Fitton, M. P., Nix, A. R., & Beach, M. A. (1997). Propagation aspects of frequency hopping spread spectrum. In Proceedings of the 8th IEEE Personal and Indoor Mobile Radio Conference, Helsinki, Finland. (Vol. 2, pp. 640 - 644). Institute of Electrical and Electronics Engineers (IEEE). 10.1109/PIMRC.1997.631110

Link to published version (if available):
10.1109/PIMRC.1997.631110

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Propagation Aspects of Frequency Hopping Spread Spectrum

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Abstract

Frequency Hopping Spread Spectrum (FH-SS) has found a number of applications in both CDMA and TDMA cellular systems, wireless local loop, and wireless Local Area Networks. In this paper, the effect of FH-SS on mobile channel characteristics is evaluated. Employing propagation studies, statistical analysis and simulation models, it is shown that the frequency hopped channel displays improved characteristics when compared to the non-hopped case. The short term fading statistics are improved, which can be exploited to provide an overall increase in quality-of-service. The short-term statistics of the frequency-hopped channel are derived, enabling prediction of the performance of an FH system.

1 Introduction

Frequency Hopping Spread Spectrum (FH-SS) has been receiving a great deal of attention for a variety of applications in the field of wireless communications. The GSM worldwide digital standard incorporates frequency hopping to improve performance and ease frequency planning requirements [1]. Furthermore, the nature of the frequency-hopped channel is applicable in other areas, such as Special Mobile Radio [2], wireless local loop, and wireless Local Area Network technology [3]. In particular, Slow Frequency Hopping Code Division Multiple Access (FH-CDMA) has been found suitable as an air interface technique for flexible third generation wireless networks [4].

The hopping parameters associated with an FH-SS system, such as hop rate and system bandwidth, are defined. The implications of these parameters are explored, in terms of providing optimum performance with coding and interleaving, or an Automatic Repeat Request scheme. In Slow Frequency-Hopped Spread Spectrum, a number of symbols are transmitted on each hop frequency. The performance of a Forward Error Correction (FEC) coding scheme can be maximised by interleaving the data, and transmitting each symbol of the codeword on a different hop frequency, affording inherent *codeword diversity*. The interleaving/de-interleaving operation randomises the position of the errors, and improves the likelihood of the coding scheme correcting the errors which are present.

In Automatic Repeat Request (ARQ) schemes, when a particular frame is detected as corrupted, then that frame is retransmitted. The nature of the frequency-hopped channel is highly suited to the application of an ARQ scheme [5]. Provided the hopping statistics are appropriate, the system will exhibit uncorrelated fading between hop frames, rendering the channel effectively *memoryless* over hop boundaries. Consequently, it is likely that any packet retransmission will experience uncorrelated channel statistics.

Theoretical and practical investigations of the frequency hopped mobile channel are employed in this paper to characterise the impact of hopping parameters on overall statistics. In particular, the relationship between hop rate and short-term channel parameters is explored, and the implications of a limited system bandwidth are evaluated. Furthermore, mathematical expressions governing the short-term statistics of the frequency-hopped channel are derived, enabling prediction of the overall performance of an FH system. A more detailled analysis of these parameters is defined in [6]. This analysis is biased towards provision of a third generation wireless network with Frequency Hopping CDMA, supporting a flexible set of services in a variety of indoor and outdoor environments. However, the hopped channel statistics developed here are equally applicable to other frequency hopping systems.

1.1 Measurement Techniques

A campaign of frequency hopping propagation measurements was undertaken in an urban environment in the city of Bristol, at 1.823GHz [7]. The transmitter, with a half-wavelength dipole antenna, was placed on approximately 300m from the measurement site, with no line-of-sight component and a *street-canyon* type environment. The mobile receiver operated at a constant Doppler frequency of approximately 20Hz, over a 100m section. The coherence bandwidth of the channel was recovered from received data, and corresponds to 1040 kHz for a threshold of 0.5, and 250 kHz for a threshold of 0.9 [7].

Furthermore, a simulation study was undertaken, to characterise the narrowband frequency-hopped channel. To accomplish this, a Rayleigh channel model was employed as an approximation to the real narrowband channel statistics.

2 Hopping Parameters

2.1 Number of Hop Bins

The number of hop frequencies (or "hop bins") available for use is determined by the overall system bandwidth available, and the separation between bins. In the case of an FEC scheme, if the codeword length exceeds the number of hop bins, it then becomes necessary for more than one symbol to be transmitted on a given frequency, resulting in a performance degradation in the coding scheme.

