An Approach to Cooperative Satellite Communications in 4G Mobile Systems

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Abstract— **In this paper we focus our attention in the main two methods of Cooperative Communications: Decode and Forward, and Amplify and Forward, and how they can be used in a new concept of Cooperative Satellite Communications. We present an analysis of both in terms of Symbol Error Rate and Power Allocation and analyze which would be more efficient when relaying information from the satellite to a mobile node in the terrestrial network. We propose a protocol that combines Selective and Incremental Relaying to optimize the cooperative scheme.**

Index Terms— **Decode and Forward, Amplify and Forward 8PSK, 16QAM, Symbol Error Rate.**

I. INTRODUCTION

Future 4G mobile systems will allow a subscriber to receive services anywhere, anytime at low costs. Such 4G systems will be capable of covering any geographical area by either using the terrestrial networks or the satellite networks. To this aim, it is necessary to combine both networks into a hybrid architecture that allows the flexibility to transmit high data rates from the source to the end user. To obtain such high data rates it is also necessary to use higher order digital modulations, i.e., M-PSK or M-QAM, along with a bandwidth efficient scheme like Orthogonal Frequency Division Multiplexing (OFDM) [15]. It is also imperative to adapt the recent trend of Cooperative Communications (CC) to this Hybrid Satellite/Terrestrial network so the link is as reliable as possible and the transmission of information is guaranteed.

CC works on the basis of a relay node that retransmits the signal to the destination node. CC combines two transmission phases; in Phase I, the source transmits a signal to both the relay node and the destination node and in Phase II, the relay node retransmits the received signal to the destination node. Two methods are being used by CC, they are known as Decode and Forward (DF) and Amplify and Forward (AF). AF is just an amplification of the signal by the relay node and then, the amplified signal is transmitted. DF is a more complex approach in which the relay node receives a signal, decodes and re-encodes it, and then is transmitted to the destination node. CC can be categorized in Fixed Relay and Adaptive Relay schemes. Fixed Relaying has the advantage of easy implementation but it is not efficient in the bandwidth usage since half of the channel resources are allocated to the relay for transmission. This reduces the overall rate. Adaptive Relaying includes selective and incremental relaying, and it is bandwidth efficient.

We will consider the case of satellite transmissions where the satellite acts as the source node. A relay node is placed in areas where the mobile users may lose link with the satellite and therefore a way of relaying the signal is needed. Examples of this can be a mobile user traveling and approaching places where the satellite link may be intermittent, or completed disrupted (tunnels, vegetation areas, building, etc.) as depicted in Figure 1.

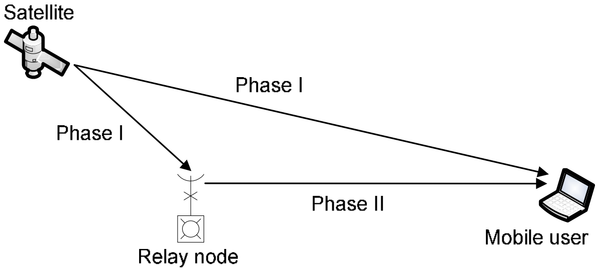

Fig. 1. Cooperative Satellite Communications showing Phase I and Phase II

In Phase I, the received signal (y) at relay and destination nodes is:

$$y_{s,d} = \sqrt{P}\, h_{s,d} \cdot x(t) + n_{s,d} \text{ and } y_{s,r} = \sqrt{P}\, h_{s,r} \cdot x(t) + n_{s,r} \quad (1)$$

where P is the transmitted power at the source, $x(t)$ is the transmitted information symbol, $n_{s,d}$ and $n_{s,r}$ are the additive noise in the source-destination s,d and source-relay s,r channels, and $h_{s,d}$ and $h_{s,r}$ are the channel coefficients for the s-d and s-r channels. The channels are considered as zero-mean, complex Gaussian random variables with variances $\delta^2_{s,d}$ and $\delta^2_{s,r}$. The noise terms $n_{s,d}$ and $n_{s,r}$ are modeled as zero-mean complex Gaussian random variables with variance N_0.

In Phase II, the relay sends a signal to the destination based on what it received from the source:

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$$y_{r,d} = h_{r,d} \cdot \kappa(y_{s,r}) + n_{r,d} \qquad (2)$$

where *r,d* represents the link between the relay and the destination, and κ varies depending on the type of scheme (AF or DF).

The destination receives two copies from the signal *x(t)* through the *s,d* link and the *r,d* link. It is necessary to combine both incoming signals at the destination. The best technique that allows the best Signal to Noise Ratio (SNR) is the Maximal Ratio Combiner (MRC). At the MRC output we obtain a SNR that is equal to the SNR from both the *s,d* and *r,d* links.

The outage probability [13], [14] is the probability that the mutual information is less than the rate *R*, in AF the outage probability is [16]:

$$P_r\left[MI_{AF} < R\right] \approx \left(\frac{\delta^2_{s,r} + \delta^2_{r,d}}{2\delta^2_{s,d}(\delta^2_{s,r}\ \delta^2_{r,d})}\right) \cdot \left(\frac{2^{2R}-1}{P/N_0}\right)^2 \qquad (3)$$

(Achieving diversity two)

where I_{AF} is the mutual information between source and destination, *R* is the rate. The same analysis can be extended to DF systems, giving an outage probability as follows:

$$P_r\left[MI_{DF} < R\right] \approx \frac{1}{2\delta^2_{s,r}} \cdot \frac{2^{2R}-1}{P/N_0} \qquad (4)$$

(Achieving diversity one)

The remainder of this paper is organized as follows. First, we describe the Adaptive Cooperation Schemes in Section II. Symbol Error rate Analysis of DF and AF are presented in section III. Section IV is dedicated to the analysis of power distribution in DF Schemes. Then, we explain the DF and AF performance in Section V. In Section VI, we present a characterization of the Satellite Channel Model. We then describe Selective and Incremental Relaying in Satellite/ Terrestrial Cooperation in Section VII. Simulation results are shown in Section VIII. Finally, we provide some concluding remarks in Section IX.

II. ADAPTIVE COOPERATION SCHEMES

With Fixed Relaying there is a 50% loss in the spectral efficiency due to the transmission in two phases. The performance of DF is limited to the weakest source-relay and relay-destination link reducing the diversity gain to one. Some other approaches [1] are aimed at resolving this limitation. They are known as: Selective Relaying and Incremental Relaying. In the following, we briefly analyze each one of them.

A. Selective Relaying

In DF Selective Relaying (SDF) the relay node decodes and forward the signal only if its SNR is above a certain value known as the threshold value [3],[4]. If the source-relay link suffers from fading or attenuations making the SNR value less than the threshold, the relay will not decode and forward the information to the destination node.

When the received signal at the relay node is strong enough (SNR > Threshold), the SNR of the combined MRC signal at the destination is the sum of the received SNR from the source and relay, as stated above. In order to an outage event to happen, both the source-destination *s,d* and source-relay *s,r* channels should be in outage or the combined source-destination, and relay-destination channel should be in the outage [7], [16], giving a diversity of two. The outage expression is given by:

$$P_r\left[MI_{SDF} < R\right] \approx \left(\frac{\delta^2_{s,r} + \delta^2_{r,d}}{2\delta^2_{s,d}(\delta^2_{s,r}\ \delta^2_{r,d})}\right) \qquad (5)$$

We can see that it has the same diversity gain as the AF case above; we can conclude that with high SNR both selective relaying DF and AF have the same diversity gain.

B. Incremental Relaying

In this case there is a feedback channel from the destination to the relay, as shown in Figure 2. The destination will send an acknowledgement message to the relay [8] if it correctly received the signal sent by the source. If this happens the relay does not need to transmit in Phase II [2]. This scheme has the best spectral efficiency among the above described approaches because the relay not always need to transmit and the Phase II transmission will depend on the channel characteristics in Phase I between the source and destination.

