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DATA TRANSMISSION OVER ADAPTIVE HF RADIO COMMUNICATION SYSTEM USING SELECTIVE REPEAT PROTOCOL

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Abstract. The paper presents throughput analysis results obtained by analyzing the application of Selective repeat, and Go-back-N protocols, to data transmission over an HF radio channel in a real communication system with a practical goal to attain optimal system utilization by maximizing system throughput in the presence of fading. An expression for the optimal information block length has been derived. The communication system is based on a multitone modem. The analysis has been performed for a channel with additive Gaussian noise and a Rayleigh fading channel. System throughput has been analyzed for 75-3600 b/s parallel data modem, for M-ary DPSK modulation schemes, without coding and with Reed- Solomon (6,4) and Golay (24,12) error correction coding, with several levels of in-band diversity.

Key words: Data transmision, selective repeat protocol, HF radio, DPSK.

1. Introduction

The HF radio medium occupies the 1.6 - 30 MHz frequency band and is valuable and very suitable for information transmission. The geographical distances at which communication is possible range from points of optical visibility distances, in case of surface waves, to very distant sites, in case of transmission with the reflection of electromagnetic waves from the Earth's ionosphere. The physical instability of the ionosphere gives rise to numerous effects that aggravate the use of this communication medium. First of all, the effect of the multipath propagation of electromagnetic waves results in frequency dispersion and in the occurrence of frequency and time selective fading. In addition, impulsive and other types of noise of high level and

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interference with the remaining stations arise at the receiving end. All these factors, and the fact that transmission proceeds over a non-stationary path, make the transmission over this type of medium rather complex. Because of this fact, communication systems and equipment are very complex.

To overcome efficiently the undesirable effects arising during transmission, various coding algorithms, modulation schemes channel equalization and adaptive control schemes have been employed. In addition, various diversity transmission techniques and data interleaving techniques are also used. It is evident that satisfactory transmission conditions can be achieved only by using all the available techniques depending on the instantaneous state of medium.

From the available literature one can note that the field of adaptive radio transmission is still open and that all elements of transmission are a subject of research. A number of papers treat the problem of the dynamic adaptation of the Automatic Repeat Request (ARQ) protocol [14], depending on the radio channel state and knowledge of the bit error probability at the receiving end. One variant of an adaptive ARQ system intended for a HF radio system, and applicable to channels subject to random and packet errors, is described in [2]. The system employs the interleaving method for error decorrelation, and uses two types of linear codes and ARQ transmission strategy. One code performs the detection and the other the correction of errors. The simulation results give a considerably higher system throughput than that obtained by classical ARQ schemes. One variant of a system with sequential decoding and a partial retransmission ARQ strategy is presented in [7]. The use of Forward Error Correction (FEC) and ARQ strategy is treated. By using a Pre-Repeat technique in a Go-back-N ARQ protocol, for error prediction, the data throughput can be improved over conventional protocols [10]. Paper [1] treats the problem of determining the system parameters in HF FSK radio links by determining the optimum parameters of modulation index and filter that provide the best transmission performance. Paper [6] addresses the problem of calculating the bit error probability of M-ary DPSK over a Rayleigh fading channel. Expressions for bit error probabilities in the case of diversity reception are given. In [4], it is shown that, in low Signal-to-noise ratios, decision erasures correcting decoding, based on a block coding, has lower error probability than Trellis Code Modulation. Some concepts of modern system planing in HF communications, is presented in [5].

This paper addresses the practical problem of the optimal utilization of a real communication system aimed at achieving a maximum system throughput in the presence of fading, by analyzing the effects of some parameters on system throughput. These parameters are: data transmission protocol, optimization information block length, the choice of modulation process and the effect of error correction coding in the data transmission. The communication system model is defined in Sec.2, and expressions for the throughput efficiency for a system using Selective repeat protocol are given in Sec.3. The expression for an optimum information block length, i.e., for a maximum system throughput, is derived in Sec.4. Transmission over a low-speed Rayleigh fading channel is analyzed in Sec.5, in which the expression for system throughput, and throughput efficiency attained by a dynamic choice of the optimal block length are derived. Sec 6. contains the numerical results of analysis, from which optimal sets of parameters can be found for achieving communication system adaptivity, i.e., a maximum system throughput. Conclusions are given in Section 7. A list of references are listed in Sec. 8.

