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Description	

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FORWARD LINK CAPACITY LIMIT OF CODED FFH/CDMA MULTIUSER MOBILE RADIOS

Indexing terms: Mobile radio systems, Codes and coding

The theoretical limit of the forward link (base to mobile) user capacity of fast frequency hopping code division multiple access (FFH/CDMA) mobile communication systems with error correction coding is investigated. The channel cutoff rate of coded FFH/CDMA channels is calculated and the optimal code rate that maximises the user capacity is determined. It is shown that with deletion-free transmission, the frequency efficiency of an FFH/CDMA channel coded at the optimal code rate is 47% higher than without coding.

Introduction: Since Goodman *et al.* presented a fast frequency hopping code division multiple access (FFH/CDMA) system and applied it to mobile/personal radio communications in 1980,[1] it has attracted much attention, and several performance improvements have been made.[2–4] In the FFH/CDMA system, the same frequency band is shared by many users and the transmitted symbol is extracted from the detection matrix indicating detected frequencies.

It was shown in Reference 1 that with deletion-free transition (all the errors are due to the interference from other users), 209 forward link (base to mobile) users transmitting 32 kbit/s speech (or data) could be accommodated with a bit error rate (BER) less than or equal to 10^{-3}, using a 20 MHz bandwidth. Reference 2 showed that by algebraically structuring the address sequence, the user capacity could be further increased by about 60%. Another power strategy is to use coding for error protection. Several practical codes suitable for FFH/CDMA channels have been proposed,[4,5] and their decoding performances have been analysed taking into account the desired signal deletions and interference insertions.

This Letter investigates the theoretical limit of the forward link user capacity of FFH/CDMA mobile communication systems with coding. The optimal code rate that maximises the forward link user capacity is then determined from the channel cutoff rate.

System model: Fig. 1 shows the system model to be analysed. The input bit stream to be transmitted is stored in a K bit shift register and segmented into K bit symbols. The K bit symbol sequence is then encoded into the coded symbol sequence of an (n, k) code defined over the Galois field of $GF(2^K)$. The coded symbol with symbol duration of T is then divided in time into L chips, each of which has a chip duration of T/L, and a random address sequence with rate L/T is added to the chip sequence with modulo-2^K. The 2^K frequencies are available for the forward link transmission, and one, corresponding to a chip modified by the random address, is transmitted over the chip interval. Prior to transmission, the chip sequence is fed to an OR logic circuit to accommodate the chips of other users hitting the same frequency slot. In the receiver, the received power of each of the 2^K frequencies is detected by an energy detector. Hard decision is used for detection. Both the transmitter and the receiver know the predetermined address sequence, and the address sequence is then added with modulo-2^K to the detection matrix which indicates received detected frequencies. The detection matrix is the input to the decoder, and the transmitted symbol is estimated and delivered to each user as the channel output.

Channel cutoff rate: The channel cutoff rate R_0 represents one of the upper bounds of the information bit rate. With bit rate $R(\le R_0)$ information bit/channel symbol, the input information can be transmitted with $BER \le e^{-N(R_0 - R)}$ where N is the code length (from this feature, communication with an information bit rate of $R \le R_0$ is referred to as 'reliable communication'). R_0 characterises only the coding channel, and is independent of the specific code employed.

Several of the formulas required to analyse the channel cutoff rate and user capacity are shown in Table 1 of Reference 1, and they will be used in this Letter without derivation. The average probability p_I of insertion due to interference is given by

$$p_I = [1 - (1 - 2^{-K})^{M-1}](1 - p_D) \qquad (1)$$

where p_D is the average deletion probability that the transmitted frequency is not detected by the energy detector. p_D is expressed as

$$p_D = 1 - \exp\left\{\frac{-\beta^2}{2(1+\Gamma)}\right\} \qquad (2)$$

where Γ is the average received signal to noise power ratio (SNR), and β is the threshold normalised with respect to the receiver noise power.[6] Another factor that affects the value of p_I is the false alarm probability p_F, which is expressed as a function of β, and was taken into account in Reference 1. However, because for large Γ values p_D is approximately expressed as a function of β^2/Γ, p_D can be set at any value independently of p_F. Thus, we assume $p_F = 0$.

The received dehopped frequencies are represented in the detection matrix Y including entries from the desired signal and interferers. If neither insertion nor delection occur, Y has a row corresponding to the transmitted 2^K-ary FSK symbol. Therefore, it is reasonable that the number of the entries in the ith row of the detection matrix Y is used as the metric for the ith symbol x_i of the 2^K-ary FSK.

