NCR Systems Engineering B.V.

SUBMISSION TO IEEE 802.4L

THROUGH-the-air Token Bus Physical Layer

COMMUNICATIONS OVER AN INDOOR RADIO CHANNEL

BRUCE TUCH **November 1988**

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WIRELESS LAN
COMMUNICATIONS OVER AN INDOOR RADIO CHANNEL

1. CONCLUSIONS

The following paper submitted to IEEE 802.4L supports the following conclusions:

1.) In our operating environment (maximum vehicle speeds of 20 mi/hr), the channel can support 1Mbps operation using Quaternary Differential Phase Detection techniques.

2.) Since the minimum fading duration is relatively long, 1.7 ms, compared to the symbol time, 1.25 µs, the Channels performance is Quasi-Static. In this report the performance is characterized by "Outage Probability", P_o. P_o is the probability that the BER of the communication link does not satisfy a set threshold. In our calculations this threshold is 1×10^{-4} (which corresponds to the wanted 10^{-8} error rate after FEC).

3.) An Output Power level of 100mW (20dBm) has been used for coverage area calculations with 915MHz as the Carrier Frequency.

4.) A coverage area, limited by man-made and Thermal Noise, in a Rayleigh Fading Channel with a Log-Normally Distributed mean, has been determined for four different environments. The parameter used to determine the coverage area is average and maximum Outage Probability, P_{oav} and P_{omax} respectively. The P_{oav} is the Outage when averaged over a circle of diameter x when any two terminals are placed randomly within this area.
P_{omax} is the Outage with two terminals at edges of this coverage area.

LOCATION	IEEE desired $P_{oav} = 10^{-5}$ x (meters)	P_{omax}	Proposed $P_{omax} = .05$ x	P_{oav}
Supermarket 10dB/Octave, σ=3.7dB)	135	$4. \times 10^{-4}$	210	$1. \times 10^{-3}$
Department Store Without Walls (10dB/Octave, σ=4dB)	120	$6. \times 10^{-4}$	190	1.5×10^{-3}
Office (11.7dB/Octave, σ=2.2dB)	85	7.5×10^{-4}	120	7.7×10^{-4}
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5.) A Direct Sequence "Spread Spectrum" Modulation Technique has been used which satisfies current FCC part 15.126 rules.
6.) These calculations and measurements (of our prototype) have been done with only one transmit/receiver pair. To increase the Coverage Area a fixed array of antenna's, coupled to a head-end can be implemented. It is noted that **this is not mandatory** if the wanted coverage area is small enough. (Running a system without a head-end gives the advantage of only one frequency for TX and RX).

7.) Technical Note:

- The reference BER of the radio channel used in system calculations is 10^{-4} which with FEC Coding is improved to the 10^{-8} 802.4 level. The wanted Outage Probability is achieved with the help of two antennas (selection diversity) and Multipath (two resolvable paths) diversity.

B. Coverage Area is assumed circular with random placement of terminals.

C. A BCH (31,21) FEC code has been assumed in the calculations.

2. ROBUST MODULATION METHOD IN SLOW RAYLEIGH FADING CHANNEL

This report deals with the communication between two terminals in a "Hostile Indoor Radio Wave Channel". It is assumed that further expansion of the coverage area will be done by an array of antenna's connected to a head-end, if needed. Also adjacent channel suppression, from other LAN's will be accomplished by using other frequency bands within the FCC rules and regulations of part 15.

2.1 THE TIME VARYING CHANNEL AND DIFFERENTIAL MODULATION

An important parameter in the LAN Protocol is the needed preamble length. This must be as short as possible for efficient communications. Within our radio channel the following conclusions can immediately be drawn:

1. A coherent form of demodulation, which requires an oscillator reference is not optimal in our situation.

a. Phase acquisition, which requires averaging over many bit times, would need large preamble lengths compared to non- coherent techniques.

b. Path Diversity, which is inherent in the Spread- Spectrum Modulation [see section 3] can not use a locked phase reference.

From the above it seems reasonable to give attention to the most optimal form of non-coherent modulation technique. Differential Phase Shift Keying is a modulation form which does not require a phase reference. It also has the advantage of being spectrally efficient, something which is quite important when our spectral resources are limited by the regulatory agencies. In the next section it is shown that DPSK modulation is robust in our channel environment.

2.2 DPSK AND DOPPLER SHIFT

DPSK is a form of modulation which compares the phase between two symbol intervals. It is the change of phase that is gives the information. For example in Quaternary Differential Phase Modulation (QDPSK) 4 phase states are possible, 0^o, $+-90^o$ and 180^o, giving 2 information bits per symbol. For this modulation technique to work the channel must be "time invariant" between two symbols otherwise phase errors will occur.

2.2.1 FADE DURATION

Time variance of the channel is determined by motion of objects within the environment. The maximum Vehicle Speed in which we have to work with is 20 mi/hr. The question that must be answered: Can we consider the channel "time invariant" within two symbol periods? The answer is yes, as is now shown.

