# Cooperative Strategies of Integrated Satellite/Terrestrial Systems for Emergencies

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**Abstract.** In this paper some simple cooperative relaying strategies which rely on the exploitation of the Delay Diversity technique and the Maximal Ratio Combining (MRC) receive diversity algorithm are proposed for a DVB-SH compliant hybrid satellite/terrestrial network. These strategies are investigated in a public emergency scenario where the adoption of an integrated heterogeneous network combined with the cooperative diversity techniques guarantees the connection between the incident area and the external areas: particularly, the drawbacks of the Non-Line-Of-Sight (NLOS) propagation are mitigated. The NAV/COM capabilities of the cooperative DD algorithm in a DVB-SH Single Frequency Network (SFN) are discussed, highlighting the suitability of these schemes in emergency situation management. A comparison analysis of the proposed schemes is performed, describing the assumptions required and the simulation results with respect to the satellite-only and the terrestrial-only cases.

**Keywords:** NAV/COM System, Cooperative, Satellite/Terrestrial network, Emergency Communication, Delay diversity, Maximal Ratio Combining.

## 1 Introduction

In the last few years the increasing number of natural or antrophic disasters pushes the scientific communities to further investigate the research topic of communications and networking technologies for public safety and security. In the provision of emergency telecommunication facilities, particular attention has been given to the integration of satellite and terrestrial segments with the goal to exploit the complementary capabilities of both systems and overcome the drawbacks of each scheme [24] [2] [22].

The integration of satellite and terrestrial segments is required for both communication and navigation systems:

- *Communication system*: The satellite can complement the terrestrial networks while the gap fillers allow the communication with an end-user whose satellite link is characterized by bad channel condition.

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- *Navigation system*: a GPS NLOS visibility receiver can achieve navigation capabilities through the exploitation of satellite and terrestrial cooperation.

Together with the integration of satellite and terrestrial components, also the integration of navigation and communication systems can be seen as one of the main needs for the emergency network [13]. The NAV/COM capabilities allow the exploitation of both navigation information for communication purpose [19] (optimization of communication techniques, interference reduction and location-based information services delivery) and communication supports for navigation purpose [16] (cooperative localization techniques, high precision achievement).

Therefore an efficient emergency rescue management is based on the fast implementation of an integrated satellite-terrestrial NAV/COM network, which enables the Emergency Control Centre (ECC) to properly coordinates the rescue teams interventions.

In this paper we study hybrid satellite/terrestrial cooperative relaying strategies which can be adopted in public emergency situations with the aim of guaranteeing communication between the emergency area and the external areas.

Simple and suitable solutions to overcome the performance loss of the NLOS environment are analysed. In particular we propose the combination of the hybrid satellite/terrestrial network OFDM-based proposed by the DVB-SH standard (SH-A Architecture) with the Cooperative *Delay Diversity* (DD) relaying technique [18] [8] [17] [7] [5]. Moreover, we analyse the adoption of the MRC receive diversity scheme together with the Cooperative Delay diversity technique with the aim of guaranteeing a more robust communication link. Finally to highlight the importance of a NAV/COM satellite/terrestrial network for emergency management we briefly address the double-use capabilities of the proposed system for communication and navigation purposes.

## 2 System Model: Hybrid Satellite/Terrestrial Cooperative Relaying Network

The basic building blocks of a satellite/terrestrial cooperative relaying system are the following: the Satellite Component (SC), the Complementary Ground Component (CGC) and the receiver (D), acting as the source, the relay and the destination respectively.

Analysing a single frequency network (SFN) we combine the hybrid cooperative relaying scheme with the Delay Diversity technique in order to cope with the NLOS propagation condition through the exploitation of the channel propagation properties.

The system model, which has been considered in this paper, is depicted in Fig.1. In particular two different types of cooperative-relay nodes are considered:

- CGC-Gap Fillers (CGC-GFs) which process the received signal according to the *Amplify and Forward* (AAF) algorithm.
- CGC-Transmitters (CGC-TXs) which complement the satellite reception in those areas where the satellite coverage is not guaranteed.

