ETHERNET COMPATIBLE 24 GHz MMIC WLAN

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Abstract. An Ethernet compatible wireless local area network (WLAN) is being implemented. The design utilizes a transceiver (18 RF functions) that will be integrated on a single GaAs microwave monolithic integrated circuit (MMIC) chip using a 0.18 μm PHEMT process. The chip is being developed under the Advanced Research Program Agency's (ARPA) Dual Use technology reinvestment program (TRP). One of the system cost drivers is the RF transceiver. Northrop Grumman's highly integrated MMIC chip is key to an affordable high speed WLAN. An exhaustive study of medium access control protocols was conducted. Multipath issues were investigated and multi-carrier modulation methods were found to be appropriate for high data rate applications in an office-like environment.

1.0 Introduction

Local Area Networks (LANs) allow multiple computer users to exchange information between other users. With multiple users running multiple applications, the network can easily become loaded to capacity and its data transfer efficiency reduced dramatically. This is increasingly becoming evident as hardware and software capabilities grow, requiring greater amounts of data to complete an application or service. Wired LAN manufacturers addressed this possibility by offering a 100 Mbps wired version of the popular 10 Mbps Ethernet standard. However, the vast majority of wireless LANs offered to date have effective data throughput well below even the 10 Mbps. This paper discusses the design of a millimeter wave frequency Wireless Local Area Network (WLAN), employing a multi-carrier modulation to offer data rates in excess of the 10 Mbps. A multiple access protocol is selected that allows high network efficiency. A WLAN was built and evaluated to demonstrate the feasibility of the technology.

2.0 System Trade-Offs

Our objective was to design an Ethernet compatible WLAN operating at a high data rate (>10 Mbps). The WLAN should support multiple users in an office like environment. To meet these operational requirements, various system parameter trade-offs were investigated including:

- Frequency Band
- RF Channel
- Modulation Schemes
- Multiple Access Protocols
- Antenna Type/Link Budget
- Fixed or Mobile Users
- Cost.

2.1 Frequency Band

For operational reasons one would like to use a compact antenna. Also, for high data rates, a wide RF bandwidth must be utilized. Since our goal was to prove the feasibility of a high data rate WLAN, we employed an FCC unlicensed band. (See Table 1 for a summary of the regulations covering operation in FCC unlicensed bands.) There are many potential interferers in the unlicensed FCC bands. Devices that fall under the category of field disturbance sensors are commonly automatic door openers. Typical industrial, scientific and medical equipment applications are the production of physical, biological, or chemical effects such as heating, ionization of gasses, mechanical vibrations, hair removal, and acceleration of charged particles.

Table 1. FCC Parts 15 and 18 Unlicensed Frequency Band Characteristics [1]

FCC Part	Frequency Bands (MHz)	Radiator Type
15.245	902-928, 2435-2465, 5785-5815, 10500-10550, 24075-24175	Field Disturbance Sensor.
15.247	902-928, 2400-2483.5, 5785-5850	Intentional Radiators.
15.249	902-928, 2400-2483.5, 5725-5875, 24000-24250	Intentional Radiators.
18.301	902-928, 2400-2483.5, 5725-5875, 24000-24250	Industrial, Scientific, Medical (ISM).

We selected the 24 GHz band under Part 15.249. In the lower unlicensed bands (900 MHz, 2400 MHz), there is not sufficient RF bandwidth available to support high data rates. The antenna size in the 24 GHz band is significantly smaller than the 5.8 GHz band. Also, since 250 MHz of RF bandwidth is available in the 24 GHz band, there is growth potential for even higher data rates. The FCC has stated that to the best of its knowledge, (since it is not required to keep records of approved ISM equipment), no commercial ISM equipment exists in this frequency band at present. Therefore, the FCC Part 15.249 24 GHz band has the advantages of unlicensed operation and suitability for high data rate operation.

