IEEE P802.15
Wireless Next Generation Networks

Project	IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)
Title	**Retrospective on Development of Radio and Wire Data Communication**
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Re:	Call for contributions for 15WNG Erik Schylander, 13 Feb 2006
Abstract	An account of: the development of phase shift keying and orthogonal frequency division multiplex with carriers positioned at spectral null of the adjacent carrier at Collins Radio 1954-58, the early development of 802.3 CSMA, 802.4 Token bus and 802.5 Token ring and the 802.4L radio PHY for token bus, the 802.6 and 802.9 committee's working on voice-data integration, the start of 802.11 from 802.4L, the original functional targets and the DFW MAC adopted as a starting point the circumstances for the development 11A and 11B.
Purpose	The intent is show the effect of early and current decision-making as influenced by function goals and obscure design considerations. Possibly some future choices may be better made with knowledge of these examples.
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Retrospective On Development Of Radio And Wire Data Communication

Original Draft Last revised May 12, 2005

Abridged version for 802.15 WNG revised March 4, 2006

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Last revised May 12, 2005 – **Abridged version** for 802.15 WNG

INTRODUCTION

This paper is a personal retrospective about the journey to present-day local area data communication with particular attention to radio transmission. The trail winds through:

a) the development of phase-keyed radio data transmission developed at Collins Radio in the '50's by Melvin Doelz,

b) highly-used radio telephone systems starting with the high-capacity mobile telephone system first described as HCMTS in 1959, the following MJ (IMTS) telephone, and subsequently "cellular," and

c) then through wired local area networks and on to wireless local area networks

This abridged version concentrates on the areas that should be of interest to current IEEE 802 attendees. The story of the radio-telephone systems has been omitted. The full version will be available on request.

ORIGIN OF ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

MSK, PSK QPSK and DQPSK all were first used in working products of the Collins Radio Company between 1952 and 1958. The technical concepts came from Melvin L. Doelz working at the new Western Division at Burbank, CA. A large engineering staff contributed some of the extensions and refinements. The first hardware experimental demonstrations of PSK were done in my group about 1952. Doelz and others soon understood that MSK and OQPSK were mathematically identical modulations.

Doelz fully understood the separate time and frequency orthogonality that is used in multi-carrier applications (now known as ***OFDM***). He also understood the vital function of integration with an appropriate weighting function. This process is an essential part of getting operation near the Shannon limit. There are a number of patents relating to this subject.[1]

At Collins, the first important product was used for the 75 Baud, 5-level "teletype" used to carry traffic generated by the arctic radar picket line called "DEW-line" (Distant Early Warning network). Collins won the contract for all of the radio equipment and other related services in the winter of 1954 (I may be off by a year). The vertical radio links were about 50 MHz and depended upon ionospheric scatter propagation for path lengths of about 1200 miles. The horizontal links, connecting outlying stations, used 400 MHz depending on tropospheric scatter for path lengths of up to 400 miles. The phase-shift keyed modulation/demodulation used in this equipment was later described in Electronics Magazine as a "predicted wave" frequency-division teletype transmission equipment.

The vertical radio equipment was linear single side band with 20 KW transmitters at 50 MHz. ***Noise figure could be translated into barrels of diesel fuel delivered in to the arctic by C-47 (WWII twin-engine transport).***

The modulation was 4-channels of DPSK at 75 Baud keying rate using closely spaced sub-carriers. The means for obtaining reference for the demodulators is described in the following box.

Phase Reference Implementation
U.S. Patent 2,905,812 M. L. Doelz

The differential PSK compared the phase of the current pulse with that of the preceding pulse. The incoming signal was heterodyned down to 25 KHz. The carrier component of each bit was applied alternately to one of two high-Q resonators. After listening to the incoming signal for a bit interval, the resonator had enough Q so that the resonator kept ringing past the following bit interval. Each resonator went through charge-detect cycle for the current bit using the ring down of the alternate resonator as a phase reference. For this scheme to work it was necessary to establish the phase and frequency of clock at the bit rate. Sampling at the end of the charge interval, determined phase to be either + or – relative to the previous bit.

The equipment for DEW line as tested with a transmitter in one screen room and a receiver in second screen room 100 feet away. The rooms were connected by a co-ax cable with attenuators in the screen rooms and in the middle. This provided about 160 dB of path loss attenuation inside and out of the screen room. I remember with certainty that the AGC threshold was 0.005 microvolts at 50 ohms. The engineers believed that the whole system was less than 5 dB from the Shannon limit.

