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Variable Rate QAM for Mobile Radio

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***Abstract*—Quadrature amplitude modulation (QAM) schemes which vary the number of modulation levels in accordance with the mobile radio fading channel variations are investigated. Important parameters considered are the fading rate and the block size used. We describe how the adaptive QAM modems can be employed and consider their use in a DECT-like TDD packet structure. System performance in the presence of cochannel interference is also considered.**

Simulations show that the variable rate system has about 5 dB improvement in channel SNR over a fixed 16-level QAM system for BER's between 10^{-2} and 10^{-5} and channel SNR's between 25 and 40 dB.

I. INTRODUCTION

QAM transmissions over Rayleigh fading mobile radio channels are subjected to error bursts due to deep fades, even when the channel signal-to-noise (SNR) ratio is high [1]–[3]. This can be ameliorated through the use of power control whereby the constellation transmitted is unchanged but the transmission level is adapted according to the channel integrity. However, this both increases transmitter power requirements, and more importantly increases the level of cochannel interference which can severely curtail system capacity. This leads us to the notion of varying the number of modulation levels according to the integrity of the channel, so that when the receiver is not in a fade we increase the number of constellation points, and as the receiver enters a fade we decrease them down to a value which provides an acceptable bit error rate (BER) [4] but maintaining a constant transmit power throughout. The number of modulation levels is varied in such a way that the short-term BER (over fast fading) is approximately constant and the short-term data rate varies, but such that the average BER (over shadow fading and large scale path variations) varies and the average data rate is constant. Such an approach achieves a constant data throughput, but helps avoid bit errors occurring in bursts. Alternatively, if we specify the required BER and switch levels accordingly, we obtain a variable data throughput. In this discourse we investigate a system whereby the throughput is maintained at an average of 4 b/sym to allow direct comparison of our results with standard QAM modems.

A variable rate system can only work with duplex transmission as some method of informing the transmitter of the quality of the link as perceived by the receiver is required. The transmitter can then respond by changing the number of QAM levels according to the quality criteria adopted. Successful variable rate transmission requires that the fast fading channel changes slowly compared to a number of symbol periods. If this condition is not met, then the frequent transmission of quality control information will significantly increase the bandwidth requirements of the system. To avoid this problem we can increase the data rate, allowing the transmission of more symbols before the channel changes significantly. The slower the mobile travels, the slower the fading rate and the lower the signalling rate required for adapting the modem to the channel. Initial simulations [5] showed that substantial gains of over 10 dB in SNR could be achieved for a mobile speed of 30 mph and a data rate 512 kSym/s when a single user per carrier system was deployed. In this paper we consider the performance of variable rate QAM systems at fading rates more likely to be encountered in current mobile radio systems. Specifically, we consider a carrier frequency of 1 GHz, a symbol rate of 32 kBaud and a range of mobile speeds from 1 m/s to 20 m/s. Since it is the fading rate which is important, the results would be identical for a 2 GHz carrier frequency and 64 kBaud data rate, for example. Our simulations used the standard Rayleigh fading channel model [6] derived from the combination of signals from two Doppler filtered AWGN generators. This was verified by comparing the resulting PDF and CDF with that derived theoretically for Rayleigh fading. Each simulation run was for 100,000 symbols ($\approx$400 000 b). Analytical results for the circular QAM constellation are not yet available, but upper bound analysis [7] shows that the fixed level simulation performs as expected.

Our initial experiments showed that varying the number of QAM levels in response to fading conditions resulted in a variable bit rate, which although nearly constant over long periods, could instantaneously vary by four times the average rate. We note that suitable buffering arrangements would be required to transmit speech over such a modem which will increase the delay experienced. This may not be acceptable for speech codecs which already suffer long delays. In our simulations, the depth of buffering which was required was approximately 2.5 times the number of bits per block. So for a typical block length of 100 symbols (400 b) a buffering of 1000 b would be required to ensure the user experienced a continuous data flow. At the transmission rate of 32 kBaud, 1000 b corresponds to 250 symbols giving a delay of approximately 7.8 ms. Whether this is acceptable depends on the delays already incurred in the system such as interleaving delays, speech coder delays etc.