The Chernoff bound of the metric difference $D(\lambda)$ is given by

$$D(\lambda) = E[e^{\lambda\{m(x_j, Y) - m(x_i, Y)\}} \mid x_i]_{x_i \ne x_j} \qquad (3)$$

where $m(x_i, Y)$ and $m(x_j, Y)$ denote the metric values for the ith and jth symbols of the 2^K-ary FSK, respectively; λ is the

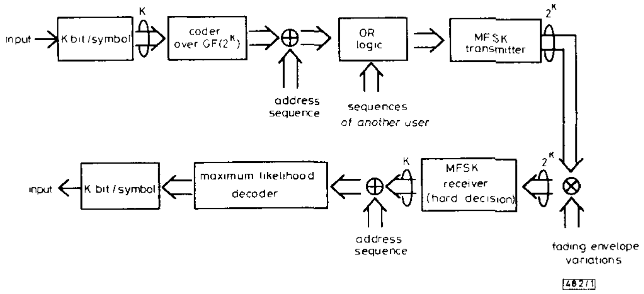

Fig. 1 *System model*

Chernoff parameter and E denotes ensemble average. Assuming that x_i is transmitted and that insertion and deletion occur randomly, $D(\lambda)$ becomes

$$D(\lambda) = \sum_{s=0}^{L} e^{-\lambda s}\binom{L}{s}(1 - P_D)^s P_D^{L-s} \sum_{t=0}^{L} e^{\lambda t}\binom{L}{t} P_I^t (1 - P_I)^{L-t} \qquad (4)$$

where $\binom{A}{B}$ denotes the binomial coefficient.

Because an FFH/CDMA channel is a symmetric channel, the channel cutoff rate R_0 is given by

$$R_0 = K - \log_2\{1 + (2^K - 1)D\} \qquad (5)$$

where

$$D = \min_{\lambda \geq 0} D(\lambda) \qquad (6)$$

Fig. 2 shows the calculated channel cutoff rate R_0 against the number M of users sharing the FFH/CDMA channel for $L = 19$ and $K = 8$ with p_D as a parameter. The minimum value of $D(\lambda)$ with respect to λ was determined numerically. It is found from Fig. 2 that R_0 approaches its maximum value of $8(=K)$ as M decreases. As p_D increases, M must be decreased further to ensure the maximum value of R_0. This is implied because R_0 is dominated by desired signal deletions rather than interference insertions.

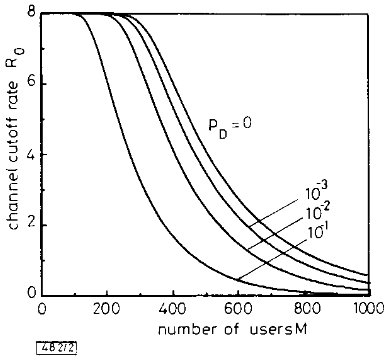

Fig. 2 *Channel cutoff rate against user capacity*
FFH/CDMA
$K = 8$
$L = 19$

Optimal code rate: The number of users can be increased by using a low rate code with large error correction capability. However, low rate codes increase the transmission bandwidth. Because of this tradeoff, there exists an optimum code rate that maximises the user capacity normalised by the code rate. The channel cutoff rate R_0 is expressed as a function of the number of the users M. Therefore, with coding rate $r = R/K$, if M satisfies

$$M \leq R_0^{-1}(rK) \qquad (7)$$

reliable communications are possible for all the M users via the coded FFH/CDMA channel having a bandwidth $1/r$ times larger than the original uncoded FFH/CDMA channel. Fig. 3 shows the number of the users normalised by the code rate Mr against code rate r for $L = 19$ and $K = 8$ with p_D as a parameter. It is found from Fig. 3 that for all values of p_D, Mr is maximised at a code rate of about 0·85. If $p_D = 0$, the coded FFH/CDMA channel can accommodate 308 users and reliable communications are possible, using the same bandwidth as that of the uncoded system. This user capacity is 1·47 times larger than that of the uncoded system with the same L and K values.[1]

Conclusion: The channel cutoff rate of the coded FFH/CDMA channel was calculated and the optimal code rate that maximises the user capacity was determined. It has been shown that the optimal code rate for 256-ary FSK with 19 hop/symbol is about 0·85. With deletion-free transmission, the capacity is 359 users (normalised capacity is 308 users), and reliable communication for all users is made possible by hard decision maximum likelihood decoding. This coded FFH/CDMA system is 47% more frequency-efficient than an uncoded system.

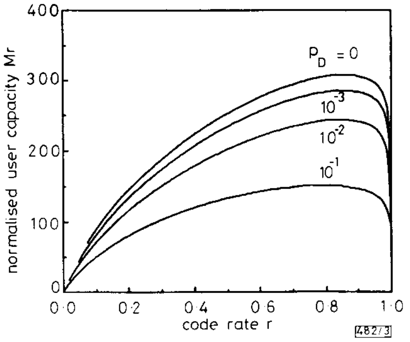

Fig. 3 *Normalised user capacity against code rate*
FFH/CDMA
$K = 8$
$L = 19$

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AUTOMATIC GAIN CONTROLLED OSCILLATING AMPLIFIER

Indexing terms: Amplifiers, Automatic control, Oscillators, Circuit design

An amplifier based on an injection-locked surface transverse wave oscillator is described and characterised. It is shown to exhibit automatic gain control. Its noise performance is discussed for the case of a 2 Mbit/s binary phase shift key signal.

Introduction: Traditional amplifier design techniques restrict the onset of oscillations by avoiding the corresponding loop phase and gain conditions. This is often accomplished by designing the circuit so that the k factor, a figure of merit that ensures unconditional stability, is greater than 1. If unconditional stability cannot be achieved, or if it requires too many compromises on the amplifier performance, then conditional stability is sought.[1]