2.2 RF Channel

The RF channel in an office-like environment will encounter obstacles in the propagation path, such as metal desks, metal partitions, and metal ceiling light enclosures. Each obstacle will intercept a portion of the transmitted power and reflect or re-radiate the transmitted signal. These multiple transmission paths are referred to as "multipath." The composite signal incident on the receive antenna is a vector sum of all the individual signals. In addition to stationary objects, people and equipment move within the environment in an unpredictable manner. This causes the reflected signals to change with time and space making a deterministic characterization of the RF channel impossible. Thus a statistical model must be used which is derived from many indoor measurements to determine probability distributions of the parameters for the RF channel.

Ideally with no multipath effects, a single impulse launched from the transmit antenna would arrive at the receiver delayed by the arrival time with a change in amplitude and phase. In an actual propagation environment, multiple reflected impulses enter the receiver in addition to the line of sight (LOS) impulse. The "delay spread profile" (amplitude of the individual multipath components as a function of time) characterizes this non-ideal propagation channel. Figure 1 shows a typical delay spread profile for a LOS RF link.

A good measure of a particular multipath delay profile is the RMS delay spread, τ_{rms}. It is defined by:

$$\tau_{rms} = \sqrt{\frac{\sum_k (t_k - \tau_m - t_o)^2}{\sum_k a_k^2}}$$

where t_k is the arrival time of the kth impulse in the profile, t_o is the arrival time of the first impulse in the profile, a_k is the amplitude of the impulses, and τ_m, the mean excess delay defined by:

$$\tau_m = \sqrt{\frac{\sum_k (t_k - t_o)^2 a_k^2}{\sum_k a_k^2}}$$

It has been shown that the performance of a wireless communication system is very sensitive to the value of τ_{rms} [3]. If the value of delay spread is comparable to the symbol length, reduced link performance will result. To recover the data in the presence of the multipath components, adaptive equalizers at the receiver are required to reconstruct the desired signal. The use of an adaptive equalizer is undesirable due to the added system complexity and cost. As a result, *rapid training* in a packet data environment would be difficult.

Since commercial interest in the 24 GHz unlicensed band is only recent, measured delay spread data are not available for the office-like environment in this band. However, measured data are available at 11.5 GHz. Since the delay spread characteristics in the two bands are likely to be similar, it was used to model the 24 GHz propagation channel. Therefore, using the experimental results at 11.5 GHz, the propagation model for the 24 GHz channel was fitted to the data and a channel frequency response generated (as shown in Figure 2). For a fixed receiver in a particular location, the channel frequency response consists of one slice cut in the spatial dimension of the frequency response. The notches in the frequency response will cause distortion of the complex envelope of the transmitted signal, resulting in intersymbol interference.

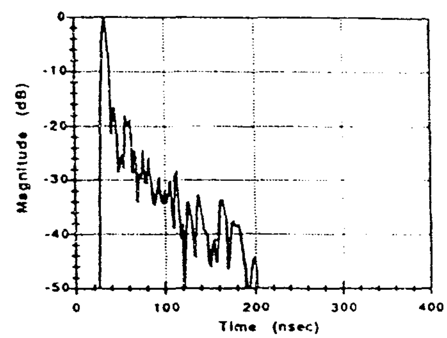

Figure 1. Typical Delay Spread Profile For a LOS (Line of Sight) RF Link [2]

