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A Preliminary Performance Evaluation of a Linear Frequency Hopped Modem

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Abstract

Recently, there has been considerable interest in 'non-military' applications of spread spectrum modulation Code Division Multiple Access (CDMA) systems. This includes cellular networks, and secondary user systems, such as those that comply with Part 15 of the FCC Regulations.

Frequency Hopping (FH) is a viable alternative to the more highly researched area of Direct Sequence (DS) CDMA.

The benefits of using linear modulation methods for a FH transmission system in a narrowband ie. voice cellular network are considered in this paper. In particular, the use of a 16 level modulation scheme derived from 16 QAM combined with Frequency Hopping is evaluated operating in a channel subject to noise and multipath fading, characteristic of the mobile environment.

1 Introduction

To date, the main thrust of commercial CDMA research has been on DS Spread Spectrum [1, 2]. However, Frequency Hopping has some distinct advantages over DS.

The stringent requirements on timing recovery and synchronisation are greatly relaxed with FH, given that the required DS pseudo noise code chipping rates are expected to be two orders of magnitude faster than the anticipated hop rate. Furthermore, the inherent path diversity available with Direct Sequence, which allows multipath signals to be exploited to gain a SNR advantage, falls down in the indoor environment. Unless large bandwidths and complex circuitry are used, the resolution necessary to separate the multipath components cannot be achieved.

In a recent investigation at the University of Bristol, the use of a spread spectrum overlay service to provide capacity enhancement to an existing mobile network was investigated. In the limited bandwidth scenario considered, it was found that the DS system was unable to provide the required processing gain to reduce primary user interference, whilst still maintaining a usable data rate. In contrast, by utilising the flexibility of Frequency Hopping, in not using a contiguous transmission bandwidth, and by incorporating intelligence at the transmitter, the FH system achieved an acceptable level of performance. Thus Frequency Hopping appears to be an attractive proposition and worthy of further investigation.

Traditionally Frequency Hopped Spread Spectrum Systems have employed FSK, which allowed a simple dehopper/demodulator implementation. However, such a modulation scheme is grossly inefficient in its use of bandwidth.

The present and increasing demand for radio spectrum by mobile radio users forces the issue of spectral efficiency to be of prime importance in any modulation/access technique being considered for use in a cellular network. Conveying message information in both the phase *and* amplitude of the RF carrier moves away from the constant envelope modulation schemes used almost exclusively to date. The use of such a technique greatly reduces the bandwidth required to transmit a message, but introduces a requirement for linear power amplification at the output stage of the transmitter. Significant improvements in linear amplifier design [3, 4] make the use of such linear modulation schemes a viable technique for reducing spectral occupancy.

This paper considers the use of a highly bandwidth efficient, multi-level linear modulation, known as 16APSK, as applied to a medium-low data rate FH CDMA wireless network.

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In order to reduce the complexity of the hopping synthesiser, and reduce the requirement of overcoming phase non-linearities introduced by the channel, the modulation utilises a differential encoding/decoding scheme. 16APSK, which is derived from 16 QAM, has a constellation particularly suited to this technique.

In this contribution, the simulation of a Linear FH Modem is described, and the performance of the differential linear modulation used is evaluated when frequency hopped in a noisy Rayleigh fading channel.

2 Linear Modulation for Frequency Hopping

In order for a narrowband linear modem to operate successfully in the mobile environment, the receiver must track out the phase and amplitude variations introduced by the channel.

The effect of hopping a narrowband signal over a wideband of spectrum is to generate independently faded data from frame to frame, provided that a hop in frequency is beyond the coherence bandwidth of the channel. Whilst coding alone of an FDMA narrowband signal could achieve a performance enhancement, it would *not* be able to handle the long error bursts that occur when a handset is stationary in a deep fade for any significant period of time. Hopping effectively provides frequency diversity, and prevents high outage of data. Thus frequency hopping *does not change the statistics* of the received signal, but merely allows *randomisation* and correction of the error bursts that occur during deep fades. This is accomplished by utilising interleaving, over the depth of a hop frame, and the application of forward error correction coding.