2.2 Hop Rate

The *hop rate* is used to characterise the number of transitions between frequencies which occur each second. This parameter impacts on overall performance in two main criteria. First, the hop rate will influence the instantaneous channel parameters, such as mean fade duration and level crossing rate [8]. Furthermore, the hop rate affects the trade-off between interleaving depth and throughput delay in a hopped system. If the modem is not hopping at a fast enough rate, the maximum interleaving depth which is allowed for intelligible voice transmission will not allow for sufficient uncorrelated symbols in the de-interleaved code word. This will then limit the effectiveness of any coding scheme which is employed. For optimal operation, it is necessary for the hop rate to be sufficient for all symbols in a given codeword to be transmitted on *different* hop frequencies, whilst observing the limitations on throughput delay.

2.3 Hop Bin Separation and Hop Pattern

The *hop bin separation* defines the frequency separation between adjacent frequencies in an FH system, and is particularly important in determining the degree of correlation between hop frames in a particular hop pattern. Insufficient hop bin separation will limit the improvement in instantaneous statistics associated with a frequency-hopped channel. For example, hopping between frequencies which exhibit highly correlated fading will result in little improvement in the mean fade duration over the non-hopped case.

Furthermore, if the separation between hop frequencies employed in a given codeword does not provide uncorrelated fading, the efficiency of any interleaving and FEC coding will be impaired. Ideally, all symbols should be transmitted on different frequencies, separated by greater than the coherence bandwidth [9].

3 Hopped Channel Statistics

Previous propagation work [7] has indicated that frequency hopping does not alter the long term statistics of the channel. In this section, the important short-term time domain statistics of a frequency-hopped mobile channel are analysed.

3.1 Channel Coherence Time

The *coherence time* is an important statistic in terms of predicting the performance of a mobile system, as it characterises the mean duration of any error bursts. The coherence time parameter indicates the time span over which the channel can be assumed to be constant. This is defined as the time offset required for the correlation coefficient to fall below a certain threshold (0.9 in this case).

If the hop frame duration exceeds the coherence time of the channel, the overall coherence time perceived for the frequency-hopped channel will be largely determined by the system hop rate. Provided that adjacent hop frequencies are separated by greater than the coherence bandwidth, fading at the different frequencies will be uncorrelated. Consequently, the hopped channel is unlikely to exhibit correlated fading over a hop boundary. Therefore, the coherence time is fixed at a level less than the hop frame duration.

Due to the difficulty of analysing the coherence time of a hopped channel, a simulation study of the mobile environment was undertaken, incorporating the effects of multipath fading and frequency hopping. In this model, a Rayleigh channel was employed, and the velocity and hop rate were altered. In all cases, the coherence time was calculated with a correlation threshold of 0.9, and a data window of greater than five wavelengths was employed. The parameter was averaged over a run of greater than 100 wavelengths. The simulation results are shown in figure 1, along with the predicted coherence time for a two-ray model [9].

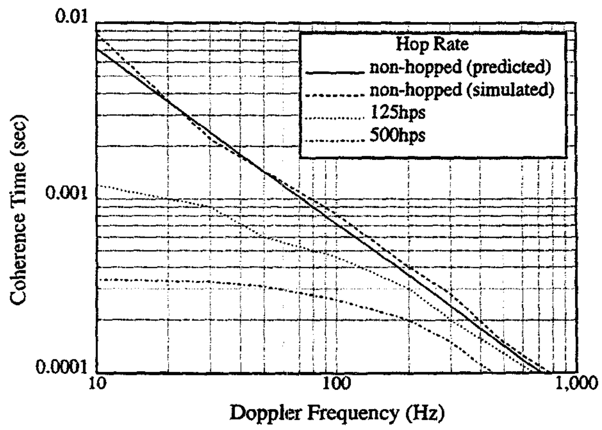

Figure 1: Hopped and Non-hopped Coherence Time

Examining the simulation results contained in figure 1, it can be seen that frequency hopping provides a significant improvement in the channel coherence time. At Doppler frequencies exceeding a certain level (say, 100Hz) hopping provides a small improvement. However, at lower Doppler frequencies, the effects of frequency hopping dominate the multi-path fading. Consequently, the hopped systems provide a coherence time which is largely independent of Doppler frequency. For example, a system operating at 500 hops per second exhibits a maximum coherence time of 0.34ms at low values of Doppler frequency. For a non-hopped system to demonstrate comparable performance, a Doppler frequency of approximately 211Hz would be required at all times (from figure 1). At the PCS frequency of 1.8GHz, this corresponds to a velocity exceeding 148km/h at all times.

