A Frequency Hopping 16-DAPSK Radio Investigation

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Abstract: A radio system supporting an end to end throughput of 2.5Mbps is proposed in this report. The intended application of the radio is in home networking products. A frequency hopping radio operating in the 2400MHz ISM band is described. The modulation format used is 16-DAPSK. This backs off to DQPSK in channels with severe time dispersion. The data traffic carried by the radio is first assessed. This is necessary to establish what error control mechanisms may be implemented in the system. The residential, indoor radio propagation environment is then considered. This enables the dominant error mechanisms in the receiver to be predicted. The analysis presented concludes that a 16-DAPSK modem with two branch diversity reception is capable of providing a satisfactory quality of service in the intended operating environment.
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Revision History

28/11/95 Draft
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1. Introduction

This document is intended to predict the performance of a narrowband frequency hopping modem proposed for stage two Panacom home networking products. In areas where there is currently insufficient evidence to predict the performance of such a system, the future work necessary to further de-risk the proposal is described.

2. Functional Specification

The radio system is intended as stage two in a family of home networking products. This would offer a throughput improvement over the stage one product. The first stage radio is likely to be an ISM band frequency hopping radio employing 2 level FSK. It is highly desirable for stage two products to be able to communicate with the installed base of stage one devices.

Stage two radios must be designed with regard to the following requirements:

- 2.5Mbit/s throughput available to the user.
- Interoperability with lower rate stage one devices.
- The targeted operating environment is residential in-building.
- Some level of service must be available in other propagation environments, such as in office space.
- The radios must be 'inexpensive'.

In addition to these, a number of performance requirements relating to the nature of the traffic are still undefined. It is unclear if the link will have to carry real time data for multimedia applications. This is important as it defines the guaranteed bandwidth and latency requirements of the link. Table 2.1 shows a number of potential uses of a home network, and the type of service it requires:

<table>
<thead>
<tr>
<th>Application</th>
<th>Connection From</th>
<th>To</th>
<th>Communication service</th>
</tr>
</thead>
<tbody>
<tr>
<td>Send a file to print</td>
<td>PC</td>
<td>Printer</td>
<td>asynchronous</td>
</tr>
<tr>
<td>Remote hard disk access</td>
<td>remote PC</td>
<td>PC</td>
<td>asynchronous</td>
</tr>
<tr>
<td>CD-ROM video playback</td>
<td>CD-ROM on remote PC</td>
<td>PC</td>
<td>broadband isochronous</td>
</tr>
<tr>
<td>CD-ROM audio playback</td>
<td>CD-ROM on remote PC</td>
<td>PC</td>
<td>broadband isochronous</td>
</tr>
<tr>
<td>CD-ROM file access</td>
<td>CD-ROM on remote PC</td>
<td>PC</td>
<td>asynchronous</td>
</tr>
<tr>
<td>CD audio playback</td>
<td>CD or CD-ROM</td>
<td>Wireless speakers</td>
<td>broadband isochronous</td>
</tr>
<tr>
<td>Telephony</td>
<td>Phone handset</td>
<td>Phone basestation</td>
<td>Narrowband isochronous</td>
</tr>
</tbody>
</table>

Table 2.1 Communication services required by end applications

Clearly then, many of the potential services require only an asynchronous, ethernet like connection. However, stage one products are capable of supporting all the asynchronous services, albeit at a lower rate. A value point clearly distinguishing stage two products from existing stage one devices is needed. The concept of a 'multimedia capable' range of radios supporting video and CD quality audio would provide this. The implications of this real-time requirement on error control in the MAC will be considered later.
3. PHY Layer Issues - 16-DAPSK and the Indoor Channel

The radio system being proposed is an unequalised 16-DAPSK receiver, with two branch switched diversity reception. The work presented here investigates if such a system can operate successfully in most indoor, residential type radio channels. The underlying premise is that within the residential indoor channel, the delay spread is sufficiently low that an equaliser is unnecessary and possibly even detrimental. This section is intended to investigate the validity of this assertion. If the system were operated in a higher delay spread environment then it would back off to QPSK in order to provide a service at half the data rate.