Given that absolute phase and amplitude information undergo gross distortion in the mobile channel, a means of overcoming this is required. The use of Feed Forward Signal Regeneration techniques to negate the effects of fading and channel non-linearity is greatly restricted with frequency hopping, due to the fact that the dwell time (the period during which the hop carrier remains at one frequency) is limited. Eg. Notch filtering of the pilot tone in the TTIB method takes of the order of 10 ms.

A fully differential modulation scheme is ideally suited to frequency hopping. Whereas carrier recovery at the receiver requires re-acquisition after each hop, the differential approach completely negates this requirement. Provided that the fade rate is such that the channel remains stationary over two consecutive symbols, differential reception overcomes the fading as
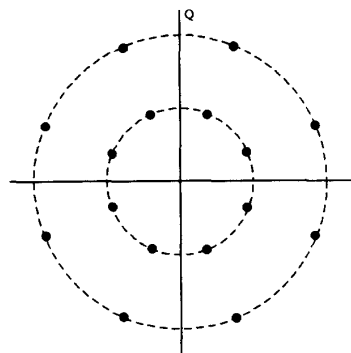

Figure 1: Constellation Diagram of 16APSK

well.

Such a modulation scheme, known as 16 level Amplitude and Phase Shift Keying (16APSK) has been researched at the University of Bristol [5, 6]. A rigourous analysis is presented in [5]. The 16APSK constellation is shown in Figure 1. Each symbol represents 4 bits, $b_0 \ldots b_3$. When operated differentially, the amplitude ring is chosen on the basis of the last amplitude, and the current b_0. Bits $b_1 \ldots b_3$ are used to Gray encode a phase, which is added to θ_{n-1}, the phase of the last symbol to determine θ_n, the phase to be transmitted for this symbol.

In AWGN, the well-known [7] performance of square 16QAM has a 5 dB advantage over differential 16APSK, since it has an optimised inter-symbol separation. However in fading, the 16DAPSK has a distinct advantage. In differential square QAM, there are 7 possible amplitude transitions, and 12 phase transitions which requires a highly complex differential decoder, whereas 16APSK is particularly suited to differential transmission as the number of possible phase/amplitude transitions in its constellation have been minimised, thereby increasing immunity to fading.

3 Frequency Hopping Model

A block diagram of the modem that has been modelled is shown in Figure 2.

3.1 Transmitter

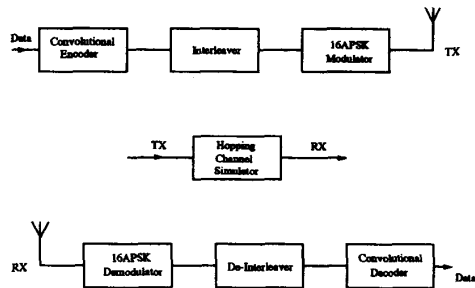The output from the 16APSK linear modulator is amplitude and phase modulated:

Figure 2: Linear Frequency Hopper Block Diagram

$$c_n(t) = \sqrt{2P_s}A_n cos\,(w_{IF}\;t + \theta_n) \qquad (1)$$
$$\text{for } nT_s \; < \; t \; \leq \; (n+1)T_s$$

where for the nth symbol of data, A_n is the amplitude ring transmitted and θ_n is the phase. P_s is transmit symbol power. The period of $c_n(t)$ is that of the coded data symbol stream, T_s.

In a practical system, the modulated data at IF would be upconverted to RF by mixing with a hopped carrier generated by a FH synthesiser. The hop frequency selected is chosen from a set of available carriers, driven by a PN sequence control word.

3.2 Channel Model

The use of a hopping narrowband channel simulator, which realistically models the characteristics of a frequency hopped channel, negates the need for simulating a separate frequency hopper, fixed broadband channel model and dehopper.