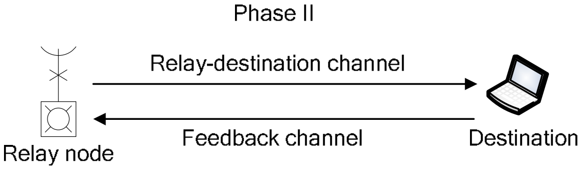

Fig. 2. Phase II occurs only if the destination node asks the relay node to forward information

If the transmission in Phase I from source to destination was successful, then Phase II will never occur and the source will use the next time frame to transmit new data. On the other hand, if the Phase I transmission was unsuccessful then Phase II will take place and the relay will send information to the destination. This could be the case when the mobile user loses the link with the satellite. The outage expression [9], [16] is given by:

$$P_r\left[MI_{AF} < R\right] \approx \left(\frac{1}{2\delta^2_{s,d}} \cdot \frac{\delta^2_{s,r} + \delta^2_{r,d}}{\delta^2_{s,r}\ \delta^2_{r,d}}\right) \cdot \left(\frac{2^{\overline{R}}-1}{P/No}\right)^2 \qquad (6)$$

$$\text{where } \overline{R} = \frac{R}{2} \cdot \left(1 + exp\left(-\frac{2^R-1}{P/No}\right)\right) \qquad (7)$$

The performance degrades when the rate R increases, but it degrades faster for incremental relaying because of the inherent loss in the spectral efficiency [11]. For high enough R, direct transmission is more efficient than relaying. Incremental relaying performs better because incremental relaying works at a much higher spectral efficiency than the rest of the relaying mechanisms and gives a diversity gain of two.

III. Symbol Error rate Analysis of DF and AF

A. DF SER analysis

We based the analysis of Symbol Error Rate using DF [6] with 8PSK and 16QAM modulations. In future 4G systems, it is necessary to use high order modulations to guarantee that high data rates are delivered to the end user. These high data rates are needed by many applications but especially by those that use multimedia such as video, data, etc.

Having the information of the channel coefficients $h_{s,d}$ and $h_{r,d}$ between source and destination and relay and destination, and assuming that the transmitted symbol x has average energy 1, the SNR of the MRC output is given by [6]:

$$SNR_{MRC} = \frac{Ps\left|h_{s,d}\right|^2 + P_R\left|h_{r,d}\right|^2}{N_0} \tag{8}$$

SER formulations for both 8PSK and 16QAM are given by the equations:

$$I_{PSK}(\vartheta) = \frac{1}{\pi}\int_0^{(M-1)\pi/M} exp\left(-\frac{b_{PSK}\vartheta}{Sin^2\theta}\right)d\theta \tag{9}$$

$$I_{QAM}(\vartheta) = 3Q(\sqrt{b_{QAM}\vartheta}) - \frac{9}{4}Q^2(\sqrt{b_{QAM}\vartheta}) \tag{10}$$

where ϑ is the SNR, $b_{PSK} = \sin^2(\pi/8)$, $b_{QAM} = 1/5$, and Q is the Gaussian function. If 8PSK is used in a DF Cooperation system, with instantaneous SNR I, then the conditional SER of the system with channel coefficients $h_{s,d}$, $h_{s,r}$, $h_{r,d}$ can be expressed as (11) and (12):

$$SER_{PSK} = I_{PSK}(SNR_{MRC}) \tag{11}$$

If 16QAM is used in the system, then the conditional SER [6] of such a system is given by the following expression:

$$SER_{QAM} = I_{QAM}(SNR_{MRC}) \tag{12}$$

In the case of QPSK and 4QAM modulation, the conditional SER given by (11) and (12) is the same. This is because QPSK and 4QAM have the same constellation so the detection of the phases has the same complexity. In Phase II if the relay node decodes the symbol correctly, it is forwarded to the destination with power $\tilde{P}_R = P_R$. If the symbol is not decoded correctly then it will not be forwarded and $\tilde{P}_R = 0$. If 8PSK is used the chances of incorrectly and correctly decoding at the relay are:

$$I_{PSK}\left(\frac{Ps\left|h_{s,r}\right|^2}{N_0}\right) \quad \text{and} \quad 1 - I_{PSK}\left(\frac{Ps\left|h_{s,r}\right|^2}{N_0}\right)$$

On the other hand, if 16QAM is used the chances of incorrectly and correctly decoding a symbol at the relay are:

$$I_{QAM}\left(\frac{P_S\left|h_{s,r}\right|^2}{N_0}\right) \quad \text{and} \quad 1 - I_{QAM}\left(\frac{P_S\left|h_{s,r}\right|^2}{N_0}\right)$$

The link between the relay node and the destination node can be modeled as a Rayleigh fading channel because the path between them can be obstructed and a direct line of sight may not exist. The Symbol Error Rate for a Decode and Forward Cooperation Scheme under a Rayleigh fading channel using 8PSK modulation can be expressed as (13), similar to the one in [11]:

$$\begin{aligned} SER_{PSK} = {} & F_{PSK}\left(1+\frac{b_{PSK}Ps\,\delta_{s,d}^2}{N_0\,Sin^2\theta}\right)\cdot F_{PSK}\left(1+\frac{b_{PSK}Ps\,\delta_{s,r}^2}{N_0\,Sin^2\theta}\right)+F_{PSK}\cdot \\ & \left(\left(1+\frac{b_{PSK}Ps\,\delta_{s,d}^2}{N_0\,Sin^2\theta}\right)\cdot\left(1+\frac{b_{PSK}Ps\,\delta_{s,r}^2}{N_0\,Sin^2\theta}\right)\right)\cdot\left(1 - F_{PSK}\left(1+\frac{b_{PSK}Ps\,\delta_{s,r}^2}{N_0\,Sin^2\theta}\right)\right) \end{aligned} \tag{13}$$

For a system using 16QAM over a Rayleigh fading channel with Decode and Forward Cooperation the Symbol Error Rate is given by (14):

$$\begin{aligned} SER_{QAM} = {} & F_{QAM}\left(1+\frac{b_{QAM}P_S\,\delta_{s,d}^2}{2\,N_0\,Sin^2\theta}\right)\cdot F_{QAM}\left(1+\frac{b_{QAM}Ps\,\delta_{s,r}^2}{2\,N_0\,Sin^2\theta}\right)+F_{QAM}\cdot \\ & \left(\left(1+\frac{b_{QAM}P_S\,\delta_{s,d}^2}{2\,N_0\,Sin^2\theta}\right)\cdot\left(1+\frac{b_{QAM}P_S\,\delta_{r,d}^2}{2\,N_0\,Sin^2\theta}\right)\right)\cdot\left(1 - F_{QAM}\left(1+\frac{b_{QAM}P_S\,\delta_{s,r}^2}{2\,N_0\,Sin^2\theta}\right)\right) \end{aligned} \tag{14}$$

where FPSK and FQAM depend on $x(\theta)$.

B. DF SER approximation

The Symbol Error Rate of Decode and Forward Cooperation [6] system using 8PSK and 16QAM modulations can be upper bounded as shown in (15):

$$SER_S \le \frac{(M-1)N_0^2}{M^2}\cdot\frac{M\,b\,P_S\,\delta_{s,r}^2 + (M-1)b\,P_R\,\delta_{r,d}^2 + (2M-1)N_0}{\left(N_0 + b\,P_S\,\delta_{s,d}^2\right)+\left(N_0 + b\,P_S\,\delta_{s,r}^2\right)+\left(N_0 + b\,P_R\,\delta_{r,d}^2\right)} \tag{15}$$

where $b=b_{PSK}$ for 8PSK signals and $b=b_{QAM}$ for 16QAM signals, M = 8 in 8PSK and M = 16 in 16QAM.

If $\delta^2_{s,d} \neq 0$, $\delta^2_{s,r} \neq 0$, and $\delta^2_{r,d} \neq 0$, it means that all of the link channels ($h_{s,d}$ $h_{s,r}$ and $h_{r,d}$) are available then P_S/N_0 and P_R/N_0 go to infinity, the Symbol Error Rate of the system using 8PSK and 16QAM modulation can be approximately as shown in (16):

$$SER_S \approx \frac{N_0^2}{b^2}\cdot\frac{1}{P_S\,\delta_{s,d}^2}\left(\frac{A^2}{P_S\,\delta_{s,r}^2}+\frac{B^2}{P_R\,\delta_{r,d}^2}\right) \tag{16}$$

where b, A, and B depends on the type of modulation [1] and will be A = 0.494, B = 0.377 for 8PSK; and A = 0.64, B = 0.53 for 16QAM.