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Section II describes our variable rate QAM system and outlines two approaches for switching the number of modulation levels. For one of these approaches, Section III presents bit error rate performance results that show the influence of vehicle speed, block size, and cochannel interference. We also consider the application of our variable rate QAM system to DECT-like packet structures.

II. SYSTEM DESCRIPTIONS

A. Duplex Arrangements

The simplest duplex arrangement for variable rate modem operation is time division duplex (tdd), where both base station (bs) and mobile station (MS) transmit over the *same* channel, but at different times. In this case both BS and MS experience similar channel fading conditions as their transmissions are typically half a TDD frame apart. The transmission received by the MS is used to estimate the channel integrity which then dictates the number of QAM levels to be used by the MS transmitter. Similarly, the transmission received by the BS enables the number of QAM levels used in the subsequent BS transmission to be determined. It is critical that both the BS and MS inform the other of the number of QAM levels used by their transmitters and that this information is not corrupted by the channel, in order for the QAM demodulations to be properly performed. In our simulations the data is divided into blocks, or packets that occupy a time slot, and the first few symbols in each block are reserved for signalling. The optimum size of the block is related to the mobile speed as the channel should not change significantly over the block duration. This issue was investigated for blocks containing 25 to 400 symbols.

At the start of each block we sent a signal representing the number of levels to be used in the QAM modulator for this block. This was encoded onto two symbols of a 4-level QAM, i.e., QPSK system, and each of these two symbols was transmitted three times. Majority voting was performed at the receiver in order to establish the number of QAM levels to be used in demodulation of the data in the current block. With this system, errors in the signalling information only occurred at low SNR's where the error rate was already high. They did not, therefore, significantly influence the overall BER.

Fig. 1 shows the TDD framing arrangement for adaptive QAM transmissions using one carrier per channel. If N channels per carrier are used the QAM symbols shown in the figure are transmitted N times faster, but the time over which the fading channel must remain essentially unchanged is the same. We assume that flat Rayleigh fading applies.

Frequency division duplex (FDD) operation is used by GSM, DCS 1800 and IS-54. In FDD the uplink and the downlink use different propagation frequencies that are typically spaced by some 20 to 40 MHz. Although the average path loss on the two channels is essentially the same, the fading on the two links may differ substantially. Both BS and MS must monitor their incoming channels and signal the required number of QAM levels to be used by the other in their transmissions on their outgoing channels. This results in twice the delay between estimating the number of levels required, and transmitting with this number of levels, compared to TDD. Consequently the mobile speed in FDD must be half that in TDD for equivalent performance. In all our simulations we use TDD, the multiple access method used by CT2, CT3 and DECT.

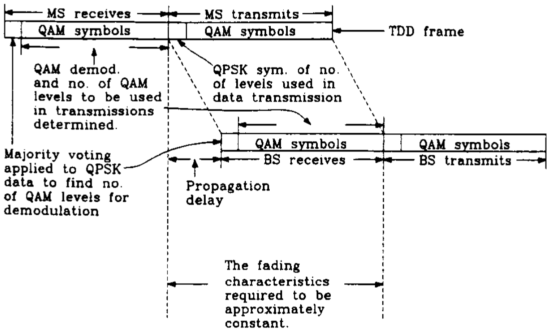

Fig. 1. The framing structure used in the variable level scheme.

B. Variable QAM Constellations

The QAM constellation changes as the number of levels is varied. We do not use the conventional QAM having a square constellation because of the difficulties with carrier recovery in a fading environment. Instead we use Star QAM having a circular star constellation, in conjunction with differential coding, as this has proved to be more successful in previous simulations [2]. The principle of Star QAM is to provide a constellation upon which differential coding can be efficiently overlaid. Both differential phase and amplitude coding is used. With 16-level Star QAM three of the four bits which constitute a symbol are differentially Gray encoded onto the phase, and the remaining bit is differentially encoded onto the amplitude of the phasor. This simplifies the receiver as AGC and carrier recovery are no longer required. Simulations have shown that BER performance is substantially improved over the square constellation whose receiver has the difficulty of accurately estimating the absolute signal phase and amplitude when both are varied randomly by the modulator and both are also influenced by the rapidly changing Rayleigh fading propagation channel. 16-level Star QAM has the further advantage over square QAM that each of the four bits constituting a symbol has a similar BER, making speech and data mapping straightforward. This is not the case for square QAM where half of the bits mapped onto a 16-level Gray-coded constellation have a significantly higher BER than the other half [1].