Motion of the antenna, or an object in which the signal scatters, will cause a Doppler Frequency Shift defined as:

$$fm = (v/\lambda) \qquad [1]$$

In our system:

$v = 20\text{mi/hr} = 32.2\text{km/hr} = 8.9 \text{ m/s}$
$\lambda = 12\text{cm}$ (2.5GHz band)

Substitution into [1] gives:

$$fm = 75 \text{ Hz} \qquad [2]$$

A useful parameter is the so called "Coherence Time" defined as

$$tc = 1/fm \qquad [3]$$

This gives the time in which the channel properties change significantly. What this time physically means is that the apparent motion (of antenna or reflection source) moves one wavelength in distance. It is known [ref.1a] that the channel Fading Characteristics with antennas spaced less than $(1/4)\lambda$ have a high correlation (greater than .5). Therefore assuming (1/8) tc as the time in which the channel does not change, a "Quasi-static time invariant channel can be assumed if the observation time is less than:

$$t_{observation} = (1/8)\ tc = (1/8)\ fm = 1.7 \text{ ms}$$

It is interesting to compare this time with the time between symbols, in which we assume a time invariant channel. We want a 1.6 Mbps Data Rate (which will be brought down to the 1 Mbps after FEC). Using a DQPSK scheme a symbol rate of 800 kBaud is then used giving a symbol time of ts = 1.25 µs. As can be seen the tobservation is more than 1300 times greater than the symbol time! This suggest quite strongly that the channel time can be considered time invariant as far as the symbol time is concerned.

2.2.2 PHASE NOISE DUE TO DOPPLER SHIFT

The discussion of section 2.2.1 has been qualitative in nature to give a "feel" of the channel's coherence time. An analysis of the irreducible error rate (only due to Phase Noise due to motion) has been done [ref. 1b]. It is noted that this analysis assumes a "flat fading" channel, when a fade occurs the total signal energy fades. During a fade the phase change is greater as the antenna moves, which will cause "Random FM" Noise. The following should be considered as worst case since in Direct Sequence Spread-Spectrum Modulation [see section 3] the fading will not effect the total bandwidth. What is important is that the amount of Spreading is not important in terms of using DPSK techniques, since the no spreading case gives us enough margin.

r DPSK the BER of such a channel can be estimated by:

$$P = (1/2)\ (\pi f m T)^2 \qquad [4]$$

Where:

P is the BER caused by Phase Noise due to Doppler Shift (From a large number of Scatters).

fm is the Doppler Shift.

T is the Symbol Period .

Substitution of the system parameters into equation [4] gives:

$$P = 4 \times 10^{-8}$$

Since our Performance Goal is a 10^{-4} BER (Before FEC) it can be seen that Differential Phase Shift Keying is a robust modulation technique with respect to Vehicle Motion.

3. DIRECT SEQUENCE SPREAD SPECTRUM

Now that we know what our Base-Band Modulation Technique will be of the Differential Phase Class[1], the next step is to determine how to satisfy the FCC part 15 Rule of Spread Spectrum. It has been decided to conform with the present FCC regulations concerning the Spreading methods. Therefore Frequency Hopping is not seen as a viable option due to the fact that the maximum modulation bandwidth is 25kHz. (Using DQPSK with a 800 kBaud symbol rate and Nyqusit Filtering gives a minimum bandwidth of 800 kHz). Therefore a Direct Sequence (Pseudonoise) Spread Spectrum Modulation System is proposed. In Figure 1. a schematic representation of Direct Sequence Spread Spectrum is shown (DSSS). In DSSS the transmitted bandwidth is greater than the information bandwidth, the ratio between transmit and information bandwidth is called the Processing Gain (PG). In the receiver the wanted signal is recovered by correlation techniques. While for Military Use Spread-Spectrum gives one an Anti-Jamming advantage, this is only significant for large Processing Gains. In our case Direct Sequence Spread Spectrum gives the following advantages:

1. Conformance with FCC Part 15. Rules. (This is probably coupled to the fact that the Power Density (Watts/Hz) is lower when the signal is spread using the same total transmit power).

2. Inherent "Path Diversity" due to the greater resolution of the system. (Using our channel and system parameters two resolvable paths are expected)

3. Less sensitive to filter aberrations (non-linear phase) and therefore cost effective filtering is possible.

4. Robust in a Multipath (ECHO) environment.

It should be noted that the main reason we are using Spread- Spectrum is due to the FCC requirements. The other advantages could be obtained with other Spectral Efficient techniques (NO SPREADING) but would not satisfy part 15 Rules.

In Figure 2. a block diagram implementing DSSS is shown for clarity. The Pseudorandom Code used for Spreading produces so called "chips" which multiply the data stream. It can be seen that the transmitted waveform has higher frequency content, since the resolution is now on the order of one chip time. Note that the Processing Gain in this system is simply the number of chips contained in one data "symbol" period. Correlation is simply multiplication of the incoming data stream with the same Pseudorandom code. In this implementation it is noted that accurate timing is needed between the receivers internal code generator and the received waveform. For low Processing Gains, which is our case, a matched filter implementation, in which this timing is no longer needed, can be implemented. (Our first prototype uses a Surface Acoustic Wave, SAW, Matched Filter).

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1 The exact modulation waveshaping is not defined in this report. It is assumed a spectally efficient, non-linear processing tolerant system with low side-band regeneration after filtering, will be implemented. (Examples are the constant envelope structures such as QOPSK, MSK and SFSK).

