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Performance Comparison of Pilot Tone Aided and Pilot Symbol Aided QAM over a Mobile Radio Channel

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ABSTRACT - This paper compares the performance of Pilot Tone Aided (PTA) and Pilot Symbol Aided (PSA) BPSK, QPSK, 8QAM, 16QAM, 32QAM and 64QAM over a narrowband radio channel. This set of modems is capable of achieving 14, 28, 48, 56, 70 and 84 kbit/s respectively in a 20 kHz channel bandwidth. Computer simulations in a Rayleigh fading channel show that PTA modems have almost the same performance as PSA modems. However PTA signals have a higher peak to mean power ratio (η) and this translates into greater amplifier linearity requirements in the transmitter. In the PSA modems, η is independent of the pilot symbols, however in the PTA modems it depends upon the pilot tone to data power ratio (R). An optimisation of R in an AWGN channel gives a value of 0.2 for QAM. A comparison of η between PSA and PTA transmitted signals show differences of 3.38, 5.1, 4.8, 4.25, 4.45 and 3.9 dB for 99.9% of the time (based on the above mentioned list of modulation schemes).

INTRODUCTION

A signal transmitted through a mobile radio environment is subject to distortion as it travels to the receiver. Multipath propagation results in gross distortion of the amplitude and phase of the original modulated waveform. Relative motion of the receiver, with respect to the transmitter, produces Doppler distortion. In multipath channels this distortion takes the form of frequency spreading. At the receiver, Additive White Gaussian Noise (AWGN) and local oscillator frequency offset distort the signal further. These effects combine to produce a grossly distorted signal that is a major challenge to reliable detection.

Until recently, constant envelope modulation schemes were considered to be the most appropriate for land mobile communication systems. Their popularity lies in the use of simple incoherent differential or discriminator detection techniques. These methods do not need rigorous amplitude and phase detection and channel compensation techniques in the receiver. However, in the 1980s, as the demand for higher data rates grew, multilevel QAM (Quadrature Amplitude Modulation) schemes came into focus. A number of techniques were investigated to accurately compensate for the amplitude and phase distortion introduced by the mobile channel. Extensive research dating back to early 1980's produced two famous methods for compensating the multiplicative distortion introduced by a narrowband wireless channel. These methods rely on the transmission of a *pilot* reference signal along with the payload data. At the receiver, this pilot signal is separated from the data and used to estimate the precise nature of the channel's amplitude and phase distortion. The first technique inserts pilot symbols into the information sequence and is commonly referred to as Pilot Symbol Aided (PSA) fading compensation [1]. The second technique transmits a continuous pilot tone together with the data spectrum and is referred to as Pilot Tone Aided (PTA) fading compensation [2].

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PSA and PTA compensation techniques can be applied to a family of QAM schemes to produce a multi-rate transmission system suitable for link adaptation. PTA is considered as the frequency dual of PSA correction. However, both systems have important practical differences in terms of complexity, amplifier linearity requirements and performance in radio channels [3]. This paper examines these issues by evaluating the peak to mean power ratio of the transmitted signal, and then compares the performance of BPSK, QPSK, 8QAM, 16QAM, 32QAM and 64QAM in Rayleigh fading channels. Both systems can achieve a gross data rate of 14, 28, 48, 56, 70 and 84 kbit/s in a 20 kHz bandwidth, depending upon the choice of QAM constellation (see previous list).

SYSTEM DESCRIPTIONS

A) Pilot Tone Aided QAM

The PTA concept was proposed in 1979 with the first mobile voice implementation published by McGeehan and Bateman [2] in 1984. In the late 1980s, Martin and Bateman [4][5] implemented a 16QAM PTA data transmission system for operation over multipath fading channels. The proposed system was referred to as Transparent Tone In Band (TTIB) and was capable of transmitting up to 9.6 kbit/s in a 2.7 kHz channel bandwidth. In a PTA modem, a pilot tone is inserted in the transmitted spectrum as shown in Figure 1. At the receiver, the tone is extracted and is used to estimate and correct the narrowband channel distortion. In this paper, a low complexity digital receive architecture proposed in [6] has been used to accurately estimate and then correct for channel distortion. A novel low IF (Intermediate Frequency) approach avoids the need for Hilbert transforms in the data extraction procedure. These transforms add significant ripple in the pass-band and while this is acceptable for BPSK or QPSK, the degradation is too severe for higher levels of QAM. This method differs substantially from the conventional approach originally proposed by Martin, Bateman and McGeehan.