It should be emphasized that at present the interest to multitone modems is growing dramatically. In addition to the conventional applications for the fading radio channels, this type of data transmission is now the basis for implementation of high speed Internet connections in the huge area of digital subscriber lines (xDSL services). For example, the recent ITU standard for ADSL (Asymmetric DSL) is based on DMT (Discrete Multitone) technology. Therefore the considered paper results will be applied not only for HF radio channel, but also for new area of xDSL services.

2. Communication System Description

We consider the communication system model, presented in Fig. 1, which includes an ARQ processor, a commercially available multitone modem and radio channel simulation. The ARQ processor uses the selective repeat transmission protocol and permits the choice of the length of data transmission blocks. The modem allows the choice of data transmission rates, with binary (2- DPSK), four-level (4-DPSK) and eight-level (8-DPSK) modulation procedures. In addition, Reed-Solomon (6,4) and Golay (24,12) error correction codes can be connected.

The parameters that characterize the performance of ARQ systems are (i) the throughput efficiency η, defined as the ratio of the number of information bits delivered to the total number of bits transmitted and (ii) the quantity referred to as system throughput (information transmission rate) R, equal to the product of line transmission rate $C(b/s)$, and throughput efficiency η.

At the receiving end, from the modem receiver and ARQ processor we obtain received data as well as data about the instantaneous received signal quality, i.e. about the instantaneous signal-to-noise (S/N) ratio of received signal. Based on these data, at the receiving end a decision is made about the optimal set of transmission parameters for the instantaneous state of the medium in order to maximize the instantaneous throughput value. System adaptation to the instantaneous state of the medium is provided in this way. Control data are sent over a return channel, of identical transmission characteristics, to the transmit end. As the fact that control blocks have shorter length than information blocks, the probability of the block error in returned channel can be ignored in comparison with block error in direct channel.

Two radio channel models have been accepted for system analysis: the model of a channel with additive Gaussian noise and the model of a low-speed Rayleigh fading channel. The analysis proceeds as follows. Appropriate equipment is used to measure the transmission error probability as a function of the S/N ratio, for different types and rates of data transmission. After that, the throughput value is calculated. The maximum throughput limits of the communication system under consideration are obtained in this way. The results obtained in this way are used to determine the zones in which transmission is optimal.

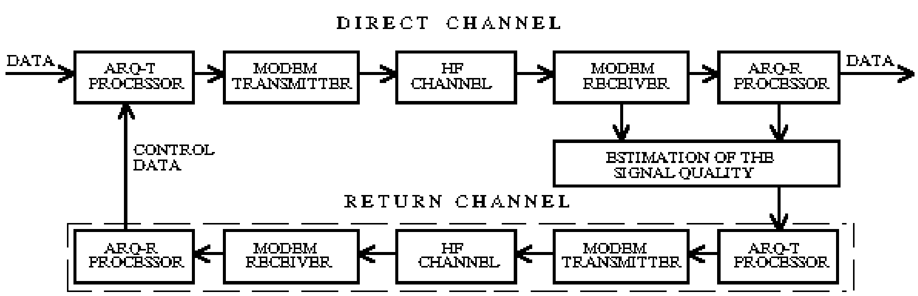

Fig. 1. A block diagram of communication system.

The communication system throughput has been analyzed using the commercially available HF modem TE233P, realized with multitone M-DPSK modulation. The analysis also applies to other modems realized on the basis of the same transmission and with transmission types compatible with the given [8].

3. ARQ Transmission Protocols

3.1 Selective repeat protocol

In the Selective repeat protocol, the information source is assumed to emit messages continuously and to have at disposal, at any moment, a sufficient number of messages to be transmitted. In addition, in this strategy the message is divided into fixed information blocks of length $(B-r)$, where B denotes a block length, and r the redundancy in every block, heads, routing information and CRC data. Transmission starts by sending the first block, and then all the remaining message blocks are transmitted. During the transmission, the transmit end is informed by a returning channel about the blocks that have not been received correctly. At the end, the incorrectly transmitted blocks are emitted again. If necessary, the procedure continues until the whole message is transmitted.

The throughput efficiency, for selective repeat protocol [13], is given by the expression

$$\eta_{sr} = \frac{(B-r)(B-P_B)}{B}, \tag{1}$$

where B is the block-length, and P_B is the block error probability.