In our simulation we have used constellations from 1 b/sym (BPSK) through to 6 b/sym. Provided the receiver noise is sufficiently low, and implementation complexity is not an inhibiting factor, we can use more than 6 b/sym. As we increase the number of b/sym we alternately double the number of amplitude rings and the number of phase points. We start with BPSK. For 2 b/sym we double the number of phase points to get QPSK. For 3 b/sym we double the number of amplitude levels to get 2-level QPSK. For 4 b/sym we

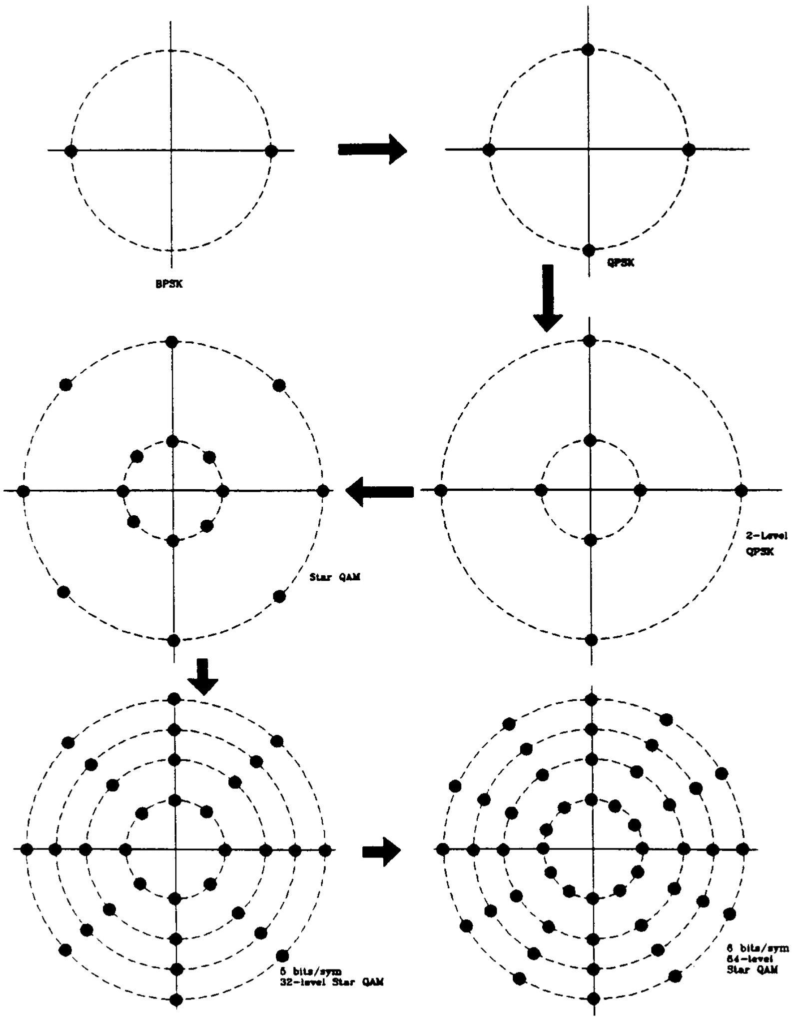

Fig. 2. Some QAM constellations used in the variable level scheme.

double the number of phase points to get to the 16-level Star constellation, and so on until with 6 b/sym we have 4 rings having 16 points per ring. The constellations for 2-level to 64-level Star QAM are shown in Fig. 2. The actual distances between the rings, and the sizes of the rings are not drawn to scale. Each constellation has the same average energy, and the radii of the rings in the 8 and 16-level constellations are in the ratio of three-to-one.