A later Collins development was a telephone carrier data modem using 16 carriers spaced 100 Hz from 600 to 2100 Hz and OQPSK modulated at 100 bps to provide 3200 bps throughput. This system used the two orthogonal relationships isolating the quadrature phase and adjacent channels. ***With tones space at the nulls in the sin(x)/x distribution, it performed by analog means the same function used in today's OFDM,*** except that pulse shape weighting and integration were more rigorous.

At that time it was known that telephone plant long distance transmission bandwidth was severely limited by some older C carrier equipment. The role of group delay variation was not given much attention. Some engineers realized the limitations were mainly from group delay distortion at the band edges. The parallel multi-carrier approach greatly substantially diluted the effect of this distortion

I heard that when H. Nyquist[2] (Bell Laboratories) heard about it, he said "I knew someone would do it someday." He was referring to getting near 2 bits of information per Hz of bandwidth.

In this period there was no thought of using multiple-amplitudes to increase bits/Hz. My first knowledge of use of this method came from the papers of Marvin K. Simon at the Jet Propulsion Laboratory 1974-76. A key word in these papers is MAMSK (Multiple Amplitude Minimum Shift Keying).

A further appearance of OFDM principles is described as part of the coverage of IEEE P802.9 in 1989-90.

INFLUENCE OF EARLY AUTOMATED TELEPHONE SYSTEMS

(Added **TEXT**) The development of automated radio telephony took the first big steps starting around 1957. Using electro-mechanical lodget, machines were made at first for detecting a particular dial pulse address for ringing and later for using the same machine for identification.

The dial pulse signaling was carried in band at first with on-off single tone and later with dual tone combinations. In the next few years duplex radio systems appeared (replacing press-to-talk). With duplex and automated station identification the radio telephone worked as a telephone should. Soon after the start of the development of the "cellular" service, it was appreciated that "interference limited system" design was critical to the level of frequency re-use necessary for a high level of spectrum utilization. In the early '70's this became the basis of the first cellular systems with idealized hexagonal coverage's. This function made a great difference.

THE FIRST IEEE 802 LANS

Before IEEE 802, packet communication was largely the province of university computer departments and the defense research organization (DARPA). It was assumed that everyone on the net was a "good guy," and this was generally true. Possibly LAN started at Xerox PARC (Palo Alto Research Center) and was further developed and embraced by Xerox-Intel-Digital Equipment as a group intending to define a *de facto* open standard. At that time, an Ethernet interface card was two or three 80 in^2 circuit boards (Multibus) with Intel 80186 processors.

For developing LAN, three MAC-PHY combinations with differing optimization criteria won sufficient constituencies to support a development project within IEEE 802 as listed below:

Project	MAC	PHY	Leading sponsor
802.3	CSMA	Bus-single coax daisy-chain	Xerox-Intel-DEC
802.4	Token bus	Bus-CATV coax with head-end	GM, Honeywell
802.5	Token ring	Dual pair cable star-wired, ring	IBM & others

The arguments and motivations of each of these groups are interesting. Token Bus and Token Ring used access protocols that avoided the contention of the CSMA. Many of the early decisions are still with us for better or worse. Much of the philosophy of 802.3 was reincarnated in the early work of the present 802.11. Before addressing the present, it is helpful to understand a little of the detail of the three methods.

Ethernet turns into IEEE 802.3 CSMA-CA

CSMA-CA (collision/contention sensing multiple access with collision avoidance) used a single quad-shielded coax cable transmission medium with bridged "vampire taps" within attachment units. By the definition of a bus, e***very station hears (or should) all other stations on the low loss cable.*** Each access starts by listening. With activity present, the station that is ready to transmit defers until idle condition is observed. When idle state starts, a back-off algorithm was used to separate multiple simultaneous access attempts. This arrangement can give advantage to closely spaced taps over the widely separated. ***A fairness principle was just ignored because there was no solution with random access.*** The packets that fail to access because of contention are unrecorded. Their frustration just disappears from performance analysis.

Note: the transmitting station, by monitoring all signals on the cable, can detect a collision while transmitting, a point not duplicated in later radio systems also labeled CSMA.

A ***major advantage*** was said to be "no common point or equipment which could bring the system down on failure."