C. *AF SER approximation*

An approximate expression for SER using Amplify and Forward can be obtained. If all the channels ($h_{s,d}$, $h_{s,r}$ and $h_{r,d}$) are available (meaning that $\delta^2{}_{s,d} \neq 0$, $\delta^2{}_{s,r} \neq 0$, and $\delta^2{}_{r,d} \neq 0$), then when P_S/N_0 and P_R/N_0 tend to infinity the SER of AF using 8PSK and 16QAM modulation is given by [5] as shown in (17):

$$SER_S \le \frac{A\,N_0^2}{b^2} \cdot \frac{P_S \delta^2{}_{s,r} + P_R \delta^{\,2}{}_{r,d}}{P^2{}_S P_R \delta^2{}_{s,d} \delta^2{}_{s,r} \delta^2{}_{r,d}} \tag{17}$$

where A and b depends on the type of modulation and are given by A= 0.3742 and b=b_{PSK} for 8PSK; and A= 0.53 and b=b_{QAM} for 16QAM.

Figure 3 and Figure 4 show Decode and Forward and Amplify and Forward Symbol Error Rate graphs versus P/N_0 [dB]. The three results showed are: the exact SER formulation, the upper bound formulation and the asymptotically tight approximation, considering $\delta^2 s,d = \delta^2 s,r = \delta^2 r,d = 1$, and $N_0 = 1$.

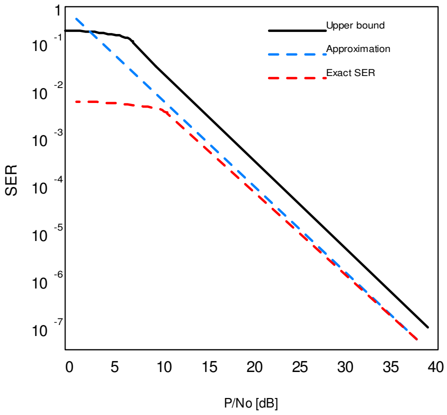

Fig. 3. DF Cooperative Communications system with QPSK

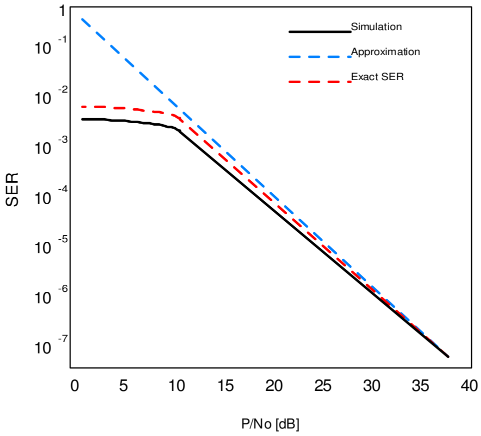

Fig. 4. AF Cooperative Communications system with QPSK

IV. ANALYSIS OF POWER DISTRIBUTION IN DF SCHEMES

In this section we aim to obtain the optimum power distribution both at the source and the relay node [12]. Note that as stated before, the power at the source is P_S and the power at the relay is P_R.

In a Decode and Forward Cooperation Scheme using 8PSK and 16QAM modulation [6], if all the channels are available ($h_{s,d}$, $h_{s,r}$ and $h_{r,d}$), and $\delta^2{}_{s,d} \neq 0$, $\delta^2{}_{s,r} \neq 0$, and $\delta^2{}_{r,d} \neq 0$ for high SNR and $P = P_S + P_R$ the power distribution [11] is shown in (18) and (19):

$$P_S = \frac{\delta_{s,r} + \sqrt{\delta_{s,r}^2 + 8(A^2/B)\,\delta_{r,d}^2}}{3\delta_{s,r} + \sqrt{\delta_{s,r}^2 + 8(A^2/B)\,\delta_{r,d}^2}} \cdot P \tag{18}$$

$$P_R = \frac{2\delta_{s,r}}{3\delta_{s,r} + \sqrt{\delta_{s,r}^2 + 8(A^2/B)\,\delta_{r,d}^2}} \cdot P \tag{19}$$

where A and B depends on the type of modulation 8PSK or 16QAM as stated in the previous section.

It is important to note that the expressions (18) and (19) do not depend on the source-destination channel; they only depend on the links between source-relay and relay-destination. We can also note that the optimum power ratio of the source power P_S over the total power P is less than one and larger than ½ [11], on the other hand the optimum ratio of P_R at the relay over the total power P is greater than 0 and less than ½ [6].

$$\tfrac{1}{2} < P_S/P < 1 \qquad \text{and} \qquad 0 < P_R/P < 1$$

It shows that we should always put more power at the source and less power at the relay. This consequence is important in our case because the satellite is the source and it has to have the greater power. If $\delta^2{}_{s,r} << \delta^2{}_{r,d}$, link quality between source-relay is less than that of relay-destination; P_S tends to P and P_R tends to 0, meaning that we must use all the power at the source given that the link quality between relay-destination is better. This should be the case when the satellite link presents strong fading due to rain, or any other atmospheric impairment. On the contrary, if $\delta^2{}_{s,r} >> \delta^2{}_{r,d}$, it means that the source-relay channel is in much better condition than that the relay-destination link. In this case P_S and P_R go to ½, and we should allocate equal power at both the source and relay. In the satellite link case, since the satellite power cannot be increased, we must find a way to increment the power at the relay every time the relay-destination link fades considerably. It is important to note that the relay-destination link is modeled as a Rayleigh fading channel which is a type of channel when there is no direct line of sight between relay and destination, thus having strong fading.

In order to obtain diversity two, the source-relay and relay-destination links should be appropriately balanced. If the source-relay link is unavailable, it is hard for the relay to perform its task of Decode and Forward the received symbol. Therefore, the forwarding task of the relay is less important, so it makes sense to put more power at the source. On the contrary, if the source-relay channel quality is very good, the relay can decode the signal from the source. In this case, we can consider the relay as a copy of the source and put the same amount of power on both. It is important to note that the amount of power also depends on the constellation size; for high order constellations such as 8PSK or 16QAM the amount of power must be greater than in the case of QPSK or 4QAM.

We now consider three cases of power allocation using Decode and Forward [10].

1. Relay-destination channel is not available ($\delta^2_{r,d} = 0$)
2. Source-relay channel is not available ($\delta^2 s,r = 0$)
3. Source-destination channel is not available ($\delta^2 s,d = 0$)

Case 1. If the relay-destination channel is not available, from (13) the Symbol Error Rate of Decode and Forward Cooperation System using 8PSK modulation can be expressed by (20):

$$SER_{PSK} = F_{PSK}\left(1+\frac{b_{PSK} P_S\, \delta^2_{s,d}}{N_0\, Sin^2\theta}\right) \le \frac{A\, N_0}{b_{PSK} P_S\, \delta^2_{s,d}} \quad (20)$$

where F_{PSK} and A are defined above for the 8PSK case.

Analyzing (14) we obtain a similar equation for the case of 16QAM when the relay-destination link is not available as shown in (21):

$$SER_{QAM} = F_{QAM}\left(1+\frac{b_{QAM} P_S\, \delta^2_{s,d}}{2 N_0\, Sin^2\theta}\right) \le \frac{2\, A N_0}{b_{QAM} P_S\, \delta^2_{s,d}} \quad (21)$$

where F_{QAM} and A are specified above for the 16QAM case.

From (20) and (21) we conclude that the optimum power distribution is P_S=P and P_R=0. As expected if there is no relay-destination link then the only option is to use direct transmission between source and destination allocating all the power at the source.

