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Adaptive Coding and Modulation Performance over Nonlinear Mobile Satellite Channels

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ABSTRACT: Mobile satellite communication experiences various channel state conditions. These channel impairments degrade overall system reliability and bandwidth efficiency. Dynamic link adaptation considers channel variations and adapts the transmission parameters respectively. This paper investigates link adaptation in mobile satellite communications through adaptive coding and modulation scheme. Average spectral efficiency improvement has been obtained by adaptation algorithms while the error probability constraints are met. To further extend our scenario in real world satellite systems, power amplifier nonlinearity is taken into account. Power amplifier nonlinear performance introduces distortion and signal to noise ratio (SNR) degradation. Hence, an optimized adapting procedure is proposed to overcome the resulting impairments. Moreover, propagation delay in satellite links are significantly large which outdates the channel state information (CSI) used for link adaptation decision. Channel states and fading conditions would change considerably in this long round trip time, especially in mobile user scenario. As a result, deploying a prediction method to predict time varying channel for reliable modulation and coding selection is required. The accuracy and performance of physical layer adaptation were improved by implementing channel power prediction, mitigating large round trip time and fast channel variations. Results indicate satisfactory link availability even in severe shadowing states of the channel.

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1- INTRODUCTION

Satellite communication provides broadband multimedia services for wide area coverage. However its performance efficiency is degraded by link impairments, which are enhanced in mobile communications where shadowing and blockage events are present. Fade mitigation techniques like link adaptation, would improve overall system performance in broadband satellite communications. Transmission specifications would be modified for alternating channel conditions in link adaptation methods [1]. Adaptive coding and modulation (ACM) scheme [2-4] is thought to be a proven technique for performing link adaptation. In this technique channel impairments are mitigated, which in turn improve link operational efficiency and reliability. This technique permits to select the best Modulation and Coding scheme (MODCOD) based on variations in link condition. However non-adaptive systems increasingly rely on a fixed modulation and coding method to provide adequate performance in worst case link scenarios, causing reduction in overall capacity utilization, spectral efficiency, and data rate.

MODCOD suitable for transmission has been defined on the basis of accurate and timely channel state information (CSI), which signal-to-noise ratio (SNR) is a common parameter for evaluating this. In poor channel conditions, a robust MODCOD is being used for transmission, due to the limited SNR, while in better link conditions and availability of line-of-sight (LOS) channel, higher order MODCODs can be selected. Channel estimation based on signal-to-noise-plus-interference ratio (SNIR) was investigated for forward and reverse link physical adaptation [5]. In addition, [6] modified the ACM procedure to cope with channel estimation errors. ACM methods are employed for broadband satellite systems based on DVB-S2 and DVB-RCS standards. The performance of this technique and its advantages in forward and return links for aforementioned standards was discussed in the literature [7-9]. In [10] a complete laboratory demonstrator investigated ACM in Ka-band multi-beam satellite systems. In this paper we consider forward link adaptation with frame structure of DVB-S2 standard [11]. In contrast to mentioned studies, here we discuss ACM in a mobile scenario which encounters rapid variations of channel states. These temporal behaviors of Land Mobile Satellite (LMS) channels are represented in [12]. In addition, ACM state-based algorithm was proposed for variable mobile speeds [13], where channel state estimations were applied for link adaptation.

Satellite's high power amplifier (HPA) introduces nonlinearities causing link performance degradation. To

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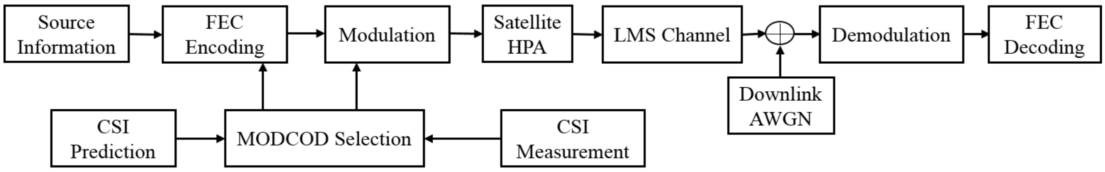

Fig. 1. System model

compensate nonlinear impairments of travelling wave tube amplifier (TWTA), pre-distortion techniques have been proposed [14]. Here we have considered linearized TWTA (LTWTA) defined by DVB-S2 committee, which still brings in destructive effects. As a result new MODCOD thresholds must be derived to mitigate nonlinear impairments in the adaptation procedure.

