MEMORANDUM **APRIL 26, 1986**

TO: D. Greenstein, Chairman, Subcommittee 802.4L
FROM: C. A. Rypinski
RE: **Radio Medium Token Bus** - First Effort on System Design

PURPOSE AND GENERAL CONSIDERATIONS

It has been proposed that the 802.4 TOKEN BUS protocol could be used on a radio system, and that the wireless service would be useful. It is immediately recognized that a radio system is inherently identical in the broadcast characteristic to the cable medium. The head-end on the broadband cable is equivalent to the mountain-top repeater in land mobile radio. The value of bandwidth and the degradation from multipath propagation are quite different. To better illustrate the considerations involved, a (duplex, then simplex) sample system design is described.

The use of TOKEN BUS protocol means that the system can be either simplex (fixed transmitters collectively, and one mobile transmitter use the frequency space alternately) or duplex (as is required for undelayed mobile-to-mobile messages). A choice must be made in which there will be significant economy if the traffic is assumed to be predominantly between fixed and mobile points with retransmission of mobile-mobile traffic.

TABLE I - PREMISES

Data Rate:	1 Mbs
Operating Frequency:	Above 900 MHz
Path length:	3 to 2000 mtr
Data Signaling Protocol:	Token Bus

There are a number of relevant facts (which are familiar to radio system designers, but which may not be obvious to those in other fields), which are recited for reference. Other premises are shown below, that are the result of experience and familiarity on the cost and limits of power output, antenna directivity, binary spectral density, information bandwidth to operating frequency ratio, and the accuracy of fundamental oscillators.

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TABLE II - FACTS AND SUBJECTIVE PREMISES

Velocity of propagation-free space:	300 meters/microsecond
Attenuation-free space:	6 dB/octave, 20 dB/decade
Information/Power Ratio:	3 dB/octave of data rate
Maximum feasible tranmitter power:	1.7 watts at 900 MHz
	.25 watt at 2.5 GHz
Economic spectral density:	1.2 bits/Hz
Practical information bandwidth:	.05 to 2 Mhz/GHz
Non-crystal oscillator accuracy:	.05% or .5 Mhz/GHz

Estimate of Transmitter Power Required

Shown below in Table III, is an estimate of the transmitter power that might be required. It uses parameters that are later chosen for the example system design. The maximum distance corresponds to a mobile at the center of a square cell 2 km on each side.

TABLE III - CALCULATION OF REQUIRED TRANSMITTER POWER

Noise power in 1.2 MHz bandwidth:		-113 dBm
Margin allowed for 10E-8 BER:	17 dB	- 96
Receiver Noise Figure:	8	- 88
Receive antenna gain 9 V, 4 H:	13	-101
Free space path loss for 1.5 km, 900 MHz:	97	- 4
Contingency for obstacle loss:	36	+ 32
Transmit antenna gain after cable loss:	6	+ 26
Required transmitter power output:	0.4 watts	

The required transmitter power is 9 dB greater at 2500 MHz if the antenna dimensions are constant in wavelength. The option of increasing the gain of receiving antennas holding physical dimensions constant is not really available because of limitations in the accuracy of pointing on mobiles.

Propagation Considerations

Any plan for the use of radio at high digital rates is formed after considering multipath propagation and uncertainty of signal level. A large part of the variation in level is caused by complex addition of many signals arriving via different path lengths and with random relative rf phase. The free space attenuation is a weak factor in determining signal level—the most important is the nature and density of obstacles.

A plan that assumes an unimpeded air path is quite different from one that will tolerate a number of interposed metallic monuments. High data rates require higher frequencies, but penetration and the cost of power favor lower frequencies.