Case 2. If the source-relay channel is not available, from (13) and (14), the Symbol Error Rate of Decode and Forward Cooperation System using either modulation are given by (22):

$$SER_P \le \frac{2\, A\, N_0}{b\, P_S\, \delta^2_{s,d}} \quad (22)$$

where A will vary if the system uses 8PSK or 16QAM and b = b_{PSK} for 8PSK and b = b_{QAM}/2 for 16QAM. In this case, the optimum power distribution is P_S=P and P_R=0.

Case 3. If the source-destination channel is not available (causing Phase II transmission, see Section VI) from (13) and (14) the Symbol Error Rate of Decode and Forward Cooperation System with 8PSK or 16QAM is given by (23):

$$SER_S = F_i\left(1+\frac{b\, P_S\, \delta^2_{s,r}}{N_0\, Sin^2\theta}\right) + F_i\left(1+\frac{b\, P_R\, \delta^2_{r,d}}{N_0\, Sin^2\theta}\right)\cdot\left(1 - F_i\left(1+\frac{b\, P_{S1}\, \delta^2_{s,r}}{N_0\, Sin^2\theta}\right)\right) \quad (23)$$

where i=1 and b = b_{PSK} for 8PASK, and i=2 and b = b_{QAM}/2 for 16QAM. If the source-relay and relay-destination are available the SER in (23) can be approximate as shown in (24):

$$SER_S \approx \frac{A N_0^2}{b^2}\left(\frac{1}{P_S\, \delta^2_{s,r}} + \frac{1}{P_R\, \delta^2_{r,d}}\right) \quad (24)$$

where b = b_{PSK} for 8PSK, and b = b_{QAM}/2 for 16QAM. A also depends on the type of modulation as expressed above [10].

In this last case the power distribution for both 8PSK and 16QAM is:

$$P_S = \frac{\delta_{r,d}}{\delta_{s,r} + \delta_{r,d}} P \quad \text{and} \quad P_R = \frac{\delta_{s,r}}{\delta_{s,r} + \delta_{r,d}} P$$

When the source-destination channel is not available, the system is modeled as a two-hop system. This conclusion is important in the case the satellite loses the link with the mobile user and needs to use the relay node to transfer the service. The mobile node may have entered a zone out of the satellite reach and then will depend on the relay node to receive the signal, as shown in Figure 5.

The power at the satellite will depend on the channel quality between the relay and destination, the channel quality between the satellite itself and the relay and the overall power P.

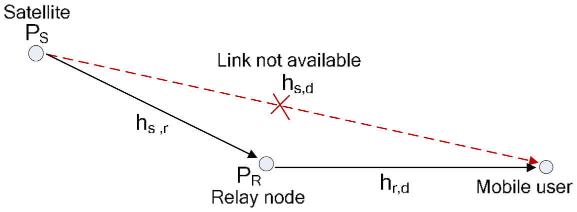

Fig. 5. Case 3 when there is no source-destination link

The optimum power distribution for an Amplify and Forward system using either 8PSK or 16QAM modulation can be expressed as (25) and (26), similar in [5]:

$$P_S = \frac{\delta_{s,r} + \sqrt{\delta^2_{s,r} + 8\,\delta^2_{r,d}}}{3\delta_{s,r} + \sqrt{\delta^2_{s,r} + 8\,\delta^2_{r,d}}}\cdot P \quad (25)$$

$$P_R = \frac{2\delta_{s,r}}{3\delta_{s,r} + \sqrt{\delta^2_{s,r} + 8\,\delta^2_{r,d}}}\cdot P \quad (26)$$

From (25) and (26) we can deduce that the optimum power distribution in an Amplify and Forward system does not depend on the type of modulation used. This differs from the Decode and Forward scheme where the optimum power distribution depends on the type of modulation. This is because in the AF case, the relay receives, amplifies and forwards the signal regardless of the modulation type.

In DF, the relay uses the modulation type in order to decode and re-encode the data that is why in DF the power distribution depends on the modulation. Also from (25) and (26) we can see that optimum ratio of P_S to the overall power P is less than 1 and larger than ½, and the ratio of power P_R to the overall power is larger than 0 and less than ½ .

V. DF AND AF PERFORMANCE

A. Decode and Forward

We saw that for high SNR the Symbol Error rate performance of a DF system is given by (16), substituting the optimum power distribution given by (18) and (19) in (16) thus, we have (27) and (28), similar in [10]:

$$SER_S \approx D_{DF}^{-2} \left(\Phi\right)^{-2} \tag{27}$$

$$D_{DF} = \frac{2\sqrt{2}\,b \quad \delta_{s,d} \quad \delta_{s,r}\ \delta_{r,d}}{\sqrt{B}} \ \frac{\left(\delta_{s,r} + \sqrt{\delta_{s,r}^2 + 8(A^2/B)\,\delta_{r,d}^2}\right)^{1/2}}{\left(3\delta_{s,r} + \sqrt{\delta_{s,r}^2 + 8(A^2/B)\,\delta_{r,d}^2}\right)^{1/2}} \tag{28}$$

where $b = b_{PSK}$ for 8PSK, and $b = b_{QAM}/2$ for 16QAM; and $\Phi = P/N0$.

Analyzing (27) we can see that adaptive DF Cooperation gives us a diversity of 2, depending only on the characteristics of the channel links. Equation (28) is known as the Cooperation gain of a DF system and it gives us an idea of the best performance gain we can obtain using DF Cooperation. If the channel between source and relay is worst than the channel between relay and destination, the Cooperation gain can be reduced to (29):

$$D_{DF} = \frac{b \quad \delta_{s,d} \quad \delta_{s,r}}{A} \tag{29}$$

On the other hand, if the channel between source and relay is much better than the channel quality between relay and destination, the Cooperation gain can be reduced to (30):

$$D_{DF} = \frac{b \quad \delta_{s,d} \quad \delta_{r,d}}{2\sqrt{B}} \tag{30}$$

B. Amplify and Forward

Similar analysis can be done in the case of Amplify and Forward scheme. The Symbol Error Rate is given by (17), combining this SER with equations (25) and (26) we can obtain (31) and (32), as in [10]:

$$SER_S \approx D_{AF}^{-2} \left(\Phi\right)^{-2} \tag{31}$$

$$D_{AF} = \frac{2\sqrt{2}\,b \ \ \delta_{s,d} \ \ \delta_{s,r}\,\delta_{r,d}}{\sqrt{B}} \ \frac{\left(\delta_{s,r} + \sqrt{\delta_{s,r}^2 + 8\delta_{r,d}^2}\right)^{1/2}}{\left(3\delta_{s,r} + \sqrt{\delta_{s,r}^2 + 8\delta_{r,d}^2}\right)^{3/2}} \tag{32}$$

Equation (32) is the Cooperation gain of a AF scheme and give us an idea of the best performance of a system using Amplify and Forward. Equation (31) shows that AF also gives us a diversity of order 2, which is the same as an adaptive DF Cooperation system.

If we compare the Cooperation gain of DF to the Cooperation gain of AF, we obtain the ration β, which is given by $\beta = D_{DF}/D_{AF}$.

Analyzing the three possible cases of channel quality:

Case 1. Source-relay channel worst than relay-destination channel ($\delta^2_{s,r} << \delta^2_{r,d}$):

$$\beta \approx \frac{\sqrt{B}}{A} > 1 \qquad \text{(DF performs better than AF)}$$

Case 2. Source-relay channel better than relay-destination channel ($\delta^2_{s,r} >> \delta^2_{r,d}$):

$$\beta \approx 1 \qquad \text{(DF and AF performs the same)}$$

Case 3. Source-relay channel equal than relay-destination channel ($\delta^2_{s,r} = \delta^2_{r,d}$):

$$\beta = \sqrt{\frac{1+\sqrt{1+8A^2/B}}{4}} \left(\sqrt{\left(\frac{6}{3+\sqrt{1+8A^2/B}} \right)} \right)^3$$

By giving the values of A and B for 8PSK and 16QAM, we have $\beta \approx 1.0670$ for 8PSK, and $\beta \approx 1.0378$ for 16QAM.