Furthermore, there are huge propagation delays in satellite communication, especially in geostationary (GEO) satellites, resulting outdated received CSI and consequently insufficient ACM utilization. In order to mitigate outdated CSI, we performed channel gain prediction. The prediction algorithms for wireless terrestrial networks [15-17] and satellite communications [18] have already been studied. In this paper we considered auto regressive moving average (ARMA) method for predicting channel power gain and compensating large round trip time, thus optimizing physical layer configuration more efficiently. Overall, our main contributions are as follows:

• We employed link adaptation for mobile satellite link, considering nonlinear power amplifier as well. Nonlinear distortion in satellite power amplifier degrades system performance and should be considered for a more realistic scenario. All simulation results are derived for the nonlinear case too.

• In order to combat the long round trip time of satellite link, we have adopted a channel prediction scheme. We considered GEO link delay which is the worst-case scenario. To the best of our knowledge this is the first work to employ prediction for ACM in nonlinear mobile satellite links. Link availability and average spectral efficiency are derived for different LMS channel states under predicted CSI.

The rest of the paper is organized as follows: Section 2 represents the system model and mobile satellite channel under study. In section 3, HPA's nonlinearity is described. The ACM adaptation algorithm and channel power prediction are discussed in section 4 and 5, respectively. Simulation results are presented in section 6, while paper findings are summarized in section 7.

2- SYSTEM MODEL

We considered a mobile broadband satellite system for GEO satellite channel. The basic system block diagram is sketched in Fig. 1. For physical layer, frame configuration of DVB-S2 standard was determined, where load density parity check (LDPC) coding concatenated with outer Bose, Chaudhuri and Hocquenghem (BCH) codes were used. DVB-S2 standard is widely used by satellite operators around the world, therefore we adopted its modulation and coding format for real case study. As can be seen from Fig. 1, both measured and predicted CSI were considered for determining the MODCOD scheme. We assumed open loop approach, so the adaptation via measured CSI is delayed half the round trip time i.e. 250ms. On the contrary, predicted CSI adapts the transmission for current channel status. We also considered LTWTA HPA model recommended by [11] for satellite transponder section. It should be noted for comparison the results were also driven for the case in which transponder's nonlinearity effect was neglected.

Statistical models for land mobile satellite (LMS) channels have been presented in the literature. Lutz's model [19] considered good and bad states described by Rice and Suzuki distributions, respectively. Loo's model [20] stated that the received signal consists of LOS component modeled by lognormal distribution and multipath interference which has Rayleigh distribution. In this paper we considered the three-state Fontan channel [21], which models LMS channel by Loo distribution with specific parameter values for different environments, elevation angles and clutter densities. Three states were defined to characterize LOS, moderate and deep shadowing conditions of channel. Variations of states were considered by state transition and state probability matrices of first-order Markov chain. As mentioned, the Loo distribution considers the received signal as sum of direct and multipath components which propose the slow and fast variations of signal amplitude. Direct signal is lognormally distributed with a mean as α and standard deviation, ψ, both expressed in dB. On the other hand, scatter component follows a Rayleigh distribution with average power MP (dB). The probability density function of Loo distribution can be defined [21] as

$$p(r)=\frac{r}{b_0\sqrt{2\pi d_0}}\int_0^\infty \frac{1}{z}\exp\left[-\frac{(\ln z-\mu)}{2d_0}-\frac{r^2+z^2}{2b_0}\right]I_0\left(\frac{rz}{b_0}\right)dz \quad (1)$$

where r is the received signal amplitude, d0, the variance of direct signal, μ, its mean value and b0, the multipath power, which can be related to α, ψ and MP, using following expressions

$$\alpha=20\log_{10}\left(e^{\mu}\right) \qquad \psi=20\log_{10}\left(e^{\sqrt{d_0}}\right) \qquad MP=20\log_{10}\left(2b_0\right) \quad (2)$$

The complete 3-state Fontan channel probability density function can be obtained by state probabilities, pi, as

$$p(r)=\sum_{i=1}^{3}p_i\frac{r}{b_{0,i}\sqrt{2\pi d_{0,i}}}\int_0^\infty \frac{1}{z}\exp\left[-\frac{(\ln z-\mu_i)}{2d_{0,i}}-\frac{r^2+z^2}{2b_{0,i}}\right]I_0\left(\frac{rz}{b_{0,i}}\right)dz \quad (3)$$