C. Level Switching Approaches

1) The RSSI Switching System: The block diagram of the transceiver is shown in Fig. 3. After recovering the baseband signal, demultiplexing is performed to separate the QPSK and Star QAM signals. QPSK demodulation is performed to obtain the number of QAM levels to be used in the QAM demodulation. This is followed by QAM demodulation to yield the recovered data. The average magnitude of the baseband signal level over a block provides an indication of the short-term path loss of the radio channel. If this average is very low the mobile is either in a deep fade or at the edge of the cell. In the first case it is more appropriate for it to transmit using relatively few QAM levels. In the second case if an average number of b/symbol over a long term must be maintained then it will not be possible to reduce the number of QAM levels. Similarily, if the average is high the channel is relatively good, enabling more QAM levels to be used in its next transmission, bearing the requirements for the long term average number of b/symbol in mind. We computed the average over a block using an exponential smoothing process which gave more weight to signal levels toward the end of the block. This average was then quantized, each quantized output signified a particular number of QAM levels to be used in the forthcoming transmission.

The baseband signal power in Fig. 3 is related to the received signal strength indicator (RSSI) at RF. Our system would function identically if the RF RSSI, instead of the

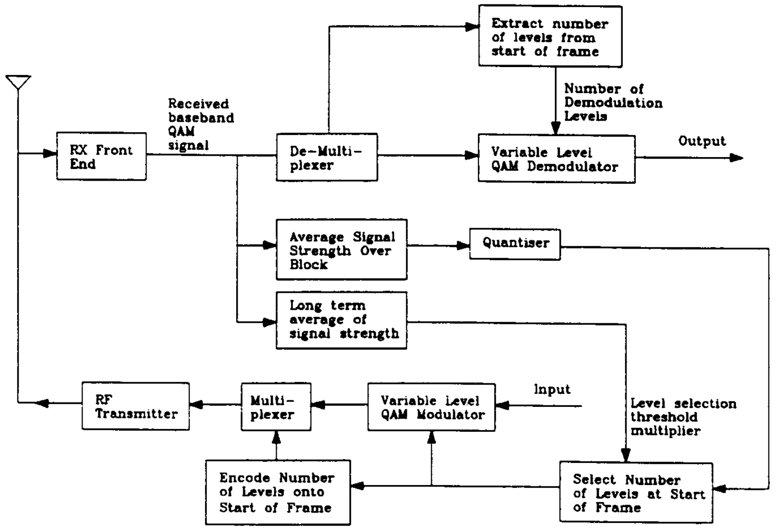

Fig. 3. Receiver block diagram for RSSI switching.

baseband RSSI indicator, was averaged over a block. For ease of nomenclature, we call this method of switching the QAM levels based on the baseband signals, baseband RSSI switching, or more simply, RSSI switching.

Two criteria were used for these switching levels, i.e., the levels generated by the quantizer in Fig. 3. One was to select the switching levels to achieve a specified BER, resulting in a variable data throughput. We conducted a simulation where graphs of BER as a function of instantaneous SNR at the input to the QAM demodulator were found for the Star QAM modem having 2^n; $n = 1, 2, \ldots, 6$ fixed levels. In this simulation we used a Gaussian channel, as over any short period of time when we do our switching the channel is essentially a constant level plus Gaussian noise. A straight line corresponding to the BER of interest was then drawn and where this horizontal line intersected the curves identified the switching thresholds. The instantaneous SNR was therefore quantized, where the quantization zones corresponded to a specific number of QAM levels in the adaptive modem. Some hysteresis was built into the switching levels to prevent continual level changing. The baseband signals in Fig. 3 are contaminated by noise, which the averaging circuit considerably reduces prior to QAM level selection at the end of the block. To ensure that the quantizer output levels correspond to the required instantaneous SNR values we appropriately scale the average value of the QAM symbols (found at the end of the block) by the known receiver noise prior to quantization. This method of switching was then used to derive the second criterion, which is the one on which our simulations have been based.