3.2 Go-back-N protocol

The Go-back-N protocol also assumes that there is a sufficient number of messages at the transmit end to be sent. There are two approaches in this case. In the first, when an incorrect block has been received, the transmit end emits again the incorrectly transmitted block continuously, till it has been received correctly and then goes back to emitting the next non emitted block. In the second approach, the transmit end returns to emitting the incorrectly received block continuously, till it has been received correctly and then continues emitting all the following blocks regardless of whether they have already been sent correctly. In both approaches, retransmission is delayed.

Delay is expressed by the number of equivalent blocks, N , i.e., by the number of blocks that can be transmitted during a specified delay. If N equals 1, returned information has been received during the emission of subsequent block. In both cases, the throughput efficiency is [9]

$$\eta_{gn} = \frac{B_r}{B\{1+P_B[E+K(N-1)]\}}, \tag{2}$$

where $E = 1/(1 - P_B)$ is the expected number of retransmissions per block. In the first case, $K = 1$, and in the second $K = 2$. Assuming that $K = 1$ and $N = 1$, equation (2) reduces to equation (1). A simple analysis of the relation (2) shows that Selective repeats gives the greater throughput efficiency than any variant of Go-back-N protocol.

The transmission protocols described assume the existence of a return channel over which information from the receive end is sent to the transmit end error free.

4. Maximization of the System Throughput

The system throughput is defined as the product of the transmission rate and throughput efficiency

$$R = C\eta, \tag{3}$$

where C stands for the nominal data transmission rate for the corresponding operation mode as listed in Table 1.

In further analysis we will accept the Selective repeat and the first variant of Go-back-N protocol ($K = 1$). By taking the expression for the information transmission rate according to relation (2), relation (3) becomes

$$R = C\frac{B - r}{B} \times \frac{1 - P_B}{1 + (N-1)P_B(1 - P_B)}. \tag{4}$$

This is the expression for the system throughput in the case when fixed block-lengths are transmitted. The block error probability is given by expression [3]

$$P_B = 1 - (1 - P_e)^B, \tag{5}$$

For the small value of bit error probability, and in case of independent transmission errors, the block error probability assumes the following simpler form

$$P_b \simeq BP_e, \tag{6}$$

where P_e is the BER. Under conditions $d\eta/dB = 0$, and the case of $N = 1$, the expression for the optimal block-length is given by [11]

$$B_{opt} = \sqrt{\frac{r}{P_e}}. \tag{7}$$

As mentioned, Selective repeat gives the greater throughput efficiency than Go-back-N, so the further analysis will be based on Selective repeat protocol.

Substituting expression (7) into (5) and then into the expression for system throughput, in the case of Selective repeat, and multiplying it by the transmission rate, finally obtain the expression for the maximal system throughput

$$R_{max} = C\frac{\sqrt{\frac{r}{P_e}} - r}{\sqrt{\frac{r}{P_e}}}(1 - P_e)^{\sqrt{\frac{r}{P_e}}}. \tag{8}$$

As can be seen, the maximum system throughput depends on the instantaneous choice of the optimum block-length. The problem remaining to be solved is to determine the bit error probability. The bit error probability can be determined from the demodulated signal by estimating the mean deviation of received signal phase from the nominal. Another way would be to determine the error probability from the protocol directly. On the basis of the number of incorrectly received blocks, short-term statistics of block error probability is determined. From this statistics, and knowing the block-length, the bit error probability can be determined by applying relation (5). In this case we obtain the value of the so-called "equivalent probability" of error, i.e., the "equivalent S/N ratio". For the block error probability given by relation (6), we obtain the approximate expression for calculating the bit error probability

$$P_e = \frac{P_B}{B}. \tag{9}$$

Substituting relation (10) into (9) gives the following practical expression for the maximum system throughput

$$R_{max} = C\frac{\sqrt{\frac{rB}{P_B}} - r}{\sqrt{\frac{rB}{P_B}}}(1 - \frac{P_B}{B})^{\sqrt{\frac{rB}{P_B}}}. \tag{10}$$

This expression obtained from the block error statistics permits the maximum system throughput to be determined.

