Using Adaptive Modulation in a LEO Satellite Communication System

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Abstract : - Adaptive modulation is a powerful technique to improve the energy efficiency and increases the data rate over a fading channel. The ground station transmitter and the satellite receiver adapt the modulation scheme and the transmitter power to the state of the channel. In this paper, we study adaptive multi-level quadrature amplitude modulation (M-QAM) schemes for LEO satellite over a Rayleigh fading channel using discrete rate adaptation strategy. This adaptation strategy maximises the capacity of the system. Results show that rate adaptation is the key top increasing system performance in term of average bit error rate assuming perfect knowledge of the channel.

Key-Words: - Fading channel, adaptive modulation, LEO, Transmitter, Receiver, average BER.

1 Introduction

LEO satellite transmission environment has been a challenge to reliable communications because of the time varying nature of the channel. Detrimental effects such as path loss and multipath fading can greatly attenuate the transmitted signal. Transmission techniques which do not adapt to the fading channel require a fixed link margin to maintain acceptable performance. Therefore, adaptive channel estimation must be designed for such channels. More over, dynamic resource allocation is an important means to transmit information efficiently through the varying channel.

The radio channel is time varying due to mobility of either the transmitter or the receiver, or even the surrounding objects mobile channel characterization and modeling are dealt with in depth in many textbooks.

2 Alsat-1 characteristics

Alsat-1 is an earth observation satellite which will evolve in a sun-synchronous retrograde circular orbit. It is designed to be part of a 5 satellites constellation for daily disaster monitoring. Therefore, it is equipped with two banks of cameras giving a total of 600km field of view at 32 meters spatial resolution in three spectral bands, the Red, Green and Near Infra-Red. In absence of disaster, Alsat-1 is dedicated for Algerian purposes. Most of the critical subsystems for the mission are redundant, such as two receivers and two transmitters to communicate with the spacecraft [1], [4], [8], [9], [10].

3 Channel modeling

The fading channel model is given by the next relationship :

$$Y(t)= \alpha(t)x(t)+n(t) \qquad (1)$$

where x(t) is the transmitted complex signal, n(t) is the complex additive white Gaussian noise (AWGN) and $\alpha(t)$ is the fading envelope. The fading envelope is a random variable with a Nakagami probability density function given by:

$$P_a(\alpha)=\frac{2m^m\alpha^{2m-1}}{\Gamma(m)\Omega^m}\exp(-\frac{m\alpha^2}{\Omega}) \quad ;\alpha \geq 0 \quad (2)$$

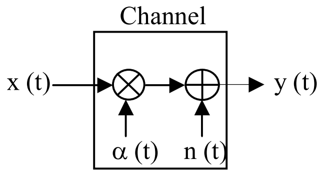

Fig.1 Channel model

with $\Omega=E[\alpha^2]$ and $\Gamma(m)$ is the gamma function, m is a positive integer. Note that for m=1, the Nakagami pdf is reduced to Rayleigh distribution.

The Reasons for choosing Nakagami pdf are that the fading envelope α is modelled as a Gaussian variable m [2], [7]. This implies that α may become negative, something which is not possible in practice. However, a Nakagami pdf may closely approximate a Gaussian pdf with a given expectation and standard deviation. The Nakagami pdf approximation is obtained by choosing appropriate value for m and Ω.

4 CNR evaluation

Let P denote the constant transmit signal power. The channel signal to noise ratio is then given by:

$$\gamma=\frac{\alpha^2 P}{BN_0} \quad (3)$$

where B is the bandwidth and N_0 is the noise power density. The expected value is:

$$\bar{\gamma}=E[\gamma]=\frac{\Omega P}{BN_0} \quad (4)$$

with $\Omega=E[\alpha^2]$.

Since a has a Nakagami distribution, the received SNR has a gamma distribution with pdf equal to :

$$P_\gamma(\gamma)=\left(\frac{m}{\bar{\gamma}}\right)^m \frac{\gamma^{m-1}}{\Gamma(m)}\exp(-\frac{m\gamma}{\bar{\gamma}}) \quad ;\gamma \geq 0 \quad (5)$$

5 Adaptive M-QAM modulation

The bit error rate (BER) of coherent M-QAM over an additive white Gaussian noise (AWGN) channel is given by [3], [5]. We have :

$$BER=\frac{4(\sqrt{M}-1)}{\sqrt{M}\log_2 M}Q\left(\sqrt{\frac{3\gamma}{M-1}}\right) \quad (6)$$

where γ is the carrier to noise ratio (CNR), $\log_2(M)$ is the number of bits per symbol (this number is even), and Q is related to the error function. It is more practical to study the performance of adaptive discrete rate (ADR) MQAM, where the constellation size M_i is restricted to 2^i for i positive integer. The strategy adopted is as follow; the CNR range is divided into N+1 fading regions, and the constellation size M_i is assigned to the nth region (i=0, 1, 2, …..,N). When the received CNR is estimated to be in the nth region, the constellation size M_i is transmitted [2].