3.1 THE PROCESSING GAIN SIZE

We are Spreading the Spectrum mainly to satisfy FCC regulations. It is proposed to use the minimum amount of Spreading consistent with the FCC requirements. This will give us more Spectral Efficiency opening up more channels for other collocated LAN systems (There is also a cost factor, as matched filter price is related to Processing Gain). It seems the FCC will allow a minimum **Processing Gain of 10X**. Further contact with the FCC must be made to set this number. (Our prototype has a PG of 31X using a minimum sequence code for spreading).

.2 PATH DIVERSITY

One of our advantages in using Spread Spectrum is the inherent resolution of the system. If an ECHO is produced which is greater than a chip time, it can be resolved by our receiver and used. Post Detection Integration [ref. 2] is assumed in the implementation of the power combining of the echo paths. Following the approximations of Kavehrad [ref. 3], a Path Diversity of 2 can be expected for our system. Together with two antennas this gives us a total of M=4 level Diversity!

SYSTEM PERFORMANCE

The question now arises, using Spread-Spectrum with a QDPSK modulation form, how is the performance in our indoor channel? First the channel parameters must be determined.

4.1 THE CHANNEL

The Indoor Radio Channel complicated by the following factors:

1. High Attenuation Levels due to obstructions. (Mean values, hence Fading is averaged out)

2. Scattering of the wave causing Multipath (Echos) and signal cancelation (Fading).

3. Time variant channel due to antenna and object motion. (As was shown in section 2.1, the channel can be considered time-invariant (quasi-static) for the time intervals of interest).

4.1.1 THE AVERAGE ATTENUATION (LARGE SCALE)

To characterize the indoor attenuation a statistical approach is taken. The attenuation distribution is log-normally distributed whose mean is a function of distance [ref. 1c, 4, 5]. The mean (dB) is expressed as:

$$m \propto 10\mathrm{Log}(Z^n) \qquad [5]$$

Where:

m is the mean attenuation (dB)
n is the attenuation exponent (n=2 for free space)
Z is the distance between the transmitter and receiver.

Therefore given n and σ (The Gaussian standard Deviation in dB's) one can characterize the large-scale avera attenuation properties of the channel.
It is noted that n can vary within one area, for example "close to the antenna" (in the order to 10m) n is closer to a free space value than further away.

Our measurements show [ref. 5] that a 11dB/octave (after 10m) σ=5dB could be expected in an indoor environment.

4.1.2 THE FADING CHARACTERISTICS

Besides the average attenuation of section 4.1.1, signal cancelation can occur due to reflections. The statistical distribution of the fading level (factor below the average value) in a small-scale area can be expressed as:

$$P[Y<y] = 1 - \exp(-y) \qquad [6]$$

Where:

P[Y<y] is the cumulative distribution of the power ratio
y is the power ratio with respect to the average power.

This is the so-called Rayleigh Fading Channel since the envelope of the signal follows a Rayleigh Distribution [ref.1].
Our measurements [ref.6] within the indoor environments of interest confirm this theory.

4.1.3 MULITPATH DELAY SPREAD

An important parameter for echo characterization is the square root of the second moment of the Power Delay Profile, trms. [ref. 4]. The actual shape of the power delay function is not vital in determining performance, and Gaussian Shapes are assumed quite often in the literature. Measurements performed by NCR [ref. 6] in our indoor environments show trms values in the 30 ns range. This agrees quite well with measurements done by Saleh & Valenzuela [ref. 8] in an indoor environment (with about 115 meters largest distance dimensions). Due to our Spread Spectrum Modulation technique intersymbol interference can be neglected, assuming a trms of 30 ns and symbol rate of 800 kBaud. (Actually such a system is quite robust in terms of trms variations. Increasing trms can lead to system improvement due to the creation of more Diversity Paths!)
,ing a minimum expected Delay Spread of 100 ns [ref. 3, 8] (this is the time delay in which an Echo is significant) the number of "resolvable paths" is approximated by a discrete model used by Kavehrad [ref. 3].

$$L = \lfloor Tm/Tc \rfloor + 1 \qquad [7]$$

Where:

- $\lfloor x \rfloor$ = the largest interger less than x.
- L = the number of resolvable Paths.
- Tm = the Delay Spread of the Channel.
- Tc = the chip time.

For calculation let us assume a processing gain of 15X. With a symbol rate of 800 kBaud (1/T) and the definition of PG = T/Tc we have:

$$Tc = (1/800K)/15 = 83 \text{ ns}$$

Subsitution into [7] gives at least L = 2 resolvable paths.

2 PERFORMANCE CALCULATIONS

1.2.1 SELECTION DIVERSITY

One way that helps to overcome being in a FADE, is to switch the input to another antenna whose response is uncorrelated with the first (this can be achieved by physical separation or different polarization). In other words the antenna which has the best Signal to Noise Ratio at the Demodulator is chosen. The new cumulative distribution, see section 4.1.2, then becomes:

$$P[Y<y] = [1 - \exp(-y)]^M \qquad [7]$$

Where:

M is the Diversity Level.