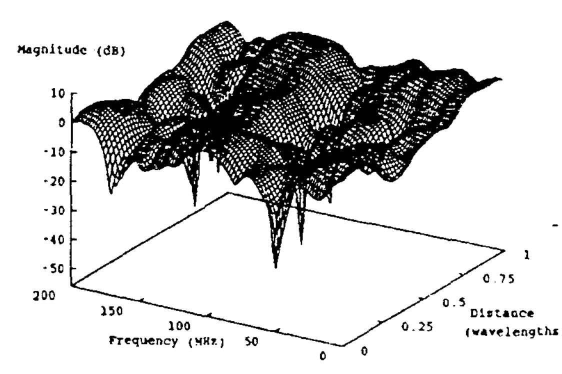

Figure 2. Frequency Response for the Indoor Channel at 24 GHz

2.3 Modulation Schemes

Transmission of data at high rates (>10 Mbps) in a multipath environment requires detailed examination of the modulation scheme trade-offs. We investigated three modulation schemes from simple to highly complex: linear Quadrature Phase Shift Keying (QPSK), non-linear Gaussian Minimum Shift Keying (GMSK), and multi-carrier Orthogonal Frequency Division Multiplex (OFDM). Simulations were performed using the Comdisco SPW simulator. Simulations of the QPSK and GMSK systems are performed in the time domain whereas OFDM simulations are performed in the frequency domain.

The simulation model for the QPSK system transmitting pseudo random data at a rate of 20 Mbps is shown in Figure 3. The QPSK modulator maps the transmit data into four symbols per bit at a symbol rate of 10 Mbaud. The transmit and receive filters are root raised cosine with 35% excess bandwidth. The QPSK demodulator is assumed to have perfect symbol timing and carrier recovery algorithms. After demodulation, the *eye* is sampled and quantized to +/- 1 on each I and Q line. The resultant received data is compared to the transmitted data to determine the bit error rate.

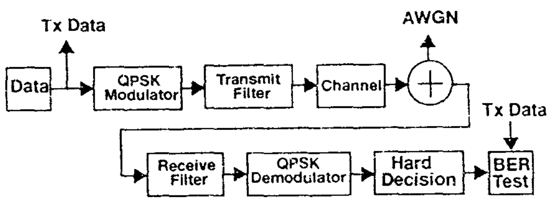

Figure 3. Simulation Model of the QPSK System

The simulation model for the GMSK system (Figure 4) transmits data at 20 Mbps. Since GMSK modulation maps only two symbols per bit, the symbol rate is twice as high, namely 20 Mbaud. The GMSK modulator filters the data with a Gaussian filter with a bandwidth-bit period (BT) product of 0.5. The pre-detection filter is a Butterworth filter of order 4 with a BT product of 1.5. The single-sided noise bandwidth of this filter is approximately equal to its 3-dB cutoff frequency. Limiter-discriminator detection is used with the addition of an integrate and dump (IAD) filter to average out spikes at the discriminator output due to abrupt changes in phase resulting from the interference of multipath components. Perfect symbol timing is assumed, such that the IAD integrates over one complete symbol period.

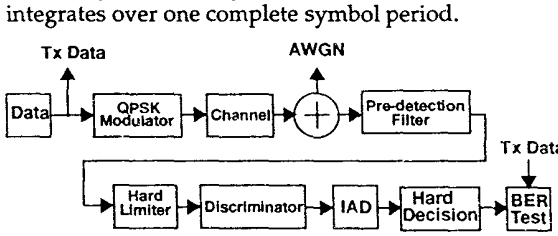

Figure 4. Simulation Model of the GMSK System

The simulation for the OFDM model (Figure 5) is performed in the frequency domain. This is a time-saving measure, as the direct implementation of an OFDM system requires taking the Inverse Fast Fourier Transform (IFFT) of the mapped data, followed by convolving the resulting time domain signal with the channel impulse response, followed by taking the FFT of the received signal. In the frequency domain, it is only necessary to take the FFT of the channel impulse response and multiply the resultant vector, element by element, with vectors of mapped data.

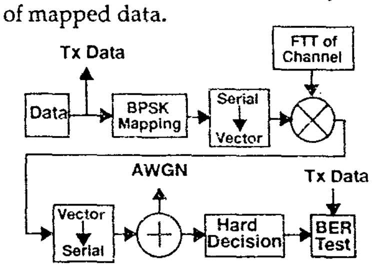

Figure 5. Simulation Model of the OFDM System

The transmitted data is first mapped to a Binary Phase Shift Keying (BPSK) constellation and loaded into vectors of length 155. The channel is sub-divided into 155 sub-channels each carrying a BPSK modulated signal. Each sub-channel has a separation of 200 kHz, and thus the occupied bandwidth of the transmitted signal is 31 MHz. The vectors of the BPSK mapped data are multiplied by the magnitude of the channel frequency response. Since perfect carrier recovery of each sub-carrier is assumed, the phase of the channel frequency response is not used. For a baud period of 5 µs with a 20% guard period totaling 6 µs per block, the symbol rate over the channel is 25.8 Mbaud. Since BPSK modulation bandwidth efficiency is 1 bit/Hz, the OFDM modulator baud rate equals the bit rate, and data transfer is at 25.8 Mbps.