VI. Characteristics of the Satellite Channel Model

We consider the Hybrid satellite/terrestrial channel to have a direct line of sight (LOS) coming from the satellite and several terrestrial receivers located in an open area, thus resulting in a propagation model with several paths. The satellite LOS path is modeled by using a Rician distribution. Rician distribution is a multipath model that is described by the factor K, which is the ratio of the power in the direct link to the power of the multipath links. Typical values for K are: 5dB, 7dB, 8dB. The terrestrial model is described as Rayleigh distribution which is a type of distribution where the LOS is non-existing, thus leaving K=0. Rayleigh fading channels affects the signal much more that Rician fading channels because all the paths that reach the receiver are reflected, diffracted or from scattering. Other variables for describing these multipath fading channels include: Delay spread and Doppler Spread. The maximum Doppler shift can be found by using the following expression:

$$f_{dm} = \frac{v}{c} f_0$$

where c is the speed of light, v- is the mobile speed, and f_o is the frequency.

Some characteristics of the Satellite channel include:

1- Non-linear distortion introduced by onboard Power Amplifier
2- Long round-trip propagation time
3- Reduced Time Diversity
4- Rain attenuation

The High Power Amplifier (HPA) is introduced in the satellite channel. HPA operates near saturation region to maximize output power and efficiency. Under the mentioned condition, a Non-linear distortion is introduced increasing spectral re-growth and in-band distortions. This can be problematic if we use higher order modulations like 8PSK, 16QAM, etc, and damage the channel capacity increasing adjacent channel interference. Some waveform pre-distorter is necessary to tackle these issues. Typically HPAs are Traveling Wave Tube (TWT).

Higher order modulations, such as 8PSK and 16 QAM, are the modulation vehicles through which the higher throughputs that broadcasters and satellite operators are now demanding are achieved. However, this brings with it challenges that have traditionally not been evident with existing QPSK modulation. Phase noise, higher C/N requirements, and increased dish sizes at downlink sites to name but a few. In order to meet this challenge it is necessary to develop a system solution that allows us to use higher modulation schemes over satellite channels and at the same time compensate for any distortions in the channel.

A satellite dynamic precorrection system will allow maximising the satellite transponder throughput, significantly reducing downlink receiver antenna sizes and increasing the link reliability. This dynamic precorrection will compensate for virtually any linear and non-linear distortion that is likely to be encountered in a typical satellite transmission chain. It also compensates for both earth and satellite distortions.

We also need to consider the effects of the satellite High Power Amplifiers (HPA) when we use OFDM to transmit high data rates over the satellite link. OFDM is highly sensitive to the presence of non-linear distortions and synchronization errors between transmitted and received signals. Digital pre-correction schemes can be applied for the compensation of the AM/AM and AM/PM distortion introduced by on board satellite HPA. This linearization can not be realized successfully unless the path delay introduced by the analog chain is previously estimated.

This type of non-linear distortion is solely dependent on the modulus of the input signal and appears at the receiver as a warped symbol constellation thereby degrading the bit error rate (BER), while in frequency domain the distorted signal undergoes spectral re-growth which generates intermodulation products and adjacent channel interference.

The time delay introduced by the analog chain responsible for frequency up-conversion to the HPA input and frequency down-conversion from the HPA output must be compensated for before estimation of the pre-correction coefficients. A time delay estimation module is necessary before any adaptive pre-correction scheme is initiated. The time delay estimation algorithm proposed in [17] is an accurate one that can be used in satellite HPA. The algorithm is based on the definition of an intelligent cross-correlation between the input and output of the HPA signals. They used a Saleh Model for the Travelling Wave Tube Amplifier (TWTA), as it introduces more significant AM/PM distortions than the Solid State Power Amplifier (SSPA). The memory less model of the HPA is defined by:

$$A[|x|] = \frac{\alpha_a |x|}{1+\beta_a |x|^2} \tag{33}$$

$$\Phi[|x|] = \frac{\alpha_\Phi |x|^2}{1+\beta_\Phi |x|^2} \tag{34}$$

$$\alpha_a = 2 \quad \beta_a = \beta_\Phi = 1 \quad \alpha_\Phi = \frac{\pi}{3}$$

If we want to use OFDM over satellite channels we must guarantee to have diversity gain. By exploiting time diversity we can use OFDM in satellite links as long as the transmission of two consecutive symbols will take place in a time interval longer that the satellite coherence time. Satellite links have long uplink and downlink paths, making the round trip very large. This affects the accuracy of the channel estimators that are used in OFDM terrestrial links in order to keep an updated channel condition. We must select a value for the time between two OFDM symbols that satisfies $T_s > C_{CT}$, it means that the time between symbols is larger than the channel coherence time C_{CT}; and two consecutive symbols will be un-correlated.

VII. Selective and Incremental Relaying in Satellite / Terrestrial Cooperation

From section V we can see that Decode and Forward performs better in two of the three cases, and performs similar to Amplify and Forward when the source-relay channel is better than the relay-destination channel.

The use of higher order modulations over satellite links [15] has to be carefully designed and strong error correction algorithms must be used. Also, as we said at the beginning of our paper, OFDM is needed to obtain a better spectral efficiency and to transmit high data rates. This brings us to consider (for most cases) that the source-relay channel may be worse than the relay-destination channel. It is important to note that, although the relay-destination channel is modeled as a Rayleigh multipath which is a type of channel with strong fading, the use of OFDM and higher modulation order is more reliable here than in the satellite-relay channel. In satellite links OFDM depends on increased time diversity, and high order modulations depend on pre-distortion to make them work in a suitable way. In this case, we see that the Cooperation gain β >1, so Decode and Forward performs better than Amplify and Forward.

By combining Decode and Forward with Selective and Incremental relaying, we can accomplish a stronger scheme. As shown in Figure 6, the destination node will request transmission from the relay node only if its SNR is less than the threshold value meaning that the signal it is not strong enough to obtain the data sent by the source. If the destination node loses the satellite link for some reasons, the SNR will drop below the threshold and it will request Phase II from the relay node. The relay node will employ Selective Relaying and will transmit the decoded signal to the destination node only if its own SNR is above the threshold value. Hence, for the relay node to transmit two things must occur: the destination node must request transmission and the SNR on the relay itself must be above the threshold.

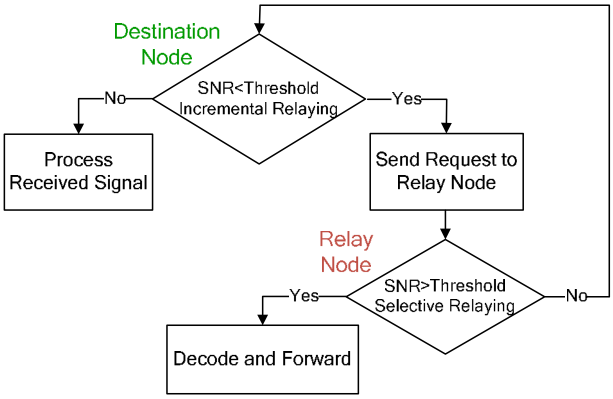

Fig. 6. Incremental and Selective Relaying

The relay node will remain idle if it does not receive a request from the destination node and/or its own SNR is low. If the relay node does not receive the request it will also remain idle even if its SNR is high. This is the main difference between this proposed scheme and Selective relaying in which the relay decodes and forwards the signal as long as its SNR is greater than the threshold. The difference between our scheme and Incremental relaying is that when the destination requests a transmission from the relay it will occur if the SNR in the relay is high. In this case the destination will totally lose the signal if both channels (satellite-destination and satellite- relay) are unavailable as shown in Figure 7.

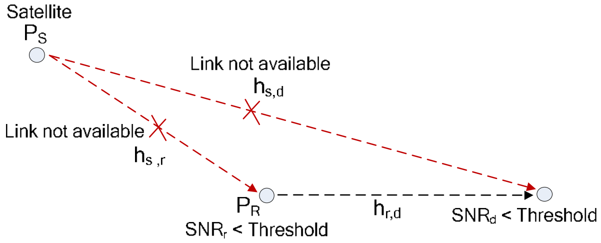

Fig. 7. Both SNRs (at destination and relay) are low

VIII. SIMULATION RESULTS

The simulation results are divided in two parts. The first part is related to Phase I transmission between the Satellite and the Relay node. The second part is related to the terrestrial link between Relay node and Destination node.

