Hybrid Satellite/Terrestrial Cooperative Relaying Strategies for DVB-SH based Communication Systems

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***Abstract*—The integration of satellite and terrestrial systems in a hybrid network permits to benefit from both systems, overcoming the drawbacks of a Non-Line-Of-Sight (NLOS) propagation. The purpose of this paper is to study simple cooperative relaying strategies which rely on the introduction of the Delay Diversity (DD) technique in a DVB-SH compliant hybrid satellite/terrestrial network with the aim of improving the performance of the network. The application of this strategy represents a promising solution to guarantee communication also in public emergency situations, such as the ones caused by fire, earthquake, flood or explosion. We investigated the pros and cons of the proposed scheme, comparing the assumptions which are required and the simulation results with respect to the satellite-only and the terrestrial-only systems.**

I. INTRODUCTION

The future key of the telecommunication systems consists in the integration of different technologies with the aim of guaranteeing connectivity everywhere and anytime: this goal is being pursued through the adoption of advanced solutions in today's telecommunications systems.

This is the exactly the situation we have in the emerging standard DVB-SH (Digital Video Broadcasting for Satellite services to Handheld devices) where some of the major boosters, as the multicarrier modulation (OFDM), the use of lower frequency bands (below 3 GHz) and the implementation of cooperative communication techniques in hybrid satellite and terrestrial networks, are gathered together [1].

The purpose of this paper is to study simple cooperative relaying strategies which can be adopted in a DVB-SH compliant satellite/terrestrial network with the aim of guaranteeing communication in public emergency situations, caused by fire, earthquake, flood or explosion. In such a context both the satellite and the terrestrial components play an important role; through the fast implementation of a hybrid network with one or more gap fillers, the satellite can support the terrestrial networks while the gap fillers allow the communication with an end-user, whose satellite link is characterized by bad channel condition. In particular we combine the satellite/terrestrial network OFDM-based proposed by the DVB-SH standard (SH-A Architecture) with the Cooperative *Delay Diversity* (DD) relaying technique [2] [3] [4] [5] [6], which represents a very simple and suitable solution to overcome the performance loss of the NLOS environment.

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II. HYBRID SATELLITE/TERRESTRIAL COOPERATIVE RELAYING STRATEGIES

In the hybrid satellite/terrestrial network we consider the elements of the relay-network, namely the source, the relay and the destination, are represented by the satellite (SC, *Satellite Component*), the gap-filler (CGC, *Complementary Ground Component*) and the receiver (D, *Destination*). In this paper two cooperative relaying schemes are considered which are based on the use of one and two relays: they are defined as 1-relay and 2-relay, respectively. In both of them independently faded versions of the transmitted signal arrive at D: one directly from SC and the others (one in the 1-relay and two in the 2-relay scheme) through the CGCs. The presence of a gap-filler, which is supposed to be in LOS (Line of Sight) with the satellite, and the transmission of the same information data from different locations make the communication possible also in bad channel condition and afford spatial diversity at the receiver end. The gap filler, acting as a cooperative node, is assumed to process the received signal according to the *Amplify and Forward* (AAF) algorithm.

A. Hybrid Cooperative Delay Diversity scheme

The DD technique is based on the transmission of one or more delayed copies of the same information data in order to increase the delay spread of the channel, and, therefore the frequency selectivity [7].

The 1-relay and the 2-relay schemes are described separately for the sake of clarity.

1) 1-Relay Network: In the 1-relay network the transmitted signal arrives at the destination through two different paths, which are characterized by different delays:

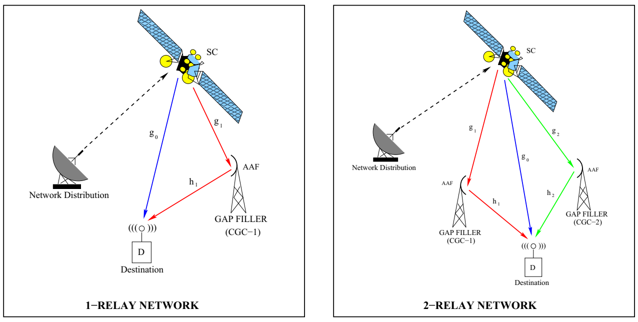

Fig. 1. Hybrid satellite/terrestrial *1-Relay and 2-Relay Cooperative Delay Diversity* system