For the ODFM system, a 5 bit Reed-Solomon (RS) code is used which can correct up to 3 RS symbol errors per block length of 155 bits. For the QPSK and GMSK systems, an 8 bit RS code is used which can correct up to 8 RS symbol errors per block length of 528 bits.

Grade-of-Service. The bit error rate of a communication system using coding is a much less important measure of performance than the block, or packet, error rate. A forward error correction (FEC) code can correct a certain number of bits errors within a block. Thus the appropriate measure of performance is the block error rate which is a measure of how often the code could not correct all of the bit errors within a block. A useful metric related to block error rate is grade-of-service (GOS) defined as:

$$GOS\,(\%) = [1 - P] \times 100$$

where P is the ratio of "bad" blocks compared to "good" blocks. A GOS of 100% means that no block errors occur, and a GOS of zero means that the bit error rate is so high that the code cannot correct all of the errors in every block such that every block is in error.

Simulations were run for three different types of RF channel propagation losses (corresponding to three different locations) in an indoor environment: 1) a typical channel with no "null" in the propagation path, 2) a medium "null" (~ 15 dB) in the propagation path and 3) a deep "null" (>25 dB). The channel frequency response is plotted across a bandwidth of 31 MHz, which is the bandwidth occupied by the OFDM signals (Figure 6). Location 1 is an optimistic expectation of a typical frequency response whereas locations 2 and 3 are more pessimistic.

Location 1

Location 2

Location 3

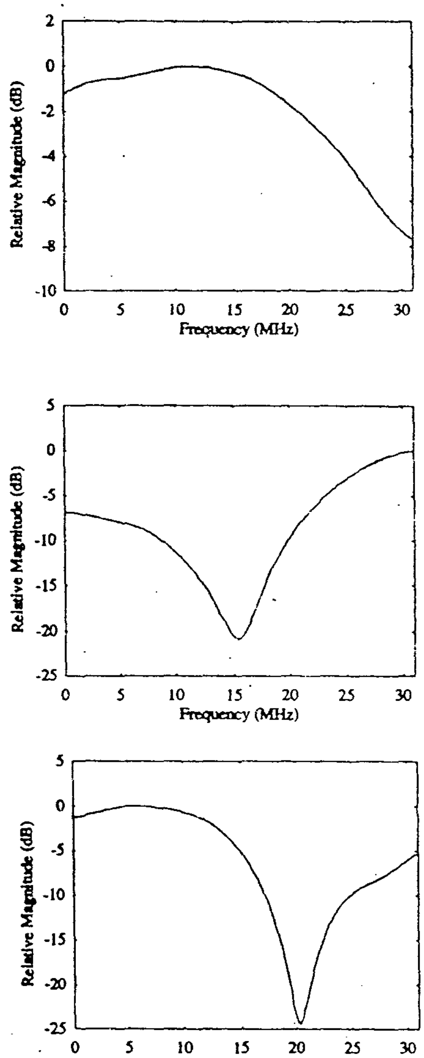

Figure 6. Channel Frequency Response for Three Different Office Locations

The GOS was computed for an appropriate range of energy per bit to thermal noise power (E_b/N_o) for the QPSK, GMSK and OFDM modulation models in the three locations. For GMSK modulation, locations 2 and 3 distorted the received signal to the point of being unusable for data transmission. For QPSK modulation, locations 2 and 3 also yielded an unacceptable grade-of-service. However, for OFDM modulation, a high grade-of-service resulted from an increase in E_b/N_o, independent of the location.