Suppose we fix a target BER to equal to 10^{-6}, then the threshold γ_i are then set to CNR required to achieve the target BER using M_i-QAM over an AWGN channel, then we can obtained the γ expression by inverting equation (6), with $\gamma_0=0$ and $\gamma_{N+1}=+\infty$.

Table 1 gives different thresholds values for N=10 regions to achieve target BER equal to 10^{-6} using M_i-QAM modulation scheme.

Table 1 Transmit modulation scheme

Step i	Transmit Modulation	Thresholds γ_i (dB)
0	No transmission	-∞
1	2-QAM	10.53
2	4-QAM	13.25
3	8-QAM	16.90
4	16-QAM	20.23
5	32-QAM	23.40
6	64-QAM	26.43
7	128-QAM	29.50
8	256-QAM	32.53
9	512-QAM	35.55

Figure 2 shows the number of bits per symbol as function of CNR γ for adaptive discrete rate M-QAM with 10 regions. According to the estimated CNR, the M-QAM scheme is transmitted. Each fading region is associated with one signal constellation and one transmit power. The choice of the number of regions to use in the adaptive strategy will depend on how fast the channel is changing as well as on the hardware constraints, which dictate how many constellations are available to the transmitter and at what rate the transmitter can change its constellation and power. However, determining how long the channel gain remains within a particular region is of interest since it determines the trade-off between the number of regions and the rate of power and constellation adaptation [3].

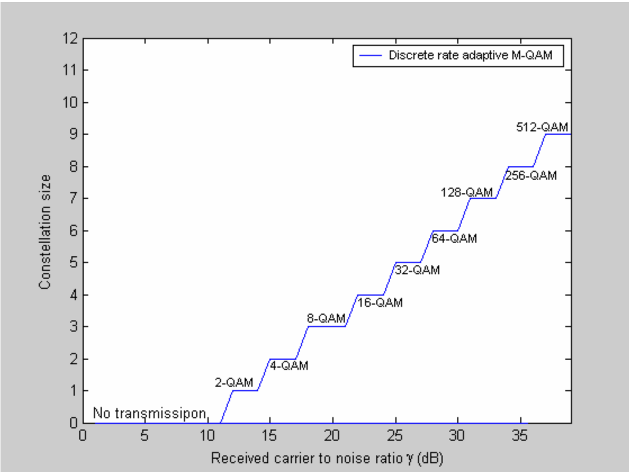

Fig.2 Modulation constellation size versus CNR

Let τ_i denote the average time duration that γ stays within the ith fading region ($\gamma_i < \gamma < \gamma_{i+1}$). The expression of τ_i is given [11] using the finite state Markov model.
For Alsat-1, the Doppler shift presents at the satellite receiver is given by Fig.3. We observe that the maximum is about ±46 KHz at horizon angle (minimum elevation angle is 1° of antenna ground station).

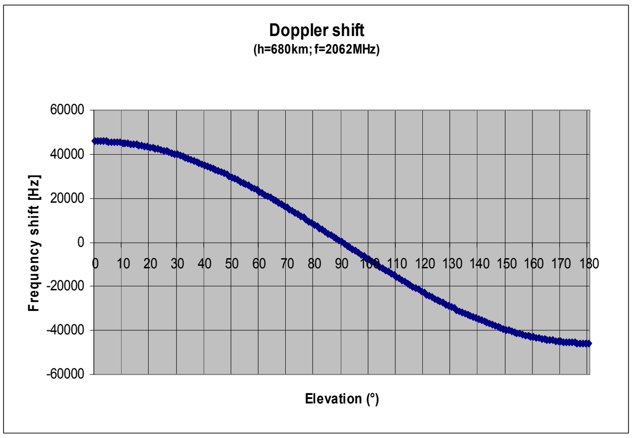

Fig.3 Alsat-1Doppler shift.

Table II gives the τ_i values corresponding to ten regions (M_j = 0, 2, 4, 8, 16, 32, 64, 128, 256, 512) in Rayleigh fading channel for f_m=29KHz (average Doppler shift) and three average power levels $\bar{\gamma}$=10dB, $\bar{\gamma}$=20dB, $\bar{\gamma}$=30dB. For data rate of 8Mbps, the ADR-MQAM technique will maintain the same constellation and transmit power (at ground station) over 5-50 of symbols. The communication channel presents a fading which obeys to a Rayleigh distribution function.

Table 2 Average time duration for f_m=29 KHz, target BER of 10^{-6}, and Rayleigh fading.