Model parameters for each state have been fitted to a comprehensive data set from experimental data in [21]. State

Table 1. System parameters

Parameter	Value
Satellite orbit	GEO
Frame configuration	DVB-S2 standard
Elevation angle	40º
Frequency band	S band
Satellite HPA	LTWTA [11]
User speed	10 m/s
Channel	Intermediate Tree Shadowed (ITS) [21]
Frame length	state1,2 =6.3m; state3=4.5m
Correlation length	1.5m
Downlink noise	AWGN $N_c(0,1)$

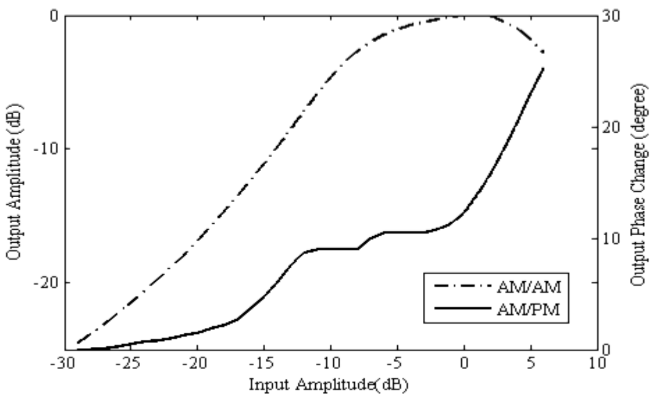

Fig. 2. Satellite LTWTA characteristics [11]

length and correlation distance for each state were defined individually and their relative time duration can be obtained, considering the speed between transmitter and receiver terminal. The main features of the system and channel parameters are summarized in Table 1.

3- SATELLITE NONLINEARITY

Satellite TWTA introduces nonlinearities, which can result in SNR degradation and consequently spectral efficiency limitation. As mentioned before we considered LTWTA for the HPA in satellite transponder and its AM/AM and AM/PM characteristics are illustrated in Fig. 2. Nonlinear effects on APSK modulations with symbols on one circumference (QPSK and 8PSK) are due to the changes in ring radius and phase rotation. More important, in 16APSK modulation with symbols lying on two concentric circles, nonlinear amplitude characteristic of HPA gains the outer ring less than the inner one making rings move towards each other. Besides, these constellation alterations are not considered in the soft decision decoder of DVB-S2, because it takes log-likelihood ratios for each code bit, referring to the original constellations, before the HPA has distorted them [14]. We used input back off (IBO) to overcome the nonlinearities operating in maximum power of HPA. IBO is the difference of input signal power Pin, with respect to the saturation power of HPA, P_{sat}, and is defined as

$$IBO(dB) = P_{in}(dB) - P_{sat}(dB) \tag{4}$$

The optimum operating point is given by a specific IBO which minimizes total degradation. Optimal IBO was obtained through simulation for each modulation order. Finally SNR thresholds in nonlinear scenario for each MODCOD could be derived using the specified IBO.

4- ADAPTIVE CODING AND MODULATION PROCEDURE

The aim of adaptive coding and modulation is to select the most appropriate MODCOD for prevailing channel conditions. SNR is the CSI parameter determined for MODCOD selection. We assumed an open loop scenario which is based on forward and reverse link channel reciprocity. Indeed this assumption would be true for both links operating in close frequency intervals. There would be differences in multipath variations but they are the same in shadowing events which are defined by channel states [13]. Herein, DVB-S2 Frame configuration was considered, so modulation and coding rates were restricted to this standard. The number of MODCODs defined in this standard is 28, which was reduced in order to have smaller set of ACM configurations. Moreover, implementation complexity for switching between schemes is further reduced [10]. Table 2, indicates driven SNR thresholds for each MODCOD, at target bit error rate of 10^{-7} over AWGN channel. For nonlinear case, optimized IBOs for each modulation are reported. It can be seen as modulation order increases more back off is needed which had been discussed in previous section. Thresholds