Figure 8 shows the simulation block diagram for Phase I. For the simulation we used OFDM 16QAM and OFDM QPSK modulations. The satellite channel is modelled as a Rician Model with a Path Loss Block that simulates the signal attenuation from the satellite to the earth terminal. The satellite is of Geostationary Orbit (GEO Satellite).

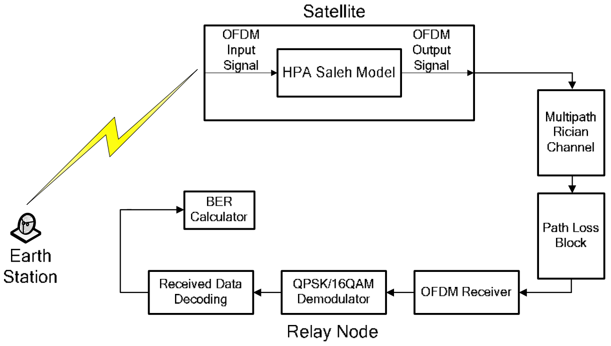

Fig. 8. Phase I Physical Layer

The parameters of the Simulation are as follows:

Bandwidth: 5 MHz
Central Frequency: 2 GHz
OFDM Subcarrier spacing: Δf = 15 KHz
OFDM IFFT Size: 2048 for 16QAM
OFDM IFFT Size: 1024 for QPSK
Tx_1 = 1 ms
OFDM Symbol Time: 83.33 μs
Number of OFDM symbols: 12
Cyclic Prefix duration: 16.67 μs
Rician Factor: K = 2
Maximum Doppler Shift: 15 Hz
Satellite-Earth Station distance: 35000 Km
Satellite Path Loss: 180 dB

Figure 9 shows the OFDM spectrum of a QPSK OFDM Uplink and Downlink signals; and the HPA Effects on the OFDM spectrum.

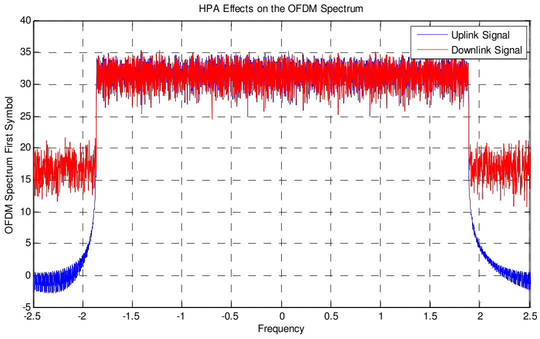

Fig. 9. QPSK OFDM Saturation Level = 0 db Relative to AM Average

As can be seen, the Downlink Spectrum is severely attenuated. This can be problematic especially for higher order modulation schemes making that the bit error rate at the receiver perform poorly. The HPA response compared to the saturation level for the values of Figure 9 is showed in Figure 10. We can see that the HPA Response is very attenuated compared to the Reference Linear value. Also, Figure 11 shows the QPSK Uplink and Downlink Constellations.

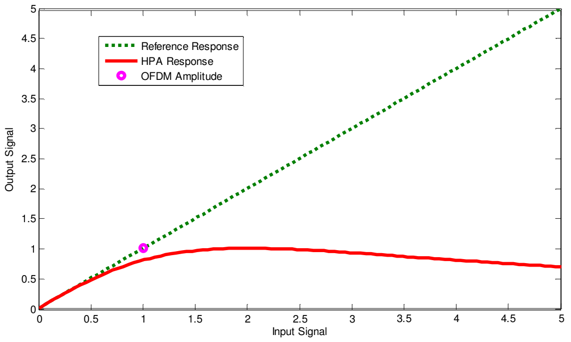

Fig. 10. HPA Response compared to Linear Reference for QPSK with Saturation Level of 0 dB

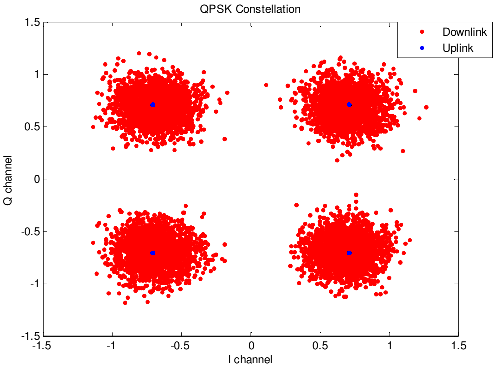

Fig. 11. OFDM QPSK Constellation Saturation Level 0 dB, K=2, Path Loss = 180dB

We now increase the Saturation Level to 5 dB. The effects on the QPSK OFDM Spectrum, the HPA Response and the QPSK Constellation are showed is Figs. 12, 13 and 14, respectively. Note the improvement of the Downlink QPSK OFDM Spectrum (in red) which is closer to the Uplink signal (in blue), as well as the improvement of the Constellation and the HPA Response.

The HPA Response with saturation Level of 5 dB becomes much closer to the Linear Response in the lower values of the Input Signal axis, making the Downlink Spectrum and Constellation less distorted and improving the bit error rate at the receiver site.

The Constellation noise and Spectrum noise and attenuation are also due to the Rician Channel and Path Loss Block contributions.

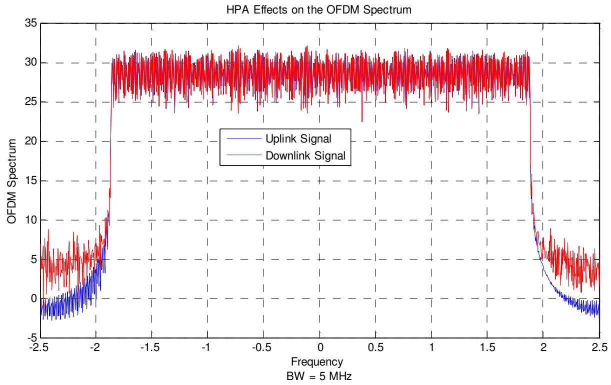

Fig. 12. QPSK OFDM Saturation Level 5 dB Relative to AM Average

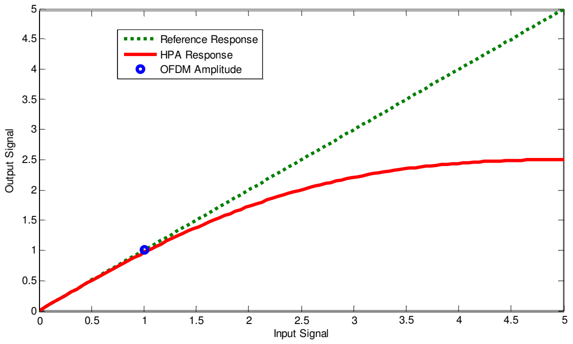

Fig. 13. HPA Response compared to Linear Reference for QPSK with Saturation Level of 5 dB

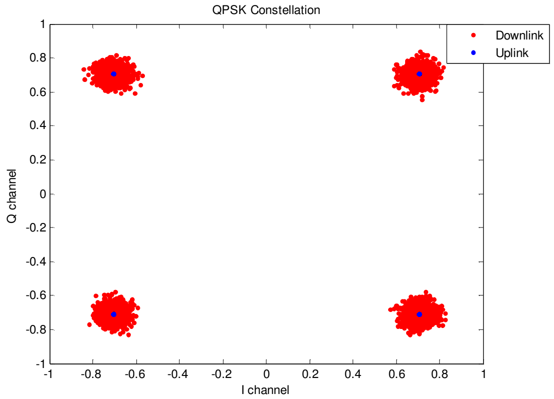

Fig. 14. QPSK OFDM Constellation Saturation Level 5 dB, K=2, Path Loss = 180dB

We now present the same results for the case of OFDM 16QAM satellite link communication with IFFT size of 2048. Figs. 15 and 16 and show the simulation results with Saturation Level of 0 dB and Satellite Channel contribution.