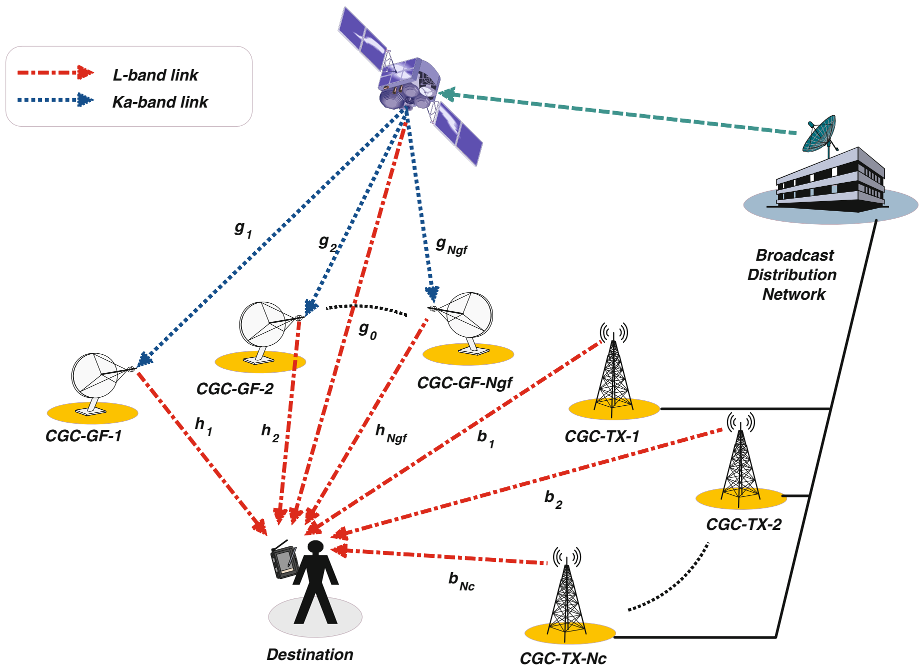


**Fig. 1.** Hybrid satellite/terrestrial *N-Relay Cooperative Delay Diversity* system with different types of CGCs: GFs (Gap Fillers) and TXs (Transmitters)

Both cooperative nodes can be seen as *relays* between the satellite or the broadcast distribution network and the destination node.

## 2.1 Hybrid Cooperative Delay Diversity Algorithm

In a satellite/terrestrial cooperative relaying network, where $N_{gf}$ relays act as gap fillers and $N_C$ relays are directly connected to the broadcast distribution network, $(N_{gf}+N_c+1)$ different faded and delayed copies of the same information data arrive at the destination node. The delay diversity gain is achieved through the increase of the delay spread of the channel, and, therefore, the raise of the frequency selectivity [25].

In order to describe the delays of the DD technique, we analyse separately the two different types of CGCs involved in the cooperative network. In particular we assume as a reference the propagation delay ($\delta_0$) of the signal through the direct path (from SC to D).

**CGC-Gap Filler Delays.** Denoting as $\delta_i$ the propagation delay of the signal of the indirect path from SC to D through CGC-CF-i (with $i = 1, .., N_{gf}$), since $d_{(SC,CGC^{(GF)}-i)} \simeq d_{(SC,D)}$, the *delays* $(\delta_{CGC^{(GF)}-i})$ of the DD scheme are:

$$\delta_{CGC^{(GF)}-i} = \delta_i - \delta_0 \simeq \frac{d_{(CGC^{(GF)}-i,D)}}{c} \qquad , \quad c = \text{speed of light.} \tag{1}$$

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, each gap filler can work according to the *Amplify and Forward* algorithm, amplifying and retransmitting the received signal.

Nonetheless, some simple operations have to be considered; in fact to make a 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 Ka-Band, while the link SC-CGC is in L-Band. Therefore the gap filler amplifies and retransmits the received Ka-Band signal after converting into L-Band. In this way different delayed L-band copies of the signal arrive at D, allowing the implementation of the DD technique in a hybrid satellite/terrestrial network.

**CGC-Transmitters Delays.** Assuming a synchronization condition between both types of CGCs (SFN network) the delays of the CGCs which are directly connected to the distribution network are the effective propagation delays between the CGC-TX-z (with $z = 1, ...N_c$) and the destination:

$$\delta_{CGC^{(TX)}-z} = \frac{d_{(CGC^{(TX)}-z,D)}}{c} \tag{2}$$

Therefore, both the delays of the signals coming from the CGC-GFs and the ones coming from the CGC-TXs depend on their position and their mutual distance.

Otherwise, assuming at D a synchronization condition between the signal coming from the SC and the one coming from the CGCs directly connected to the distribution network, the cooperative nodes have to delay artificially the transmitted signal with the aim to create a time diversity at the receiver end. In particular the delays can be taken equal to the effective propagation time intervals between the CGC-TXs and the destination.