Also, OFDM was found to be effective at combating the effects of delay spread. Even under conditions of deep fades and severe delay spread (locations 2 and 3), an increase in transmission power can reduce the block error rate to an acceptable level. However, increase in transmitted power will increase the system cost. (Also, it may not be feasible to increase the transmitted power due to FCC regulations.) A careful examination of the RF channel model in Figure 2 reveals that considerable spatial decorrelation is available in a single wavelength. As a consequence, a simple antenna diversity scheme would prove beneficial in ensuring a successful link. Coupled with a robust modulation such as OFDM, a highly reliable data link would result.

2.4 Multiple Access Protocols

The operational environment for our WLAN consists of a base (fixed) station and N terminal stations (where N is the number of users and N>1) operating in half-duplex mode. Such a system requires that the base station transmit to all terminal stations on one frequency and then only one of the users (terminal stations) transmits to the base station on that same frequency. The problem is to ensure that only one station transmits at a time on the inbound channel and yet the greatest possible utilization of the channel (commensurate with minimum delay) must be achieved.

A survey of non-deterministic medium access control (MAC) protocols including the ALOHA (pure as well as slotted), the CSMA (Carrier Sense Multiple Access), Ethernet standard protocol CSMA/CD (CSMA with Collision Detect), CSMA/CA (CSMA with Collision Avoidance), the Tree-and-Window Collision Resolution Algorithms (CRA) using control minislots (CMS), and "Reservation System" was performed. It was found that a contention protocol developed at the Illinois Institute of Technology called Distributed Queuing Random Access Protocol (DQRAP) [5] provided the maximum network efficiency when network loading was taken into consideration.

Modeling and simulations indicate that DQRAP using three minislots achieves a performance level that approaches that of a hypothetical perfect scheduling protocol (M/D/1 system) with respect to throughput and delay. The DQRAP would provide immediate access at light loads and then seamlessly move to a "reservation system" at high loads.

2.5 Antenna Type/Link Budget

The physical implementation of the WLAN is heavily influenced by how far the signal will travel and still be received without error. To determine the useful distance between transmitter and receiver, a link budget was developed with the following operational parameters:

- *Receiver Noise Figure:* 6 dB.
- *Data Rate and Signal Bandwidth:* OFDM modulator at 25.8 Mbps data rate (requiring 31 MHz RF bandwidth).
- *Eb/No:* 15 dB to provide an 95% grade-of-service for OFDM modulation.
- *Modem Loss Margin:* 3 dB.
- *Path Loss:* Free space path loss based on line-of-sight transmit and receive antennas.
- *Transmit Power:* 12.6 dBm effective radiated power (ERP).
- *Transmit Antenna Gain:* Omnidirectional antenna with 2 dBi gain.
- *Receive Antenna Gain:* Omnidirectional antenna with 2 dBi gain or Directional antenna with 17 dBi gain.
- *Shadow Loss:* 8 dB.
- *Co-channel and Adjacent channel Interference:* 6 dB.

Two scenarios were analyzed: a) omnidirectional antennae on both the receive and transmit side of the link and b) an omnidirectional antenna at the transmit side and a directional antenna at the receive side of the link. For case (a), the link would operate up to 39 feet only. For case (b), an operational distance of > 200 feet was calculated. Therefore, to meet the goal of 100 feet operating distance within the maximum permissible transmit power in the 24 GHz unlicensed band, a directional antenna must be used at one end of the link (case b).

2.6 Mobile vs Fixed Users

A WLAN can consist of fixed (terminal station) users, mobile users, or both. In addition, a WLAN that supports mobile users may allow the mobile user to roam between wireless local area networks. A common attribute of mobile users is that the antenna employed is omnidirectional. (An omnidirectional antenna allows the mobile to communicate with the network it is leaving, and listen to the network it is about to enter.) As discussed above (link budget analysis), for an operational WLAN at 24 GHz and high data rate, use of a directional antenna at one end of the link is required. The directional antenna must always be pointed at the other end of the link. In a mobile environment, this cannot always be guaranteed. Therefore, our WLAN design will support a scenario where users must employ terminal stations at fixed locations.