Table 2. MODCOD thresholds

Modulation	Code Rate	Spectral Efficiency (bps/Hz)	Required E_s/N_0 (dB) FEC@BER=10^{-7}(50 itr.) Linear	Nonlinear	IBO (dB)
QPSK	1/4	0.49	-2.4	-2.2	0.2
QPSK	1/3	0.66	-1.3	-1	0.2
QPSK	2/5	0.79	-0.4	0.2	0.2
QPSK	1/2	0.99	0.9	1.5	0.2
QPSK	3/5	1.19	2.2	2.8	0.2
QPSK	2/3	1.32	3.1	3.7	0.2
QPSK	3/4	1.49	4.1	4.7	0.2
QPSK	4/5	1.59	4.7	5.5	0.2
8PSK	3/5	1.78	5.7	7.5	1
8PSK	2/3	1.98	6.7	8.6	1
8PSK	3/4	2.23	8	10.6	1
16APSK	2/3	2.64	9	12.9	3
16APSK	3/4	2.97	10.3	15.4	3
16APSK	5/6	3.30	11.6	18.6	3
16APSK	8/9	3.52	12.8	21.4	3

for nonlinear case relative to the optimized IBOs are also represented.

Satellite communication struggles with much higher amount of delay compared to terrestrial ones. The idea of ACM technique is to adapt physical configuration to current channel conditions, however in our scenario we have large delay which makes the CSI outdated, especially in high mobile speeds where channel variability is increased. Two procedures including threshold margins and CSI prediction were selected to reduce delay effects. Threshold margins are described here and CSI prediction would be defined in section 5.

As a result of propagation delays and channel impairments, it is not possible to directly use channel CSI for MODCOD selection and link adaptation. Consequently, we used margins which mitigate mismatches of SNR thresholds for AWGN channel and ones with respect to tree-state channel model, as well as SNR variations due to propagation delays. Fixed and adaptive margins have been proposed in literature [10]. There are possibility of severe destructive effects in non-LOS states of channel, thus fixed margin is not an optimum option. We assumed different margins for both transmit power values and channel states and obtained the minimum margin values which met the required bit error rate. Average spectral efficiency can be expressed as

$$ASE = \sum_{n=1}^{N} SE_n P_n \tag{5}$$

where SE_n is the spectral efficiency for nth MODCOD in the set and N is the subset size that is equal to 15 in here. The probability of selecting nth MODCOD is represented by P_n defined as

$$P_n = P\left(SNR_{th_n} \le SNR_{dec} < SNR_{th_{n+1}}\right) \tag{6}$$

where SNR_{thn} is the nth MODCOD threshold and SNR_{dec} is the SNR for deciding MODCOD scheme of each transmitting frame that is

$$SNR_{dec} = SNR_{est} - M\left(P_{inp}, h_{state}\right) \tag{7}$$

where SNR_{est} is the estimated SNR at the transmitter and $M(P_{in}, h_{state})$ represents margin as a function of input power, Pin, and channel state, h_{state}. The probability of error due to selecting higher order MODCOD from what should be actually selected, should satisfy the required bit error probability, P_0, this can be written as

$$P_{err}\left[SNR_{dec}(t) > SNR_{act}(t+D)\right] < p_0 \tag{8}$$

where SNR_{act} is the actual channel SNR value at time $t+D$, which D indicates the propagation delay. Maximizing average spectral efficiency in (4) should be done subjected to above equation. The optimized margin for each channel state and input power was obtained numerically, as the solution cannot be expressed in closed form.

5- PREDICTION MODEL

AMC process is affected by the long delay period in satellite links which outdates the CSI used for link adaptation decision. Thus, if the current channel is in better conditions compared to CSI at hand, the link capacity will be wasted. In contrast, when the received CSI represents good channel state and the current channel is in poor conditions, then outage would occur. In order to adapt the transmission scheme without exceeding bit error limitation, margins were derived for threshold shifting, as described in section 4. It should be emphasized that this margins are overestimated to prevent outage events, thus the spectral efficiency is limited. By predicting the channel power we can optimize the margins and enhance link adaptation performance. Autoregressive moving average (ARMA) model was considered for prediction of channel power values. For time series $\{X_t\}$, ARMA (p,q) is expressed as [22,23]