Multipath is best understood by assuming a very short (100 nsec) transmitted pulse. The received signal can be displayed on a time base triggered by the first pulse to arrive. The display, for a cluttered urban path, will show hundreds of replicas of the transmitted pulse scattered for many microseconds after the intial signal. The same may be expected over a factory floor occupied by many large metal machines, though with a different scale factor. For short transmitted pulses, the received signal may be described as follows:

TABLE IV - PROPAGATION ASSUMPTIONS

1. The first pulse to arrive is the highest amplitude, usually, but not always.
2. The average amplitude of the delayed pulses will decrease in proportion to the excess distance/time traveled, but exceptional high amplitude pulses can be received from large reflectors.
3. The excess loss for an impaired path with obstacles should be assumed to be 30 to 40 dB relative to the free space loss.
4. The default assumption is that a pulse which has traveled more than 10 times the distance of the main pulse has an amplitude at least 20 dB down and can be assumed non-interfering.

The interference from delayed replicas of the desired signal can be greatly reduced by directive antennas and multiple antenna diversity reception.

PARAMETER SELECTION WITHIN THE ASSUMPTIONS

If a 10 Mbs data rate were absolutely necessary, the system would have to be designed to work above 6 GHz with only optically clear paths. At the higher microwave frequencies, it would be impossible to work unless horizontally directive antennas were used in the mobile equipment. Vertically directive antennas are probably required with any type of system.

The direction of this plan is toward a system at lower frequencies with modest capabilities to penetrate an intermittently obstructed path by secondary reflections, but a data rate of 1 Mbs is about as high as is thinkable. Even then, use of diversity and antenna directivity appears imperative.

Using these multipath propagation premises, a channel used to transmit one bit (or data symbol) may not be reused except after a time interval = 10 x max range = 10 km = 33.3 microseconds. A single frequency channel is limited to 30 kbs give or take an octave.

For a first pass simple system at 1 Mbs, 33 parallel or sequential bandwidths are required. If 1.2 MHz are required for this bit rate, the occupied spectrum will be about 40 MHz. This spectrum requirement is unthinkable below 900 MHz, and it would be barely thinkable if it were about 10 or 15 MHz. The inducement for using methods which reduce the allowance for multipath is very large. It is also possible to get a large gain from assuming a smaller maximum path length.

OPERATING FREQUENCIES

There are two radio frequency bands where unlicensed operation is permitted at 915 and 2550 MHz approximately. Even though these frequencies might not be used, the assumption would show the use of two major types of equipment and components.

DIVERSITY SYSTEMS

It is assumed that the mobile is a single transmitter, but that there are 4 fixed receivers at the corners of a square pointed inwardly. It would require elaborate art to combine these 4 signals bit by bit, but it would be possible to accept the packet if any of the receivers got an error free copy. The chances of successful reception over one of the 4 paths would be greater than the gain from a large increase in transmitter power with a single receiver.

The equivalent arrangement for the reverse direction is not simple, unless 4 different frequencies are used for the transmitters at the corners and 4 independent receivers at the mobile. A solution using less equipment is probably possible but requires another step in ingenuity to avoid the fourfold increase in frequency occupancy.

A possibility considered, but not chosen, would use a switching diversity system with cochannel transmitters at the 4 corners, but only one would transmit depending on a logic determination that it was the best transmitter to reach a particular mobile.

It is possible to linearly combine (power addition) the signals from two or more independent antennas at a receiver. This technique is not simple, particularly for more than two ports. A possibility considered uses two omni-directional mobile receive antennas. This was not selected because there is no discrimination against the multipath from reflectors close to the mobile.

ANTENNA DIRECTIVITY

Vertical directivity is imperative. An 8X power gain corresponds to a beam width of 22.5 (out of 180) degrees. This is a limit on how much a mobile can tilt in going up a ramp or in varying its height relative to the fixed antenna. The corresponding aperture is 8 half-wavelengths (52.5" at 900 MHz). Half this size might be workable in a mobile.

At 2500 MHz, the vertical dimension would be about 40%, but probably a different technique would be required (like stacked biconicals). At this frequency, resonant design is difficult because of critical dimensions. It is not easy at 900 MHz, but it is possible.