Region (i)	$\bar{\gamma}$=10 dB	$\bar{\gamma}$=20 dB	$\bar{\gamma}$=30 dB
0	7.1 µs	4.9 µs	1.47 µs
1	6.01 µs	1.93 µs	0.6 µs
2	8.03 µs	3.47 µs	1.07 µs
3	6 µs	4.64 µs	1.4 µs
4	4.11 µs	6.16 µs	1.98 µs
5	2.9 µs	7.18µs	2.77 µs
6	2.04 µs	6.3 µs	3.9 µs
7	1.45 µs	4.57 µs	5.4 µs
8	1.03 µs	3.2 µs	6.87 µs
9	0.7 µs	2.3 µs	7.28 µs

6 Probability of error

In AWGN the probability of bit error depends on the received SNR or, equivalently, on γ. In a fading environment, the received signal power varies randomly over distance or time. Thus, in fading γ is a random variable with distribution $p_\gamma(\gamma)$, and therefore *BER* (γ) is also random. The performance metric when γ is random depends on the rate of change of the fading. The main performance criteria that can be used to characterize the random variable BER is the average error probability, P_e, averaged over the distribution of γ. The average probability of bit error applies when the signal fading is on the order of a symbol time, so that the signal fade level is constant over roughly one symbol time. Since many error correction coding techniques can recover from a few bit errors, and end-to-end performance is typically not seriously degraded by a few simultaneous bit errors, the average error probability is a reasonably good figure of merit for the channel quality under these conditions [6], [7].

Since the choice of M_i is ADR M-QAM is done, the technique operates at an average BER smaller than the target BER. Thus, we are interesting to calculate the average pit error rate given by :

$$P_e = \int_0^{+\infty} BER p_\gamma(\gamma) d\gamma \qquad (7)$$

Finally, the average bit error rate in a Rayleigh fading channel using the ADR-MQAM techniques is given by:

$$P_e = \frac{2(\sqrt{M}-1)}{\sqrt{M}\log_2 M}\left[1-\sqrt{\frac{3\bar{\gamma}\log_2 M}{2(M-1)+3\log_2 M}}\right] \qquad (8)$$

Figure 4 shows the bit error rate comparison in case of Rayleigh fading channel and AWGN channel. We observe that the difference is dramatic: average BER is inverse in average γ rather than exponential, as for AWGN channel. For the fade margin, we should plan an additional increase in SNR to keep the same average BER as in a fixed AWGN channel or use the ADR-MQAM technique.

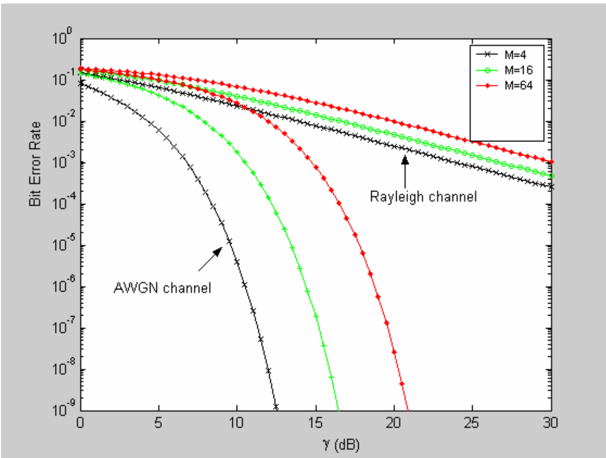

Fig. 4 BER for M-QAM in Rayleigh Fading and AWGN channel.

Figure 5 shows the average BER for Rayleigh fading channel using ADR-MQAM technique. We observe that the average BER is below the 10^{-6} target BER . Because ADR-MQAM often uses the high constellation sizes at high average γ the closed-form approximate average BER for ADR-MQAM tightly upper bound the exact average for $\bar{\gamma}$ >10dB.

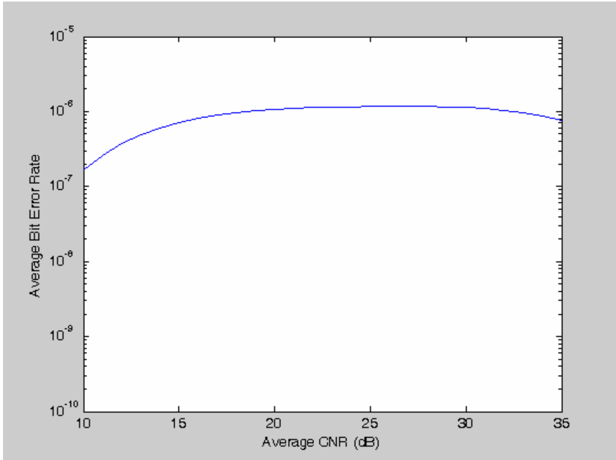

Fig.5 Average BER versus average CNR for ADR-MQAM Rayleigh fading channel (18)

7 Conclusions

We have studied a LEO satellite performance evaluation in a fading environment by adopting an adaptive discrete rate M-QAM strategy over a Rayleigh fading channel assuming perfect channel estimation and negligible time delay. This technique adapts to the channel variation by changing the constellation size and power at ground station transmitter. We show that, using 10 fade regions, the average BER approach 10^{-6} target BER when the average CNR is more than 10dB, and the ADR-MQAM has more than 20 dB of power gain over nonadaptive modulation.

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