- δ_0 is the propagation delay of the signal through the direct path (from SC to D);
- δ_1 is the propagation delay of the signal through indirect path (from SC to D through CGC);

The *delay* (δ) of the DD scheme is the difference between these two delays:

$$\delta = \delta_1 - \delta_0 = \frac{d_{(SC,CGC)} + d_{(CGC,D)}}{c} - \frac{d_{(SC,D)}}{c} \quad (1)$$

where $d_{(i,j)}$ denotes the distance between i and j and c represents the speed of light. Since $d_{(SC,CGC)} \simeq d_{(SC,D)}$ the (1) becomes:

$$\delta = \frac{d_{(CGC,D)}}{c} \quad (2)$$

Therefore, the DD technique can be seen as a natural cooperative-relaying transmission: in fact no additional operation is required at the destination node. In order to keep the complexity low, the gap filler can work according to the *Amplify and Forward* algorithm, amplifying and retransmitting the received signal (Fig.1).

Nonetheless some simple operations have to be considered; in fact to make the gap-filler simultaneously receive and retransmit the signal a frequency conversion is needed. According to the DVB-SH standard the satellite transmits the same signal to D and CGC on different frequencies: in fact, the link SC-D is in L-Band, while the link SC-CGC is in Ka-Band. Therefore the gap filler amplifies and retransmits the received Ka-Band signal after converting into L-Band. In this way two different delayed L-band copies of the signal arrive at D, allowing the implementation of the DD technique in the hybrid satellite/terrestrial network.

2) 2-Relay Network: In the 2-relay network the transmitted signal arrives at the destination through three different paths (Fig.1), which are characterized by the following delays:

- δ_0 is the propagation delay of the signal through the direct path (from SC to D);
- δ_i is the propagation delay of the signal through indirect path (from SC to D through CGC-i, with $i = 1, 2$);

The *delays* (δ_{CGC-i}, with i=1,2) of the DD scheme are:

$$\begin{aligned}\delta_{CGC-i} &= \delta_i - \delta_0 \\ &= \frac{d_{(SC,CGC-i)} + d_{(CGC-i,D)}}{c} - \frac{d_{(SC,D)}}{c} \\ &\simeq \frac{d_{(CGC-i,D)}}{c} \end{aligned} \quad (3)$$

Both the gap fillers, which are assumed to be in LOS with the satellite, operate according to the AAF algorithm with the same operations described for the 1-relay scheme.

As highlighted in the next section the presence of two relays increases the frequency selectivity of the channel transfer function, affording a performance improvement in term of bit error rate with respect to the single relay cooperative network.

III. Delay Diversity's Effects on the Channel Transfer Function

In a hybrid satellite/terrestrial cooperative relaying network with N_{gf} gap fillers, denoting with $s(n)$, $n = 0, \cdots, N-1$ the transmitted OFDM symbol (where N is the number of subcarriers), the received signal at the destination, after the removal of a cyclic prefix and neglecting the AWGN noise, can be written as:

$$y(n) = \alpha g_0 s(n) + \sum_{i=1}^{N_{gf}} \sum_{p=0}^{N_{max}} \beta_i g_i h_i(n,p) s(n - \delta_i - \tau_p) \quad (4)$$

where

- $h_i(n,p)$ is the complex coefficient of the p-path of the terrestrial multipath channel between CGC-i and D, τ_p the delay of the p-path and N_{max} the number of paths;
- g_i is the complex coefficient of the satellite channel between SC and CGC-i (g_0 is the one between SC and D);
- α_i and β_i are the power scale factors.

