in Figure 6, clearly shows the 12 modulated carriers, six either side of the unmodulated zero-frequency carrier. The link bit rate is 54 Mbit/s ( $45 \text{ MHz} * 2 \text{ bit/symbol} * 12/20$ ).

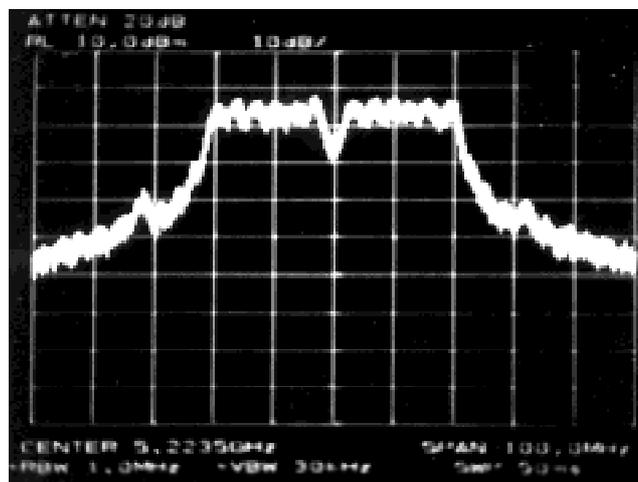


Figure 6 Measured spectrum of the WLAN Tx signal showing 12 modulated carriers.

On the receive side, the input is a quadrature pair of baseband signals that are digitised by 8-bit analog-to-digital converters. After cyclic extraction to complement the transmit cyclic extension process, a fast Fourier transform circuit separates the multi-carrier signals. Synchronisation circuits (not shown) obtain frequency, symbol and frame sync. Information carrying tones are fed to a soft-decision differential demodulator before de-interleaving and soft decision Viterbi decoding. The decoded bits are compiled into a slot, checked for errors and processed by the MAC and SMT entities.

The modem is implemented largely using Xilinx programmable logic parts with a custom FFT design, similar to that described by Ryan *et al* [1995], and a commercial Viterbi decoder. The maximum clock speed of the implementation is limited to 45 MHz by both the FFT and Viterbi decoder. Much higher speed operation can be expected of a custom chip implementation of the back-end, the design of which is entirely feasible.

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

- cell bandwidth is quantised into slots of fixed length

- each mobile station 'owns' some fraction (one or more slots) of the total radio cell bandwidth, which it obtains upon registering with the hub station, and is guaranteed access to that bandwidth at all times if needed.
- mobile stations may access any unused slots, which may or may not be the slots they own; the hub station has the responsibility of marking the 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 base their transmissions on hub timing

A heavily loaded cell operates essentially in TDM mode with each mobile using its owned slots . In a lightly loaded cell, the MAC protocol provides a service that allows any station to access a substantial proportion of the cell bandwidth. The transition between this and TDM mode is a smooth and seamless one.

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

### **4.3 Link Performance**

The simulated BER performance of the link is shown in Figure 7 for two channels. The steep waterfall curve is for an AWGN channel. The second BER curve is for a representative hostile indoor channel consisting of a line-of-sight signal plus four multipath signals. The rms delay spread of the channel is 7 nsec and the maximum delay is 26 nsec.

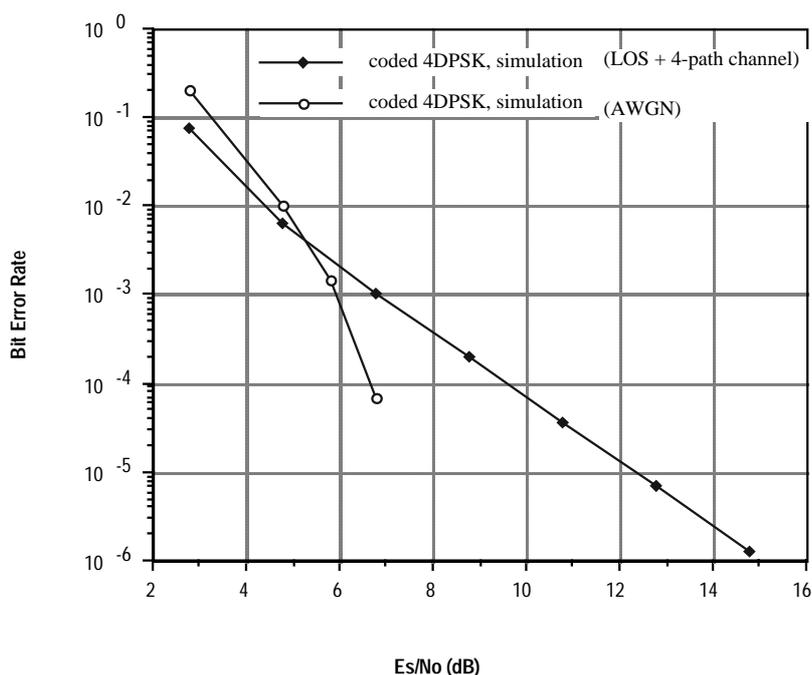


Figure 7 BER curves for AWGN channel and for channel with line-of-sight plus four multipaths