Figs. 17 and 18 shows the simulation results with Saturation Level of 5 dB and Satellite Channel contribution due to the Multipath Rician Model and the Path Loss Block for 16QAM OFDM .

We can note the improvement of the Downlink Signal (in red) compared to the Uplink Signal (in Blue) and compared to the Downlink Signal of Figure 18.

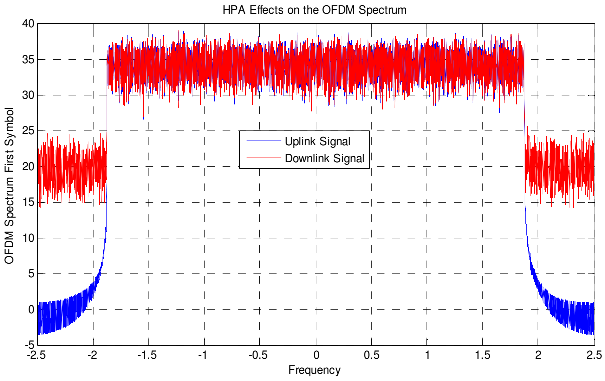

Fig. 15. 16QAM OFDM Saturation Level 0 dB Relative to AM Average

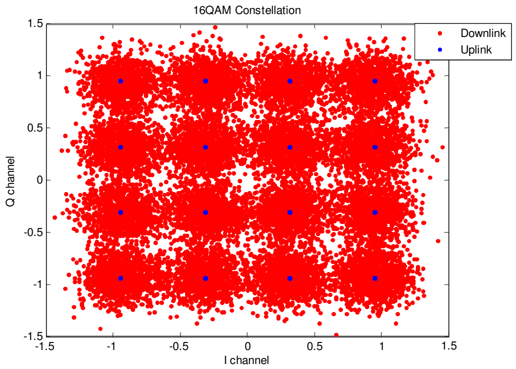

Fig. 16. 16QAM OFDM Constellation Saturation Level 0 dB, K=2, Path Loss = 180dB

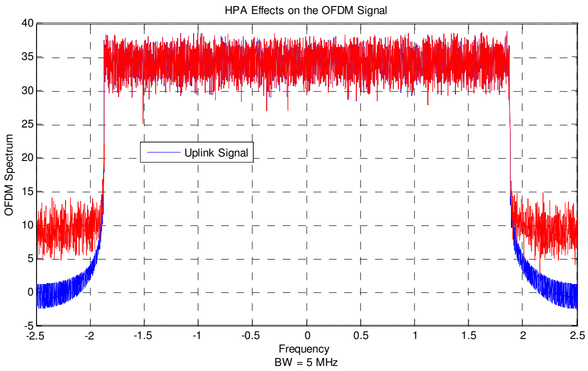

Fig. 17. 16QAM OFDM Saturation Level 5 dB Relative to AM Average

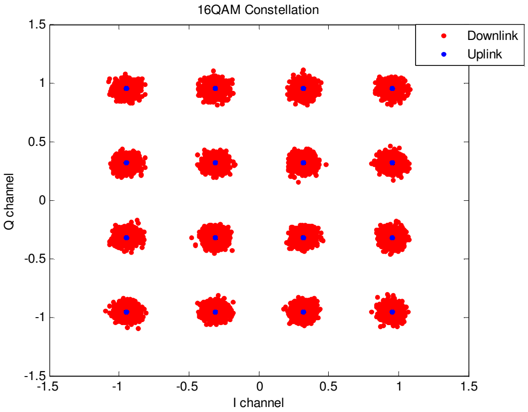

Fig. 18. 16QAM OFDM Constellation Saturation Level 5 dB, K=2, Path Loss = 180dB

The Table 1 and 2 show the Bit Error Rate (BER) and Modulation Error Rate (MER) measures at the receiver as follows.

Table 1. Modulation Error Rate Results

Saturation Level (dB)	*OFDM 16QAM IFFT = 2048, BW =5 MHz*	*OFDM QPSK IFFT = 1024, BW = 5 MHz*
-1.5	-11.9	-11.8528
-1.0	-12.509	-12.5185
-0.5	-13.1643	-13.2822
0	-13.8105	-13.8527
0.5	-14.6612	-14.5654
1.0	-15.299	-15.4131
1.5	-16.4789	-16.2171
2.0	-17.38	-17.2688
2.5	-18.4151	-18.4182
3.0	-19.4805	-19.8186
3.5	-20.7649	-20.7854
4.0	-22.0552	-22.1705
4.5	-23.6023	-23.311
5.0	-24.9787	-24.6751

Table 2. Bit Error Rate Results

Saturation Level (dB)	*OFDM 16QAM IFFT = 2048, BW = 5 MHz*	*OFDM QPSK IFFT = 1024, BW = 5 MHz*
-4.0	0.2642	0.003295
-3.5	0.2377	0.0022816
-3.0	0.2133	0.0011951
-2.5	0.19045	0.0004345
-2.0	0.15841	0.0007605
-1.5	0.12584	0.0001086
-1.0	0.097611	0.0001024
-0.5	0.069653	$4.392\,e^{-5}$
0	0.044951	$3.294\,e^{-6}$
0.5	0.026764	$2.089\,e^{-7}$
1.0	0.014278	$1.002\,e^{-8}$
1.5	0.0060261	$1.0\,e^{-8}$
2.0	0.0015201	$1.0\,e^{-8}$
2.5	0.00070575	$1.0\,e^{-8}$
3.0	$5.4289\,e^{-5}$	$1.0\,e^{-8}$
3.5	$9.2454\,e^{-6}$	$1.0\,e^{-8}$
4.0	$4.3759\,e^{-7}$	$1.0\,e^{-8}$
4.5	$5.9221\,e^{-8}$	$1.0\,e^{-8}$
5.0	$1.2562\,e^{-8}$	$1.0\,e^{-8}$

Figures 19 and 20 show the graphs of Bit Error Rate for both QPSK and 16QAM OFDM over the satellite channel for different values of the Rician factor K.

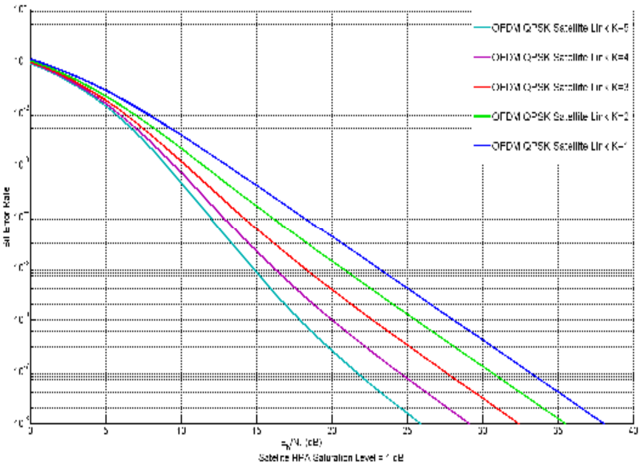

Fig. 19. BER values QPSK OFDM Satellite Channel

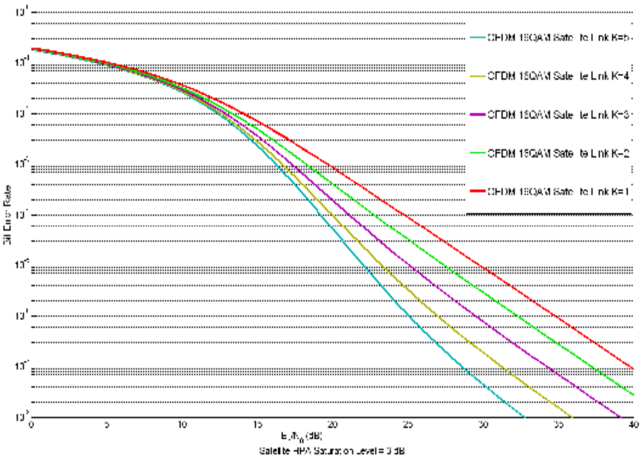

Fig. 20. BER values 16QAM OFDM Satellite Channel

If a Channel Coding Block is added to the Simulation the BER results improve considerably as shown in Figure 21 and 22.