### 2.2 Validation of the Proposed System

With the aim to validate the efficiency of the scheme described in the previous subsection and highlight the importance of the cooperation between the satellite and the terrestrial segments, we analyse a particular case of the proposed system: the N-Way Relay cooperative DD scheme, which is characterised by the absence of the direct link SC-D ($g_0 = 0$, see Fig.1). Particularly, D selects and processes only the signals coming from the CGCs involved in the transmission scheme. As the simulation results confirm (see Section 1.7), neglecting the signal coming directly from the satellite does not imply any advantages, even if the channel between SC and D is modelled as an alternation of LOS/NLOS cases. On the contrary, we can observe a performance degradation, which also depends on the environment considered. The absence of a path implies a reduction of the frequency selectivity of the equivalent channel transfer function and therefore the diversity introduced by the DD technique is less with respect to the one introduced in the original system.

Besides, it is important to highlight that the implementation of the proposed cooperative DD schemes does not require any change in the standard. In fact:

- the CGCs considered in the paper are the ones which are defined in the standard specs;
- the frequency conversion at the gap filler is standard-compliant;
- the SFN synchronization performed in DVB-SH network allows the presence of a delayed replica of the original signal, which fulfil the DD constrain.

## 2.3 Receive Diversity in a Hybrid Cooperative DD System

In order to increase the diversity order we can assume the presence of two antennas at the receiver-end. In particular we consider the N-relay scheme depicted in Fig.1, replacing D with a double antenna equipped destination node.

A Maximal Ratio Combiner (MRC) is adopted with the aim to not increase the complexity of the destination node by the implementation of additional operations. Due to the frequency used and the height of the receiver, it is realistic to consider that the several copies of the transmitted signal, which arrive at D, are affected by independent channel coefficients.

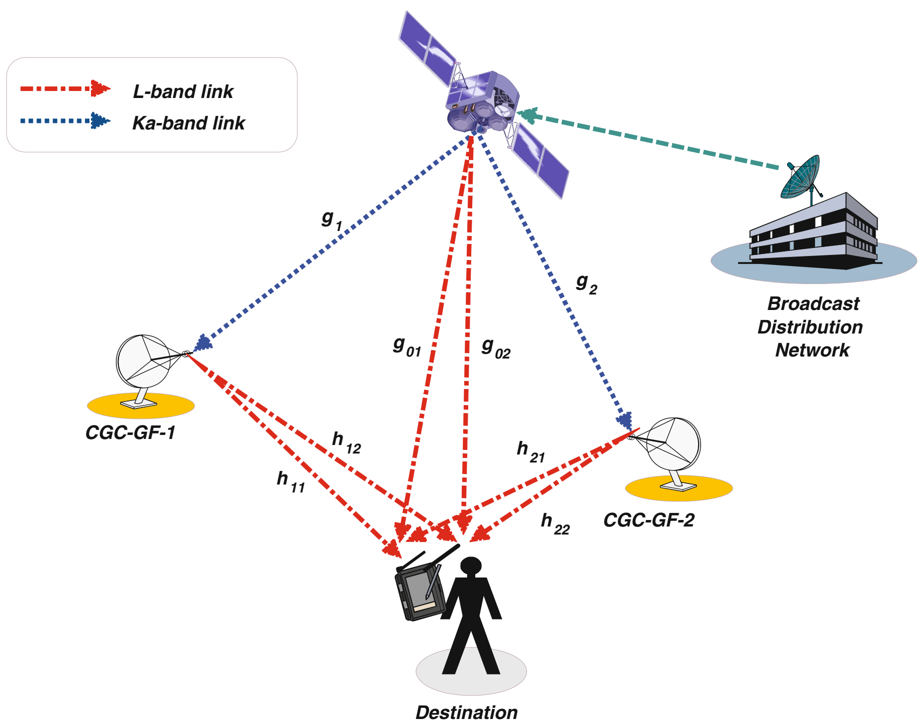


**Fig. 2.** Hybrid satellite/terrestrial *2-Relay Cooperative Delay Diversity* with MRC at the double antenna equipped receiver-end

Without losing in generality, we consider the two gap fillers case which is depicted in Fig.2: in this case independent faded copies of the transmitted signal are received either from the SC or from the gap fillers; this is true for both the elements of the receiver antenna. In particular the copies coming from each gap filler are characterized by a specific delay, which can be derived from the expression 1.