Analysing the DD effects in terms of channel impulse response, (4) can be rewritten as:

$$y(n) = s(n) * h_{equ}(n) \quad (5)$$

where $h_{equ}(n)$ is the equivalent channel impulse response:

$$h_{equ}(n) = \alpha g_0 + \sum_{i=1}^{N_{gf}} \sum_{p=0}^{N_{max}} \beta_i g_i h_i(n,p) \delta(n - \delta_i - \tau_p) \quad (6)$$

Therefore, assuming $h_i(n,p)$ constant during an OFDM symbol with respect to the time index and denoting with $H_i(l)$ the frequency domain channel fading coefficients for l-th subcarrier of the transmitted OFDM symbol from CGC-i to the receiver, the equivalent channel transfer function $H_{equ}(l)$ is:

$$H_{equ}(l) = \alpha g_0 + \sqrt{N} \sum_{i=1}^{N_{gf}} \beta_i g_i H_i(l) e^{-j\frac{2\pi}{N}\delta_i l} \quad (7)$$

According to this analysis, switching from the non-cooperative to a cooperative mode, the Destination experiences an increase of the frequency selectivity of the propagation channel; in fact the receiver cannot discriminate whether the propagation path comes from the effect of the cooperative relaying DD technique or the channel itself. Therefore, as highlighted in (6) and (7), transmitting delayed copies of the same signal through a propagation channel changes the MISO channel (Multiple-Input Single-Output) into a SISO (Single-Input Single-Output) channel with increased frequency selectivity [8]. We can conclude that in the cooperative schemes proposed the spatial diversity is transformed into frequency diversity, which makes the error distribution change: this feature can be exploited by the use of FEC codes with a remarkable improvement of the performance.

In the previous expressions, the satellite channel between SC and both the gap fillers and D is assumed to be in LOS or NLOS condition, while the one between the CGCs and D is supposed to be a NLOS multipath channel (Rayleigh Distribution). It is important to notice that the equivalent channel perceived by D is a hybrid channel, which consists in terrestrial and satellite components and is characterized by a mixed LOS/NLOS propagation channel. In general the adoption of the DD technique, in a non cooperative system, combined with the presence of a LOS component leads to a loss in performance: particularly, the increase of frequency selectivity involves the presence of deep fades which are the reasons for the performance degradations [9]. However we analyse hybrid cooperative schemes, which have to be evaluated with the satellite channel model (Lutz-model), described in Section IV. Therefore, since the satellite channel can be both in LOS or NLOS state, the DD technique is more suitable with respect to the terrestrial case.

IV. Working conditions: DVB-SH hybrid network

The cooperative schemes which have been described in the Section II are applied to a DVB-SH network (SH-A architecture) with the aim of improving the performance of the network.

A. *A hypothetical scenario*

As for the scenario, a situation of public emergency (fire, earthquake, flood, explosion) is considered. The integration of the satellite and the terrestrial component is strongly required in order to guarantee communication services to users in emergency areas. In particular, as depicted in Fig.2, we consider the first response phase of a disaster, where several rescuers organized in teams act with the aim of saving lives and preserving the environment during emergencies. In this context the relays are represented by gap fillers which enable the rescue teams to communicate with the emergency control center in absence of the terrestrial infrastructure network, which is often only partially available or completely destroyed due to the disaster effects. In particular the gap fillers can be represented by a temporary, mobile stations placed at the perimeter of the disaster site. The application of the hybrid cooperative scheme proposed allow the connection of the rescuers operating in the emergency area with the outside world even when the satellite-team link is characterised by bad channel condition.