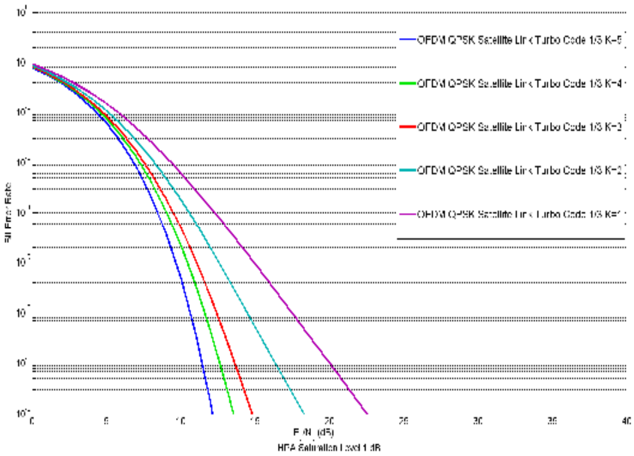

Fig. 21. BER values QPSK OFDM using Turbo Code

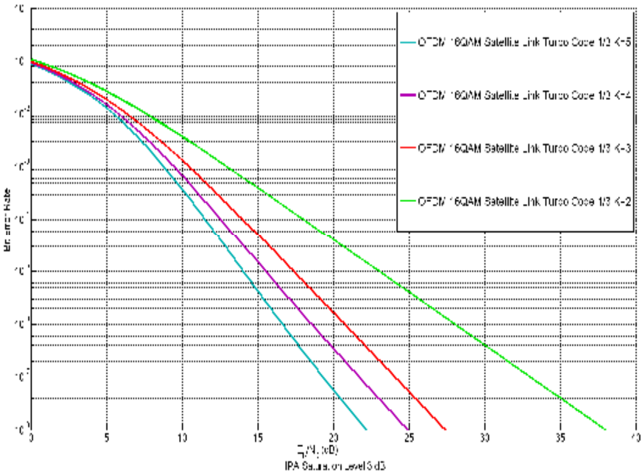

Fig. 22. BER values 16QAM OFDM using Turbo Code

As mentioned before, Phase II will take place when the destination node requests it and SNR at the relay is above certain value. A Simulation of Phase II consist of the relay node using OFDM 8PSK and 16QAM, a Rayleigh multipath fading channel and the destination node where the SER is measured, as depicted in Figure 23.

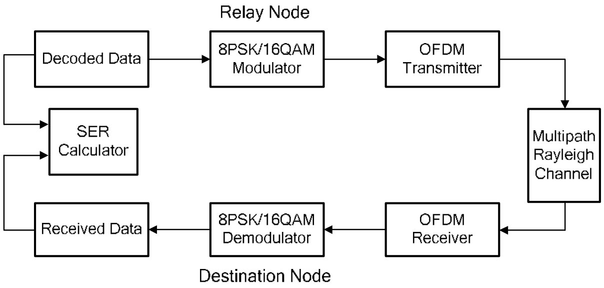

Fig. 23. Phase II Physical Layer

The signal spectrum at the output of the relay node and at the input of the destination node shows how the Rayleigh channel affects the overall frequency distribution. By using a strong error correction method these impairments can be overcome and the resulting SER (13) is within limits of performance. Figure 24 shows the signal spectrum and the eye diagram of the transmitted and received signals.

The effects of the Rayleigh multipath over the frequency response can be seen at the destination node (in red). The OFDM signal is attenuated at different frequency components. Since the OFDM signal is composed of several individual carriers, this uneven attenuation effect is not as destructive as in a single carrier modulation. The individual carriers are therefore detected over a small bandwidth.

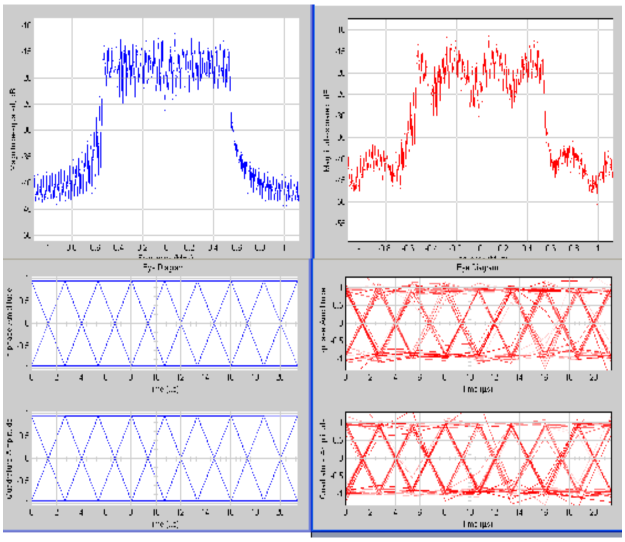

Fig. 24. OFDM spectrum and Eye Diagram in Phase II $E_b/N_0 = 10$ dB

The Simulation results for SER depend on the E_b/N_0 value and the error correction employed as shown in Figures 25.a and Figure 25.b.

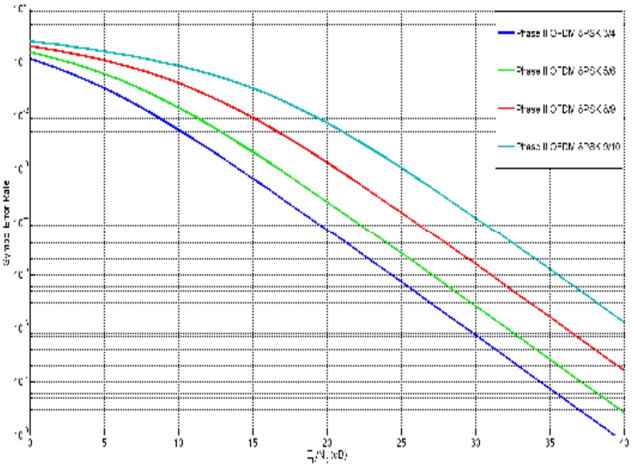

Fig 25.a. E_b/N_0 vs SER OFDM 8PSK Phase II

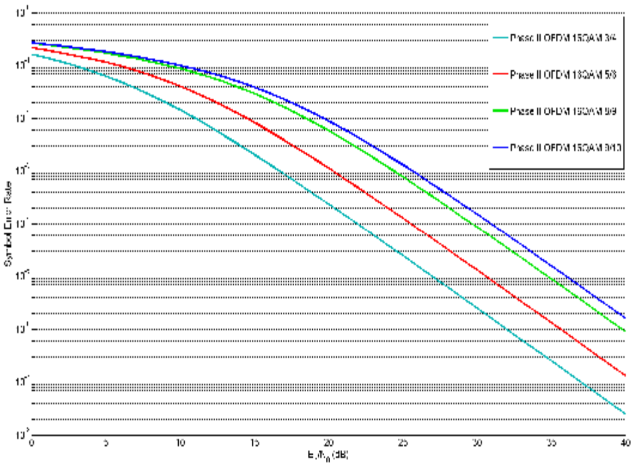

Fig 25.b. E_b/N_0 vs SER OFDM 16QAM Phase II

IX. CONCLUSIONS

Cooperative Satellite Communications will be an important part of future 4G systems. We need to guarantee a constant transfer of information from the satellite to the mobile unit, even when the mobile unit travels into areas that are unreachable by the satellite. We think that Decode and Forward is the best option for the Cooperating protocol since it is never outperformed by the Amplify and Forward alternative. It is important to note here that even AF is easier to implement than DF. AF does not allow us the flexibility to adapt to bandwidth constrains that may be present when transferring the signal from the satellite link to the terrestrial one. OFDM and high modulation techniques such as 8PSK and 16QAM are needed in both channels. When the satellite-destination channel is not available, the power distribution will depend on the channel characteristics between the satellite-relay and the relay-destination.

To allow better bandwidth efficiency we think that the combination of Selective and Incremental relaying is the best option. As stated in section VI, the transmission from the relay to the mobile user will take place only when the mobile user does not receive the signal from the satellite, and the signal at the relay node is strong enough.

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