Table 3. Link availability

		Link availability for line of sight state				Link availability for moderate shadowing state				Link availability for deep shadowing state					
Satellite Output Power(dBW)		5	10	15	20	5	10	15	20	5	10	15	20	25	30
Ideal CSI	Linear	100	100	100	100	94.1	100	100	100	0	0	50.1	100	100	100
	Nonlinear	100	100	100	100	92.7	100	100	100	0	0	44.5	100	100	100
Delayed CSI	Linear	100	100	100	100	8.5	55.3	100	100	0	0	0	50.7	100	100
	Nonlinear	100	100	100	100	0	48.9	100	100	0	0	0	41.4	100	100
Predicted CSI	Linear	100	100	100	100	49.2	100	100	100	0	0	28.3	83.6	100	100
	Nonlinear	100	100	100	100	28.6	84.2	100	100	0	0	17.6	74.1	100	100

$$X_t = \varphi_1 X_{t-1} + \varphi_2 X_{t-2} + \ldots + \varphi_p X_{t-p} + \varepsilon_t - \theta_1 \varepsilon_{t-1} - \ldots - \theta_q \varepsilon_{t-q} \quad (9)$$

where $\varphi_1, \varphi_2, \ldots \varphi_p$, and $\theta_1, \theta_2, \ldots \theta_q$, are the coefficients of p order autoregressive (AR) and q order moving average (MA) model parts, respectively, which should satisfy stationary and identifiability conditions. ε_t stands for random variable with zero mean and variance σ^2. The l–step prediction can be performed by calculating $X_{t+1}, X_{t+2,\ldots,}X_{t+l}$ from X_t with (9). It was assumed that channel estimations were obtained every 1ms. A 250-step prediction is needed to mitigate 250ms link delay. This long step prediction degrades the model efficiency and tends to averaging not forecasting. We aimed to reduce the steps with data smoothing as mentioned by [17] and achieve better performance in prediction algorithm. Thus, we no longer need 250-step prediction but only 50-step would be sufficient. The steps regarded in prediction algorithm are (1) smoothing data set, (2) estimating coefficients for predefined p and q values, and (3) applying ARMA model for 50 steps. This algorithm was done for every frame in order to predict channel coefficient and select the best MODCOD accordingly.

6- SIMULATION RESULTS

In this section we present simulation results performed on two system scenarios, one neglecting satellite HPA's nonlinear effects and another using nonlinear HPA described in section 5. Simulation parameters were listed in section 2. System performance under bit error probability of 10^{-7} was considered for three channel states separately. According to data suggested by [21] channel state probabilities are: LOS state, 39.3%, moderate shadowing, 35.7% and deep shadowing, 25%. It was assumed that there is perfect channel power estimation and the propagation delay was considered to be equal 250ms.

Appropriate margins for each channel state and transmit power, to satisfy the bit error probability was derived via extensive computer simulations. Table 3 represents link availabilities versus transmit powers for each channel state under different conditions, namely: ideal, delayed and predicted CSI values. Link availability is defined as the percentage of time where the link properties are worsen than the most robust MODCOD. In other words, if SNR_{dec} is lower than the first MODCOD threshold of represented subset, we are not supposed to send the frame, otherwise loss would occur. Ideal case is chosen when we have instantaneous knowledge of channel power at the receiver, hence the best MODCOD is selected for the ongoing channel condition. It is possible to see that the link availability increases with respect to transmit power. For delayed CSI, larger margins are determined in order to prevent bit errors, subsequently link availability decreases with respect to ideal case. However, by predicting channel power at transmitter, additional margins are canceled, resulting in link availability increment. Figs. 3-5, illustrate ACM algorithm performance in terms of average spectral efficiency (ASE). As it can be seen, considering satellite HPA nonlinearity resulted in performance degradation. This reduction in ASE worsen with transmit power enhancement. Indeed, at low powers robust MODCODs are chosen which encounter less distortion, hence SNR thresholds for nonlinear case are not much bigger than linear ones. In addition, there is not any significant difference in ASE results when smaller IBOs are used. Otherwise in high transmit powers, high order selected MODCODs result in greater IBOs and thresholds that cause reduction in overall spectral efficiency. The performance of predicted channel gain lies between instantaneous CSI knowledge and delayed CSI that implies performance improvement with prediction algorithm. Meanwhile, it still does not reach to ideal case, since the prediction method is not claimed to be optimal and a simplified scheme was adapted in order to reduce processing complexity and delay.