5. System Throughput in Rayleigh Fading Channels

So far we have studied the system behavior at the level of an instant or, in other words, the system behavior in short times intervals. Now, we will start considering phenomena occurring in long time intervals and assuming they are affected by Rayleigh low-speed fading. By definition, the mean system throughput is

$$\overline{R} = C\overline{\eta}. \tag{11}$$

The mean throughput efficiency coefficient is obtained by averaging over all the values of S/N ratio in Rayleigh fading

$$\overline{\eta} = \int_0^\infty \eta(\rho^2) W_r(\rho^2) d\rho^2, \tag{12}$$

where ρ^2, the S/N ratio, is defined as the ratio of signal power to the mean power of white Gaussian noise in the frequency range 0-3000 Hz.

In Rayleigh fading, the distribution of signal-to-noise power ratio is given by [12]

$$W_r(\rho^2) = \frac{1}{\rho_m^2} e^{-\frac{\rho^2}{\rho_m^2}}, \tag{13}$$

where ρ_m^2 is the mean S/N ratio.

Substituting relations (8) and (13) into (12), and then into (11), gives the expression for the throughput for fixed block lengths

$$\overline{R} = \int_0^\infty R(\rho^2) W_r(\rho^2) d\rho^2. \tag{14}$$

After appropriate substitutions, this expression becomes

$$\overline{R} = \int_0^\infty C\frac{B-r}{B}[1-P_e(\rho^2)]^B \frac{1}{\rho_m^2} e^{-\frac{\rho^2}{\rho_m^2}} d\rho^2. \tag{15}$$

In the case of block length optimization, the expression for the throughput would be obtained in the following way. Substituting (10) and (13) into (12), and then into (11), gives the expression for the throughput

$$\overline{R}_{max} = \int_0^\infty R_{max}(\rho^2) W_r(\rho^2) d\rho^2. \tag{16}$$

After appropriate substitutions, this expression becomes

$$\overline{R}_{max} = \int_0^\infty C \frac{\sqrt{\frac{r}{P_e(\rho^2)}} - r}{\sqrt{\frac{r}{P_e(\rho^2)}}} [1 - P_e(\rho^2)]^{\sqrt{\frac{r}{P_e(\rho^2)}}} \frac{1}{\rho_m^2} e^{-\frac{\rho^2}{\rho_m^2}} d\rho^2. \qquad (17)$$

Numerical integration of expressions (15) and (17), when using the measured results of transmission error probability, gives the value of throughput in the presence of Rayleigh fading.

6. Numerical Results of Analysis

6.1 Error probability diagrams

The transmission error probability as a function of S/N ratio at modem receiver input has been measured in laboratory conditions. The S/N ratio at receiver input is defined as the ratio of the mean signal power to the mean power of white Gaussian noise in the frequency range 0-3000 Hz. Different operation modes and different data transmission rates have been taken into account in the measurement. The basic data for the measured operation modes and transmission rates are given in Table 1.

Table 1.

Operation mode	Nominal-transmission rate $C(b/s)$	M-DPSK modulation	In-band diversity	Error correction-code
1.	3600	8-DPSK		
2.	2400	4-DPSK		
3.	2400	8-DPSK		Reed-Solom.(6,4)
4.	1200	4-DPSK	×2	
5.	1200	4-DPSK		Goley(24,12)
6.	600	2-DPSK	×2	
7.	600	4-DPSK	×2	Goley(24,12)
8.	600	2-DPSK		Goley(24,12)
9.	300	2-DPSK	×4	
10.	300	4-DPSK	×4	Goley(24,12)
11.	300	2-DPSK	×2	Goley(24,12)
12.	150	2-DPSK	×8	
13.	150	4-DPSK	×8	Goley(24,12)
14.	75	2-DPSK	×16	
15.	75	4-DPSK	×16	Goley(24,12)

Fig. 2 shows the error probability curves for operation modes 1-5 (Table 1.), i.e., for 3600, 2400 and 1200 b/s data transmission rates. Operation mode 3 assumes the use of Reed-Solomon error correction code and operation mode 5 the use of Golay (24,12) code. Fig. 3. shows the error probability curves for operation modes 6-15, i.e., for 600, 300, 150 and 75 b/s transmission rates. Operation modes 7, 8, 10, 11, 13 and 15 assume the use of Golay error correction coding.