4.2.2 WIRELESS PATH RELIABILITY MODEL

It is now time to calculate the performance (in terms of Outage) of our Radio Communications. The BER in which we want to meet, before error correction, is set at 10^{-4}. The instantaneous Signal to Noise Ratio needed for such performance is 14 dB [ref. 7]. The maximum amount of instantaneous signal attenuation (with respect to one meter) of 73.5 dB has been calculated, see section 5. With this and Indoor Propagation Parameters (from measurements) performance predictions are made:

Using the combined Statistics of the **Large-Scale (Log-Normal)** and **Rayleigh Distributions**, each giving their component attenuation in dB's, the following results are obtained [ref.5]:

LOCATION	IEEE desired $P_{oav} = 10^{-5}$ x (meters)	P_{omax}	Proposed $P_{omax} = .05$ x	P_{oav}
Supermarket 10dB/Octave, σ=3.7dB)	135	4. $x10^{-4}$	210	1. $x10^{-3}$
Department Store Without Walls (10dB/Octave, σ=4dB)	120	6. $x10^{-4}$	190	1.5 $x10^{-3}$
Office (11.7dB/Octave, σ=2.2dB)	85	7.5 $x10^{-4}$	120	7.7 $x10^{-4}$
Department Store With Many Divisions (23.5dB/Octave, σ=5dB)	65	4. $x10^{-3}$	78	5. $x10^{-4}$

5. RADIO PROPAGATION BUDGET

Note: Since Spread-Spectrum has no performance effect with White Gaussian Noise, it is not taken into account.

Thermal Noise No(dBm) = -174 + 10LogB (Hz) Using a 1MHz Noise BW		-114 dBm
Noise Figure (Receiver, Switch, Cable and Filter)		8 dB
Receiver Thermal Noise	(a)	-106 dBm
Man-Made Noise (18dB above Thermal Noise)	(b)	- 96 dBm
Receiver's Input Noise Level (Power Sum of (a) and (b)		- 96 dBm
Instantaneous S/N for 10^{-4} BER (No FEC) QDPSK Modulation		14 dB
Detector Margin		2 dB
Required Instantaneous Receive Level	(c)	- 80 dBm
Isotropic Antenna Path Loss . 1 meter)[2] -27.6dB + 20Log F(MHz) Using F=915MHz		- 31.6 dB
Dipole Antenna Gain[3] (RX and TX each 2dB)		+ 4.0 dB
Transmit Power		20 dBm
Power one Meter Away	(d)	- 7.6 dBm
Signal Attenuation at the Receiver's Noise Limit with respect to one meter.	A = [(d) - (c)]	73.4 dB

2 It is assumed that at one meter away the attenuation follows a free space (n=2 or 6 dB/Octave) law. This would be the case when both antenna's can "see" each other.

3 A small antenna has been assumed (low gain) due to ergonomic requirements.

6. REFERENCES

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b. Pg [233-234]
c. Pg [119-123]

[2] Introduction to Spread-Spectrum Antimultipath Techniques and Their Application to Urban Digital Radio.
George L. Turin
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John G. Proakis
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ISBN # 0-07-Y66490-0

SPREAD SPECTRUM MODULATION

THIS IS A MODULATION TECHNIQUE IN WHICH THE TRANSMITTED BANDWIDTH IS LARGER THAN THE INFORMATION BANDWIDTH.

SPREAD SPECTRUM TECHNIQUES WAS FIRST USED IN MILITARY SYSTEMS DUE TO ITS ANTI-JAM, ANTI-EAVESDROPPING PROPERTIES.