## 3 Analysis of the Equivalent Channel Impulse Response

In order to highlight the relationship between the Cooperative Delay Diversity technique and the channel properties, we describe the effect of the application of this scheme on the channel impulse response.

In particular we analyse a hybrid satellite/terrestrial cooperative relaying network, where $N_{gf}$ relays act as gap fillers and $N_C$ relays are directly connected to the broadcast distribution network, while the receiver is equipped with two receive antennas. Denoting with $s(n)$ the complex-valued transmitted signals in the time domain, after the removal of a cyclic prefix and neglecting the AWGN noise, the received signal at the $r$-antenna ($r = 1, 2$) of the Destination node can be written as:

$$\begin{aligned} y_r(n) &= \alpha g_{0r} s(n) \\ &+ \sum_{i=1}^{N_{gf}} \sum_{p=0}^{N_{max}} \beta_i g_i h_{ir}(n,p) s(n - \delta_i - \tau_p) \\ &+ \sum_{z=1}^{N_C} \sum_{q=0}^{N_{max}} \gamma_z b_{zr}(n,q) s(n - \delta_z - \tau_q) \end{aligned} \quad (3)$$

where

- $h_{ir}(n,p)$ is the channel complex coefficient of the p-path of the terrestrial multipath channel between the CGC-GF-$i$ and the $r$-antenna of the receiver D, $\tau_p$ the delay of the $p$-path and $N_{max}$ the number of paths;
- $b_{zr}(n,q)$ is the channel complex coefficient of the $q$-path of the terrestrial multipath channel between the CGC-TX-$z$ and the $r$-antenna of the receiver D, $\tau_q$ the delay of the $q$-path and $N_{max}$ the number of paths;
- $g_i$ is the channel complex coefficient of the satellite channel between SC and the CGC-GF-$i$; in particular $g_{0r}$ is the one between SC and the $r$-antenna of the receiver D and it assumes the value 0 if the N-Way Relay system is considered;
- $\alpha$, $\beta_i$ and $\gamma_z$ are the power scale factors.

Analysing the DD effects in terms of channel impulse response, the expression (3) can be rewritten as:

$$y_r(n) = s(n) * h_{equ}^{(r)}(n) \quad (4)$$

where $h^{(r)}_{equ}(n)$ is the equivalent channel impulse response which is perceived by the $r$-antenna at the receiver:

$$h^{(r)}_{equ}(n) = \alpha g_{0r}\delta(n) + \sum_{i=1}^{N_{gf}} \sum_{p=0}^{N_{max}} \beta_i g_i h_{ir}(n,p)\delta(n - \delta_i - \tau_p) + \sum_{z=1}^{N_C} \sum_{q=0}^{N_{max}} \gamma_z b_{zr}(n,q)\delta(n - \delta_z - \tau_q) \quad (5)$$

According to this analysis, switching from the non-cooperative to a cooperative mode, the Destination node 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 (5) , from the $r$-antenna point of view, transmitting delayed copies of the same signal through a propagation channel makes the MISO channel (Multiple-Input Single-Output) transform into a SISO (Single-Input Single-Output) channel with increased frequency selectivity [11]. We can conclude that in the cooperative scheme 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 the gap fillers and D is assumed to be in LOS or NLOS condition, while the one between the CGCs (both types) and D is supposed to be a NLOS multipath channel (with Rayleigh Distribution). It is important to notice that the equivalent channel perceived by D is an hybrid channel, which consists in terrestrial and satellite components and is characterized by a mixed LOS/NLOS propagation conditions. In general the adoption of the DD technique combined with the presence of a LOS component carries to a loss in performance: particularly, the increase of frequency selectivity involves the presence of deep fades which are the responsible of the performance degradation [12]. However, we analyse hybrid cooperative schemes, which have to be evaluated with the satellite channel model. Therefore the alternation of LOS/NLOS state (environmental dependent) of the satellite channel makes the DD technique more suitable with respect to the terrestrial case with a LOS component.

Despite the low complexity of the proposed system, the increase of frequency selectivity of the channel propagation perceived by the receiver involves an accurate channel estimation. In fact, the reduction of the coherence bandwidth as far as the delays increase make a conventional SISO channel estimator unable to correctly estimate the channel. [6] addresses the problem of the channel estimator in a DD OFDM system, while a trade off study of the maximum tolerable delay with respect to the channel estimation impacts has been conducted in [23]. Even though all these topics are beyond the aim of this paper, they are under investigation and will be considered in the future works.