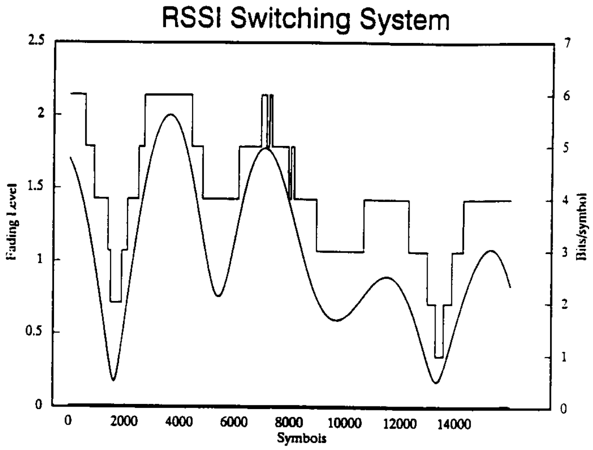

Fig. 4. Example of RSSI switching for constant bit rate.

The second criterion for choosing the switching thresholds achieved a constant average bit rate whilst accepting a variable BER. Here we used the thresholds derived above for the constant BER system and multiplied them all by the same number at the start of each block. This number was derived from the baseband signal averaged over a number of fades. This is performed by the long-term averaging circuit which has an averaging window increased over that used to average over a block in Fig. 3, so that it covered many blocks. Therefore as the average signal level rose, for example when moving closer to the base station, the switching thresholds increased accordingly maintaining a near constant average throughput, but variable BER. The average b/sym could be set to any level within the maximum number of b/sym by changing the scaling factor associated with the long term average input. Fig. 4 shows an arbitrary fading profile and the corresponding variation in the number of b per symbol for this constant throughput scheme when an average SNR of 30 dB was used.

Channel coding can be added to both the above systems if required. We note that in this case, the variable QAM schemes have the advantage over the fixed QAM scheme that errors occurred in smaller blocks because of the use of fewer QAM levels in poor channels. This allowed the channel codecs to perform more efficiently, or the interleaving depth

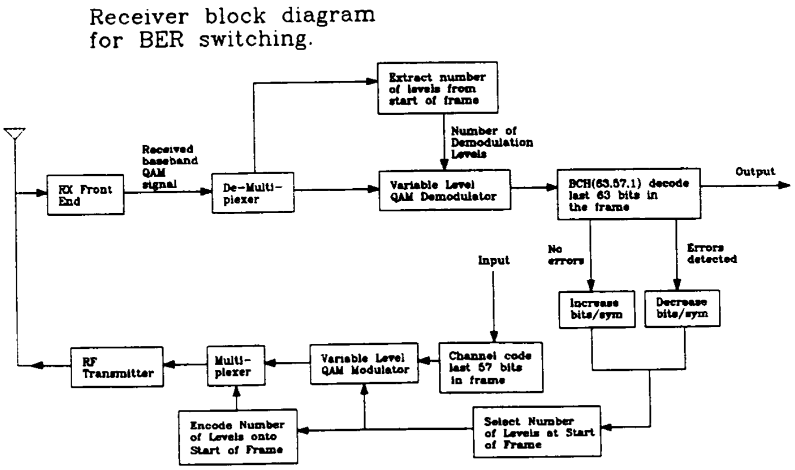

Fig. 5. Block diagram of BER switching receiver.

to be reduced. The latter helps compensate for the increased delays required when buffering speech for transmission over the variable rate modem.

2) The Error Detector Switching System: Rather than switching the QAM levels on RSSI we can do so on the command of a channel codec, in this case a systematic BCH codec. Fig. 5 shows a simplified block diagram of the BER switching transceiver. In order to obtain an estimate of the channel during each received data packet, a BCH (63, 57, 1) code was overlaid onto the last 57 b of input data in each block. The input data may already have been channel coded and interleaved, the additional coding was overlaid onto whatever data was present. This codec was generally ineffective at correcting errors as it was overwhelmed by the noninterleaved errors in a typical error burst, but it informed the receiver that channel conditions were poor. Such a coding system involved little overhead as it was only applied to the final 57 b in a block which contained an average of 100 symbols corresponding to 400 b. The coded data was applied to the adaptive QAM modulator and the modulated output was up-converted and transmitted.