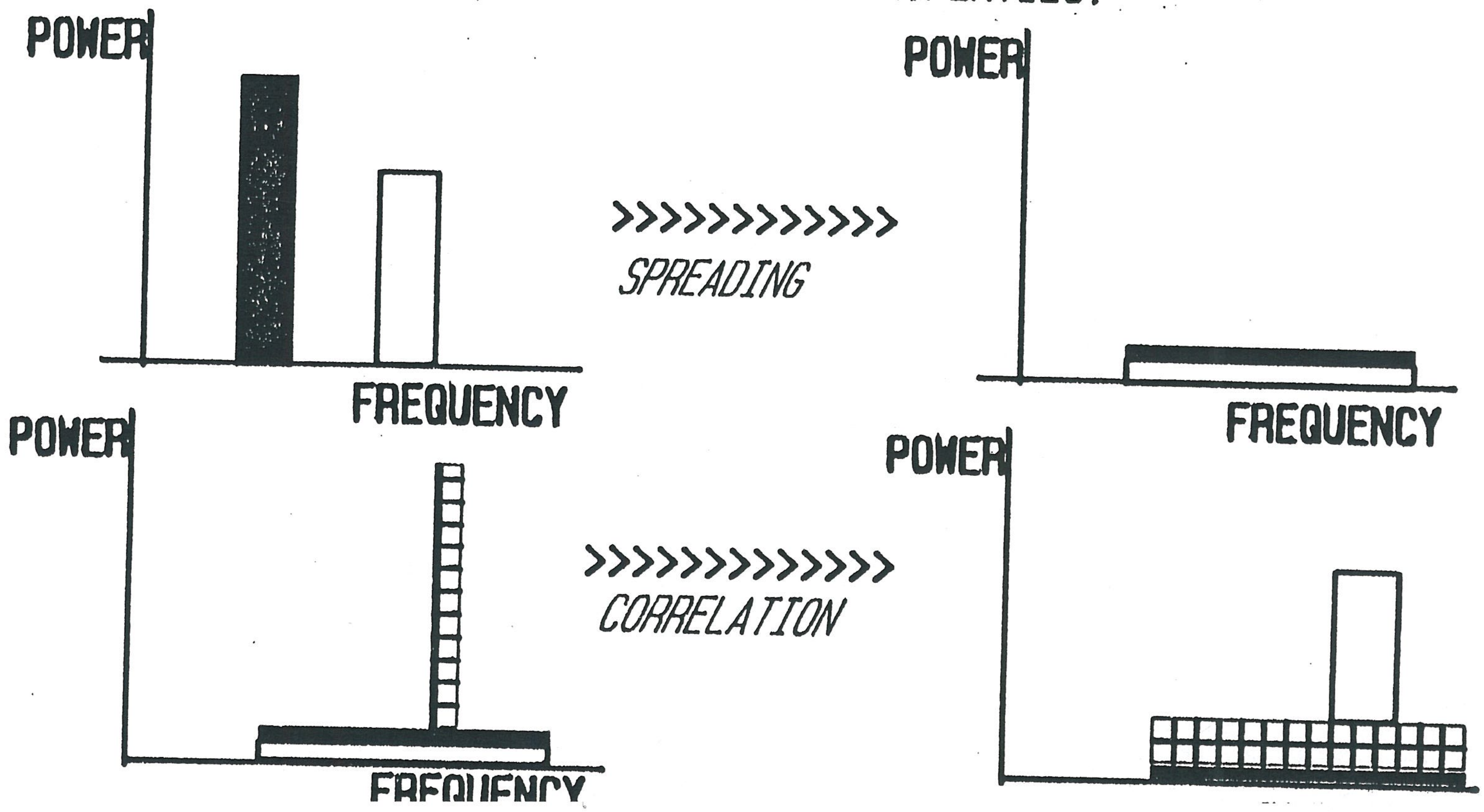
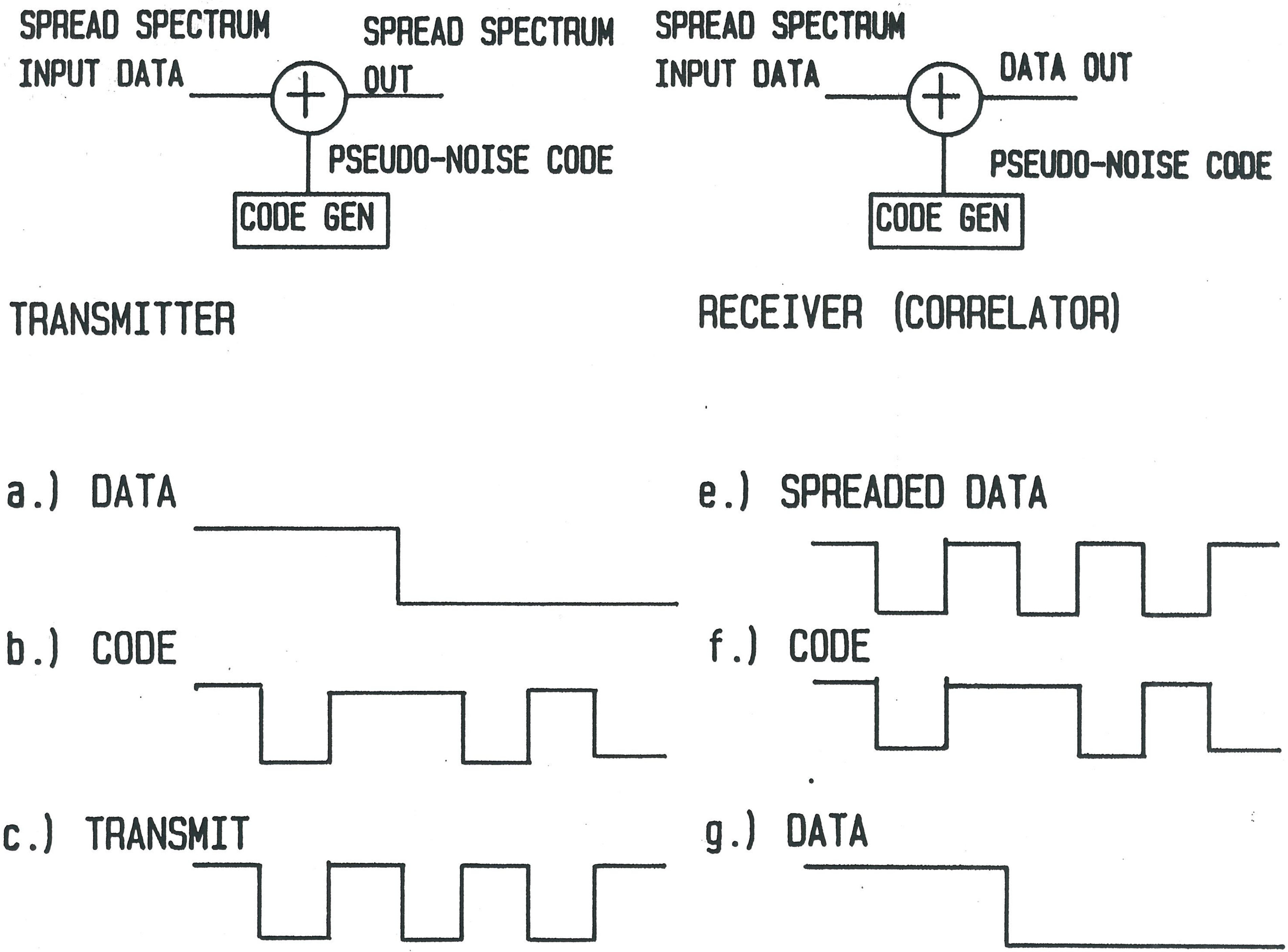