## 4 Some Consideration on NAV/COM Integration through Hybrid Cooperative Relaying DD System

The integration of NAV/COM capabilities is strictly required in an emergency context. The hybrid cooperative delay diversity system proposed can easily make the receiver in GPS NLOS visibility acquire self-positioning information. The receiver can estimate its location through the combination of the cooperative relaying scheme in a Single Frequency Network (SFN) and the implementation of the Time Differences of Arrivals (TDoA) algorithm. In particular we address to the case, where almost three (2D-positioning) or four (3D-positioning) CGCs are in GPS LOS visibility or alternatively their positions are known. The synchronization of the CGCs, which is the fundamental requirement for navigation applications based on TDoA, is achieved in a DVB-SH SFN of emitters. In this context the receiver through an accurate channel estimation can obtained the required TDoA measurements, which enable the positioning [20].

Therefore the implementation of the cooperative system proposed allow the receiver to:

- improve the performance of the communication system, which can be evaluate in terms of coverage extension, power consumption reduction or robustness of the radio link;
- estimate its position even in case of GPS NLOS visibility.

## 5 Emergency Scenario

Among the different phases of a public emergency situation management (preparedness, response, recovery and mitigation), we consider the first response phase of a disaster (fire, earthquake, flood, explosion), where several rescuers organised in teams act with the aim of saving lives and preserving the environment during emergencies.

The implementation of the hybrid cooperative system proposed in the emergency scenario (Fig.3) allows 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.

In this context the relays can be represented by:

- CGC-gap fillers which enable the rescue teams to communicate with the Emergency Control Centre 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.
- CGC-TX, assuming a partially available terrestrial infrastructure; in particular we supposed the presence of a still available CGC, which is directly connected to the broadcast distribution network.

Besides the destination node equipped by a two element antenna, which implements the MRC receive diversity scheme, can be represented by an anchor

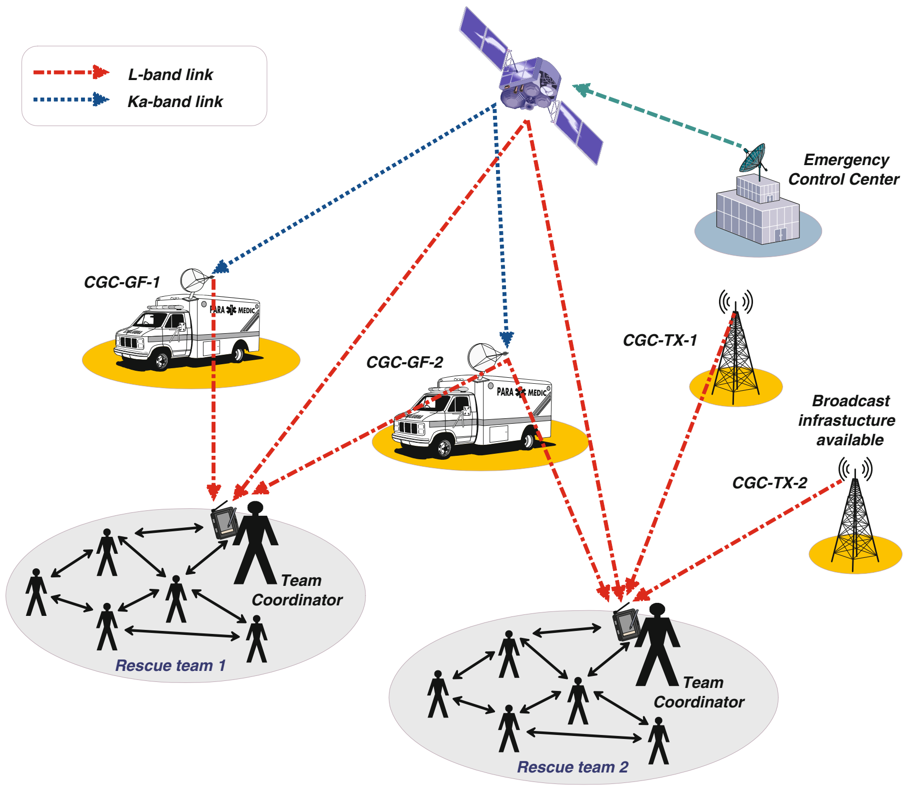


**Fig. 3.** Hypothetical emergency scenario

node able to coordinate the rescuers of its team according to the information received from the emergency control centre. With these assumptions the presence of two antennas at the receiver end does not represent a limitation in terms of equipment cost and size. In fact, thanks to the performance achieved with this diversity scheme, just one anchor node is required for a team of rescuers.