In order to investigate the performance of a 16-DAPSK radio in the indoor residential environment, the following issues are discussed:

- Description of indoor residential radio channel characteristics.
- Assessment of the importance of the various error mechanisms in the Indoor Channel.
- Quantitative analysis of 16-DAPSK and QPSK performance given these error mechanisms.

3.1 Characteristics of the Residential Indoor Channel

A considerable amount of work has been published describing the simulated performance of 16-DAPSK under various operating conditions. In order to analyse this work it is first necessary to understand the parameters of the proposed Panacom Stage 2 receiver and its operating environment. These can be summarised as follows:-

- Frequency hopping transmission in the 2400MHz ISM band.
- 3 Mbps on air data rate.
- 100mW (20dBm) maximum transmit power.
- 20 dB modulated bandwidth is 1MHz.

The following statements describe the typical intended operating environment of the radio:

*Delay Spread*

- A typical rms delay spread will be 20ns giving a normalised delay spread of 0.06 for a 3Mbps system.
- Delay spreads of 100ns will only be encountered in office space, which is not the target operating environment, so a half speed service is acceptable under these conditions, giving a normalised delay spread of 0.15 and a 1.5Mbps data rate.

*Path Loss*

- In a 'typical' brick built house, the path loss is such that a range of greater than 10 meters cannot be guaranteed, given a transmitted power of 20dBm and a receiver sensitivity of -85dBm.
- In a 'typical' timber constructed house, the path loss is generally lower and so range is increased.

Experimental evidence suggests these assumptions are valid, although path loss predictions are a notoriously inexact science. The delay spreads are low in a residential environment as the path loss is quite high over a relatively short distance. This is in contrast to an office environment which has greater distances of open space, so the receiver is subjected to rays with greater power and longer delays.

Simulation and experimental work further investigating the performance of the indoor channel will be described in a later report.
3.2 Overview of Radiowave Propagation Error Mechanisms

The radio propagation environment limits the performance of radio systems. Signals arrive at the receiver via a scattering mechanism. The existence of multiple propagation paths with different time delays, attenuations and phases gives rise to a highly complex, time varying transmission channel. It is necessary to characterise the nature of the channel in order to determine how a modulation scheme will perform.

There are a number of error mechanisms which exist in the radio propagation channel which can cause errors in a multilevel demodulator. These are listed below:

- Thermal noise
- Fast fading
- Random FM
- Time dispersion

It is important to exercise caution when attributing errors to each of these mechanisms as they are not entirely independent processes. All of these effects are a result of the scattering mechanism of the radio propagation channel. However, considerable insight into the performance of the system can be gained by starting with a channel which contains no error mechanisms, and then adding each in turn to establish its relative importance. The performance of the 16-DAPSK receiver will be analysed in this way in the following section.

3.3 Performance Analysis of 16-DAPSK

Now consider the error mechanisms which limit the performance of a 16-DAPSK radio. Each of the mechanisms listed above will be added in turn to the analysis.

3.3.1 Thermal Noise

This represents the errors caused by the reduction in signal strength due purely to path loss. The error mechanism here is the introduction of additive white Gaussian noise. The $E_b/N_o$ performance curve for 16-DAPSK in thermal noise is shown in figure 3.3-1.

From this curve, it is possible to define the sensitivity of the receiver. If an average bit error probability of $10^3$ is defined as the worst error rate acceptable, then the curve shows that an $E_b/N_o$ of 15dB is required at the receiver.