The QAM demodulation was performed using the number of QAM levels extracted from the header, as described in the section on the RSSI switched QAM system. Most of the data was passed to the output where it might be subjected to de-interleaving and channel decoding. However, the final 63 b of the recovered bit stream were passed through the BCH (63, 57, 1) codec before proceeding to the output. If no errors were detected by this BCH codec then the number of QAM levels used in the next block was doubled, otherwise they were halved.

Simulations of such a system showed consistently worse results than for the RSSI switching system. The reason for this was that the BER switching system was only able to reduce its levels when errors were detected, which in many cases was too late. Furthermore, the BER switching system is unable to maintain an average throughput of any specified level regardless of the SNR. For this reason, investigations with the BER system were not continued.

III. RESULTS

A. Influence of Vehicular Speed

The performance of the RSSI switched variable level Star QAM system with an average throughput of 4 b/symbol compared to a fixed 16-level (4 b/sym) Star QAM system is shown in Fig. 6 for a range of mobile speeds. The necessary signalling information of the number of QAM levels used has been taken into account in calculating the throughput of the variable rate modem. The simulation was performed for a propagation frequency of 1 GHz, a range of vehicular speeds, and a transmitted symbol rate of 32 kBaud. We can see that there is a significant improvement in the performance of the adaptive over the fixed modem for mobile speeds of up to almost 20 m/s. The gains are particularly significant at low mobile speeds suggesting that such a system would be most useful for communications to pedestrian and slow moving vehicles. As a high SNR is required by QAM schemes, which is compensated by their reduced bandwidth requirements, this suggest they are most likely to be used in urban areas where these low mobile speeds may be widely encountered.

B. Block Size Variation

The length of the block used in variable level transmission is important. If this block length is too long, the channel will have changed significantly during the transmission of the block and the number of levels in use will no longer be suitable. If the block size is too short, then unnecessary level changing information will be sent which will reduce the overall throughput. Simulations were performed with a range of block lengths. In all cases the average throughput was maintained at 4 b/sym. This was done by decreasing the switching thresholds as the block size decreased. In this manner the modem chose a higher number of levels more frequently and so compensated

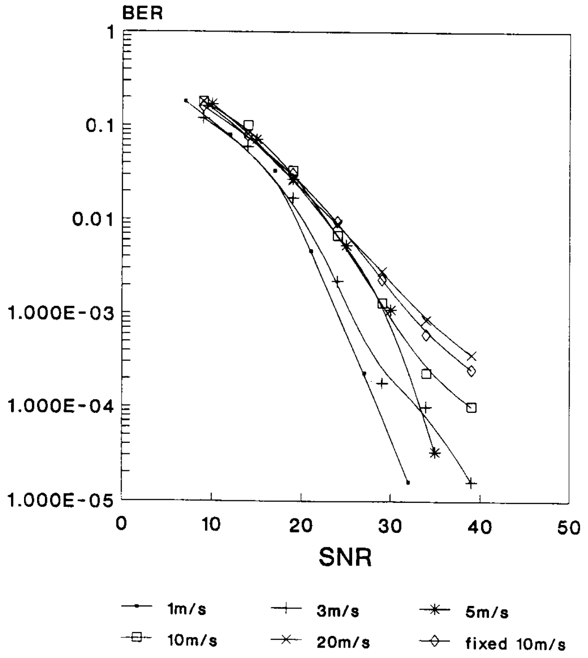

Fig. 6. BER comparison of variable and fixed systems.