A ***disadvantage*** was that the capacity was not analytically determinate. A number of simulations were presented where traffic was generated with random numbers/ ***With models using traffic assumptions it was possible to estimate capacity, but much more difficult to derive an access delay distribution.*** It was possible in high service demand to be indefinitely delayed if service requests got close to or larger than capacity.

Inherent characteristics were: a) that receivers had to listen at all times, b) a MAC that made large use of broadcast message to discover status facts, at the moment of message origination, and c) absence of an acknowledgment function at the MAC level.

The resulting standard from the 802.3 committee was a system that could co-exist on the same cable as Ethernet, but it would not inter-work with the older system.

A few years after 802.3 came into use, a bus with 3,000 user stations was attempted at the Cleveland Clinic (Ohio). It did not take long for them to realize that there is practical upper limit to the number of users on one LAN. This was a serious problem at that time because the few available routers were very expensive.

IEEE 802.4 Token Bus

My first IEEE 802 meeting was at San Diego in 1984. The reason for interest was because the 802.4 group was using a radio-like physical medium.

This token bus LAN used CATV type coax with duplex up and down radio-frequency links. The frequency division duplex used 6 MHz bandwidth channels at 54-88 and 174-216 MHz. A head-end was essential repeating all received messages on the up-link to the down-link. This met the condition that any station could hear all others. The station could hear its own transmitted messages coming back on the down-link which was used to detect collisions. An Intel part (1986) integrated this function as proof of successful transmission without undetected failure.

One objective of this group was to reduce the cost of the "orange" cable used in 802.3. Moreover, the modems for transmitting AM duo-binary were built and demonstrated for both 5 and 10 Mbps (9-QPR) in the 6 MHz channel. Another objective was to get a more **deterministic access protocol.**

The MAC avoided contention by token-passing. A first station, detecting no activity, would originate a token to be accepted by a second station (if present). The token holder had permission to transmit on the bus. The token-passing sequence used a set-up phase established at start-up of the net. The token was passed from station to station, each holding it until finished sending its traffic. This worked well until a station failed to pass the token as defined. Then the absence of token-passing had to time-out, and the remaining group had to begin again to set up the new sequence. There was also a procedure for detecting stations wishing to join the group.

This protocol was sufficiently deterministic to satisfy the factory automation people, but this protocol was unacceptable to the random access believers as an alternative to 802.3.

This standard was completed, and to this day has some commendable points, but in 1990 GM gave up on its development of the manufacturing automation protocol (MAP) deciding to use market available technology. Token bus has continued to be used in the petroleum industry with maintenance by suppliers of refinery and pipeline electronics without reference to IEEE standards..

IEEE 802.5 Token Ring

This protocol was initially used with a custom two-pair shielded cable later found to have good transmission characteristics to at least 400 MHz. The first proposed line signal was 4 Mbps Manchester later increased to 16 Mbps. The distance goals were based on the range with logic level receivers rather than that of data modulated on a carrier. As a result, there was gross under-estimate of the potential transmission distance. The capacity to communicate was very well analyzed and designed on the basis of “comparator ICs” for the receivers.

This technical precedent was used more than a decade later for the wired ATM (Asynchronous Transfer Mode) rate of 25.6 Mbps which with 4/5 block coding has the same baud rate as the 16 Mbps Manchester coding.

There was also an unusual hermaphrodite (identical parts mating) connector designed for this system. It would be much too big for modern use.

The ring as installed was not point-to-point. All user points were wired with two-pair cable between the user access point and a wiring closet with a hub/patch panel. The topography of the ring was defined at this panel. The possibility of a station being off-line was accommodated by a hub function that by-passed non-connected ports. The hub had a sensing relay on each port that performed the by-pass switching.

The hub was simple and indispensable. The MAC used token-passing around the ring. The system was contention-free. The token-holding station listened to the repeated traffic, read any incoming message, and put any messages to be transferred on the ring for one lap. The originating station removed any messages that it had put on the ring knowing that it had past through the destination station. All stations heard all messages and read only those for which it was the addressee. This system was deterministic, because of the absence of contention with its statistical probability.

Avoiding PBX data-voice integration

When functional requirements were first taken up in 802.3, the over-reaching motivation was avoiding any common element with PBX and telephone wiring. The main reason was that the PBX wiring in large companies was often the realm of a petty manger who would not respond to a request for direct pairs between work positions. The computer people were only offered pairs into the central cross-connect and back out again. And that was “when we get around to it.” At that time, the distance limits for serial data interfaces (RS-232) were not much more than a few hundred feet. Computer users were then seen as a group within a department. Outside network access was through one of the computers or an adjoining communication server.