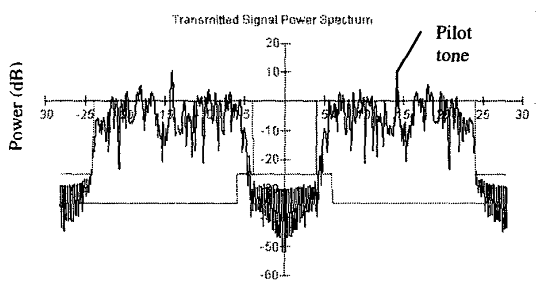

Figure 1: Transmitted spectrum at low IF

PTA Transmitter

Figure 2 shows the block diagram of the PTA QAM transceiver implemented at low IF. A pilot tone is inserted in the centre of the transmit spectrum by splitting the incoming data into two parallel subbands. Each subband operates at half the gross data rate with data mapped onto separate QAM constellations. This results in a symbol rate of 14 kbaud/s (7 kbaud/s per subband).

The two subbands are modulated onto an upper intermediate frequency (U_{IF}) and a lower intermediate frequency (L_{IF}) with a gap remaining for the required tone insertion. The gap bandwidth depends on the maximum frequency offset and Doppler shifts to be corrected in the system. In this particular design, a gap bandwidth of 700 Hz has been used at a centre frequency (C_{IF}) of 14 kHz. This choice results in a relaxed specification for the bandlimiting root raised cosine filters with an excess bandwidth factor of 0.38 being used.

PTA Receiver

When the signal arrives at the receiver it is corrupted by the radio channel distortion, as well as AWGN. Demodulation and detection of the received signal requires accurate compensation for the channel's amplitude and phase distortion. The pilot tone is extracted by digitally filtering the received signal spectrum at baseband. The channel estimation and compensation block is used to estimate the amplitude and phase distortion from the extracted tone. This information is used to generate pre-distorted upper and lower subband carriers. Each carrier is multiplied with the received signal to automatically translate the subbands to baseband while correcting for local oscillator frequency drifts and radio channel distortion. The baseband signals contain images that are removed by passing them through low pass root raised cosine (RRC) filters. The filtered subband signals are sampled to bring the rate down to 7 kbaud/s. It has been assumed that the optimum symbol sampling time is available from the synchronisation algorithm implemented on the *distortionless* filtered signals. For PTA systems, symbol timing is not required in the fading correction process. Hence, channel estimation becomes independent of symbol timing (a significant advantage in a fading channel). The sampled subband signals are sent for hard decision and QAM demapping. The original binary signal is recovered finally by combining the two subband data streams.

