TIME DIVERSITY FOR DIGITAL MOBILE RADIO

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Summary

Both the AMPS and TACS cellular communication systems use a "three out of five" majority-voting time-diversity scheme as well as a BCH (40,28) error correcting code for data transmissions over the forward control channel. This implies that for each 28 bits of information 200 bits need to be received. Although the combined diversity/coding system will ensure and maintain reliable transmissions, it utilises the channel very inefficiently.

A software investigation has been undertaken to assess the performance of signal transmissions over a Rayleigh fading mobile radio channel and to compare the effective utilisation of the channel by other time diversity techniques. It involved the simulation of a typical communication system using Manchester-encoded data with a bit rate of 8 kbits/sec, PSK modulation and ideal coherent demodulation. The diversity techniques investigated are voting, selection and combining with different signal strength weighting factors.

The results obtained show that postdetection linear combining (unity weighting factor) yields the maximum diversity improvement. It has also been shown that an improvement in the BER performance is possible without increasing the number of repeated words. Alternatively, is possible to reduce the number of repeats whilst maintaining the same BER performance. For example, the linear combining technique using three repeats offers the same BER performance as a five repeats voting scheme. This implies that the use of linear combining will improve the utilisation of the channel by a factor of 67 percent.

1. Introduction

Over the years system designers have tried to meet two main requirements for implementing large-scale mobile radio services [1]:

(i) The system must be capable of growing to serve many thousands of subscribers within a local service area.

(ii) The provision of service must not be contingent upon the continual enlargement of the allocated spectrum.

The cellular radio system concept, developed initially by Bell Systems Laboratories in the U.S.A., resulted in the Advanced Mobile Phone Service (AMPS). Subsequently it has been introduced, with modifications, into the U.K., where it is known as the Total Access Communications System (TACS). In cellular systems each base station provides two types of radio channel, a duplex control channel to set up calls and a duplex voice channel, which is used for telephone conversations. TACS and AMPS employ frequency modulation for transmission of speech and supervisory tones. Control data messages are, however, transmitted using binary Frequency Shift Keying (FSK) [2].

To combat the effects of fading and interference on signals transmitted over these channels, and because of the importance of having very reliable transmission over the control channel, all data words are encoded and repeated several times at the transmitter. A bit-by-bit, 3-out-of-5 majority vote is undertaken at the receiver and error correction is then performed using a BCH error coding scheme (40,28) bits in the forward direction and (48,36) in the reverse direction). This code structure, which uses 12 parity bits per word, is capable of correcting 1 bit error and detecting 4 bit errors [2-3]. To ensure reliable transmissions over the control channel, 200 bits have to be received for each 28 bits of information. This seems a very expensive solution in terms of channel utilisation.

Majority voting is a simple unweighted form of time diversity. It relies on the fact that if a given data bit is received at a time when the signal is in a fade, and is therefore likely to be received in error, this situation is unlikely to recur if the bit is repeated at later times. This paper reports the results of an investigation into more complicated forms of time diversity which attempt to improve channel utilisation whilst maintaining reliability. The investigation has been undertaken using a software simulator which offers good flexibility in changing the system parameters (number of repeats, word length, fading frequency, etc). The software simulation has been implemented for

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an 8 kbits/second data stream (the rate used in TACS) and PSK modualtion. It is well-known that PSK systems outperform coherent FSK systems by 3 dB [4]. Therefore, all the results presented in this paper could be used for coherent FSK systems.

Manchester-coded signalling has been used in the simulator rather than NRZ signalling because in real systems it facilitates the separation of the analog voice and the digital control signalling information and it contains better timing information [5].

2. Mobile Radio Channel

Propagation in mobile radio channels is dominated by scattering and reflection from natural and man-made obstacles so the received signal fluctuates or fades as the receiver moves. There are two approximately separable effects known as fast and slow fading. Fast fading is characterised by deep fades which occur within fractions of a wavelength and is caused by multiple reflections from buildings and other obstacles in close proximity to the vehicle. It is most severe in heavily built-up areas where the number of waves arriving from different directions with different amplitudes and phases is often sufficient to cause the signal amplitude to follow a Rayleigh distribution over relatively small distances. Slow fading is caused by variations in both the terrain profil and the general nature of the environment [6]. In the present work, only fast fading will be considered.

Rayleigh fading places the most severe limits on the quality of voice and data transmissions at UHF. As the vehicle moves through the fading signal pattern, interruption of voice transmission or losses of bits in data transmission can occur [7].