The telephone wiring in place was usually undocumented making pair identification at different places very difficult. The wiring people were often independent contractors. In a big multi-tenant office building, there were multiple contractors and telephone company craftsman. The fear of these people was breaking some unknown person’s connection while installing new pairs. Always, new wire was installed over the existing wire. Rarely, was anything taken out even though it was no longer used. (material omitted)

SWITCH COMPANIES TRY DATA-VOICE INTEGRATION

There were two efforts within IEEE 802 to define a means for integration of connection and connectionless services. Since the same problem is likely to arise, in radio it may be useful to summarize these efforts.

The two committees were:

Project Identity	Name description	Years Active	Leading sponsors
IEEE 802.6	Metropolitan Area Networks City or regional area size	1985-91	Bellcore
IEEE 802.9	Line interface for integrated Voice data twisted pair interface	1988-93	Avaya (Bell Labs)

IEEE 802.6 DQDB Metropolitan Area Network

The distributed queue dual bus (DQDB) metropolitan area network used two counter rotating rings with provisions for looping back on failure. When brought into service, the rings operated at 45 or 155 Mbps often with optical fiber.

The first two years of this committee included a battle between two methods of providing the service and a further battle with ANSI FDDI 100 Mbps (fiber-optic distributed data interface) where it was asserted that the IEEE project was redundant and should be halted. Supporting the IEEE activity was Burroughs that wanted to use it mainly for interconnection of main frames. ***The chairs of the ANSI FDDI and of the IEEE 802.6 conducted some of the most energized and vituperative arguments ever heard by the 802 executive committee.***

As the work of the committee proceeded, two factions developed within 802.6 concerning one time division multiplexing method vs. the DQDB method. An asynchronous access proposal satisfactory to CSMA believers was argued and voted. The telecom supporters had the votes to select DQDB type of TDM in 1991. In this phase, **Bellcore** was the main sponsor of this effort.

Technology and application description

The technology defined in this standard became SMDS (switched metropolitan-area data/distribution services) offered by many local telephone companies for high bandwidth internet access and isochronous trunks on the same medium. It was/is one of the more economical wide-band services offered by Pacific Bell and some other local telephone companies (circa 1992-98). The physical medium was usually a pair of optical fibers.

This standard was the first to multiplex the physical medium for both telecom connections with reserved capacity and asynchronous packet traffic on demand as resources became available. The frame structure and protocol were developed jointly by Telstra (Australian telephone company) and the University of Western Australia at Perth. This development had the distributed queue feature. ***With organized queuing of asynchronously offered traffic, it was possible to load the medium to near 100% of capacity as compared with 30% for random access CSMA systems.***

The dual-path, counter-rotating ring included the capability of working around a break in the ring at one point.

This protocol supports ATM (asynchronous transfer mode) including the SAR (segmentation and reassembly) function for both packets and connections. *The 802.6 standard appears to be unique for its function and scope of interface capability.*

Demonstrations from the IEEE 802.6 standard

This standard is first a demonstration of the special functionality obtainable from a ring topology at speeds of 45 and higher data rates. It further demonstrates the mixing of connection-type and asynchronous services on the same physical medium (radio, wire or fiber). However, the 802.6 example does not prove that this protocol is satisfactory for short reach LANs. It is probably suitable for networks connecting clusters of houses or industrial buildings or the clusters in a campus environment. These are applications for which LAN is not suitable though it can and will be used.

This protocol has been used for backbone trunks connecting concentrated traffic sources. There is a potential for connecting groups of sectoral access points using this protocol.

IEEE 802.9 IVD Line Interface

The IEEE 802.9 committee effort to develop a LAN type service integrating voice and data started in 1988 with leadership from Northern Telecom and from Bell Labs (Avaya).

The committee took considerable time to arrive at a model for the function: **The standard would define an interface between a user station and a subpart of a PBX called AU** (Attahment Unit). It would not design the interior circuit function of either end on the line. The physical medium for the line to the station was a telephone pair for each user. The pair presumable would be part of 25 pair cable with like independent use of the other pairs. As this model emerged, the makeup of the group became largely PBX companies who wanted to add a LAN equivalent station function to the line interface. The necessary reach was defined as 95 meters of line plus 5 meters of cable from outlet to the user device.