Fig. 3, indicates the ASE for LOS channel state. For the scenario without nonlinearity assumptions, at higher powers the channel impairments were mitigated. As a result, higher order MODCODs were selected and ASE tends to the maximum spectral efficiency value of the defined MODCOD subset. Moreover as can be seen, the results for predicted

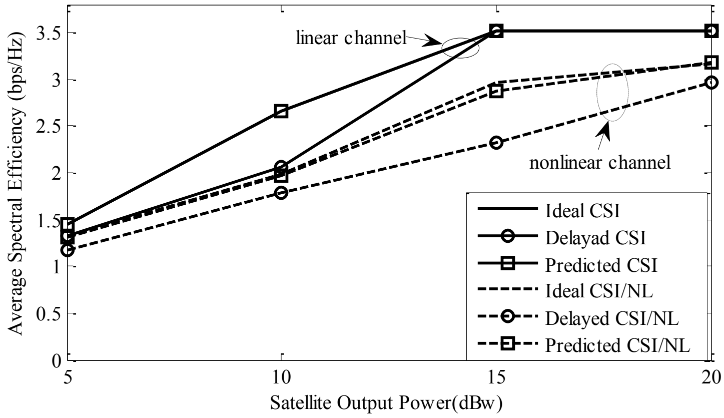

Fig. 3. ASE under line of sight channel state

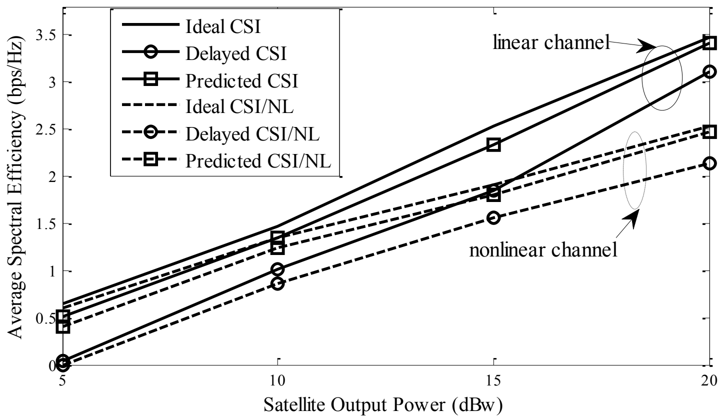

Fig. 4. ASE under moderate shadowing channel state

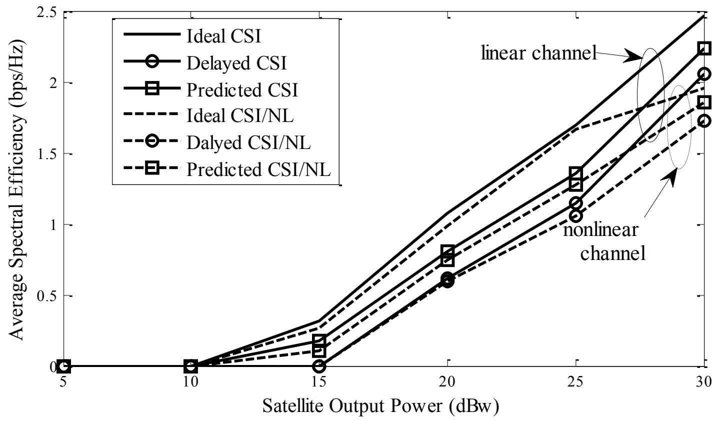

Fig. 5. ASE under deep shadowing channel state

CSI in both scenarios are almost the same as the ideal case. This could be explained by the fact that there are less severe fluctuations in this state, hence prediction scheme performed flawlessly.

ASE performance for moderate shadowing state is presented in Fig. 4. In this state, channel loss enhances and link experiences greater variations. Thus, general ASE performance and specifically prediction utilization efficiency degrades for this channel state with respect to LOS one. This was also evident in link availability percentages. System performance in terms of ASE and link availability for deep shadowing channel state encounters significant degradation which is expected due to the severe channel fading. Higher transmit power values are needed to compensate channel losses as indicated in Fig. 5. Also prediction performance in this state deteriorates due to the fast channel variations which cause imperfect channel gain tracking.

7- CONCLUSIONS

ACM implementation performance was assessed for tree state LMS channel model in DVB-S2 physical layer configuration. The results showed performance gain in terms of average spectral efficiency and link availability, while at the same time bit error probability was kept under a given threshold. System average spectral efficiency was also calculated considering non-linear impairments of satellite TWTA. It was demonstrated that linearized TWTA also causes nonlinear distortions and its impact must be considered in implementing ACM algorithm for practical satellite networks. A prediction scheme was further developed in order to reduce ACM performance degradation caused by long propagation delays in GEO satellite systems. It was shown that spectral efficiency enhanced with this approach specifically for LOS and moderate shadowing states, which channel variations are tractable.

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