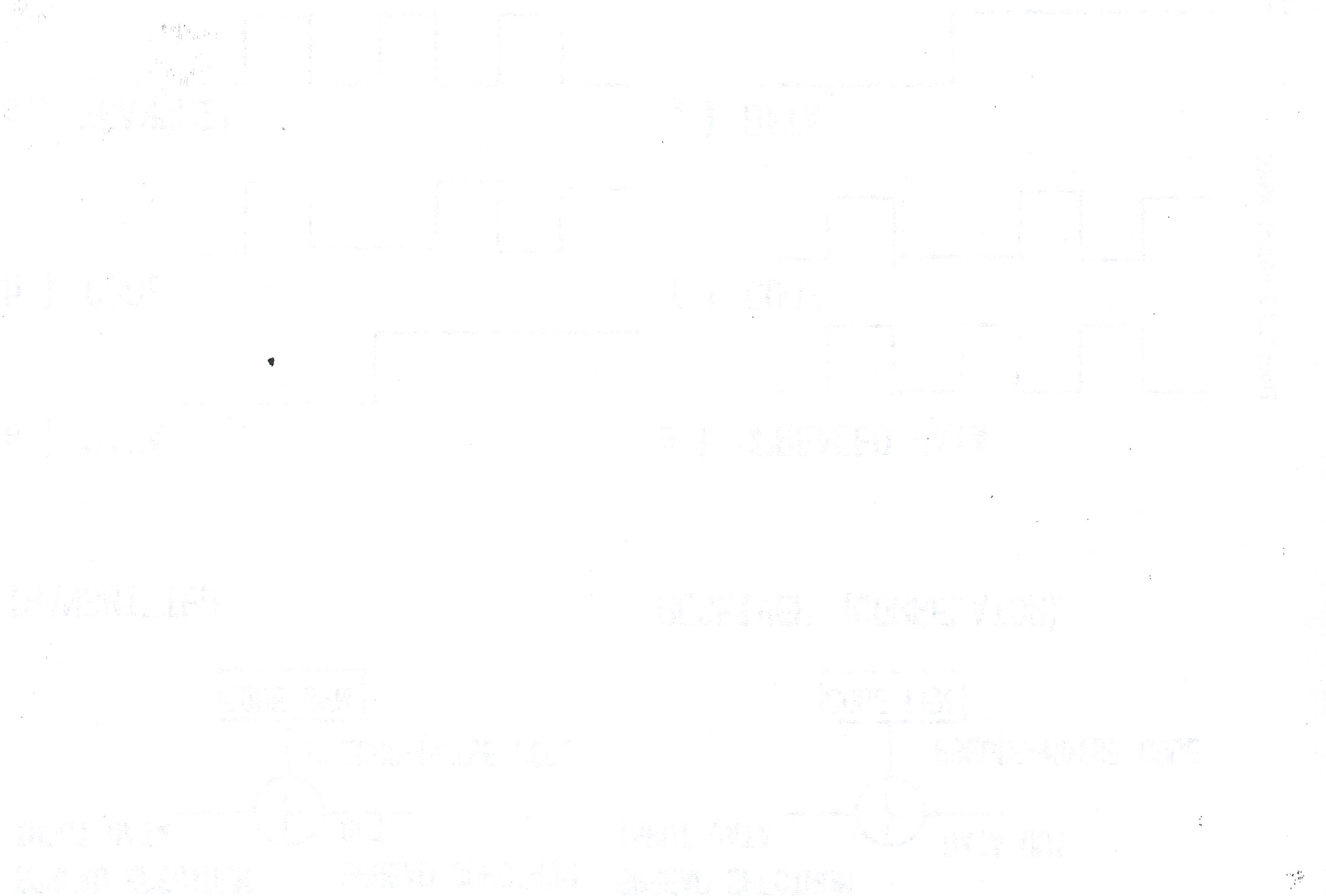