In 1989, all proposals for data over telephone pairs were at a low rate. AT&T supported the definition of a 1 Mbps PHY for defined by **802.3-1base5**. Northern Telecom offered 802.9 a 2.56 Mbps solution, and Bell Labs a 2.48 Mbps modem. Work on 802.3 10baseTP (twisted-pair medium) started in 1990.

At an 802.9 meeting soon after these proposals were first presented, the representative of Northern Telecom came in and reported on their market studies. He said: **"any line rate less than 10 Mbps is unmarketable."** *All along, I had advised that much higher rates were possible. My advice was that 16 Mbps is possible. For me, it was time to put up or shut up.* The committee accepted the "unmarketable" opinion and went away to regroup.

There was a substantial question as to how far and fast pair transmission could be used. The EIA 568 building wiring standard that would later define Category 5 cable was a working project that had not completed its task.

The high-rate twisted pair PHY

C. A. Rypinski Co., then largely supported by AMP Inc., designed a test bread board of a 4-carrier system at frequencies of 2, 3, 4 and 5 time symbol rate. Each carrier had I and Q phase PSK. This was built, and quite satisfactory test results (more than 600 feet) reported to the committee limited by crosstalk with like signal on adjoining pairs. This may have been the

seed for the later Bell Labs* OFDM *(this designation not in use at that time) development. *On a visit to BTL (Middletown), I heard the comment they rather preferred this proposal over our later pre-distortion offering.*

The second and final proposal for modulation was conceived by ***G. L. Somer****.*[3] *This was based on advance knowledge of the impulse response of the medium. Using a suitable FIR filter, a compensating shape was put on the transmitted signal. The 20 Mbaud medium was 4/5 block coded and scrambled so that the signal would pass through transformers. Since the 5th bit was a parity check, we also got an indication of symbol time alignment and PHY quality. This modulation was called* ***NRZST.*** *Acquisition was aided by spectral lines at multiples of the symbol rate. This implementation was an order of magnitude simpler than the 4-carrier scheme above.*

Excellent results were obtained at ***16 Mbps*** *and 600 feet with a far simpler modem. Several demonstration modems were built on circuit boards 4x5" using an FPGA for logic.* ***The setup (including racks of DIW inside wiring cable with interfering signals on adjacent pairs) was taken to an 802.9 committee at a meeting in San Rafael, CA.***

When the consolidation of proposals was done, there were three candidates: NEC **PR4** (partial response type 4), Bell Labs **4-CAP** (combined amplitude and phase) near baseband and **NRZST**. It appeared that all of these were functionally satisfactory. The NEC proposal, though very good, was eliminated. 4-CAP and NRZST had almost equal voting support.

The NRZST presentation, like some others, was an exhaustive showing resistance to NEXT (crosstalk) and impulse noise. The reach-rate trade-off showed more than 600 feet at 16 Mbps with EIA specified crosstalk. The experiment with real cable showed no degradation from this cause (for 8 Mbps, 1150 feet and for 4 Mbps, 2,000 feet). [4]

The committee then considered time to IC availability. AT&T with the Allentown semiconductor facility (now Agere) promised to put 4-CAP into production, and that was chosen for the standard. Ours could be built immediately from off-the-shelf parts. *Citing insufficient market, the Agere promise was not kept. A few years later, I was told that the group wished with hindsight that NRZST had been chosen.*

The first 802.9 MAC

Using one pair per user, there is no contention problem on the line interface, though there might be on the backplane of the AU. The committee defined the frame structure with multiplexing of the frame to carry reserved capacity first and asynchronous packet information following. Like wire telephones, there was no transport of the user identification. That information is obtained from the particular pair on which the signaling appears. The strong point of this MAC is its coordination with ISDN digital signaling for call setup and frame space reservation.

There has not been much use of this standard, in part do to the absence of suitable PHY components. More important is that whatever a PBX company developed, the computer community would not use it.

Later 802.9 MAC

Later, versions of the MAC used PHY layer separation of the path into completely separate virtual channels for the data and telephone services. The primary advocate was from National Semiconductor.

The first part of the frame was used exclusively for 6 Mbps of isochronous services, and the second part of the frame was used exclusively for 10 Mbps of 802.3 type packets.

Knowledge gained on high-rate over copper pairs

The primary flaw of early users of twisted pair transmission was the use of line-driver and line receiver ICs which were essentially voltage threshold devices. A very large gain was available from using methods familiar to radio designers working against noise added in the medium.