Horizontal directivity is very valuable, if not imperative, to reduce multipath. With a beamwidth of 90-180 degrees, the elimination of the effect reflectors which are behind the line of direction is very valuable. If the beamwidth is down to 90 degrees, a significant reduction in the maximum distance to side reflectors is gained. A width of 8 to 16" is required for this controlled directivity at 900 MHz.

These directivity preferences are almost the same (in angular dimensions) at all frequencies. It is slightly biased by assumed size limitations toward less directivity at lower frequencies. Non-directional receiving antennas capture less energy as frequency increases. The energy capture is related to aperture or physical size. This factor discourages use of extreme microwave frequencies.

"CELLULAR" TELEPHONE SYSTEM TECHNOLOGY

The use of known "cellular" radio telephone practice for this system may be considered. It is a misapplication in a broad sense because of major differences in premises, the most important being:

1. Dependence on distance attenuation of 34 dB per decade.
2. No consideration of multipath as a limit on information rate.
3. Frequency division channelization added to time division multiplexing.

Nonetheless, many different configurations for continuous radio coverage have been evaluated in this context. There is quite of bit of knowledge concerning interference limited (from cochannel operation) system layout which is reusable.

While cellular plans are based on "honeycombs" of hexagons (until they have to be fitted to existing cities), it may be better to select a cartesian plan better fitted to factories with aisles. The efficiency of frequency reuse may be lower but the fit to operating needs much better. From this theory, it is possible to relate the number of independent base frequencies required for a given signal to noise ratio depending solely on the distance attenuation factor in flat terrain.

DIGITAL MODULATION

Efficient digital modulations usually depend upon phase continuity and coherence in the input signal. For this reason many types of modulation which are successful on wirelines, satellites or point-to-point microwave will not work in a mobile environment with complex multipath. The fewer the states possible for one symbol, the more resistant the modulation to noise and interference. For these reasons, "Minimum Shift Keying" is the initial choice.

This modulation is the same in the medium as 4 Offset Quadrature Phase shift Keying (4OQPSK), and it has much history of practice and analysis. The modulation is essentially frequency shift keying with the difference in frequencies reduced to where there is only 90 degrees phase difference (average) between the two possible frequencies during one bit interval—hence the term minimimum.

SYSTEM PHYSICAL LAYOUT

The geometry chosen for this first cut model assumes uses switch selection of 1-of-4 directional receiving antenna. The cell is square (or rectangular) with omni-directional transmitting and sectoral receiving at each corners of the square. The transmitters at each point operate on different frequencies (at any given instant), but each transmitter serves 4 squares in the contiguous cells. The length of one side of each square might be up to 2 km.

A most painful shortcoming of this plan is that each fixed transmitter will generate multipath from reflectors behind the line of direction to a mobile. A first try at avoidance of this problem would quadruple the number of transmitters, transmitting antennas and frequencies used. Another way of looking at the same problem is to accept the generation of the multipath, and then to use other measures to increase the discrimination as required. This is the choice made.

It is necessary for the mobile to observe fixed transmitter frequencies and directions to determine the parameters to obtain the strongest signal. One measurement will take at least one bit interval of time with the receiver operating frequency stationary waiting for fixed transmitters to scan past. For tests on 4 antennas, 4 bits is the minimum (and 8 more likely) interval to setup the diversity and selection functions.

MODULATION AND FREQUENCY UTILIZATION

At a data rate of 1 Mbs, it is assumed that MSK modulation with a bandwidth of 1.2 MHz is used. As an arbitrary temporary assumption, each bandwidth is reused once every 24 microseconds; and during this interval, 24 bits are transmitted. At any time and on one directional antenna, the mobile may be receiving 4 different fixed transmitters and may need additional time for discrimination.

Rather than use a transmitter that steps 1.2 MHz between bits, it is assumed that a linear frequency modulation can be applied at a rate of 1.2 MHz per microsecond resulting in a scan of 28.8 MHz. To avoid the problem of instant change at the end of a scan, two oscillators may be used alternately.