2.7 Cost

The RF transceiver and the OFDM modulator/demodulator (modem) are the two major cost drivers in the 24 GHz high data rate WLAN systems. Cost of the RF transceivers can be lowered by using highly integrated (preferably a single) monolithic microwave integrated circuit (MMIC) chip(s). (See Section 3 for Northrop Grumman's single GaAs MMIC chip details.)

Digital signal processor (DSP) IC chips required to implement the OFDM modems are very expensive at present. However, the cost of the DSP chips is falling at a fast rate (by a factor of two every two years) and will be affordable for WLAN use in very near future.

3. The MMIC WLAN Demonstrator

An Ethernet compatible 24 GHz MMIC-based WLAN at data rates >10 Mbps supporting multiple fixed users at a distance of >100 feet was designed, built and evaluated. (See Figure 7.) To demonstrate the applicability of GaAs MMICs, a 24 GHz transmit and receive module was implemented using discrete MMICs. (An ultimate low cost version will utilize a single 24 GHz transceiver GaAs MMIC chip, as described later.)

The receive chain consists of a MMIC Low Noise Amplifier (LNA), followed by a MMIC amplifier which sets the noise figure of the receiver (< 6 dB). A 6 pole edge-coupled microstrip filter with 3-dB points at approximately 24000 to 24250 MHz limits the image noise incident on the downconverter mixer, and reduces out-of-band spurious. The input signals are downconverted directly to a 140 MHz IF using a MMIC mixer, with built-in LO amplifier. The IF signal is amplified and demodulated by a frequency discriminator.

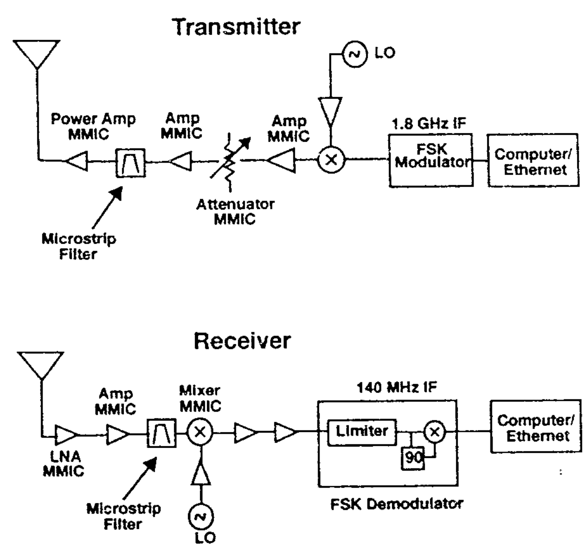

Figure 7. The MMIC Based WLAN Link Demonstrator System

On the transmit side, data packets modulated a carrier at 1.8 GHz. The modulated carrier was upconverted to 24 GHz, preamplified and filtered by a 5-pole edge coupled microstrip filter. A MMIC power amplifier is used to boost the effective radiated output power to +12.6 dBm at the antenna.

A binary Frequency Shift Keying (FSK) modem was substituted for an expensive OFDM modem to implement the modulation and demodulation functions for evaluation of the WLAN link. An OFDM modem would be required to solve a "real" operable scenario whereby an omni-directional antenna would be employed for "base station" and a directional antenna for the "fixed (user) station." This link will perform at low BER with multiple reflection from metal walls and people walking around in the vicinity of the WLAN link. We found that an FSK modem employed under the same conditions but with "directional" antennas at the "base station" and "fixed station," emulated a similar RF link.

The transmitter and receiver were connected to 17 dBi directional antennae. Both antennae were aligned for line-of-sight transmission with no shadow loss or blockage. Ethernet packets were successfully transmitted up to 400 foot distance at 6 Mbps Manchester coded data rate with no errors in data transmitted. (WLAN speed was limited by the bandwidth of the FSK modem .)