FIG 1


SPREAD SPECTRUM
INPUT DATA
SPREAD SPECTRUM
OUT
PSEUDO-NOISE CODE
CODE GEN
TRANSMITTER
SPREAD SPECTRUM
INPUT DATA
DATA OUT
PSEUDO-NOISE CODE
CODE GEN
RECEIVER (CORRELATOR)
a.) DATA
b.) CODE
c.) TRANSMIT
e.) SPREADED DATA
f.) CODE
g.) DATA

fIG



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Since our Performance Goal is a 10^{-4} BER (Before FEC) it can be seen that Differential Phase Shift Keying is a robust modulation technique with respect to Vehicle Motion.

3. DIRECT SEQUENCE SPREAD SPECTRUM

Now that we know what our Base-Band Modulation Technique will be of the Differential Phase Class[1], the next step is to determine how to satisfy the FCC part 15 Rule of Spread Spectrum. It has been decided to conform with the present FCC regulations concerning the Spreading methods. Therefore Frequency Hopping is not seen as a viable option due to the fact that the maximum modulation bandwidth is 25kHz. (Using DQPSK with a 800 kBaud symbol rate and Nyqusit Filtering gives a minimum bandwidth of 800 kHz). Therefore a Direct Sequence (Pseudonoise) Spread Spectrum Modulation System is proposed. In Figure 1. a schematic representation of Direct Sequence Spread Spectrum is shown (DSSS). In DSSS the transmitted bandwidth is greater than the information bandwidth, the ratio between transmit and information bandwidth is called the Processing Gain (PG). In the receiver the wanted signal is recovered by correlation techniques. While for Military Use Spread-Spectrum gives one an Anti-Jamming advantage, this is only significant for large Processing Gains. In our case Direct Sequence Spread Spectrum gives the following advantages:

1. Conformance with FCC Part 15. Rules. (This is probably coupled to the fact that the Power Density (Watts/Hz) is lower when the signal is spread using the same total transmit power).

2. Inherent "Path Diversity" due to the greater resolution of the system. (Using our channel and system parameters two resolvable paths are expected)

3. Less sensitive to filter aberrations (non-linear phase) and therefore cost effective filtering is possible.

4. Robust in a Multipath (ECHO) environment.

It should be noted that the main reason we are using Spread- Spectrum is due to the FCC requirements. The other advantages could be obtained with other Spectral Efficient techniques (NO SPREADING) but would not satisfy part 15 Rules.

In Figure 2. a block diagram implementing DSSS is shown for clarity. The Pseudorandom Code used for Spreading produces so called "chips" which multiply the data stream. It can be seen that the transmitted waveform has higher frequency content, since the resolution is now on the order of one chip time. Note that the Processing Gain in this system is simply the number of chips contained in one data "symbol" period. Correlation is simply multiplication of the incoming data stream with the same Pseudorandom code. In this implementation it is noted that accurate timing is needed between the receivers internal code generator and the received waveform. For low Processing Gains, which is our case, a matched filter implementation, in which this timing is no longer needed, can be implemented. (Our first prototype uses a Surface Acoustic Wave, SAW, Matched Filter).

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1 The exact modulation waveshaping is not defined in this report. It is assumed a spectally efficient, non-linear processing tolerant system with low side-band regeneration after filtering, will be implemented. (Examples are the constant envelope structures such as QOPSK, MSK and SFSK).

3.1 THE PROCESSING GAIN SIZE

We are Spreading the Spectrum mainly to satisfy FCC regulations. It is proposed to use the minimum amount of Spreading consistent with the FCC requirements. This will give us more Spectral Efficiency opening up more channels for other collocated LAN systems (There is also a cost factor, as matched filter price is related to Processing Gain). It seems the FCC will allow a minimum **Processing Gain of 10X.** Further contact with the FCC must be made to set this number. (Our prototype has a PG of 31X using a minimum sequence code for spreading).

3.2 PATH DIVERSITY

One of our advantages in using Spread Spectrum is the inherent resolution of the system. If an ECHO is produced which is greater than a chip time, it can be resolved by our receiver and used. Post Detection Integration [ref. 2] is assumed in the implementation of the power combining of the echo paths. Following the approximations of Kavehrad [ref. 3], a Path Diversity of 2 can be expected for our system. Together with two antennas this gives us a total of M=4 level Diversity!

SYSTEM PERFORMANCE

The question now arises, using Spread-Spectrum with a QDPSK modulation form, how is the performance in our indoor channel? First the channel parameters must be determined.

4.1 THE CHANNEL

The Indoor Radio Channel complicated by the following factors:

1. High Attenuation Levels due to obstructions. (Mean values, hence Fading is averaged out)

2. Scattering of the wave causing Multipath (Echos) and signal cancelation (Fading).

3. Time variant channel due to antenna and object motion. (As was shown in section 2.1, the channel can be considered time-invariant (quasi-static) for the time intervals of interest).

4.1.1 THE AVERAGE ATTENUATION (LARGE SCALE)

To characterize the indoor attenuation a statistical approach is taken. The attenuation distribution is log-normally distributed whose mean is a function of distance [ref. 1c, 4, 5]. The mean (dB) is expressed as:

$$m \propto 10\mathrm{Log}(Z^n) \qquad [5]$$

Where:

m is the mean attenuation (dB)
n is the attenuation exponent (n=2 for free space)
Z is the distance between the transmitter and receiver.

Therefore given n and σ (The Gaussian standard Deviation in dB's) one can characterize the large-scale average attenuation properties of the channel.
It is noted that n can vary within one area, for example "close to the antenna" (in the order to 10m) n is closer to a free space value than further away.

Our measurements show [ref. 5] that a 11dB/octave (after 10m) σ=5dB could be expected in an indoor environment.

4.1.2 THE FADING CHARACTERISTICS

Besides the average attenuation of section 4.1.1, signal cancelation can occur due to reflections. The statistical distribution of the fading level (factor below the average value) in a small-scale area can be expressed as:

$$P[Y<y] = 1 - \exp(-y) \qquad [6]$$

Where:

P[Y<y] is the cumulative distribution of the power ratio
y is the power ratio with respect to the average power.