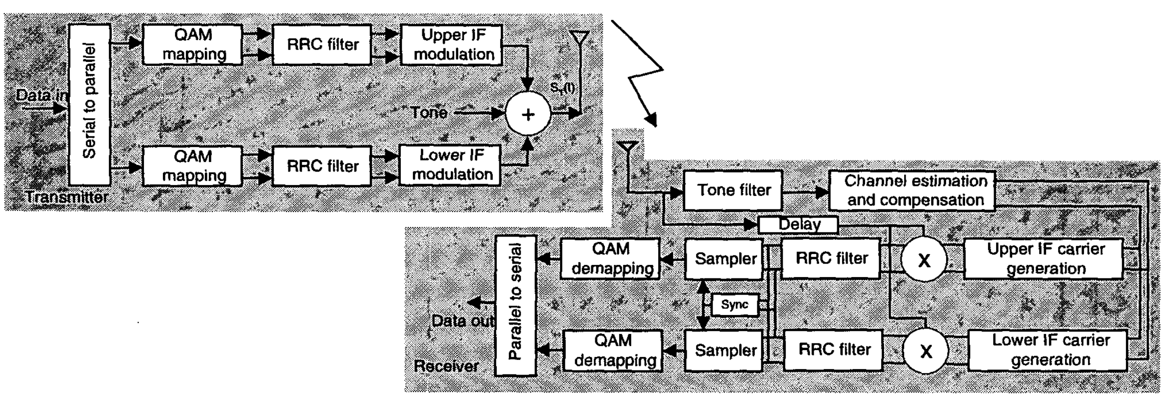

Figure 2: Block diagram of PTA QAM system

B) *Pilot Symbol Aided QAM*

PSA compensation was investigated by Sampie in 1989 to compensate for narrowband Rayleigh fading channel distortion in 16QAM [1]. In this technique, a known pilot symbol sequence is inserted periodically in the information signal in the time domain. In the receiver, these pilot symbols are separated from the received data stream and used to estimate samples of the channel response. These samples are converted to estimates during the data fields via interpolation. The estimated channel is scaled, rotated and multiplied with the received signal to cancel its effect and recover the information symbols.

The frequency of pilot symbol insertion in the information sequence gives rise to the definition of the pilot frame. Each pilot frame has one pilot symbol placed at the start as shown in Figure 3. The PSA system analysed in this paper uses a 2nd order Gaussian interpolator and a pilot frame duration of 1msec.

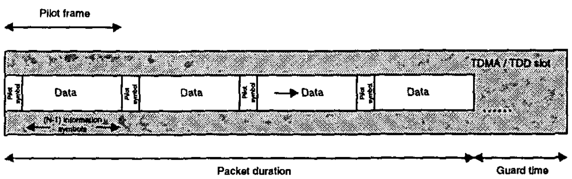

Figure 3: Pilot symbol frame structure

PSA Transmitter

A block diagram of the baseband PSA QAM transmitter and receiver is shown in Figure 4. After QAM mapping, a known pilot symbol is inserted every (*N*-1) data symbols and the multiplexed data is sent for RRC filtering.

PSA Receiver

At the receiver, the baseband received signal is passed through the RRC filter and sampled at the rate of 14 kHz. The synchronisation algorithm in this case operates on the *distorted* signal and provides an optimum sampling time to the sampler, as well as the pilot frame timing to the channel estimation and compensation block. In PSA receivers, the accuracy of sample timing effects the accuracy of the channel compensation process. Errors in sample timing will introduce additional distortion in the channel estimation process. The dependence of channel estimation on timing recovery is an unavoidable limitation of PSA receivers. The sampled signal is split into two branches for channel estimation and delay compensation.

The channel estimation procedure extracts the pilot symbols from the data packet and interpolates between them to estimate the channel fading. The signal is also received with some frequency offset error. Hence the channel estimation and compensation procedure not only compensates for channel distortion, but also corrects residual frequency offset. The precision of the channel estimation process depends upon the frequency of the pilot symbol insertion and the type of algorithm used for interpolation. The channel estimation process accumulates a number of pilot symbols before the interpolation process begins. This introduces some delay in the input of the estimated channel samples to the channel compensation algorithm. This delay can be limiting for radios requiring a fast turn around time. The received samples and the channel samples are synchronised by inserting a fixed matched delay line in parallel with the channel estimation block. For a 2nd order Gaussian interpolator, the resulting delay is two pilot frames. The estimated channel samples are then inverted and multiplied with the delayed received samples to cancel the amplitude and phase distortion in the channel. The QAM demapper makes decisions (based on the current constellation) on the channel compensated received samples. The output from this demapping block is ideally the original transmit binary data stream.

COMPLEXITY COMPARISON

The operation of a PTA modem can be better viewed in the frequency domain, as compared to a PSA modem, which is based on time domain concepts. A quantitative comparison of complexity between PTA and PSA modems is difficult to perform [3]. However, simply comparing the block diagrams of both systems indicates that the PTA system needs more hardware compared to the PSA system. The additional hardware arises from the subbands present in a PTA system, which needs an extra pair of operations at both the transmitter and receiver.

At the receiver, as mentioned earlier, PTA modems only require symbol timing recovery, whereas PSA modems need both symbol timing, as well as pilot frame timing, recovery. A functional comparison of the proposed receiver architecture for the two systems shows that pilot tone insertion does not link the channel estimation and fading compensation procedure to the synchronisation process. In a PTA modem, the synchronisation procedure is implemented *after* channel estimation and compensation, whereas in a PSA modem, it is performed *before* this activity. A received signal with some frequency offset, in addition to the channel distortion, makes the synchronisation process much more complex to achieve for PSA modems, compared to PTA modems.