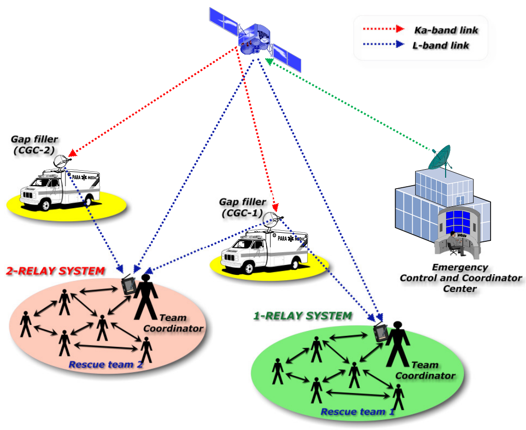

Fig. 2. Hypothetical emergency scenario

B. *Simulation Parameters and Assumptions*

According to the DVB-SH (SH-A Architecture) specifications [10] [11] , an OFDM system is implemented both at for satellite component and for the CGCs and a cyclic prefix is introduced to avoid ISI at the receiver. In particular the most important DVB-SH compliant parameters which are adopted in the simulations are: signal bandwidth 5 MHz, mode 1K, OFDM Sampling Frequency $40/7$ MHz, OFDM Symbol Duration $179.2\mu s$, OFDM Guard Interval $44.8\mu s$, QPSK modulation, Turbo Code (coderate $1/4$). Besides at the receiver after the removal of the cyclic prefix, the Zero Forcing equalization is performed, assuming the knowledge of channel state information.

The channel propagation models which are used in the simulations are:

- Satellite Channel Model: Lutz model which represents the channel by a two states Markov chain. The *good* (LOS) state and the *bad* (NLOS) state, which are modelled as a Ricean and a Log-normal Rayleigh channel, respectively. Besides, each state is characterised by its state probability, which depends on the environment considered.
- Terrestrial Channel Model: TU6 model which consists 6 paths, each affected by Rayleigh distributed fading with different average power.

In the DD cooperative schemes, in order to perform equalization, besides the channel state information, D also must know the *delay*: this information can be derived by D through position information acquisition.

In the simulations we also assume that:

- the satellite channels between the satellite and the gap fillers are always in LOS and in Ka-Band, while the link between the satellite and the receiver can be characterised by *good* or *bad* state in L-Band. Since a static channel

model is simulated, both channel states have to be considered in the simulations;
- the noise introduced by the gap filler is negligible and no amplification is performed. Therefore, CGC can be seen as a transparent relay, with the exception of the specific operations required for the DD cooperative scheme;
- the DVB-SH interleavers are not introduced: this choice makes clear the advantages of the cooperative strategies proposed.

V. Simulation Results

The performance of the proposed systems has been verified by simulations. The hybrid satellite/terrestrial cooperative relaying systems are compared with the satellite and the terrestrial stand-alone systems, assuming the same total transmitted power. It is worth pointing out that the terrestrial system has been considered as a term of reference: in the considered scenario a stand-alone terrestrial infrastructure is not available due to the disaster effects.

We consider two different environments: City and Highway, which represents the worst and the best case within the range of the environments [12]. Besides, the BER-performance is reported for different values of the delay in order to represent the impact of this value on the DD scheme.

In Fig.3 and Fig.4 the 1-relay and 2-relay systems are compared with the non cooperative one, respectively: we assume different strategies of power allocation, namely same and different power between the CS and the CGC. These two situations represent the worst and the more realistic cases in terms of power allocation: particularly, the latter implies that the copies of the signals coming from the CGCs are characterised by a higher level of power with respect to the signal directly transmitted from the satellite. In Fig.3 we observe a remarkable improvement with respect to the satellite-only system and a performance gain of the 1-relay cooperative scheme with unequal power for $SNR \leq 6-7dB$ with respect to the terrestrial-only system. On the other hand in Fig.4 we note that the 2-relay cooperative scheme gains 2-3dB and 2-4dB (δ-depending) for BER=10^{-3} respectively in the equal an unequal power cases over the terrestrial-only system.

In order to highlight the BER-performance of the 1-relay and 2-relay cooperative systems we analyse Fig.5 and Fig.6, where the two cooperative relaying schemes are compared respectively in the City and in the Highway environment. In particular the 2-relay system gains 4-5dB and 2-4dB (δ-depending) for BER=10^{-3} over the 1-relay system in the City and Highway cases, respectively.