The GaAs Transceiver MMIC Chip. A highly integrated single GaAs transceiver MMIC chip (Figure 8) for the 24 GHz band has been designed. It incorporates an LO amplifier with a power divider, a low noise receive chain, a linear transmit chain, and an SPDT transmit-/receive (T/R) switch. It will replace discrete MMICs used in the demonstrator discussed above. Only five external bypass capacitors are required. It contains 18 RF functions and was designed using a 0.18 µm P-HEMT technology which provides low noise and medium power. The chip will provide 14 dBm of transmit power with 18 dB conversion gain in the transmit chain. It has a 5 dB receive noise figure and 20 dB down conversion gain. The transmit and receive chains can be powered independently to conserve power. The T/R switch offers fast switching time and high transmit and receive isolation (>30 dB). The external LO drive required is -5 dBm. The current drain is 320 mA @ 4 V in the transmit mode and 100 mA @ 4 V in the receive mode. The chip size is only 100x150 mils for a total chip area of ~10 mm^2. Use of high density layout techniques maximize chip functionality, provide critical isolation within the chip, and minimize chip size. The chip's small size will provide high-yield and hence lower the system cost.

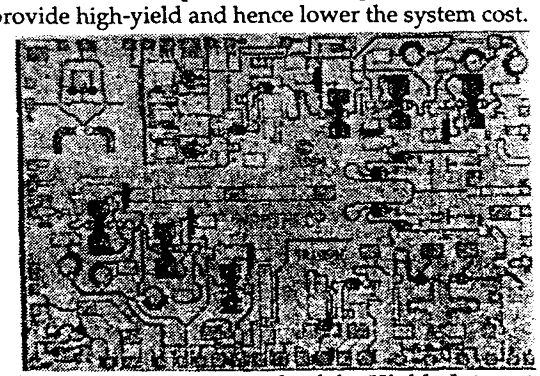

Figure 8. Microphotograph of the Highly Integrated 24 GHz Transceiver GaAs MMIC Chip

4.0 Conclusion

Several technical and practical problems challenge the design of any high-speed wireless network. WLAN system architecture trade studies were performed. Based on these trade-offs, we found the optimum solution to be:

1. *Operate in the unlicensed band.* The 24000-24250 MHz unlicensed FCC Part 15.249 band was chosen because of the lack of interfering sources, wide bandwidth available to support high data rates, future growth potential and unlicensed operation. Also, the antenna sizes are small at these frequencies. Furthermore, WLAN will have small operating cell size due to high propagation losses (at 24 GHz). At first, high propagation loss may appear to hinder the system performance, but it works to the WLAN designer's advantage since it will reduce the interference from adjoining operating cells.

2. *Use multi-carrier complex modulation, such as, orthogonal frequency division multiplex (OFDM).* Computer models were used to determine the best modulation to maintain an acceptable quality of service in the office propagation channel. Results indicated that OFDM modulation will yield a high speed link with minimal errors, even in the presence of severe multipath.

3. *Use directional antennae for users (terminal stations) and an omnidiretional antenna for base station.* To provide reliable data communications over a 100-foot distance and remain FCC compliant, a directional antenna at one end of the link must be employed. Directional antennae are not well suited for mobile scenarios where the user may move from the front lobe to the back lobe of the other user. Consequently the network must consist of fixed users.

4. *Use DQRAP multiple access communication protocol.* A survey of all applicable multiple access protocols was performed and it was determined that Distributed Queuing Random Access Protocol (DQRAP) yielded the greatest throughput and least delay for a wireless LAN system.

5. *Integrate most of the RF functions onto a single multi-function monolithic mirowave integrated circuit (MMIC) GaAs chip to implement an affordable WLAN system.* A significant cost driver is the RF portion of the link. Using packaged discrete devices to implement the transceiver would be cost and size prohibitive. By using a single highly integrated GaAs MMIC chip, a commercially affordable WLAN can be implemented.

Acknowledgment

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