This is the so-called Rayleigh Fading Channel since the envelope of the signal follows a Rayleigh Distribution [ref.1].
Our measurements [ref.6] within the indoor environments of interest confirm this theory.

4.1.3 MULITPATH DELAY SPREAD

An important parameter for echo characterization is the square root of the second moment of the Power Delay Profile, trms. [ref. 4]. The actual shape of the power delay function is not vital in determining performance, and Gaussian Shapes are assumed quite often in the literature. Measurements performed by NCR [ref. 6] in our indoor environments show trms values in the 30 ns range. This agrees quite well with measurements done by Saleh & Valenzuela [ref. 8] in an indoor environment (with about 115 meters largest distance dimensions). Due to our Spread Spectrum Modulation technique intersymbol interference can be neglected, assuming a trms of 30 ns and symbol rate of 800 kBaud. (Actually such a system is quite robust in terms of trms variations. Increasing trms can lead to system improvement due to the creation of more Diversity Paths!)
Us: a minimum expected Delay Spread of 100 ns [ref. 3, 8] (this is the time delay in which an Echo is significant) the number of "resolvable paths" is approximated by a discrete model used by Kavehrad [ref. 3].

$$L = \lfloor Tm/Tc \rfloor + 1 \qquad [7]$$

Where:

- $\lfloor x \rfloor$ = the largest interger less than x.
- L = the number of resolvable Paths.
- Tm = the Delay Spread of the Channel.
- Tc = the chip time.

For calculation let us assume a processing gain of 15X. With a symbol rate of 800 kBaud (1/T) and the definition of PG = T/Tc we have:

$$Tc = (1/800K)/15 = 83 \text{ ns}$$

Subsitution into [7] gives at least L = 2 resolvable paths.

4.2 PERFORMANCE CALCULATIONS

4.2.1 SELECTION DIVERSITY

One way that helps to overcome being in a FADE, is to switch the input to another antenna whose response is uncorrelated with the first (this can be achieved by physical separation or different polarization). In other words the antenna which has the best Signal to Noise Ratio at the Demodulator is chosen. The new cumulative distribution, see section 4.1.2, then becomes:

$$P[Y<y] = [1 - \exp(-y)]^M \qquad [7]$$

Where:

M is the Diversity Level.

4.2.2 WIRELESS PATH RELIABILITY MODEL

It is now time to calculate the performance (in terms of Outage) of our Radio Communications. The BER in which we want to meet, before error correction, is set at 10^{-4}. The instantaneous Signal to Noise Ratio needed for such performance is 14 dB [ref. 7]. The maximum amount of instantaneous signal attenuation (with respect to one meter) of 73.5 dB has been calculated, see section 5. With this and Indoor Propagation Parameters (from measurements) performance predictions are made:

Using the combined Statistics of the **Large-Scale (Log-Normal)** and **Rayleigh Distributions**, each giving their component attenuation in dB's, the following results are obtained [ref.5]:

LOCATION	IEEE desired $P_{oav} = 10^{-5}$ x (meters)	P_{omax}	Proposed $P_{omax} = .05$ x	P_{oav}
Supermarket 10dB/Octave, σ=3.7dB)	135	$4. \times 10^{-4}$	210	$1. \times 10^{-3}$
Department Store Without Walls (10dB/Octave, σ=4dB)	120	$6. \times 10^{-4}$	190	1.5×10^{-3}
Office (11.7dB/Octave, σ=2.2dB)	85	7.5×10^{-4}	120	7.7×10^{-4}
Department Store With Many Divisions (23.5dB/Octave, σ=5dB)	65	$4. \times 10^{-3}$	78	$5. \times 10^{-4}$

5. RADIO PROPAGATION BUDGET

Note: Since Spread-Spectrum has no performance effect with White Gaussian Noise, it is not taken into account.

Thermal Noise No(dBm) = -174 + 10LogB (Hz) Using a 1MHz Noise BW		-114 dBm
Noise Figure (Receiver, Switch, Cable and Filter)		8 dB
Receiver Thermal Noise	(a)	-106 dBm
Man-Made Noise (18dB above Thermal Noise)	(b)	- 96 dBm
Receiver's Input Noise Level (Power Sum of (a) and (b)		- 96 dBm
Instantaneous S/N for 10^{-4} BER (No FEC) QDPSK Modulation		14 dB
Detector Margin		2 dB
Required Instantaneous Receive Level	(c)	- 80 dBm
Isotropic Antenna Path Loss (at meter)[2] -27.6dB + 20Log F(MHz) Using F=915MHz		- 31.6 dB
Dipole Antenna Gain[3] (RX and TX each 2dB)		+ 4.0 dB
Transmit Power		20 dBm
Power one Meter Away	(d)	- 7.6 dBm
Signal Attenuation at the Receiver's Noise Limit with respect to one meter.	A = [(d) - (c)]	73.4 dB

2 It is assumed that at one meter away the attenuation follows a free space (n=2 or 6 dB/Octave) law. This would be the case when both antenna's can "see" each other.

3 A small antenna has been assumed (low gain) due to ergonomic requirements.

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