Now determine the received signal power that corresponds to an $E_b/N_o$ of 15dB. It is known that:

$$\frac{S}{N} = \frac{E_b}{N_o} \frac{R}{B}$$  \hspace{0.5cm} (3.3-1)

$$\frac{E_b}{N_o} dB = S dBW - 10 \log(kTB) - 10 \log(NF) + 10 \log(B) - 10 \log(R)$$  \hspace{0.5cm} (3.3-1)

$$\frac{E_b}{N_o} dB = S dBm + 99 dB$$ \hspace{0.5cm} NF = 10dB \hspace{0.5cm} (3.3-1)

$$R = 3Mbps$$
So, a received signal power of -85dBm results in an average bit error rate of $10^{-3}$ and is therefore the sensitivity limit of the receiver. Figure 3.3-2 shows the mapping between $E_b/N_0$ and received signal strength. An upper limit can be placed on the received signal strength. The transmitted power is 20dBm and the coupling coefficient for two isotropic radiators is 38dB. So, the received power will never be greater than -20 dBm. This defines the required dynamic range of the receiver to be 65dB.

A channel containing only AWGN is the ideal operating environment for a radio receiver. Other channel effects will now be considered. The objective is to determine how much these added effects worsen the performance of the receiver beyond the -85dBm theoretical noise performance limit.
3.3.2 Fast Fading

Rayleigh fading is an interference mechanism which results from the constructive and destructive superposition of radio waves. Rayleigh fading affects the magnitude and phase of a received signal. The received signal power variation has the statistics of a Rayleigh random variable. The phase angle variation is uniformly distributed.

In a channel containing only thermal noise, a given signal strength produces an $E_b/N_0$, which has a corresponding average BER. In a channel which fades with Rayleigh statistics, the instantaneous signal strength may vary by up to 40dB. During fades, the error rate increases dramatically because of the worsened $E_b/N_0$, in deep fades the signal strength may drop below the receiver sensitivity limit. Consequently, a fading channel with the same average received power as an AWGN channel will suffer more errors. Alternatively, the average signal strength needed to achieve a given BER in fading is greater than the signal strength needed to achieve that BER in noise alone.

As $E_b/N_0$ dropout is the error mechanism, increasing the transmitted power can reduce the error rate caused by this mechanism. The rate of change of envelope and phase fluctuation is a function of the normalised Doppler shift. The Doppler shift is given by equation (3.1-2):

$$f_d = f_c \cdot \frac{v_d}{c} \quad (3.3-2)$$

$$f_d = 16Hz$$

As the symbol rate is 750 kbaud, the normalised doppler, $f_d/T_s$ is $2.4 \times 10^{-5}$. This is negligibly small and so quasi-stationary Rayleigh fading occurs. The performance for quasi-stationary Rayleigh is described by a Rayleigh fading curve, with a normalised Doppler of zero. Figure 3.3-3 clearly shows that the average signal strength needed to achieve a particular BER in a fading channel is greater than that in a channel containing only AWGN.

![Figure 3.3-3 Performance of 16-DAPSK in Quasi-stationary Rayleigh Fading](image)

- Performance in quasi-stationary fading
- Performance in thermal noise

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3.3.3 Random FM

Rayleigh fading also introduces phase fluctuations, or random FM. The greatest rate of phase change occurs at the bottom of fades. However, unlike the previous mechanism, it isn't possible to increase the transmit power to reduce the fade depth and therefore improve the error rate. Increasing the transmitted power will increase the received power at the bottom of a fade, but the amount of phase change at the bottom of the fade will be unaffected. Consequently, random FM results in an irreducible error rate, which is unchanged with increasing signal strength.

The irreducible error rate worsens with increasing normalised Doppler. This is because the frequency of fading is determined by the Doppler rate. So, the higher the Doppler, the more often fades and therefore rapid phase changes occur. Figure 3.3–4 shows the performance of 16-DAPSK with increasing levels of normalised Doppler.

![Figure 3.3-4 Performance of 16-DAPSK in Rayleigh Fading](image)

The irreducible nature of errors caused by random FM is clearly shown in Figure 3.3-4. As the normalised Doppler in the indoor channel is significantly below the values plotted on this graph, the irreducible due to random FM will never be reached. So, the error curve due to Rayleigh fading in the indoor channel has no random FM induced irreducible. Consequently, an increase in signal strength always yields an improvement in error rate.