COMPARISON OF PEAK TO MEAN POWER RATIO

A major problem with multi-level QAM schemes is their requirement for linearity, particularly in the transmit power amplifier. A signal with a high peak to mean power ratio (η) needs greater amplifier linearity than a signal with a lower (or ideally unity) peak to mean power ratio.

For PTA QAM systems, the peak to mean power ratio is directly related to the pilot tone to data power ratio (R). High pilot tone powers result in a larger peak-to-mean power ratio. This also reduces the power in the data bands and makes the QAM constellation difficult to detect.

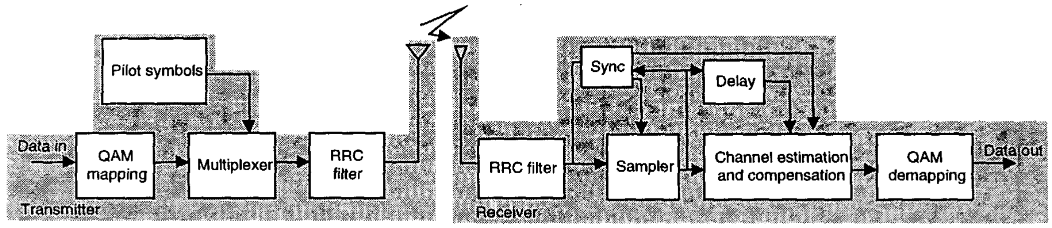

Figure 4: Block diagram of PSA QAM transmitter and receiver

On the other hand, if the pilot tone is made too low, it becomes buried in noise and this results in a noisy reference that degrades system performance.

To calculate η, a simulation has been performed for PTA QAM modems to calculate the cumulative density function (CDF) of the peak to mean ratio. The value of η is based on a CDF probability threshold of 0.999, i.e. for 99.9% of the time the peak to mean ratio remains below the quoted level. The results are plotted in Figure 5. The value for η starts small. As R increases, the peak-to-mean ratio rises reaching a peak when the pilot power becomes comparable to the subband powers. If R is further increased, η falls due to very small power levels remaining in the subband spectrums.

In this study, the pilot tone to data ratio has been optimised by performing a simulation in AWGN for each of the PTA QAM modems. The simulation results indicate that R = 0.2 minimises the error rate for all QAM constellations. Hence this value is used in all subsequent simulations for the PTA modems.

For PSA QAM modems, pilot symbols can be randomised to make the peak to mean power ratio independent of the pilot symbol power. Similar to PTA modems, a simulation has been performed to calculate η for PSA modems. A comparison is given in Table 1.

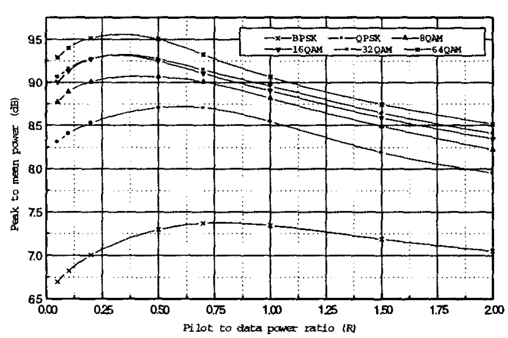

Figure 5: Peak to mean power of the transmitted PTA signal for 99.9% of the time versus pilot to data power.

Table 1: Comparison of Peak to mean transmit signal power of PTA and PSA modems for 99.9% of time

Modulation	PTA $\eta(\pm 0.1)$dB	PSA $\eta(\pm 0.1)$dB	Difference dB
BPSK	7.0	3.62	3.38
QPSK	8.5	3.4	5.1
8QAM	9.0	4.2	4.8
16QAM	9.25	5	4.25
32QAM	9.25	4.8	4.45
64QAM	9.5	5.6	3.9

PERFORMANCE COMPARISON IN AWGN CHANNEL

The performance of PTA and PSA QAM modems has been evaluated in an AWGN channel. A SER comparison between both systems (see Figure 6) indicates that PTA QAM outperforms PSA QAM in noisy environments (for the systems investigated in this paper).

