

**Transmission of SBC Speech Via 16-Level QAM
Over Mobile Radio Channels**

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Abstract

The transmission of 16 kb/s sub-band coded (SBC) speech via Reed-Solomon (RS) coding and 16-level QAM modulation over Rayleigh fading channels is addressed. An average locking AGC method is described, which requires no side-information to be transmitted. Different RS coders were used to code the SBC bits depending on their perceptual significance and their position in the Gray coded QAM words. Proposed schemes operating at 5.3 and 6.7 kbaud yielded near toll quality speech for channel SNRs in excess of 29 and 22 dB, and delays of 180 and 144 ms, respectively, for vehicular speeds of 30 and 60 mph.

1. Introduction

Although the current cellular mobile radio systems use analogue modulation techniques to transmit speech signals, the next generation systems [1],[2] will use digital modulation in either an FDMA or a narrow band TDMA format. With the advent of small sized microcells [3],[4], which will enable the use of linear power amplifiers and encouraged by the results of Steele et.al.[5]-[7] we embarked on the investigation of a spectrally efficient toll quality 16-QAM/AGC/RS/SBC system shown in Fig.1.

2. 16-Level QAM

In 16-level QAM the bit stream is suitably assembled into 4-bit symbols and each symbol is transmitted by a carrier wave having a unique amplitude and phase. The duration of each symbol determines the bandwidth of the QAM signal. Figure 2 shows a 16-level constellation where each cross represents the position of the phasor relative to the intersection of the axes marked I (for inphase) and Q (for quadrature). Gray codes

01, 00, 10 and 11, are assigned to levels 3d, d, -d and -3d, respectively for both the I and Q components to minimize the BER after demodulation. Representing the two bits of the inphase code by i_1, i_2 and the quadrature code by q_1, q_2 , the 16 QAM phasors are assigned a unique 4-bit word by interleaving the most significant and least significant bits of its two component signals forming the word i_1, q_1, i_2, q_2 .

Observe that in the process of demodulation, the positions of the bits in the words associated with each point in the QAM constellation have a profound effect on the probability of them being in error. In the case of the two MSBs the distance from a demodulation decision boundary of each AM component is 3d for 50% of the time, and d for 50% of the time; assuming that each phasor occurs with equal probability. The 'average protection distance' for these bits is 2d. By contrast, the two least significant bits (LSB) are always at a distance of d from the decision boundary and consequently the average protection distance is decreased by 50% compared to the MSBs. Thus we may consider our QAM system to have two data sub-channels, namely, that associated with the MSBs and that associated with the LSBs. We will refer to the former as a class I and the latter as a class II sub-channel. Clearly bits transmitted via the class I sub-channel are received with a lower probability of error compared to those bits in the class II sub-channel. Since the Gaussian and Rayleigh fading channels constitute the best and worst cases of the real mobile radio environment, we investigate the performance of our system over both of them.

2.1. Performance over Gaussian channel

Consider independent pseudo random binary sequences (PRBS) to be applied to the class I and class II sub-channels of the 16-level QAM constellation shown in Figure 2. The QAM signal is transmitted over an additive white Gaussian noise (AWGN) channel to a receiver that maintains perfect carrier recovery. For the least significant bits (LSB) of the Gray

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coded QAM words, i.e., those associated with the class II sub-channel, a bit error will occur if the noise exceeds d in one direction or $3d$ in the opposite direction. Dismissing the latter as insignificant, the probability of a class II bit being in error is

$$P_{II} = Q\left(\frac{d}{\sqrt{N_0/2}}\right) = \frac{1}{\sqrt{2\pi}} \int_{d/\sqrt{N_0/2}}^{\infty} \exp(-x^2/2) dx \quad (1)$$

and N_0 is the one-sided spectral density function of the Gaussian channel noise. As the average symbol energy of the 16-level QAM constellation is

$$E = 10 d^2, \quad (2)$$

we may write

$$P_{II} = Q\left(\sqrt{\frac{E}{5N_0}}\right) \quad (3)$$

For the class I sub-channel data, the probability of a bit error is

$$\begin{aligned} P_I &= \frac{1}{2} Q\left(\frac{d}{\sqrt{N_0/2}}\right) + \frac{1}{2} Q\left(\frac{3d}{\sqrt{N_0/2}}\right) \\ &= \frac{1}{2} \left[Q\left(\sqrt{\frac{E}{5N_0}}\right) + Q\left(3\sqrt{\frac{E}{5N_0}}\right) \right] \quad (4) \end{aligned}$$