This is an important result in the provision of high quality service, since outage duration will be determined by hop rate, rather than the Doppler frequency. It is demonstrated above that a non-hopped system can experience considerable periods of outage in a slowly changing channel. Conversely, a hopped system provides a coherence time which will not exceed a certain level, irrespective of the Doppler frequency.

3.1.1 Coherence Time Propagation Results

Propagation studies were employed to test the validity of the simulation results presented in section 3.1. Furthermore, the impact of correlated fading between adjacent hop frequencies is examined. Separating hop frequencies by at least the coherence bandwidth provides optimum, uncorrelated fading in a given codeword. However, it is problematic achieving this when the coherence bandwidth is large, for example in an indoor environment.

The coherence time of the hopped channel is shown in figure 2 for a variety of hop bin separations. A correlation threshold of 0.9 was employed, with a data window of approximately 5 wavelengths. The measured value without hopping was 4.3ms, at a Doppler frequency of approximately 20Hz. This agrees well with analysis of a two-ray model which predicts a coherence time of 3.6ms (figure 1).

The action of frequency hopping sets the coherence time of the channel at a level determined by the hop rate, approximately 0.3ms, in this case. As indicated in section 3.1 the value predicted by simulation is approximately 0.34ms, demonstrating good agreement. Examination of the coherence time statistic in figure 2 indicates that a hop bin separation considerably less than the coherence bandwidth can still provide significant performance enhancement.

3.2 Level Crossing Rate

The level crossing rate (N_R) [8] is defined as the number of positive going transitions of the signal magnitude with

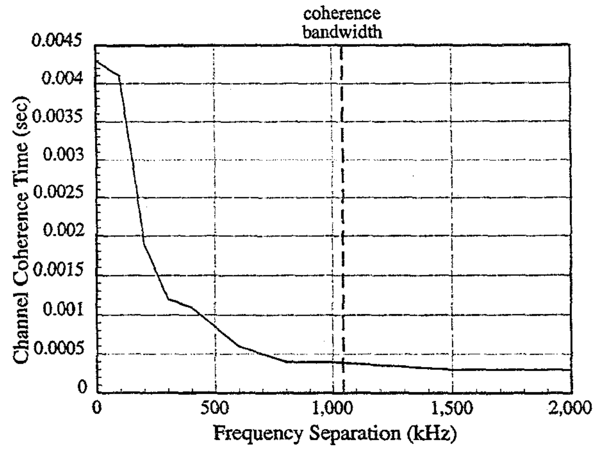

Figure 2: Hopped Channel Coherence Time (500 hps)

respect to a certain threshold. A high level crossing rate implies a rapidly changing channel, with problems arising from static nulls becoming statistically unlikely.

To simplify the analysis of level crossing rate in a frequency-hopped channel, it is assumed that the channel is constant over a hop period, so that the instantaneous characteristics due to channel variations can be neglected. For this assumption to be valid, it is necessary for the coherence time of the narrowband channel to exceed the hop frame duration. If the channel is not stationary over the hop period, the short term statistics which are experienced will be a combination of the effects of frequency hopping and multipath fading.

Employing the assumption that the channel is constant over a single hop period implies that the instantaneous characteristics due to channel variations can be neglected. Consequently, the level crossing rate can be calculated from the cumulative statistics of the channel envelope distribution. In this case a Rayleigh distributed channel is assumed [8]. The level crossing rate of a hopped channel is calculated from the channel statistics both before and after a hop boundary. Calculations are greatly simplified if the envelopes before and after the hop boundary are assumed to be uncorrelated. This condition will be satisfied if the hop frequency spacing exceeds the channel coherence bandwidth. The level crossing rate of a hopped channel is given by equation 1, where f_{hop} is the hop rate (in hops per second).

$$\begin{aligned} N_R &= f_{hop} P[r_1 < R] P[r_2 > R] \\ &= f_{hop} e^{-R^2/2\sigma^2} (1 - e^{-R^2/2\sigma^2}) \end{aligned} \quad (1)$$

3.2.1 Level Crossing Rate Propagation Results

Comparison of real and predicted statistics for non-hopped and hopped systems is shown in figure 3. The hopped system is operating at a rate of 500 hops per second, and adjacent frequencies are separated by 1.5MHz. The diagram indicates reasonable agreement between real and predicted data. In particular, the hopped performance is accurately predicted by equation1 at high magnitude thresholds. At lower values, the statistics of the channel dominate, and thus the measured hopping characteristic tends towards the non-hopped theoretical curve.