2.1 Diversity

Diversity techniques are very effective in counteracting fading effects. Space diversity is used for base station reception in TACS and experimental schemes have been used on mobiles at VHF and UHF. With sufficient spacing between antennas, the fast fading fluctuations of the signal received at one antenna tend to be independent of the fluctuations o the signal received on the second antenna. There are a number of other mechanisms for achieving independently fading signals: frequency diversity, angle (of arrival) diversity, polarisation diversity and time (signal-repetition) diversity.

Once it has been decided which method to use for obtaining independent signals (in the present work, time diversity), the next step is to select a method for processing the signals for the purpose of obtaining the best results. Alternatively to majority-voting, combining methods have been commonly identified: selection combining, maximal-ratio combining and equal-gain combining.

2.2 Time Diversity

The basic principle underlying time diversity is that each signal is transmitted several times. If the time intervals between the repeated bits of information are comparable with the reciprocal of the average fading rate, the fade levels associated with the various repetitions will be essentially independent and appropriate combinations of repetitions will give a diversity improvement. Of the various possibilities for achieving independent fading signals, time diversity has the major advantage over other systems of only requiring a single antenna (space diversity requires two or more antennas) and hence is simple to implement [8]. Obviously, time diversity requires information storage both at the transmitter and receiver. Such storage and diversity combination of the processed signal repetitions are particularly simple for digital transmissions.

2.3 The Majority-Voting Process

The process best known and most widely used for processing signals in the time diversity technique is majority-voting. The process assumes that each word is transmitted J times (J is usually an odd number). The received repeats must be aligned bit-by-bit and a majority-voting process is used to determine each valid message bit. The process is as follows: if (J + 1)/2 or more among the repeated bits are 1s, then the received bit will be assumed to be 1, otherwise it will be 0. The resulting majority-voted message words then constitute the improved message stream.

The improved bit-error rate, P_e' for J repeats with the majority-voting process, can be expressed as [9].

$$\langle P_e' \rangle = \sum_{k}^{J} C_k^J \langle P_e \rangle^k (1-\langle P_e \rangle)^{J-k} \qquad (1)$$

where $k = \dfrac{J+1}{2}$

$\langle P_e \rangle$ is the bit error rate in fading conditions (without diversity), and

$$C_k^J = \frac{J!}{(J-k)!k!} \qquad (2)$$

2.4 Combining Techniques

In principle, all the diversity processing techniques (selection, maximal ratio and equal gain combining) can be used with time diversity systems. However, since some kind of delay is required for processing the repeated messages, only postdetection processing seems appropriate for time diversity. There is little difference between postdetection and predetection combining when linear demodulation is involved [4].

The BER for a M-branch selection diversity system using PSK modulation is [10].

$$P_{eM} = \frac{1}{2} \sum_{k=1}^{M} \frac{(-1)^k C_K^M}{1+(k/\gamma_o)} \qquad (3)$$

where γ_o is the mean CNR on each branch.

3. Software Description

In order to investigate the performance of various diversity techniques a software simulation was implemented. A simplified model is shown in Figure 1. It was decided to generate a random data sequence because testing with this kind of input allows an accurate simulation of the real system. The binary phase-shift keying signal $V_{BPSK}(t)$ can be written, with no loss of generality, as

$$v_{BPSK}(t) = p(t) \cos \omega_o t \qquad (4)$$

where

$$p(t) = \begin{cases} +1 \text{ when a mark is transmitted} \\ -1 \text{ when a space is transmitted.} \end{cases}$$

The additive bandlimited Gaussian noise is given by

$$n(t) = x(t) \cos\omega_o t - y(t) \sin\omega_o t \qquad (5)$$

After low pass filtering, the signal output of a synchronous demodulator is

$$z_{BPSK}(t) = \frac{1}{2} [p(t) + x(t)] \qquad (6)$$

Thus the simulation deals only with the baseband transmission of signals. The modulator, in the simulation, encodes the data in Manchester format and then converts the new data stream to an analogue waveform by sampling each bit a number of times. In choosing a suitable sampling rate, two conflicting requirements have been taken into account: a high sampling rate allows the signal to be reconstructed precisely from its samples, whereas a low sampling rate increases the speed of computation. Hence, it was found appropriate to use 20 samples per bit.

The multiplicative Rayleigh fading signal was generated using N_o (N_o = 8) low-frequency oscillators with frequencies equal to the Doppler shifts ω_n (n=1,2,...,N_o), plus one oscillator with a frequency ω_m (refer to ref.[11] for detailed information).

The radio receiver contains an IF bandpass filter in order to reduce the noise power at the input of the demodulator. In the baseband case, however, an equivalent lowpass filter with the same 3 dB bandwidth was used. It has been stated in reference [12] that optimum system performance can be achieved with a bandwidth bit-rate ratio (BT) of about 1.2 in the case of a bandpass filter with a very sharp cut-off and about 1.0 for a filter with a more gradual roll-off. Therefore, a bandwidth bit rate BT = 1.0 was used together with a third order filter.