The probabilities P_I and P_{II} as a function of E/N_0 are given by Equation (3) and (4) and displayed in Figure 3. Also shown is the probability of bit error for the 16-level QAM system as

$$P = (P_I + P_{II})/2 \quad (5)$$

Simulations gave nearly identical curves of P_I , P_{II} and P . The essential feature of the AWGN performance is that there is only a small advantage in using the class I sub-channel over using the class II sub-channel.

2.2 Performance over Rayleigh channel

We have analytically computed the BER of both the class I and class II sub-channels over Rayleigh fading channels, but due to lack of space this piece of theory is the subject of a companion paper to follow. We have found that the analytical results exactly coincide with those obtained from simulations using Rayleigh fading envelope sampled at 16 k samples/s for a vehicle travelling at 30 mph. By changing the sampling we were able to produce a range of envelopes for different vehicle speeds. The propagation frequency was 900 MHz. The other parameters conformed to those in the AWGN experiments.

In contrast to the AWGN channel where there

was little difference in BER performance between the two sub-channels, the difference became profound when the transmissions were over a Rayleigh fading channel. The results are presented in Figure 3. Whereas the BER decreased with increasing channel SNR, reaching 10^{-2} at 20dB and 10^{-3} at 30dB, for the class I sub-channel; the class II sub-channel was virtually independent of channel SNR and above 0.15. Thus the class I sub-channel did have an adequate performance for channel SNRs in excess of 20dB, while the class II sub-channel was unusable.

3. Average Locking AGC Method For QAM

Our approach to enhance the BER performance is to implement some degree of channel equalisation in the form of an automatic gain control (AGC). By decreasing the BER to an acceptable level, practical error coding techniques can be successfully deployed. Our AGC arrangement used a method referred to as average locking based on the continuous time averaging of the received QAM phasors.

This method computes the arithmetic mean square value \hat{R} of the previous k phasors and compares this average with the expected mean square value E of the 16-level QAM signal. As all symbols are transmitted with equal probability, E is $10d^2$. The received phasor R to be demodulated is scaled by the ratio of these values, namely,

$$G = E / \hat{R} \quad (6)$$

and demodulation follows.

The performance of the average locking system was investigated for various channel SNRs over a range of k values. Since it did not significantly alter the BER for the class I sub-channel, our attention was focused on the class II sub-channel performance. Figure 4 shows the variation of BER as a function of k when the channel SNR was either 20 or 30 dB and the vehicular speeds ranged from 15 to 120 mph. These simulations were performed such that for each sample of the Rayleigh fading envelope a QAM sample was transmitted. The transmission rate was therefore 16 kbaud. Thus a curve in the figure corresponding to 120 mph was equivalent to one at 60 mph when the transmission rate was 8 kbaud. We observed that for each channel SNR there was an optimum value of k for each speed. For the lower SNR the optimum k varied over a wide range with speed, but the corresponding variation of BER was relatively small. At the higher SNR the variations of the BER with the optimum k were much larger, but the range of k was smaller. Operating with channel SNRs in excess of 20

dB, we decided to use a fixed k of 4 because when the SBC/QAM system operates at 6.7 kbaud with vehicular speeds of 30 and 60 mph, the equivalent curves in Figure 4 would be curves at 72 and 144 mph.