The occupied spectrum is 24 times that required by the information, however it is intended to obtain the separation of cochannel base stations by using this time interval for discrimination between base stations which all occupy the same frequency space All base stations will transmit on all frequencies, but only 1/24th of the time in one bandwidth. A mobile receiver monitoring a fixed frequency will be scanned by the fixed transmitters; and it will hear the 4 to 9 nearest transmitters at intervals depending upon relative distance. The probability of hearing two different transmitters at the same time and at the highest level is very small because of the switch selected directional receiving antennas at the mobile. This property could be strengthened by using a large number of receiving antennas.

DUPLEX-SIMPLEX CONSIDERATIONS

This description has implied independent inward and outward frequency bands for the mobile. This is not required unless the fixed equipment is defined as a multi-port, one channel repeater. This definition is necessary if all mobiles are to hear the transmission of any one mobile. If it is accpepted that all traffic received from mobiles is analyzed in a fixed Server equipment and retransmitted if and only if it is addressed to another mobile; then a single frequency band will be sufficient for alternate fixed and mobile use.

A further consideration is the time required for token passing. One pass will require two message durations and two propagation times, at least, in a simplex system. In the duplex system, the mobile receiving the token would hear the pass message almost as transmitted, but probably delayed by propagation time to and from a central logic.

TRANSMITTER SELECTION BY TIME DISCRIMINATION

If all transmitters use the same relative timing, a mobile, which is 1400 meters from a desired transmitter, could hear another transmitter in the same time slot from a distance of 8500-8700 meters, but not from intermediate distances.

The intent of the plan is to discriminate against signals from unwanted but received stations using both amplitude and time. **The art of this proposal is that the same frequency dispersal is used for avoiding interference from: a) multipath and from b) cochannel operation of many transmitters.**

SUMMARY SYSTEM DESCRIPTION

On the average, there is somewhat more than one fixed transmitter per square cell. Transmitting antennas, fixed and mobile, are omni-directional; and receiving antennas are quadrant beam width. The entire system uses 24 times the frequency space of one cell with a single frequency; and for contrast, a typical cellular system uses 21 times. If the information rate is changed by an octave up or down, this ratio does not change; but a number of system paramters would have to be changed so that no frequency was reused more often than once every 24 microseconds regardless of the data rate.

TABLE V - SYSTEM PARAMETERS

Data rate:	1 Mbs
Operating frequency band center frequency:	900-1200 MHz
Information bandwidth:	1.2 Mhz
System allocation bandwidth (simplex/duplex):	30/60 Mhz
Type of frequency:	linear, saw-tooth
Period of frequency sweep:	24 microsec
End point separation of sweep frequency:	28.8 Mhz
Digital modulation:	MSK - .5 Mhz pk-pk
Design maximum range mobile-fixed, fixed-mobile:	1.5 km
Antenna pattern shape - inward/outward equal:	omni xmt, quadrant rcv
Cell description:	square, 2 km/side
Design margin for path obstruction:	36 dB

GATEWAY VS. REPEATER CONNECTION TO BACKBONE

While a gateway interconnect may be indicated because of rate differences, it is imperative to limit the traffic on the radio system to that involving only radio-linked stations. It would be prohibitively costly to provide the capacity to carry all traffic on the radio system regardless of its relevance.

THE ONE CELL SYSTEM FOR ONE BUILDING

A single open building might be considered as one cell illuminated from each of the four corners. A quadrant coverage directional antenna could be used with each of the fixed transmitters avoiding the multipath from reflectors around and behind the fixed sight. A building one mile on each side could be covered this way. If the dimensions are smaller, the system would be exposed to far less multipath degradation.

The four site illumination is very important. Few locations will be blocked on all sides from visibility to one of the fixed sites. Indirect paths become more certain, the larger the number of possibilities from which a selection can be made.

The 4 dB increase in transmitting power from the fixed antennas could be spent as a corresponding decrease in the vertical directivity and size of the mobile antennas which might then be 13" high.

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