3.3.4 Diversity Reception in Rayleigh Fading

Diversity reception is a powerful means for mitigating the effects of Rayleigh fading. The previous two sections conclude that signal strength fluctuation is the dominating error mechanism as fading in the indoor channel is quasi-stationary. Using two branch diversity will result in an observed signal strength envelope which has fewer deep fades. So, for the same average \( E_b/N_0 \) with 2 branch diversity there are fewer error bursts due to deep fading.
Figure 3.3-5 shows that selecting the better of two Rayleigh fading envelopes results in an observed signal strength which has fewer deep fades. This acts to reduce the errors caused by deep fading. Figure 3.3-6 clearly shows that adding two branch diversity in a channel with quasi-stationary Rayleigh fading takes the performance curve closer to that of a receiver operating in a channel containing only AWGN.

**Figure 3.3-5 Reduction of deep fading through diversity reception**

**Figure 3.3-6 Performance of 16-DAPSK with diversity in quasi-stationary fading**
3.3.5 Time Dispersion

Time dispersion in the radio channel acts to spread the received energy in time. This gives rise to inter-symbol interference. Figure 3.3-7 demonstrates the effect of delay spread on 16-DAPSK systems, without diversity, and with two branch diversity. The system simulation includes raised cosine channel filtering with an alpha of 0.5, this is tighter than the alpha of 0.6 which will be implemented in the real system.

![Figure 3.3-7 Irreducible error rates for 16-DAPSK in a dispersive channel](image)

**Figure 3.3-7 Irreducible error rates for 16-DAPSK in a dispersive channel**

Table 3.3-1 shows how a system with two branch diversity would perform.

<table>
<thead>
<tr>
<th>Data Rate</th>
<th>RMS Delay spread</th>
<th>Modulation format</th>
<th>Normalised delay spread</th>
<th>Bit error probability</th>
<th>Error rate acceptable?</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Mbps</td>
<td>20 ns</td>
<td>16-DAPSK</td>
<td>0.06</td>
<td>2e-5</td>
<td>Yes</td>
</tr>
<tr>
<td>3 Mbps</td>
<td>40 ns</td>
<td>16-DAPSK</td>
<td>0.12</td>
<td>5e-4</td>
<td>Yes</td>
</tr>
<tr>
<td>3 Mbps</td>
<td>100 ns</td>
<td>16-DAPSK</td>
<td>0.3</td>
<td>3e-2</td>
<td>No - backoff</td>
</tr>
<tr>
<td>1.5 Mbps</td>
<td>100 ns</td>
<td>DQPSK</td>
<td>0.15</td>
<td>5e-4</td>
<td>Yes</td>
</tr>
</tbody>
</table>

**Table 3.3-1 A 16-DAPSK modem with QPSK backoff in a dispersive channel**

These irreducible error rates due to delay spread in the channel assume that the receiver is working on the irreducible error floor. This is true when there is a high signal strength at the receiver. However, at the limit of the receiver range there will always be a region where errors are being caused by noise related error mechanisms as well as by the delay spread performance of the receiver. Performance in this region will be considered next.
3.3.6 Dominant error mechanisms in the Indoor Channel

The analysis in the previous sections has shown that two error mechanisms dominate in the indoor channel. These are:

- Fast Fading
- Time dispersion

Fast fading causes received signal strength fluctuations, this in turn causes errors due to poor received signal strength. The curves in figure 3.3-6 describe the error rate due to this mechanism. As the errors are related to signal strength, this mechanism does not result in an irreducible error rate.

Time dispersion in the channel causes inter-symbol interference. Increasing the signal strength cannot reduce the level of ISI, so this error mechanism results in an irreducible error rate. The curves in figure 3.3-7 show the irreducible error rates due to this mechanism.

Error mechanisms which are not relevant in the indoor channel are:

- Thermal noise
- Doppler induced random FM

The noise performance curve alone for 16-DAPSK does not give any insight into the performance of 16-DAPSK in a channel with quasi-stationary Rayleigh fading. However, signal strength dropout is the error mechanism in fast fading and the noise performance curve can be used to determine the instantaneous BER in quasi-stationary fading.