It surprised me that everyone, particularly including 802.3 1baseTP (1 Mbps on twisted pairs), seemed to be designing modems without understanding from the beginning some very important properties of the pair medium. The most important points that must be considered are as follows:

a) *Pairs have slower velocity of propagation at low frequencies because of the transition of current flow across the area of the conduct to flow only on the surface ("skin effect"). By avoiding using transmission frequencies below 1 MHz, most of time dispersion is avoided.*

b) *Avoidance of degradation from cross-talk is better with simpler modulations that are more tolerant of like signal interference.*

c) ***The impulse response of telephone pairs <u>is</u> a consistent pattern for other gauges of wire and differences in distance.*** *The compensation well-suited to a long run, work just as well for shorter runs. In part, this is because getting the shape right is more important at long distances than it is at shorter distances with a higher level.*

d) *Use of higher frequencies makes it important to use pairs with better insulation and more twists per foot. This same consideration avoids sensitivity to relay transients and noise which can be substantial at lower frequencies.*

Category 5 or 6 cable (that didn't exist at the time of the 802.9 committee) meets the physical requirements, but still benefits from compensation or spectrum shaping.

THE FIRST RADIO PHY FOR LAN (802.4L)

Radio LAN was first thought of as an alternate PHY for 802.3. Doing this without changes in the MAC was never proposed. In 802.4, it was thought that the token bus protocol has a better chance of working on radio. **802.4L** was organized to define a suitable radio PHY. The Chair elected was from General Motors, and I was elected vice-chair. When GM abandoned its support of the MAP (manufacturing automation protocol) and when the elected chair failed to show up, I became acting chair. I explained to the 8-people meeting that I could not serve as permanent chair, and asked for volunteers who could be chair. At the next meeting, Vic Hayes (NCR>AT&T>Agere>Proxim) volunteered and was elected the new chair of 802.4L.

The 802.4L committee decided that 802 MAC was not a good radio MAC. Therefore the radio had to have its own project, MAC and PHY. This started the effort to prepare the PAR (project authorization request) for the new project. The PAR was approved in 1992 as P802.11.

THE P802.11 STANDARD

Flushed with the satisfaction of an approved project, a number of individuals who really wanted a good solution started out defining the problem to be solved (1992). Contributions covered propagation and system concepts. The PHY was first of all to be FCC compliant in the license-exempt 2.4 GHz band with a required means of energy spreading. The strong differences of opinion between frequency hop and direct sequence advocates were immediately apparent.

There were eight proposals for the MAC (medium access control) at the start of the down selection. Four of these (including mine and IBM) were soon eliminated. A group coalesced including NCR, TI, Symbol Technologies and others, which in common believed in CSMA then called LBT (listen-before-talk). They decided to call it DFW (though they had a meeting at Dallas-Fort Worth airport that was not what the initials stood for). IBM had a good, carefully crafted proposal that was eliminated early because they had no constituency. The DFW MAC was chosen as the starting point for the standard.

The MAC that I proposed [5] was based on central management of the use of channels with an access-point for each coverage. The MAC was capable of approaching 100% use of channel time in the isolated system mode. My plan also included coordinated multiple access-points for area coverage and a provision for overlapping coverage. This was probably where the term "ACCESS-POINT" came into 802.11. At the time of presentation, an access-point was considered inconsistent with a peer-to-peer network.

The model for which the MAC was designed was primarily a spontaneous, autonomous, ad-hoc, peer-to-peer group exchanging files and messages with each other. Internet access was little considered. Pressed the advocates said that any user could have a separate link to the internet through which all others in the LAN could have access. In a pure peer-to-peer network, any one station could provide a server function. There was no consideration of bottle-necks in traffic flow that can occur in this configuration.

This constituency was committed to the need for every station to hear all others, to having receivers on all the time, to support broadcast messages, and to using listen-before-talk access management. This seemed normal to this constituency, because it was largely individuals who had worked with and used 802.3 LAN. They could see no difficulty with a radio system that worked similarly. These decisions supported station operation independent of any central control.

The committee makeup started to change as those with different preferences dropped out. The standard document now had to be written. There were plenty of matters not covered in the DFWMAC[6] document, which had to be defined in the draft standard. When approved, this document would become 802.11 without an appended distinguishing letter.

Channels and channel hopping

The **frequency hopping** (FH) concept enable continued use of narrowband modulation, and it spreads the average energy over N times as much frequency space (this concept will reappear when WPAN is discussed) where N is the number of channels available for frequency hopping.