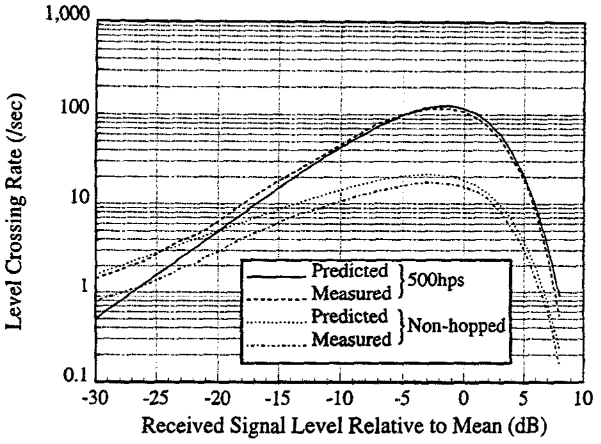

Figure 3: Predicted and Measured Level Crossing Rate

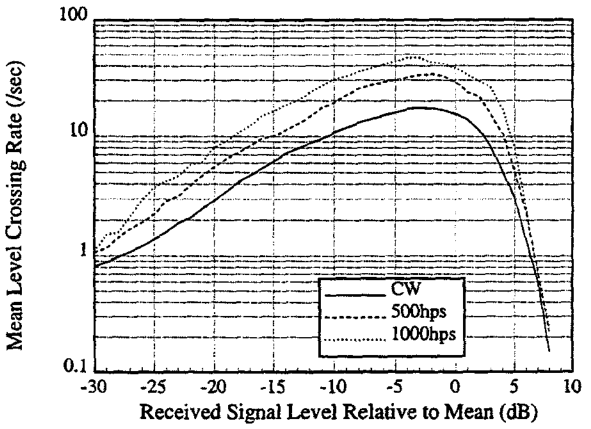

Figure 4: Level Crossing Rate (100 kHz spacing)

Further propagation measurements contained in figure 4 shows the improvement in level crossing rate resulting from increasing the hop rate. As predicted in section 3.2, performance is improved with increased hop rate, even at a relatively low hop bin separation of 100kHz. However, the initial performance improvement associated with hopping is not reflected by a continued increase in the hop rate. The trade-off between hardware complexity and improved channel characteristics becomes unfavourable as hop rate is increased too far.

3.3 Mean Fade Duration

Mean fade duration ($\langle T_f \rangle$) [8] is defined as the time spent with a magnitude less than a certain threshold in a particular fade. It is possible to relate fade duration to an indication of system quality, such as outage duration.

The mean fade duration of a frequency-hopped channel can be calculated in a similar fashion to level crossing rate with hopping. It is assumed that the channel is stationary over a hop frame, and that all hop frequencies exhibit uncorrelated fading. The fade duration is calculated from the cumulative statistics and the level crossing rate. The approximation to mean fade duration in a hopped channel is shown in equation 3 for a Rayleigh distributed channel.

$$\langle T_f \rangle = \frac{P[r \leq R]}{N_R} \quad (2)$$

$$= \frac{1}{f_{hop} e^{-R^2/2\sigma^2}} \quad (3)$$

Employing the expression for fade duration (equation 3), the statistics for a number of hop rates are plotted in figure 5. These results illustrate the improvement in fade duration associated with hopping. For example, a system operating at 500 hops per second will experience a fade duration relative to 10dB below the mean of approximately 2ms. This is a significant improvement over the non-hopped case, with a mean fade duration of 7ms at a Doppler frequency of 20Hz for the same threshold. Alternatively, for a non-hopped system to provide a similar mean fade duration would require a mobile velocity of at least 80km/h at 1.8GHz.