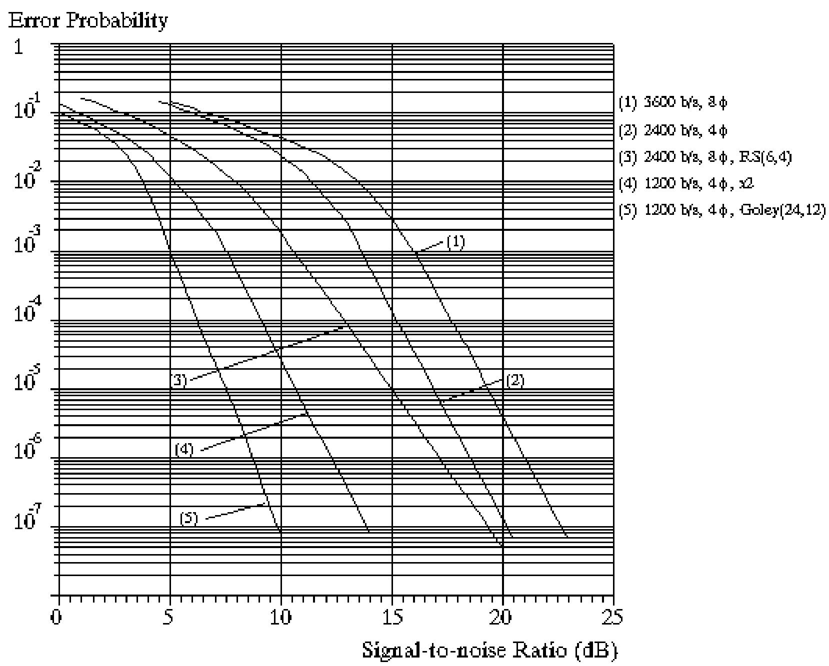

Fig. 2. Results of measuring the bit error probability as a function of S/N ratio for higher data transmission rates

6.2 System throughput in the presence of additive Gaussian noise

As can be seen, a decrease in data transmission rate permits the transmission with a significantly less favourable, i.e., smaller values of S/N ratio. In addition, it can also be seen that the transmission rate decrease to 75 b/s permits the transmission with a satisfactory error probability value $< 10^{-3}$

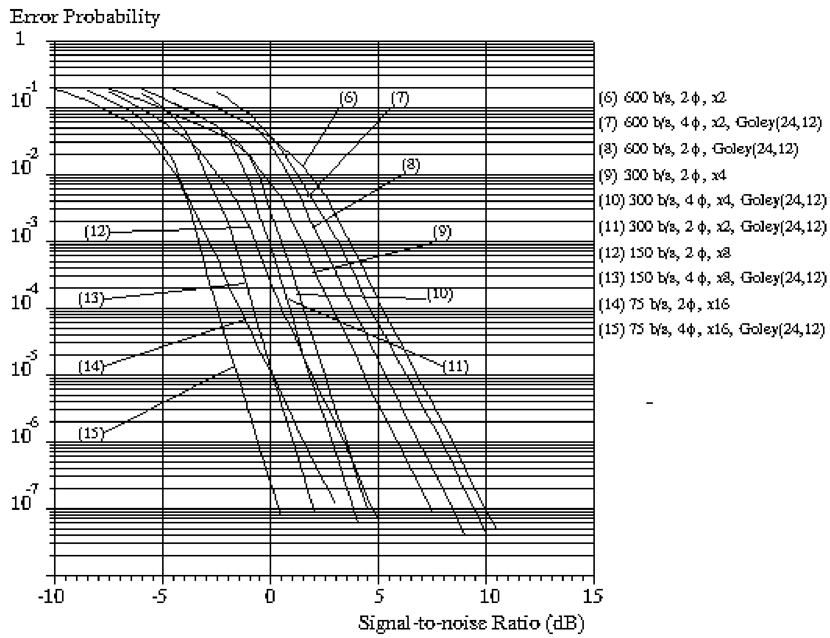

Fig. 3. Results of measuring the bit error probability as a function of S/N ratio for lower data transmission rates

at a S/N ratio equal to -4 dB. This, practically, means that transmission is achievable even in the case when the signal level is lower than the noise level by 4 dB. Thus, very robust radio communication systems are in question.

The use of error correction coding results in a decreased transmission error probability. As can be noted from Figures, the transmission with 4-DPSK modulation procedure and with error correcting codes gives a lower error probability than the transmission with 2-DPSK without error correction coding. This indicates that the use of error correcting codes provides code gains in the S/N ratio that are larger than the losses resulting from the increase in the number of levels of the modulation procedure. An appropriate gain in the S/N ratio is also obtained by the use of in-band diversity.