The range of channel characteristics encountered in a practical indoor environment will be great and the best indicator of overall performance is the ability to achieve an acceptable BER throughout a radio cell. A set of measurements taken for each of four beam directions at sites in an open-plan office environment (Room E6A256) at Macquarie University is shown in Figure 8 for a link rate of 50 Mbit/s. The room has eye-height partitions defining some 32 work corners (open cubicles), a lab measurement area and meeting area. The room has numerous metal filing cabinets, wooden bookshelves and desks, with overhead metal light fittings and several 0.5m square structural support columns. The laboratory area and left side wall contain many metal racks, cupboards and shelves. The bottom of Figure 8 is an exterior wall with 1.7m high windows approximately 1m from the floor occupying approximately 75% of the wall. The hub was placed at height 2.7m.

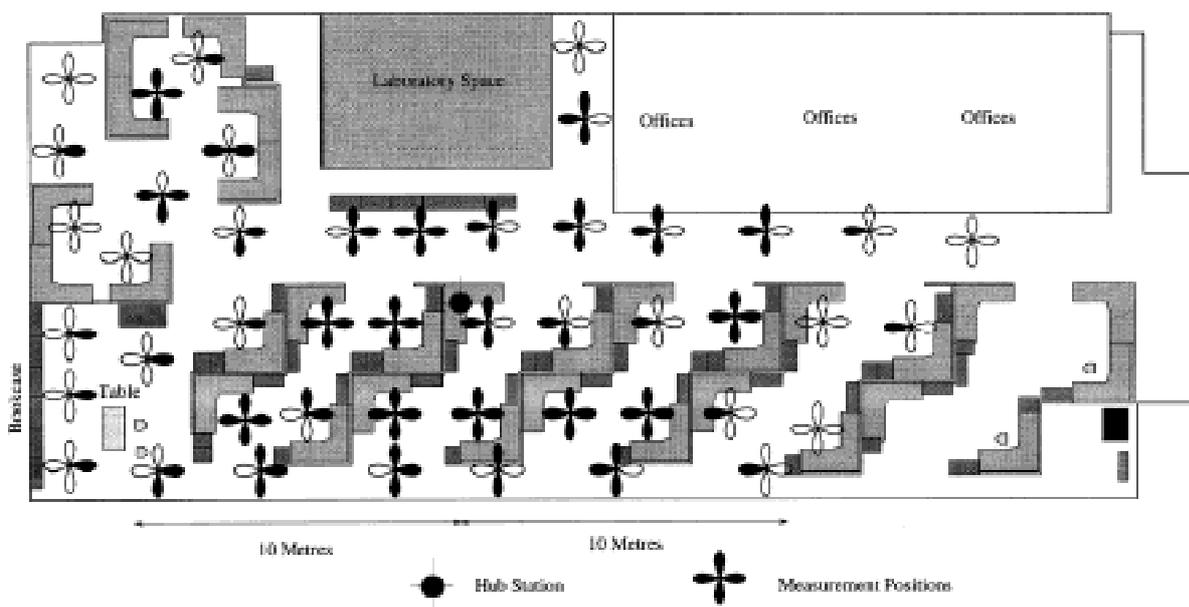


Figure 8 40 GHz link BER measurements in Rm E6A256 at Macquarie University. Shaded clover patterns indicate beam directions for which the BER <math>10^{-5}</math>

Four beams are shown at each measurement site. Dark shaded beams show directions in which the measured BER was less than  $10^{-5}$ , an error level which is considered satisfactory for computer network operation since at this level higher-layer protocols are readily able to recover from the resulting packet errors. Note that coverage even close to the hub requires the use of some form of diversity. Satisfactory performance is obtained everywhere within a 10m radius of the hub with the exception of a small region at the main entrance to the room between the Laboratory Space and Offices (at centre top of the figure).

## 5 CONCLUSION

The prototype WLAN transmits at a link speed of 54 Mbit/s to achieve reliable data transfer at 27 Mbit/s (after decoding) through the use of a robust coded multicarrier modulation scheme. Antenna diversity is needed to obtain good coverage in a typical indoor office environment. We believe that this system is the fastest WLAN yet reported and that it demonstrates the feasibility of indoor multimedia mobile communications. However, the cost of mm-wave radio systems is currently too high for consumer use. Estimates show that cost effective solutions will exist in a 5 year time frame [Meinel, 1995b; Skellern & Percival, 1994]. For shorter term solutions, lower frequencies must be considered. The prototype modem described here is also suited to lower radio frequency carriers but spectrum availability to date has concentrated our efforts on mm-wave carriers. Recent regulatory changes may open the way for lower frequency multimedia WLANs.

The FCC announced in April 1996 a proposal to allocate 350 MHz of spectrum for use

for unlicensed operation of high speed data links [FCC, 1996]. This is referred to as the National Information Infrastructure (NII) or SUPERNet band. This band overlaps the 5.2 GHz HIPERLAN band and the 5.7 GHz ISM band, which are allocated for similar use in many countries. The cost of 5 GHz radio systems is dropping and should reach acceptable prices in the next 2-3 years.

## ***ACKNOWLEDGMENTS***

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