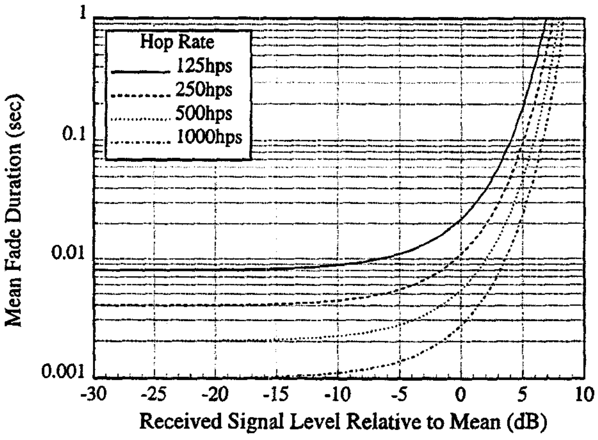

Figure 5: Frequency-Hopped Channel Fade Duration

3.3.1 Mean Fade Duration Propagation Results

The mean fade duration statistic of the hopped channel was calculated from propagation data. Figure 6 indicates the mean fade duration for both narrowband and hopped systems, with results obtained from theory and propagation data. There is good agreement between analytical and measured data. The hopped system in figure 6 is operating at 500 hops per second. Since the hop bin separation is set at 1.5MHz, and exceeds the coherence bandwidth, the fading is largely uncorrelated with the adjacent hop frequency.

Examination of the results contained in figure 6 indicates reasonable similarity between theoretical and propagation

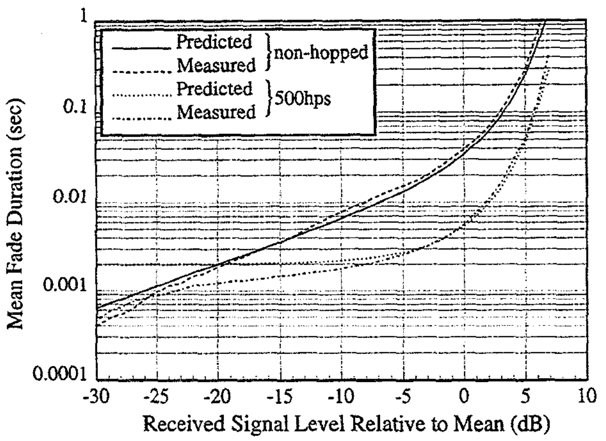

Figure 6: Predicted and Measured Mean Fade Duration

data, particularly at higher magnitude thresholds. At low magnitude levels, the innate channel statistics arising from multipath fading have more influence on composite performance. Consequently, the real hopped system performance tends towards the non-hopped case.

4 Conclusions and Implications

This paper explores the requirements and impact of the hopping parameters in a frequency-hopped system. Frequency hopping improves the instantaneous characteristics of the channel, whilst leaving the long term statistics unchanged [7]. The short-term statistics of the hopped channel are derived, and can be employed to predict the performance enhancement associated with frequency hopping. Ideally, a frequency-hopped channel will become effectively memoryless. Consequently, the efficiency of an interleaved FEC scheme will be maximised. Alternatively, the required retransmission time of an ARQ approach will be minimised.

Results obtained from propagation and simulation studies confirm the improvement in instantaneous channel statistics associated with frequency hopping, especially at low vehicle velocity. Increasing the hop rate improves the hopped channel characteristics, although results indicate that the improvement becomes less significant at higher hop rates. Consequently, the hop rate can be set at a feasible value (say, 500 hops per second).

Further propagation studies were applied to examine the necessity for uncorrelated fading between frames in the hop pattern. Propagation results indicate that, whilst it is advantageous to separate hop frequencies by greater than the coherence bandwidth, it is possible to reduce this stringent limitation. Results contained in figure 2 demonstrate that a frequency separation of approximately one half the coherence bandwidth can be employed with only a slight performance degradation. This is an important result, especially when limited spreading bandwidth is available, and it is unfeasible to provide large separation between hop channels. This is especially problematic in lightly dispersive environments, when the coherence bandwidth is large. For example in an indoor channel, it is not atypical to experience delay spread in the order of 50ns, and coherence bandwidth of 3MHz. If the hop separation is not required to be significant with respect to the coherence bandwidth, the limitations of system bandwidth become less stringent.

It is shown that frequency hopping sets the coherence time at a level determined by hop rate, and largely independent of Doppler frequency. This is important as the performance of ARQ and FEC schemes are linked to the coherence time, which characterises any error bursts which occur. Consequently, it becomes possible to characterise the performance of the transmission protocol, irrespective of mobile speed. Hence, frequency hopping finds many applications in wireless LAN [3] and wireless local loop technology.

5 Acknowledgements

The authors would like to thank the Engineering and Physical Sciences Research Council (EPSRC) for their financial support, and grateful acknowledge the facilities and guidance provided by Prof. J.P.McGeehan.

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