Fig. 4. illustrates the dependence of throughput value on the S/N ratio, at 3600 b/s transmission rate, for different values of fixed block length. The same diagram also shows the throughput function for variable block length values and it represents the envelope of the curves with fixed block lengths. Similar characteristics may also be realized for the remaining oper-

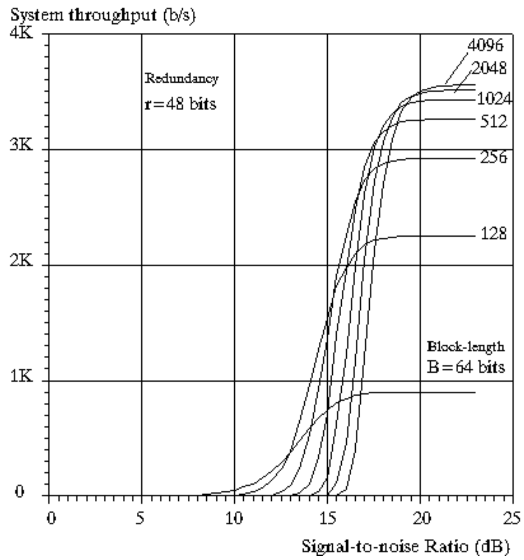

Fig. 4. Throughput as a function of S/N ratio for fixed block lengths

ation modes and transmission rates.

As can be seen from these diagrams, the throughput value depends essentially on block length. Small block length values provide a wider range of S/N ratio values for which communication is possible, measured at the level of 50 % of the maximum throughput value for a given type of transmission, but the maximum throughput value remains relatively small. Increasing block length values narrow the application range and shift it to higher S/N ratio values but increase the maximum throughput value. These facts suggest the existence of an optimal block length which maximizes the system throughput. The value of optimal block length is given by relation (7) and it is a function of redundancy and transmission error probability.

Figs. 5 and 6 illustrate the dependence of throughput on the S/N ratio in data transmission with optimal block lengths.

In a general case, better results are obtained in case of transmission with error correction codes than without them. It is therefore recommended to use this coding whenever possible. In addition, a considerable gain in throughput is provided by the use of diversity which permits the transmission to be achieved even with an unfavourable S/N ratio, i.e., when the noise intensity is of a higher level than that of the signal.

The maximum throughput value is achieved with 3600 b/s transmission

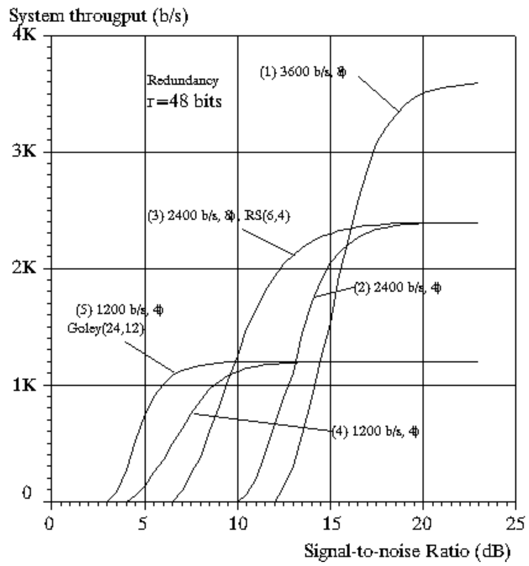

Fig. 5. Throughput as a function of S/N ratio for variable block lengths at higher transmission rates

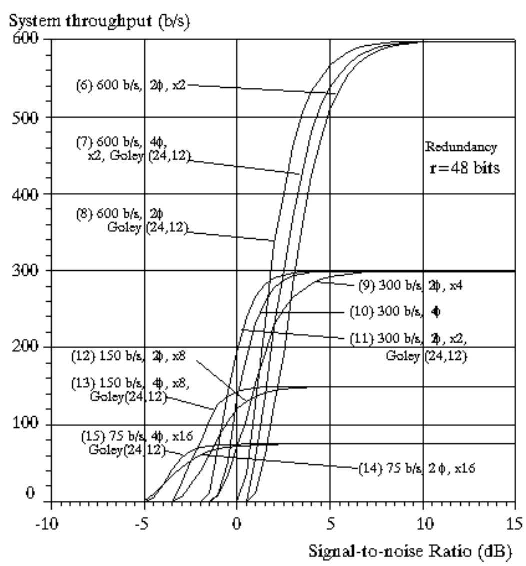

Fig. 6. Throughput as a function of S/N ratio for variable block lengths at lower transmission rates

rate (curve 1) only at S/N ratios higher than 16 dB. At the point of 16dB, the error probability is near 10^{-3}, so the optimal block length is 219 bits, with 48 bit of redundancy. As the control blocks in particular system are much shorter, the assumption that returned channel are error free, is valid.