The adherents of frequency hopping believed that the cost is lower because no new technology is needed for design, and that interference susceptibility is avoided from foreign narrow band signals except for 1/Nth of the time. They are silent on the channel time used for acquisition after each hop, and the search time to become adapted to one of several hopping plans that may be in use. Also, synthesizers require some time to respond.

The concept of **direct sequence** (DS) is that the data is encoded by especially chosen symbols of N bits length, and it spreads the average energy over N times as much frequency space but with a noise bandwidth consistent with the information actually transported.

The chosen symbol for DS was an 11-bit Barker character. With 11 Mcps (mega-chips/sec) BPSK, a throughput of 1 Mbps was available, and this was longest reach modulation. Using a second 11 Mbps channel in phase quadrature, the throughput was 2 Mbps. ***This DS PHY is still the longest reach PHY within the 802 wireless standards.***

There are many other considerations than those touched upon. ***The proponents argued to a standoff that was resolved when 802.11 put both FH and DS in the standard.*** There is also channelization for the purpose of separating more than one user group in a common area or other user groups in contiguous areas. This consideration was addressed by providing three radio frequency channels in the DS system without a coordination plan.

The FH system has a number of hopping patterns that would reduce interference between groups to a low probability. It is not possible to make an efficient system this way, because the regulatory rules forbid the level of coordination necessary.

Multiple coverage's

There was no organized plan under early 802.11 for coordinating multiple coverage's as might be used in an office building or factory. Such systems do work provided that the traffic load is light and the repeat-send function in the upper layer protocols is not overloaded. Walls can improve separation of radio systems in adjacent rooms some of the time. In a building with acoustic (suspended) ceiling, isolation from walls is not predictable because of the signal paths through the over-ceiling plenum.

At the 802.11 meeting in Leiden, the Netherlands, I presented a paper addressing the number of radio channels necessary for continuous coverage of a large area. The model assumed overlapping circular coverage patterns arranged on a ***square grid****. The maximum range points for each coverage were at the four places where four coverage circles intersected. The data for signal-interference ratios were taken from NCR simulation and testing. It was found that 25 separate channel frequencies on a 5 x 5 grid were needed so that each coverage was sufficiently free of interference from the nearest places where that frequency was reused. This was uncomfortable for the DSSS advocates who had provided this data. At a subsequent meeting, transmitter power control was offered to moderate this problem, but it was never added to the standard.*

The problem continues to exist and is even worse for the more complex modulations with lower interference resistance. It is a statistical problem where the stations far from each other are most affected. This is statistically a minor fraction of transmissions unless the system is dependent on all stations hearing all other station.

Strong points

The strong point of this Standard is its solid compatibility with normal computer protocols at transport and network layers above the LAN. There are a number of special problems created by radio-linked stations. They could only be solved by cooperation between the specialists in all of the involved protocol layers. It has been much easier for subsequent MAC-PHY standards to do this again because of this example.

There are some radio specific status facts and controls which need to be passed up and down the protocol stacks. This type of transfer can only be crafted by experts in the existing communication protocol stacks. My preference would be to make knowledge of the radio system unnecessary for users.

Nonetheless, there are limitations in application and efficiency which deserve better solutions than 802.11 has provided.

CREATION OF ADDITIONAL LICENSE-EXEMPT BANDS

Starting primarily with effort of Apple, AT&T, Nortel and Motorola, an open industry committee, "WINForum," was formed to secure for industry further license-exempt frequency allocations for short reach radio systems (1994-99). The first effort of this committee resulted in the 1910-1930 MHz (FCC R&R Part 15.3) regulatory provision. This allocation provides 10 MHz for channelized narrow band services such as wireless PBX and 10 MHz for wideband data.

WINForum participated in a following effort to create the new 5.150-5.350 GHz band and a second set of rules for the 5.700-5.825 GHz band for a National Information Infrastructure NII) band. The NII rules are differentiated from existing rules in dropping the requirement for spreading and replace by a requirement to use digital data rates above 8 Mbps. These additional Rules for the NII band are in FCC R&R Part 15.4.

Much of this frequency space is a second use of bands primarily used for communication satellites. Global Star made every possible effort to prevent the allocation of the 5.15-5.35 band because it is also used for satellite up-links. This is the reason for the lower power limits in the 5.15-5.25 GHz band. There was much political courage shown by the Engineering Bureau of the FCC and the Bureau Chief to bring this allocation into the Rules. WINForum provided much of the technical information and political support to achieve this result.