4. Sub-band Coded Speech Via 16-Level QAM Over Rayleigh Fading Channels.

The lowering of the BER by our AGC technique is sufficient for channel coding to further decrease the BER to a value where toll quality speech can be obtained for SBC speech transmitted via 16-level QAM over Rayleigh fading channels. For the bursty nature of these channels Reed-Solomon coding is appropriate. Experiments showed that the application of an RS(120,60) code with 8 bits per symbol to the class II sub-channel decreased the BER to slightly below the BER of the class I sub-channel. Because of this finding we conceived two strategies for mapping the SBC data on to the QAM constellation. One method arranges for the class I and class II sub-channels to be independent and of differing quality. The acceptable perceived speech quality is achieved by mapping perceptually important SBC bits to the higher performance sub-channel. The second strategy uses techniques to render the class I and class II sub-channel BER performance to be nearly identical. In such a situation there is no advantage in bit mapping of the SBC data.

4.1. The sub-band codec

The sub-band coder [7] produces eight sub-bands each of 500 Hz bandwidth by means of a quadrature mirror filter (QMF) bank. Each sub-band signal is encoded using Jayant's one-word memory quantizer whose number of bits is either 0, 2, 3 or 4, depending which signal classification is used. The classification, given in the first column in Table 1, is determined by the distribution of spectral energy in the speech signal. Each input speech sample results in 15 bits being produced from the sub-band quantisers and yields a rate of 15 kb/s as each sub-band is sampled at 1 kHz. The bit allocation is reviewed every 6ms, and the classification adopted is represented by a 2-bit word that is repeated twice for channel protection. Thus a SBC frame consists of $(6 \times 15) + 6 = 96$ bits with a duration of 6ms.

4.2. The 5.3 kbaud system

Even with the application of AGC the BER of the class II sub-channel remains unacceptably high. By contrast the class I QAM data sub-channel has a BER that is sufficiently low for transmission of the least significant bits

(LSB) in the SBC data frame. By RS coding the bits passing through the class II sub-channel its BER can be decreased below that of the unprotected class I sub-channel. However, the effect of RS coding also results in an increase in the bit rate, and as class I and II sub-channels must each have two bits in each Gray coded constellation point it follows that the information throughput on the class II channel is reduced. It is essential to RS code the classifier bits, and it is desirable that the most significant bit (MSB) of each coded sub-band signal in the SBC frame be RS coded. However, there are too many MSBs to be RS coded. For example, in the presence of either an intermediate or unvoiced SBC frame, 66 bits in each 96-bit frame would need to be error protected. The weakest RS code with sufficient error correction capability to improve the BER of the class II sub-channel to an acceptable level is the RS(120,60) code operating in 'Galois Field' GF(256). This code fixes the data capacity of the class II sub-channel at 1/2 of that of the class I sub-channel allowing 32 bits of each 96-bit frame to be transmitted via the higher performance route. The resultant data throughput is 21.3 kbit/s for 16kbit/s speech. This is equivalent to a symbol rate of 5.3 kbaud using the 16-level QAM system.

As erroneous reception of the classifier information bits can cause severe degradation of the recovered speech they are always transmitted via the RS coded, class II sub-channel. The MSBs of the code words from up to four sub-bands are also mapped onto class II locations in order to optimise performance. These sub-bands are chosen to be those where the main proportion of the speech energy is likely to be distributed. The mappings are displayed in Table 1. For the voiced speech classification we see that the solid vertical lines separate the sub-bands which increase in frequency from left to right as 0 - 0.5, 0.5 - 1.0, 1.1 - 1.5, 1.5 - 2.0, and 2.0 - 2.5 kHz. Also see Table 1. The number of columns within each sub-band represent the number of bits used to quantise each sub-band signal. Each row has 15 bits representing the SBC output for each input speech sample. The six rows constitute the SBC output for the frame, although the first bits 1 to 6 in the frame (representing the classification) are not shown. The numbers in Table 1 indicate the bit position in the frame, where bit 96 is the last in the frame. We see that for voiced speech the LSBs for the sub-band 0.5 to 1.0 kHz are 11, 26, 41, 56, 71, 86, while the MSBs are 14, 29, 44, 59, 74 and 89. The bits assembled for RS coding are those encircled.