The optimum receiver for BPSK needs only to make a decision on the difference between two given alternatives based on an observation over a finite time interval. Hence a matched filter can be used for the detection of the difference between the two signals. In the simulation, the integration, associated with the matched filter, was replaced by a summation in which the 10 samples per bit were added. (The duration of 10 samples is one half the complete duration of the Manchester encoded data bit). The integrator output, indicated in Figure 1 as p[k], can be written as

$$p[k] = \sum_{s=1}^{10} y[n] \qquad (7)$$

The following ways of producing a combined output related to different weighting factors, were investigated.

(a) exponential

$$z = \sum_{k=1}^{M} e^{R[k]} p[k] \qquad (8)$$

(b) square

$$z = \sum_{k=1}^{M} [R[k]]^2 p[k] \qquad (9)$$

(c) square root

$$z = \sum_{k=1}^{M} \sqrt{R[k] p[k]} \qquad (10)$$

(d) linear

$$z = \sum_{k=1}^{M} R[k] p[k] \qquad (11)$$

(e) logarithmic

$$z = \sum_{k=1}^{M} \{\log R[k] + \text{factor}\} \quad p[k] \qquad (12)$$

For the equations (8-12) R[k] is the envelope of the Rayleigh fading signal at kT (T is the bit interval). p[k] is the output of the integrate and dump filter. M is the number of repeats. "Factor" (equation 12) is a real number which ensures that the expression {log{R[k]} +

factor} is always positive.

The different diversity schemes (a - e) are named corresponding to the weighting factor, e.g. diversity scheme (e) is named "logarithmic" because the weighting factor is equal to log R[k]. A decision as to whether a mark or a space has been sent can be made by checking the polarity of the combined output. If $z > 0$, a mark is assumed to be transmitted, otherwise a space is assumed to be transmitted.

4. Simulator Performance

The simulator has been validated by checking the error rates against SNR for both fading and nonfading signals. The results obtained are shown in Figure 2 and good agreement between the experimental and the theoretical results is apparent. Figure 3 shows the improvement obtained from the simple majority voting process for 3 and 5 repeats per word respectively. Considering the BER = 10^{-3} level as an example, a 13 dB improvement is obtained by using a 3-repeat transmission and 17 dB from the use of 5 repeats. Figure 3 also shows the theoretical results which can be obtained using equation (1). The theoretical and experimental results were found in general to be in good agreement.

Results giving BER as a function of SNR for the combining techniques with 3 repeats are shown in figure 4. It is clear that the combining technqiue using a linear weighting factor ($n = 1$) for the Rayleigh envelope gives marginally the best performance when compared to the other combining techniques. In view of the fact that the actual mobile receivers provide, as one of their outputs, a voltage proportional to the signal strength, on a logarithmic scale (RSSI - received signal strength indicator), it seems that the logarithmic combining scheme could be implemented with less complexity, and it can still provide a significant improvement in the BER performance. Although the performance of the exponential combining technique is not plotted in figure 4, its performance was similar to the other schemes.

Figure 5 compares the combining techniques with majority voting and selection diversity for the 3-repeats case. It is clearly seen that all combining techniques outperformed majority voting and selection diversity. In figure 6 the results obtained for linear combining are compared with the results obtained for majority voting. It is easily seen that 2 repeats linear combining was equivalent to 3 repeats majority voting. 3 repeats linear combining and 5 repeats majority voting were also equivalent. Figure 7 shows the BER against the vehicle speed for a twice-repeated word and a number of time diversity schemes. Although the best performance was obtained for a vehicle speed in excess of 40 km/h, it is observed that a significant improvement can be achieved at 5 km/h.

5. Conclusion

The aim of this work was to investigate some alternative techniques for transmission of data over the control channel of a cellular radio system, in order to optimise the channel utilisation and maintain the reliability of the system. This investigation has been undertaken using a software simulator because it provides a great deal of flexibility. The software simulation was implemented for Manchester encoded data with a bit rate of 8 kbits/sec and PSK modulation.

The main conclusion of this study is that linear combining (unity weighting factor) yields the maximum diversity improvement. This linear combining method with two repeats produces a BER performance similar to that of majority voting with 3 repeats. The same linear combining scheme with 3 repeats performs as well as majority voting with 5 repeats.

It is important to note that the performance of the system depends on the velocity of the mobile, i.e. is a function of the correlation between the repeated words. For a 63 bits word and 8 kbit/sec data rate the best performance was found for velocities equal to or greater than 40 km/h. However, for velocities as low as 5 km/h a significant reduction (around 10 times) in the error rate was also observed.