IEEE P802.11 ADDS PHY LAYERS FOR HIGHER SPEEDS

802.11 started two new projects:

P802.11a Higher speed PHYsical layer in the 5 GHz NII band.

P802.11b Higher speed PHYsical layer at 2.4 GHz ISM band

The main requirement was that the new PHY layers must use the existing 802.11 MAC. Many of us saw the new projects as an opportunity to expand some of the protocol possibilities, but this was not to be. ***The majority of the committee's supporting companies were invested in that MAC and would not allow a competing MAC to appear. This was to be the continuing 802.11 position.***

There were separate subcommittees that met at the same time for the two projects. Whatever won more than 50% of the subcommittee would be brought up to the full 802.11 committee where a 75% vote is required. The voter predisposition in the full committee was more strongly associated with CSMA than in the 5 GHz subcommittee. ***This was a vote in which the outcome was much influenced by the voting of individuals normally participating in other groups***

voting in another when the circumstances needed them to defend the MAC and later other PHY layuers.

Using the NII band

After listening to many proposals, the 802.11A committee narrowed down to two each supported by several companies:

> OFDM—(orthogonal frequency division multiplex) parallel transmission on 48 0f 53 data-bearing carrier frequencies
>
> Single carrier multi-amplitude QPSK with FEC

The OFDM provided a guard band and 4 indoor only channels for the 5.15—5.25 GHz band. Various signaling rates for at 11, 22 and up to 55 Mbps were available within a 20 MHz channel.

The single carrier advocate group had a similar selection of rates from increasing levels of amplitude coding. Trellis demodulation and a strong FEC were used.

There was no great difference in the end result for the two modulations, but there was a completely different approach to multipath propagation mitigation.

OFDM: By making the symbol length long compared with the average time dispersion, no equalization is necessary, however Rayleigh (narrow band) fading occurs. This type of fading is susceptible to cancellation fades which often result in rf phase reversals between one side of the fade and the other viewed in either time or frequency.

Single carrier: The bit rate is sufficiently high to resolve much of the time dispersion. Delayed paths appear as inter-symbol interference which in turn appears like noise attached to the signal. If this noise makes occasional errors, forward error correction provides advantage.

The adherents of direct sequence spreading, using a single carrier, value the flexibility of choice in the coding, the possibility of using more than one code to increase the bits/Hz as a tradeoff against interference resistance, and the simplification of a single frequency LO without frequency changes in the time domain of fractions of a second.

OFDM was chosen by one vote in the PHY committee. It was later confirmed by an over 75% vote in the full committee.

> *The OFDM advocates had only one technical design to promote that had been first created mainly by a Bell Labs group at Middletown NJ. The early adopters had a stable definition to work with. The choice was largely due to better organization and assembly of constituency than to the technical points involved.* ***The single carrier advocates were late in arriving at a collective position. These were unrelated companies several of which had their own proposal, and who very quickly had to become allies. This proved to be a decisive handicap in the down selection.***

Using the 2.4 GHz ISM band

OFDM was not a candidate for this PHY because it was though to be non-compliant with the FCC spreading rules for the ISM band, and it hadn't yet been adopted by an 802 standard.

Operating principle: Many 11-bit symbols on the I phase and many 11-bit symbols on the Q phase produce the same level of interference as with just the 11-bit Barker, and therefore comply with the requirements of the regulation. With additional allowed symbols and combinations (MBOK), sufficient bits per symbol could be derived to enable 11 Mbps throughput.

While the signal-noise requirement of this technology is much higher than for only Barker symbols, it does get more throughput at shorter distances without changing the rules. This was "good enough" to advertise, and it was the committee choice for 802.11b.

A few years later this standard was superseded by a version of OFDM rearranged for the 2.4 GHz ISM band.**—IEEE P802.11g**.

GENERAL CONCLUSIONS

There is much need for a variety of means for providing data network connectivity. There are many precedents and prejudices from 10-20 years ago are which are so embedded in current structures, that it will be difficult to attain serious system reliability under 802 rules and constituency.

A good system for efficient use of many coordinated access points cannot be accomplished without going past the level-2 barrier. Some people figure out ways to do higher level functions without making it apparent. I doubt that good large scale radio systems can be done within the scope of 802. The problem goes back to the choice and emphasis on peer-to-peer systems and CSMA access control in the first LANs.

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