In the simulations two speech sentences were SBC encoded. For every frame the appropriate sub-table (a), (b), (c) or (d) in Table 1. was

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used and the encircled bits RS(120, 60) coded. The class I and the RS coded class II sub-channels were transmitted via 16-level QAM over a Rayleigh fading channel. Upon demodulation, RS decoding, and SBC decoding, the speech signal was recovered and the segmental SNR computed. The variation of segmental SNR as a function of channel SNR (E/N_0) is displayed in Figure 5 for vehicular speeds of 30 and 60 mph. For near toll quality speech the channel SNR should exceed 30 dB, and less than 1.5 dB separates the channel SNRs when the mobile speed was doubled.

4.3. The 6.7 kbaud system

The philosophy behind this system is to add channel coding to both sub-channels in such a way that the BER of each is not only low enough to carry toll quality SBC speech, but also nearly matched. As a consequence no special mapping strategies are required.

In the absence of RS coding, but in the presence of average locking AGC, the BER for the class II sub-channel is approximately three times that encountered in the class I sub-channel. Therefore we select the RS code for the class II sub-channel to have three times the error correcting capability of the RS code used for the class I sub-channel. Because the total protected data rate passing via each of the sub-channels must be equal, the redundancy of the code used with the class I sub-channel to that used in the class II sub-channel must be an integer ratio. Furthermore, it is convenient to arrange that a single RS coded frame be composed of an integer number of SBC frames. The channel codes selected to meet these criteria were RS(120,96) for the class I sub-channel and RS(120,48) for the class II, both having 8-bit symbols. Thus bits in successive SBC frames were sorted into two contiguous streams by placing every third bit in stream A and the others in stream B. For every 12 frames, i.e., 1152 bits, 768 bits in stream A were RS(120, 96) coded to yield the class I sub-channel data. The class II sub-channel data was composed of 384 bits from stream B that were RS(120, 48) coded.

The segmental SNR of the speech signal as a function of E/N_0 is shown in Figure 5 for vehicular speeds of 30 and 60 mph. Near toll quality speech can be obtained when the channel SNR is several dBs less than for the 5.3 kband system. More importantly, the optimum performance of the SBC can be achieved for channel SNRs in excess of 25 dBs.

5. Conclusion

The transmission of 16 kb/s SBC speech via 16-level QAM has been investigated. With the aid of an average locking AGC system and a mapper employing Reed Solomon coding we were able to achieve near toll quality speech at transmission rates of 6.7 kbaud and 5.3 kbaud. The overall delays for the 6.7 and 5.3 kbaud systems were 144 and 180 ms, respectively. It is anticipated that these delays can be reduced by using shorter RS codes and deploying symbol interleaving. The channel SNR needs to be in excess of 22dB, a number easily realisable in the small cell system to be used in the next generation of digital mobile radio systems. Thus near toll quality speech from a relatively simple SBC codec can be transmitted over mobile radio channels within a bandwidth of 10 kHz.

References

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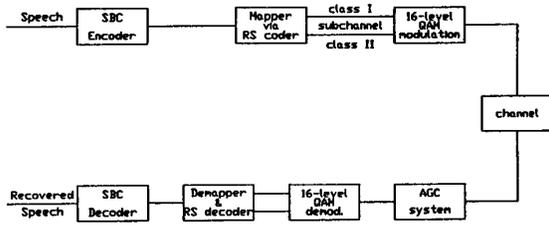


Figure 1. Systems block diagram.

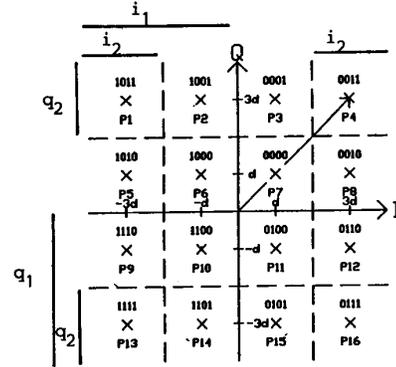


Figure 2. 16-level QAM constellation.