In the zone below this value, 2400 b/s transmission rate gives the most favourable results with the use of error correction coding (curve 3). The zone in which it is the most favourable is the range 10-16 dB. The most favourable transmission with the nominal transmission rate of 1200 b/s (curve 5), with error correction coding, is achieved in the zone 4.5-10 dB. The most favourable transmission with the nominal transmission rate of 600b/s (curve 8), with error correction coding, is achieved in the range 1.5-4.5 dB. The most favourable transmission with the nominal transmission rate of 300 b/s (curve 11), with error correction coding, is achieved in the range -0.5 to 1.5 dB. The most favourable transmission with the nominal transmission rate of 150 b/s (curve 13), with error correction coding, is achieved in the range -2.5 to -0.5 dB. Finally, the most favourable transmission with the nominal transmission rate of 75 b/s (curve 15), with error correction coding, is achieved in the range below 2.5 dB.

The most favourable zones in which, at particular data transmission rates, maximum throughput values are achieved have been determined in this way. For transmission rates 2400-75 b/s, the changing in transmission parameters had to be done when error probability reached the value $2 \cdot 10^{-3}$. The minimal optimal block length in those cases was 155 bits.

6.3 System throughput in the presence of Rayleigh fading

The mean S/N ratio is the basic quantity characterizing Rayleigh fading channels.

Fig. 7. illustrates the dependence of throughput on the mean S/N ratio for 3600 b/s transmission rate and for different values of fixed block lengths. The same diagram also shows the throughput function for variable block length values. Similar characteristics may also be realized for the remaining operation modes and transmission rates.

As can be seen from the diagram, the throughput value depends essentially on block length. For small block length values, the maximum throughput is limited to a relatively low value. The increase in block length increases the final system throughput value but decreases the zone of the mean S/N ratio in which higher throughput values are achieved. In any case, there

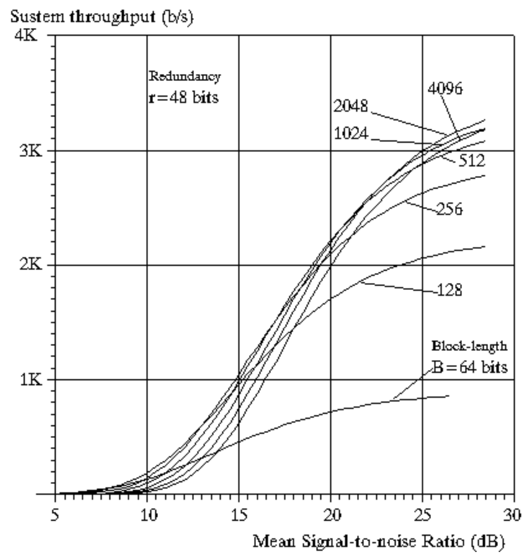

Fig. 7. Throughput in Rayleigh fading channels as a function of the mean S/N ratio for fixed block lengths

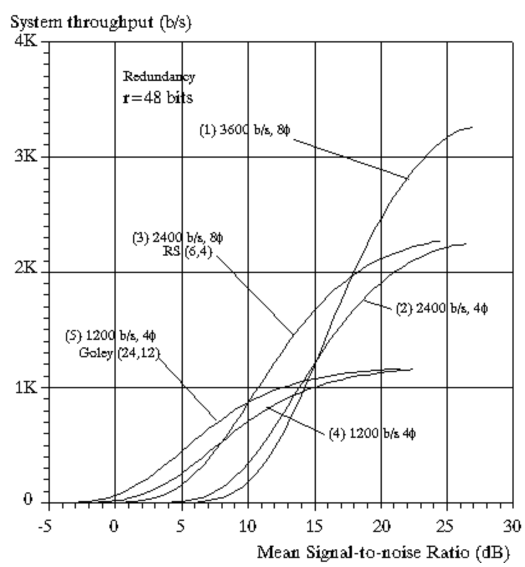

Fig. 8. Throughput in Rayleigh fading channels as a function of the mean S/N ratio for variable block lengths at higher transmission rates

exists an optimal block length value that maximizes the throughput value.