Random FM is a result of Doppler and results in an irreducible error rate. However, normalised Doppler is insignificant in the indoor channel.

3.3.7 Overall performance curves for 16-DAPSK

Given any particular average received $E_b/N_0$, a bit error can be generated by one of two mechanisms:

- Fast fading
- Time dispersion

So, the probability of an error due to either mechanism is given by the binomial theorem and is illustrated in figure 3.3-8. A bit may be correctly received if an error is caused by both fast fading and time dispersion. This is an unlikely event ($P_e P_e$) and its inclusion acts to reduce the implied probability of bit error. In order to determine an upper bound on the combined probability of bit error, this effect will be ignored. So, the combined probability of bit error due to either mechanism is given by:

$$
\begin{align*}
P_e &= P_{ef} + P_{ti} (1 - P_{ef}) + (1 - P_{ti}) P_{ef} \\
&= P_{ef} + P_{ti} - P_{ti} P_{ef}
\end{align*}
$$

So, this expression can be used to generate a family of overall performance curves for 16-DAPSK in increasing levels of delay spread.
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![Diagram](image)

**Figure 3.3-8 Combined probability of bit error given two error mechanisms**

Figure 3.3-9 shows that in the target operating normalised delay spread of 0.06, the receiver works down to an average received power of -82dBm. This is within 3dB of the theoretical noise limited sensitivity. The receiver is working on the irreducible error floor down to a received power of -70dBm. For received powers lower than this, fast fading also introduces errors.

![Graph](image)

**Figure 3.3-9 Two branch diversity 16-DAPSK in a dispersive, quasi-stationary channel**

It is now possible to describe the predicted performance of the system given a number of channel conditions. Consider each condition in turn:

- Good received signal strength (>70dBm) and normal rms delay spread (<20ms)
This channel is likely to be found in a residential building, up to 10 meters from the transmitter. It is expected that this would be the most common operating condition for the receiver.

The receiver is working on the irreducible error floor, with an error rate of $2.10^{-5}$, this error rate is quite satisfactory.

- **Poor received signal strength ($<-70$dBm)**, normal rms delay spread (20ns).

  As the distance from the transmitter increases to 20 meters, the received signal strength may start to drop below -70dBm. However, the rms delay spread is unlikely to rise above 20ns.

  The receiver is no longer working on the irreducible error floor. Fast fading now contributes to the overall error rate. The error rate rises to $10^{-3}$ when the average received power is -82 dBm. So, for this amount of delay spread, the receiver works down to within 3dB of the theoretical sensitivity limit in noise. The increased error rate would result in a throughput hit. It is expected that the errors would be bursty, causing packets to be lost. The implications of this on the coding will be considered in a later section.

- **Any signal strength, increased rms delay spread (40ns).**

  It is possible, but unlikely that areas of delay spread of this magnitude will exist in the indoor residential environment. It is most likely to be seen when the receiver is well separated from the transmitter, and is likely to be accompanied by poor received signal strength.

  The receiver works on the irreducible error floor down to a received power of -75dBm, with an irreducible error rate of $5.10^{-4}$. For received power below -75dBm, fast fading contributes to the error rate. The error rate reaches $10^{-2}$ at a received power of -78dBm. So, the link will provide satisfactory performance.

- **Any signal strength, high rms delay spread (100ns).**

  This condition is unlikely to be found in a residential channel. It may be found if the system were operated in an office environment, with large open plan spaces of more than 50 meters in length.

  Under these conditions the 16-DAPSK 3Mbps system produces an irreducible of $6.10^{-3}$, which is unacceptable. The system would then back off to DQPSK modulation with a 1.5Mbps data rate, halving the normalised delay spread. This results in an irreducible error rate of $5.10^{-4}$. This error rate becomes worse than $10^{-3}$ when the average received power is -78 dBm. So, a service is maintained at half the data rate. This is considered acceptable as the receiver is not really intended for this operating environment.
4. MAC Layer Issues - Error Control for Asynchronous and Multimedia Services

Stage two products offer both asynchronous and real time data services. These various types of service require a number of different error protection methods. The indoor radio channel results in bursty errors. This means that generally, a packet is received entirely without error, or the entire packet is highly in error. This means FEC coding within one packet has little value. One transmit packet will have a length of approximately 1ms. This understanding of the radio channel is important as it allows the most appropriate error control scheme to be chosen for each of the transmitted data types.