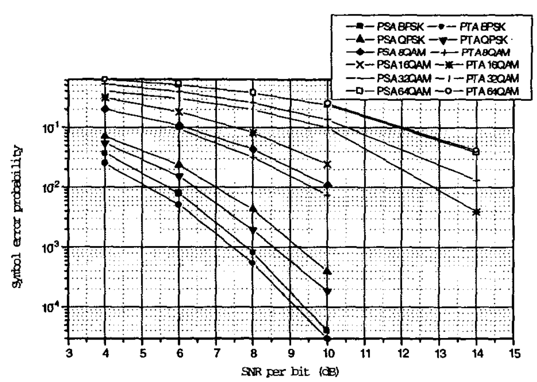

Figure 6: SER of PTA and PSA QAM in AWGN

PERFORMANCE COMPARISON IN RAYLEIGH FADING CHANNEL

The performance of PTA and PSA QAM in a Rayleigh fading channel for a maximum Doppler spread of 100 Hz is shown in Figures 7 and 8. The bit error rate (BER) and symbol error rate (SER) plots were obtained by computer simulation. The results show that both pilot aided systems have a similar performance until the point at which error floors begin to appear for high level modulation schemes. Figure 6 shows that for a BER of 1 in 1000, BPSK and QPSK need 25 dB, 8QAM, 16QAM, 32QAM and 64 QAM require 27 dB, 27.5 dB, 31 dB and 32.5 dB per bit respectively. The SER graphs given in Figure 7 indicate that for a SER of 1 in 100, QPSK, 8QAM, 16QAM, 32QAM and 64QAM need 17.9, 21, 23, 25.8 and 28.5 dB per bit respectively.

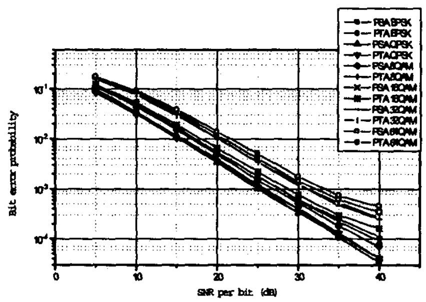

Figure 7: BER of PTA and PSA QAM in Rayleigh fading channel (Doppler = 100 Hz)

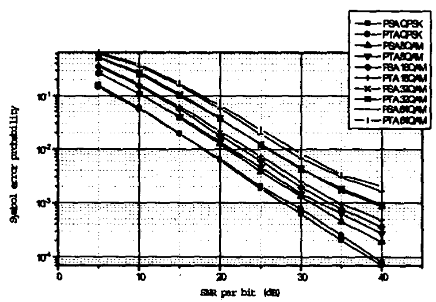

Figure 8: SER of PTA and PSA QAM in Rayleigh fading channel (Doppler = 100 Hz)

CONCLUSIONS

In this paper, a comparison has been performed between pilot tone aided (PTA) and pilot symbol aided (PSA) narrowband channel compensation techniques for BPSK, QPSK, 8QAM, 16QAM, 32QAM and 64QAM. Both systems are capable of achieving 14, 28, 48, 56, 70 and 84 kbit/s respectively in a 20 kHz channel bandwidth. In terms of complexity, the PTA technique involves low IF processing and requires more changes to be made to the modem architecture. However, it does not link channel estimation and compensation with the timing recovery. This makes the PTA technique more robust and potentially better suited to higher-level modulation schemes (particularly in severe fading channels). The peak to mean power ratios of a transmit PSA waveform is much lower than a corresponding PTA signal. A comparison of transmit signal peak to mean ratios (for 99.9% of the time) for PTA and PSA systems has shown differences of 3.38, 5.1, 4.8, 4.25, 4.45 and 3.9 dB for the above mentioned modulation schemes. The increased values of peak to mean power ratio required in a PTA modem translate into greater amplifier linearity requirements and reduced coverage ranges, assuming a fixed peak power transmit level. A comparison of performance in an AWGN channel for both systems indicates that PTA QAM is slightly better than PSA QAM. The performance in a Rayleigh fading channel indicated an insignificant difference between the two pilot aided systems.

ACKNOWLEDGEMENTS

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