In general, a hop will be to a frequency beyond the coherence bandwidth of the channel, and thereby it will provide an independently faded signal at the receiver and reduce the length of an error burst in a deep fade. In this case, there is an advantage to be gained from hopping. However, when hopping a narrowband signal, with a bandwidth smaller than the coherence bandwidth, under control of a pseudo random sequence, it is possible that hopping to an adjacent frequency slot will result in correlated fading, and will thus not improve performance. The hopping channel model used reflects these aspects.

The channel under consideration is a simplistic model, where the transmitter signal is propagated through a noisy Rayleigh fading multipath channel. The fading and noise are assumed to be independent. The
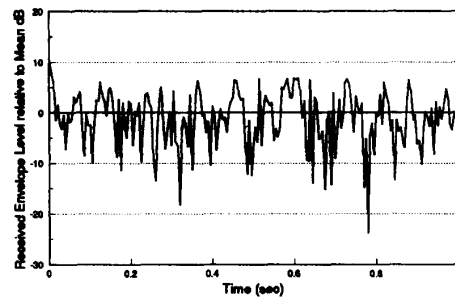

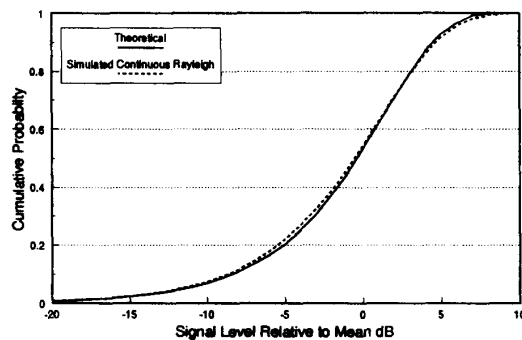Figure 3: Time Slice of Continuous Rayleigh Fading Envelope

Figure 4: Cumulative Probability Density of Continuous Rayleigh Fading Envelope

Rayleigh fading model used follows the simulator as described in [8]:

$$r(t) = \sum_m \alpha_m(t)exp(j\phi_m(t)) \qquad (2)$$

An unmodulated carrier would be received as the sum of a number of time variant phasors, having amplitude α_m and phase β_m, with an envelope that may be described by the Rayleigh probability density function:

$$p(R) = \frac{R}{\sigma^2}\;exp\left[\frac{-R^2}{2\sigma^2}\right] \qquad (3)$$

A time slice of the Rayleigh faded envelope from the fading simulator is shown in Figure 3. The validity of the model is demonstrated in Figure 4, a cumulative plot of the simulated fading compared to the expected theoretical values.

By adjusting the random seeds used in the model by an appropriate amount, hopping is simulated by, in effect, taking a different time slice of the envelope. This is illustrated in Figure 5, where the envelope of continuous and hopped fading are compared. The hopped fading
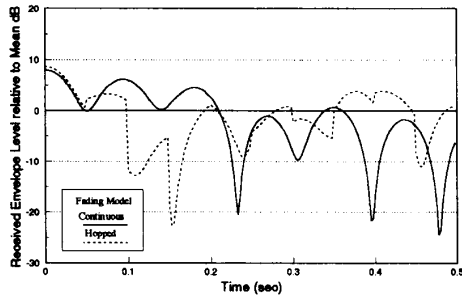
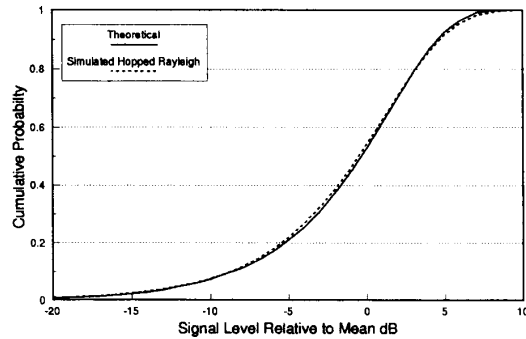Figure 5: Comparison of hopped and continuous Rayleigh Fading Envelope

Figure 6: Cumulative Probabilty Density of Hopped Rayleigh Fading Envelope

envelope shows discontinuities in the received signal level at 0.05 second intervals; the instant of each hop. The statistics of the received envelope have not been significantly altered by this technique for simulating hopping, as shown in the cumulative plot of Figure 6. This is to be expected, as the effect of hopping is to simply randomise the faded received time waveform.