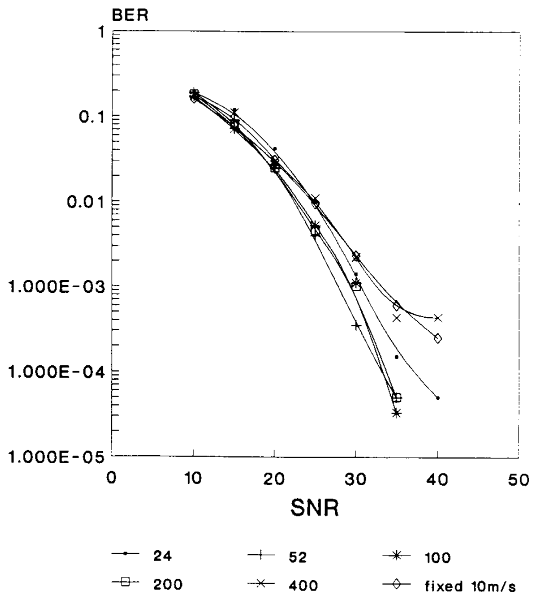

Fig. 7. Performance of the modem for a range of block sizes.

for an increase in signalling information. The results of this simulation are shown in Fig. 7. The results show that the performance is nearly identical for block sizes of 52, 100, and 200 symbols. Block sizes shorter or longer than this range produced a significant degradation. At lower speeds we expect the 400 and 800 block sizes to approach that of the 100, and at higher speeds we would expect the larger block sizes to perform worse. Therefore, block sizes of 50 or 100 symbols would seem to represent a suitable compromise. In this paper block sizes of 100 symbols have been used unless stated otherwise.

C. Cochannel Interference

Cochannel interference is nearly always present in mobile communications. Accordingly we needed to ascertain whether improvements in performance could be obtained using variable level Star QAM compared to fixed level Star QAM in the presence of a single cochannel interferer, this being the worst case interference. In all simulations the channel between the interferer and mobile was independently Rayleigh fading. If the number of interferers was increased, by the central limit theorem their interference would become more like Gaussian noise, which is less problematic to the mobile than a single strong interferer which might influence the clock and carrier recovery process. However, as we will show that the effects of a single interferer at a SIR ratio x are nearly identical to that of no interferer but a SNR of x, we would expect our results to be valid for both single and multiple interferers.

We might expect the variable level modem to suffer more severely than the fixed level modem as cochannel interference will both mislead the RSSI switching system, and increase the chance of the signalling information being in error. Fig. 8 shows the performance of the variable level system (V) compared to the fixed level system (F) for SIR's of 20 dB, 30 dB, and for no interference. At 20 dB SIR the fixed system outperformed the variable system due to RSSI inaccuracies and bit/symbol decoding errors. However, the minimum BER at this SIR was 0.05, which is too high for most purposes, suggesting that a 16-level QAM system would not be operated at this value of SIR. For an SIR of 30 dB the variable level modem has become superior to the fixed level modem, offering a BER of about half that of the fixed modem at high SNR values. With the BER of the fixed modem only just below 0.01, this may be the minimum SIR which would be acceptable. Finally, the curves for no interference show gains in excess of 5 dB at high SNR's. These gains would be higher for a lower mobile speed than the 5 m/s used. This suggests that the gains of variable rate QAM will increase over the fixed rate modem as the SIR increases.

Whilst it might appear that the need for the SIR to be above 30 dB will reduce efficiency due to increasing the required cluster size in a cellular system, a systematic analysis [8] has shown that a variable rate QAM modem operated in this manner provides a highly spectrally efficient link.

D. Application to a DECT-Type System

The digital European cordless telecommunications (DECT) system uses TDD, supporting 12 channels per carrier. The 12 down-link and 12 up-link channels constitute a 24 slot frame lasting 10 ms. Each time-slot containing a packet has a duration of 0.417 ms. The data in the packet consists of 320 b which are transmitted at 1152 kSym/s. We replaced each bit by a QAM symbol to increase system capacity. The header