Finally, in order to highlight the effect of the cooperative DD systems with equal and unequal power, we analyse the BER performance of the 1-relay (Fig.7) and 2-relay (Fig.8) systems in the City setting, assuming the LOS condition for the SC-D link. As explained in Section III, the introduction of the cooperative DD scheme in presence of a LOS channel component causes both a performance gain (depending on the number of gap fillers) and the suppression of the Turbo Code error floor with respect to the satellite system. On the other hand, the LOS channel originates a performance loss of the unequal power system with respect to the equal power case: this is probably due to the power which is allocated to the delayed version of the original signal so creating deep fades in the equivalent channel transfer functions.

VI. Conclusions

In this paper we have studied two simple cooperative relaying strategies which rely on the introduction of the Cooperative *Delay Diversity* technique in a DVB-SH compliant hybrid satellite/terrestrial network. The investigated cooperative schemes are characterized by a significant gain with respect to the satellite system and therefore represent a promising solution to guarantee communication also in public emergency situations, particularly, in the first response phase of a disaster, without any additional complexity requirements. Both the cooperative schemes achieve interesting BER-performance overcoming the performance of a terrestrial system, which has been considered as a term of reference (Section V).

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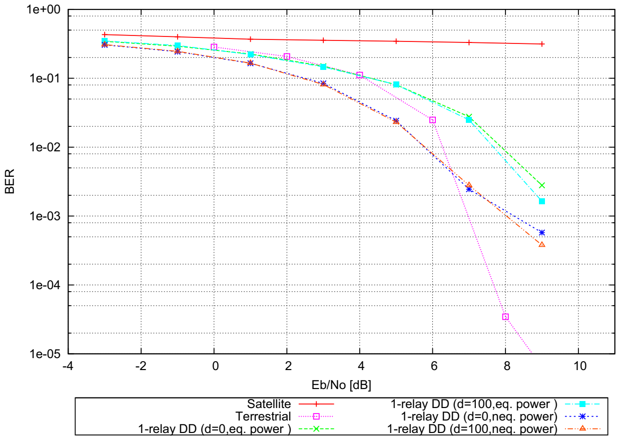

Fig. 3. Performance comparison of DVB-SH system among: satellite-only, terrestrial-only and Hybrid Cooperative Delay Diversity 1-relay ($\delta = 0$ and $\delta = 100$) scheme in City environment.

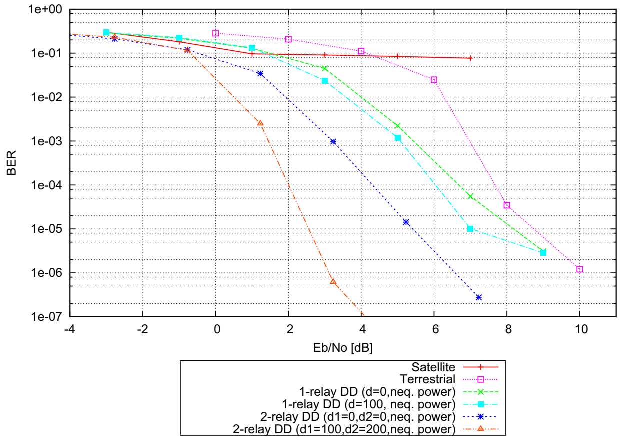

Fig. 6. Performance comparison of DVB-SH system among: satellite-only, terrestrial-only and Hybrid Cooperative Delay Diversity 1-relay and 2-relay schemes in Highway environment.