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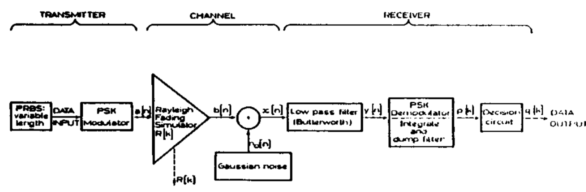

Figure 1 Simulated communication system

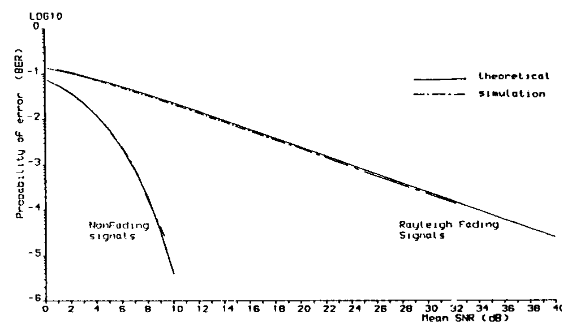

Figure 2 Theoretical and simulated BER for nonfading and fading signals

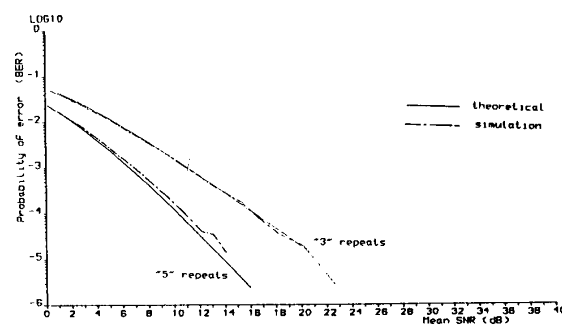

Figure 3 Comparison of improved BER for PSK systems using majority voting process

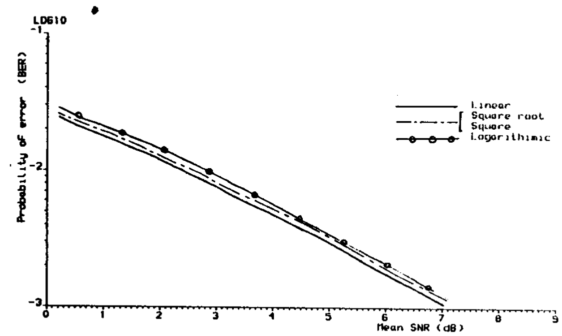

Figure 4 BER vs. SNR For 3 repeats combining techniques

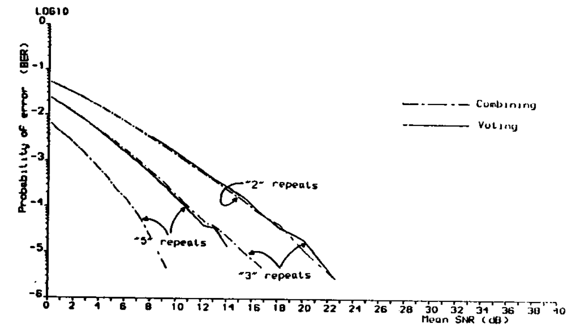

Figure 6 BER: Linear combining 2, 3 and 5 repeats, and majority voting 3 and 5 repeats

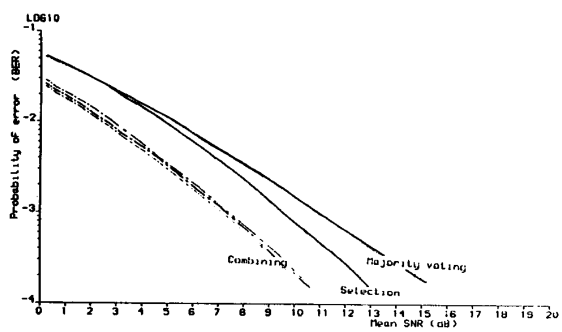

Figure 5 BER vs. SNR comparing combining techniques with majority voting and selection (3 repeats)

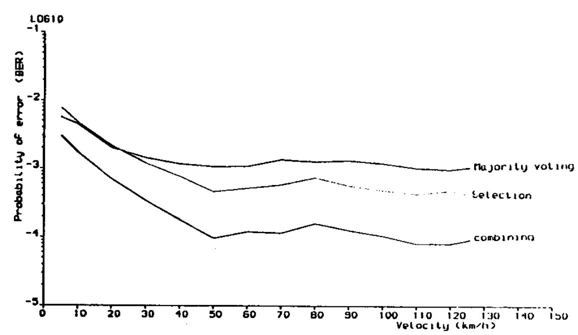

Figure 7 BER versus velocity (2 repeats, SNR: 10.6 dB)