3.3 Receiver

At the demodulator, after having passed through the hopping channel, the signal may be considered as having been dehopped. The demodulation process is fully described in [5], and involves mixing with a symbol delayed version of the data, to generate the differential phase term.

Due to the fact that there is an unpredictable change in both phase and amplitude in hopping from one carrier to another, within each hop frame a reference symbol must be inserted in order to allow the differential receiver to re-acquire.

In order to achieve well-defined spectral occupancy, a raised cosine filtering operation is performed. This has a tightly defined frequency response, but extends over several symbols in the time domain. When hopping, there may be a significant difference between the received signal strength of consecutive symbols, transmitted at the tail of one hop frame and the start of the next. This is due to the gross amplitude variations that arise through hopping across the channel. The fluctuation between such symbols has an adverse effect on the matched filtering process, resulting in ISI and degraded BER performance.

The approach adopted to resolve this is to perform AGC on the received hop frames and normalise out the amplitude distortion introduced by the hopping channel. The symbol used as a differential reference in each frame thus conveniently doubled as a power control pilot symbol.

4   Simulation Results

The following assumptions have been made in the simulation that has been developed:

- The hopping channel model is sufficient to negate the need for simulation of a frequency hopper/dehopper sub-system;

- As such, the effects of transients at the instant of hopping are ignored;

- Perfect linear power amplification at the transmitter, such that the only distortion at the receiver is due to that introduced by the channel;

- Perfect symbol timing has been assumed in the demodulator.

Figure 7 shows the performance of the linear Frequency Hopping modem in a noisy Rayleigh fading channel compared against a fixed frequency differential modem. Two FEC schemes were assessed as the method for coding of the hopped data; a convolutional code, rate 1/2 and constraint length 7, and a BCH block code rate 7/15.

It is seen that the irreducible error rate encountered with fixed frequency operation has been overcome.

Due to the nature of convolutional codes, breakdown has occurred at high error rates, with the decoder actually introducing errors [9].
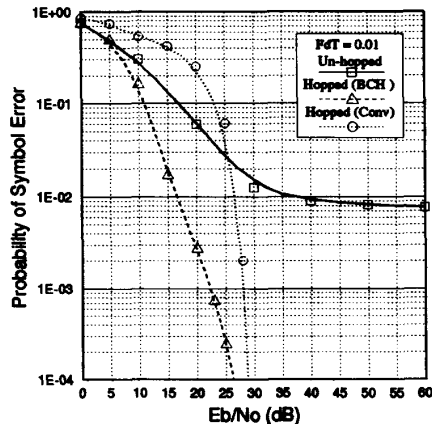
Figure 7: Performance of Hopped Linear Modem in Rayleigh Fading

5 Conclusion

This paper has presented the motives for considering Frequency Hopping of a linear modulation scheme, and has presented preliminary results for its performance operating in a narrowband scenario.

The potential improvements to be gained from using such a system have been clearly demonstrated:

- Linearised power amplifiers are now a viable proposition [3, 4], allowing the consideration of a highly bandwidth efficient linear modulation format;

- The use of a fully differential modem minimises receiver complexity, and produces the rapid response necessary to demodulate a relatively short frame of data at any given hop frequency;

- FEC coding of a fixed narrowband signal would provide a performance improvement but *could not* overcome the outage of data that occurs when the receiver remains in, or passes slowly through a deep fade. Only by Frequency Hopping can the length of such error bursts be minimised and coded out.

Measurements are currently underway at the University of Bristol in the characterisation of a narrowband hopped channel.

Future work includes an evaluation of the modem performance in a multi-user cellular environment, an investigation into the optimum linear amplifier strategy

and the building of a practical demonstration system for the Linear Frequency Hopped Modem.

6 Acknowledgements

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