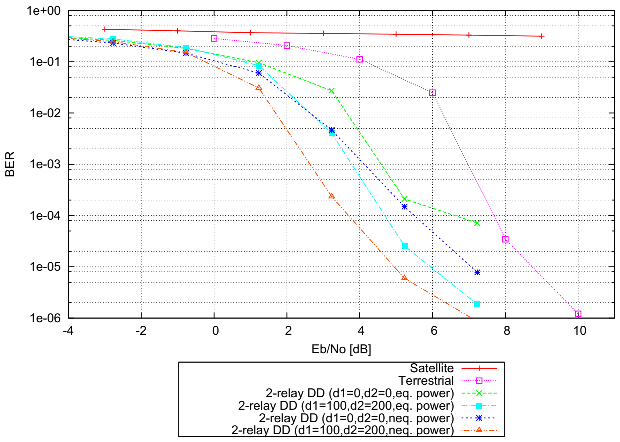

Fig. 4. Performance comparison of DVB-SH system among: satellite-only, terrestrial-only and Hybrid Cooperative Delay Diversity 2-relay ($\delta_1 = 0, \delta_2 = 0$ and $\delta_1 = 100, \delta_2 = 200$) scheme in City environment.

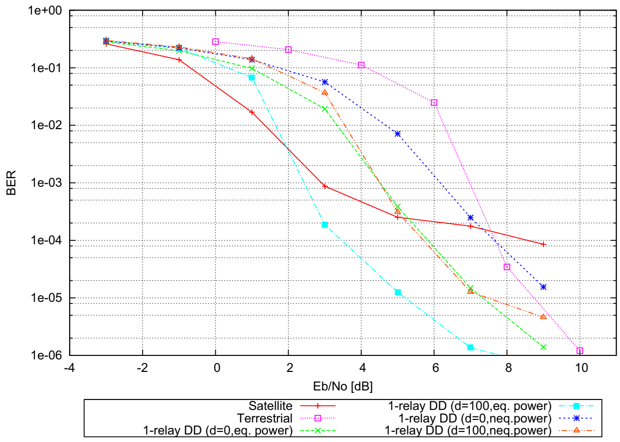

Fig. 7. Performance comparison of DVB-SH system among: satellite-only, terrestrial-only and Hybrid Cooperative Delay Diversity 1-relay scheme in City environment with SC-D link in LOS.

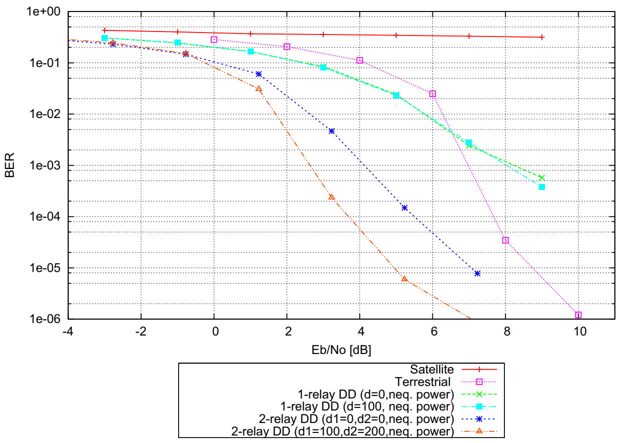

Fig. 5. Performance comparison of DVB-SH system among: satellite-only, terrestrial-only and Hybrid Cooperative Delay Diversity 1-relay and 2-relay schemes in City environment.

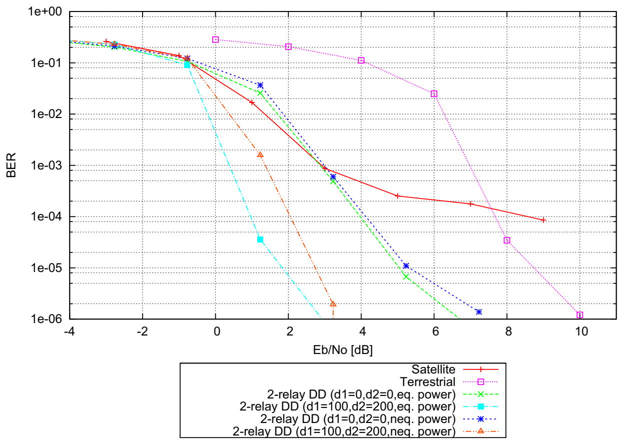

Fig. 8. Performance comparison of DVB-SH system among: satellite-only, terrestrial-only and Hybrid Cooperative Delay Diversity 2-relay scheme in City environment with SC-D link in LOS.