Figs. 8 and 9 illustrate the dependence of throughput on the mean S/N ratio when optimal block lengths are transmitted. Transmission with error correction codes in Rayleigh fading channels gives more favourable results than transmission without these codes. In addition, one can also note a certain gain in throughput resulting from the use of in-band diversity.

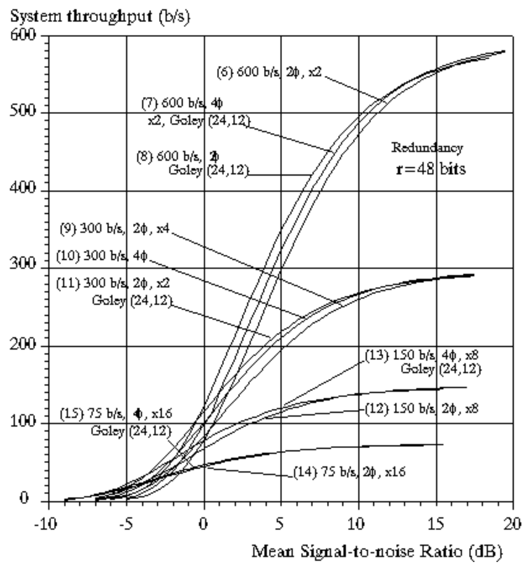

Fig. 9. Throughput in Rayleigh fading channels as a function of the mean S/N ratio for variable block lengths at lower transmission rates

The maximum throughput value is achieved with 3600 b/s transmission rate (curve 1) only at mean S/N ratios higher than 17.5 dB. In the zone below this value, 2400 b/s transmission rate gives the most favourable results with the use of error correction coding (curve 3). The zone in which it is the most favourable is the range 10-17.5 dB. The most favourable transmission with the nominal transmission rate of 1200 b/s (curve 5), with error correction coding, is achieved in the zone 3-10 dB. The most favourable transmission with the nominal transmission rate of 600 b/s (curve 8), with error correction coding, is achieved in the range 0-3 dB. The most favourable transmission with the nominal transmission rate of 300 b/s (curve 11), with error correction coding, is achieved in the range -4 to 0 dB. The most favourable transmission with the nominal transmission rate of 150 b/s (curve 13), with error correction coding, is achieved in the range −6 to −4 dB. Finally, the most favourable transmission with the nominal transmission rate of 75 b/s (curve 15), with error correction coding, is achieved in the range below −6 dB.

The most favourable zones in which, at particular data transmission rates, maximum throughput values are achieved have been determined in this way. As can be seen from the diagrams, at higher transmission rates the boundaries of the zones of S/N ratios with a maximum throughput value are clearly distinguishable, whereas at lower transmission rates these boundaries are hardly discernible, i.e., these zones are concentrated in the S/N ratio range from −6.5 to 0 dB.

7. Conclusion

The paper presents the results of the analysis of various transmission protocols for the purpose of selecting the optimal transmission parameters, relevant for achieving a maximal system throughput in HF radio systems. It is shown that the Selective repeat provides the most favourable value of throughput efficiency. The analysis has covered the transmission involving fixed block lengths and the transmission involving a variable, optimal block length that maximizes the system throughput. It has been shown that the introduction of variable block lengths increases the system throughput. In addition, it has also been shown that, within the entire set of the possible transmission modes of a parallel modem, there exists a set of a few transmission modes that provide a higher throughput in wider ranges of the S/N ratio and that these are the transmission types involving error correction coding. These transmission types give better results for both Gaussian and Rayleigh fading channels. The boundaries of S/N ratios in which certain transmission types provide a maximum throughput value have been determined. It has also been shown that a decrease in transmission rate, with error correction coding, permits data transmission under unfavourable conditions, when the system input signal level is lower than that of the noise. The results described in this paper offer the elements required for realizing an appropriate data transmission protocol that provides a higher system throughput in comparison with classical, nonadaptive protocols. This protocol includes the function of monitoring the S/N ratio at the receiving end and determining the optimal transmission type for given conditions and the optimal block lengths. This function is implemented continuously in accordance with changes occurring on the transmission path.

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