Now consider the requirements for each of the service types:-

Asynchronous (File transfer)

Frame retransmit ARQ is suitable for asynchronous data as there are no real time constraints on the arrival time of the data.

Narrowband Isochronous (Real time voice / telephony)

For voice telephony, there is a tight time constraint, an end to end delay of less than 10ms is required. Given the 1ms packet length, an ARQ protocol could potentially be operated here. If several retransmits are unsuccessful, the packet is then dropped as the data has no value once another sample from the voice coder has arrived. The end to end data rate is very low, 32kbps.

Broadband Isochronous (Video / CD quality audio)

CD-ROM players are capable of streaming data out at the following rates:

<table>
<thead>
<tr>
<th>Speed</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>1.2 Mbps</td>
</tr>
<tr>
<td>Double</td>
<td>2.4 Mbps</td>
</tr>
<tr>
<td>Quad</td>
<td>4.8 Mbps</td>
</tr>
</tbody>
</table>

Table 2.2 CD-ROM output data rate

The single speed CD-ROM standard was designed to ensure it could stream out MPEG, which produces 1.2Mbps continuous rate data. It will be a number of years before the MPEG2 standard, requiring 4.8Mbps will become available.

MPEG encoded data can be read out of a player at either a variable or a fixed rate. Decoding MPEG naturally results in a variable rate data stream. This is because different screen images and rates of change of image result in different levels of compression. However, most networks cannot handle variable rate data, so MPEG players generally operate in their continuous rate mode. In this mode, an output buffer is used, variable rate data fills this buffer whilst it is read out to the network at the 1.2Mbps continuous rate. This introduces a time delay. So providing the latency introduced by the radio link is negligible in comparison to this delay, end to end performance will be unaffected.

Clearly then, the throughput across the radio link must be at least 1.2Mbps. Given the proposed on air rate is 3Mbps, it should be possible to support this with ease. Even a packet retransmit ARQ scheme would introduce less than a 10ms delay, which is trivial compared to the delay introduced by the output buffer in the MPEG decoder itself.
5. Conclusions

This report has described the communication modes required of a stage two Panacomm system. An analysis of 16-DPSK performance has demonstrated that this modulation formation may provide satisfactory performance in an indoor residential channel when combined with two branch diversity reception. The simulation work presented assumes post detector combination diversity. In a practical system switched diversity would be used as it requires only one receiver chain. It is necessary to establish if the performance of switched diversity is comparable with post detector combination diversity. As the channel is quasi-stationary, it is possible that the performance degradation will be minimal.

The characteristics of the residential indoor channel have been considered. It has been suggested that the channel exhibits quasi-stationary Rayleigh fading, with modest levels of ms delay spread. The error mechanisms in the channel are therefore:

- Fast fading
- Time dispersion

Analysis has demonstrated that a 3Mbps 16-DPSK modem combined with two branch diversity could potentially yield satisfactory performance in a channel such as this. In areas of good signal strength, the error rate of the receiver is determined by the irreducible generated by dispersion in the channel. In areas of poor received signal strength, the error rate has a contribution from fast fading as well as time dispersion.

The error coding implications of different communication services were then considered. The required communication services can be categorised as follows:

- Asynchronous (File transfer)
- Narrowband isochronous (Real time voice / Telephony)
- Broadband isochronous (Video / CD quality audio)

It was considered feasible to support all these types of traffic with the proposed radio system. Real time services such as telephony have a low throughput requirement. Non-realtime services such as video have a much greater throughput requirement, but less stringent delivery time needs. This is because buffering can be used to overcome jitter introduced by the error correction mechanism in the network.

6. References