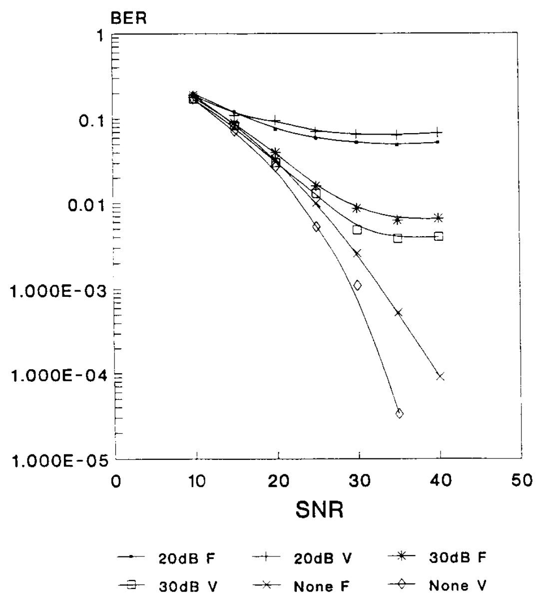

Fig. 8. The effect of cochannel interference on the variable and fixed modems.

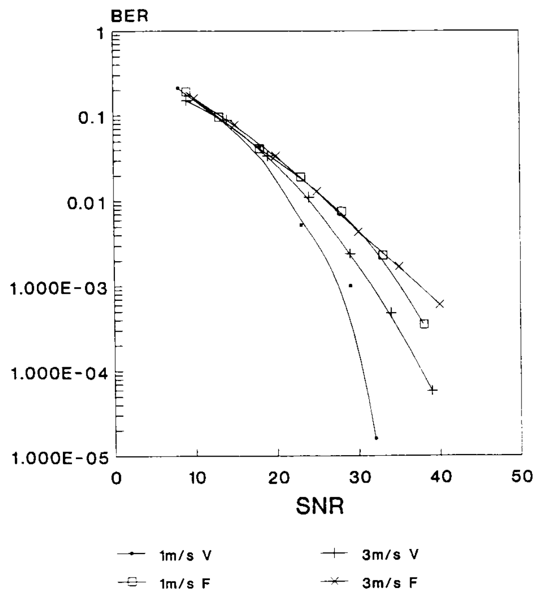

Fig. 9. Performance in a DECT-like system.

informed the receiver of the number of constellation points. We did not consider the use of channel coding, and the RSSI switching system was employed. It should be noted that DECT is a far from perfect framework for variable rate modulation as the channel is assessed in the BS-MS transmit time slot, for example time slot one, but the number of levels determined are not used until the MS-BS transmit time-slot, for example slot 13. Nevertheless, simulations were carried out to determine the performance of a variable rate scheme in such a scenario.

Fig. 9 shows the variation of BER as a function of channel SNR for this DECT-like system for MS's travelling at different speeds, and for fixed and variable QAM modems. No cochannel interference was present. Since DECT is designed for office use, the speeds simulated of 1 and 3 m/s correspond to slow and fast walking pace and are typical of those likely to be encountered. The DECT framing meant that the transmission and reception were separated by 12 slots or 5 ms, and consequently the channel could occasionally experience considerable changes between transmission and reception of data and therefore generate an inappropriate number of levels.

The results show an improvement in performance over the fixed level modem for both speeds simulated. The improvement in channel SNR for a mobile speed of 1 m/s was about 10 dB for a BER of 1×10^{-3}, or over an order of magnitude in BER for a SNR of 30 dB. At 3 m/s the gain in channel SNR became about 6 dB and the improvement in BER at a SNR of 30 dB was a factor of 3.

IV. CONCLUSION

An adaptive Star QAM modem for transmission of data over Rayleigh fading channels using a variable number of modulation levels has been investigated. Criteria for deciding how to vary the number of modulation levels to give a required performance characteristic are presented. The adaptive modem provides the flexibility to vary both the BER and the bit rate in a prescribed manner to suit a particular application. Earlier work showed that at high data rates the variable rate modem substantially outperformed the fixed rate modem. Here we considered Baud rates of 32 kBaud at a carrier frequency of 1 GHz and a range of mobile speeds. The block size was investigated and found not to be critical, with block sizes of 100 symbols appearing suitable. We found that the adaptive modems have a better performance than the fixed modems, both with cochannel interference when the SIR exceeds about 25 dB, and without cochannel interference. We also speculate on using a DECT-type system and show that at low mobile speeds the BER of a fixed 16-level QAM system can be reduced by an order of magnitude for SNR >25 dB by employing a variable rate modem.

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