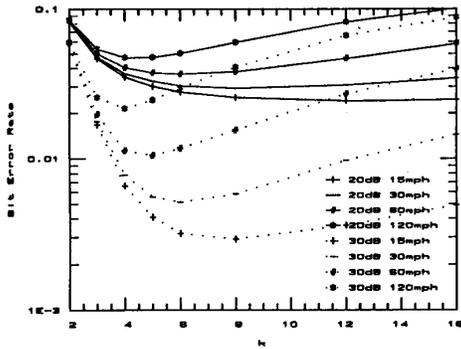


Figure 4. BER as a function of parameter k for class II sub-channel when average locking AGC was used. The transmissions were over Rayleigh fading channels.

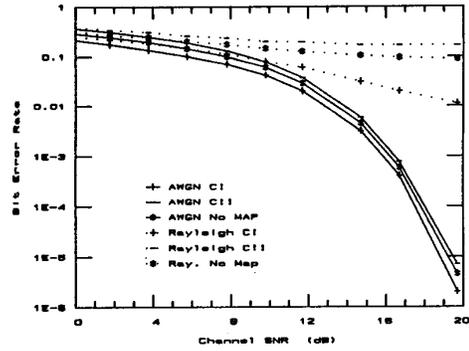


Figure 3. Variation of BER as a function of channel SNR for class I and class II sub-channels when the transmissions were over Gaussian and Rayleigh fading channels.

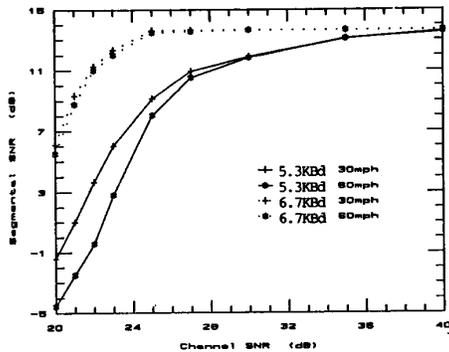


Figure 5. Variation of segmental SNR of the speech signal as a function of channel SNR for the 5.3 and the 6.7 kbaud systems for vehicular speeds of 30 and 60 mph.

5.3 baud system
The bits for RS coding in the SBC frame

CLASSIFICATION	SUB-BANDS IN kHz				
	0.0 - 0.5	0.5 - 1.0	1.0 - 1.5	1.5 - 2.0	2.0 - 2.5
VOICED (a)	7 8 9 (10)	11 12 13 (14)	15 16 (17)	18 (19)	20 (21)
	22 23 24 (25)	26 27 28 (29)	30 31 (32)	33 (34)	35 36
	37 38 39 (40)	41 42 43 (44)	45 46 (47)	48 (49)	50 51
	52 53 54 (55)	56 57 58 (59)	60 61 (62)	63 (64)	65 (66)
	67 68 69 (70)	71 72 73 (74)	75 76 (77)	78 (79)	80 81
	82 83 84 (85)	86 87 88 (89)	90 91 (92)	93 (94)	95 96
ONLY CIRCLED NUMBERS LISTED IN SUB-TABLES (b) - (d)					
INTERMEDIATE (b)	10 13 15 17 19 25 28 30 32 40 43 45 47 55 58 60 62 64 70 73 75 77 85 88 90 92				
UNVOICED (c)	8 11 14 17 19 26 29 32 38 41 44 47 49 53 56 59 62 64 71 74 77 83 86 89 92 94				
VOICE BAND DATA (d)	10 13 14 18 21 25 29 33 36 40 44 48 51 55 58 59 63 66 70 74 78 81 85 89 93 96				

Table 1. SBC bit-allocation and embedded RS coding scheme

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