## 6 Simulation Parameters and Assumptions

According to the DVB-SH (SH-A Architecture) specifications [3] [21] [4] , an OFDM system is implemented both 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 (code rate 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: Lutz model and TU6 model for the satellite and the terrestrial channel, respectively [4]. Even though more accurate satellite channel models have been proposed in [9], with the aim to not loose in generality, we consider the Lutz model, which is one of the models suggested in the DVB-SH implementation guidelines.

In the simulations we also assume that: the satellite channels between the satellite and the gap fillers are always in LOS, the gap fillers can be seen as a transparent relay (no amplification is performed) and the DVB-SH interleavers are not introduced to make clear the advantages of the cooperative strategies proposed.

## 7 Analysis of Simulation Results

In this section we verify the performance of the hybrid cooperative DD system, analysing some of the most significant comparisons among the possible cases of the general scheme proposed. In particular in all BER-performance graphs the satellite and the terrestrial stand-alone systems are depicted as a terms of reference and the same total transmitted power is assumed.

With the aim to maintain the complexity of the system low we consider the one-relay and two-relay schemes in two different environments: City and Highway, which represents the worst and the best case within the range of the environments [15]. The BER-performance is reported for different values of the delay in order to represent the impact of this value on the DD scheme; besides, to implement a more realistic case, different power allocation between the CS

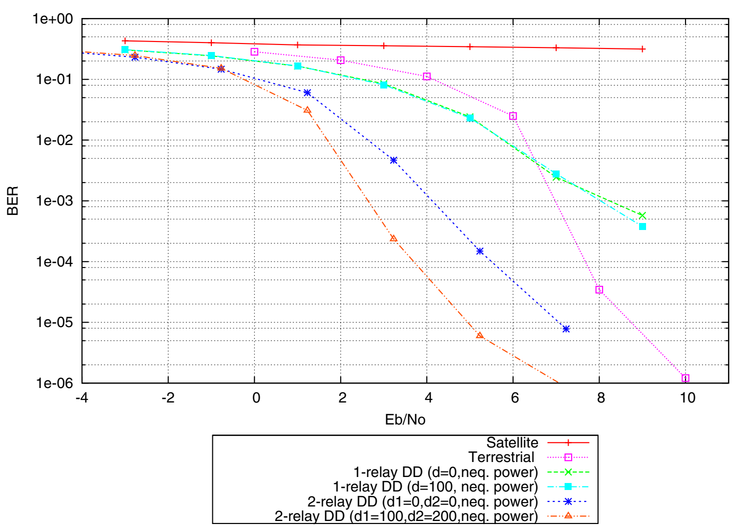


**Fig. 4.** Performance comparison of DVB-SH system among: satellite-only, terrestrial-only, 1-Relay Cooperative DD and 2-Relay Cooperative DD in City environment

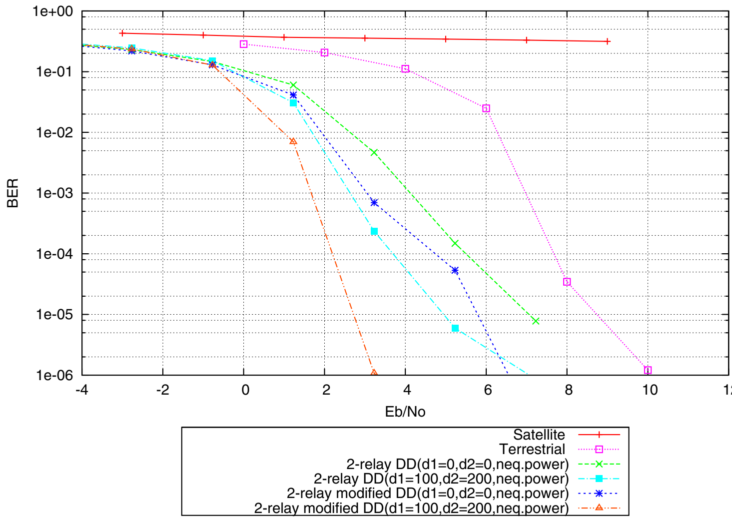


**Fig. 5.** Performance comparison of DVB-SH system among: satellite-only, terrestrial-only, N-Relay Cooperative DD and N-Relay Modified Cooperative DD, with $N = 2$ in City environment

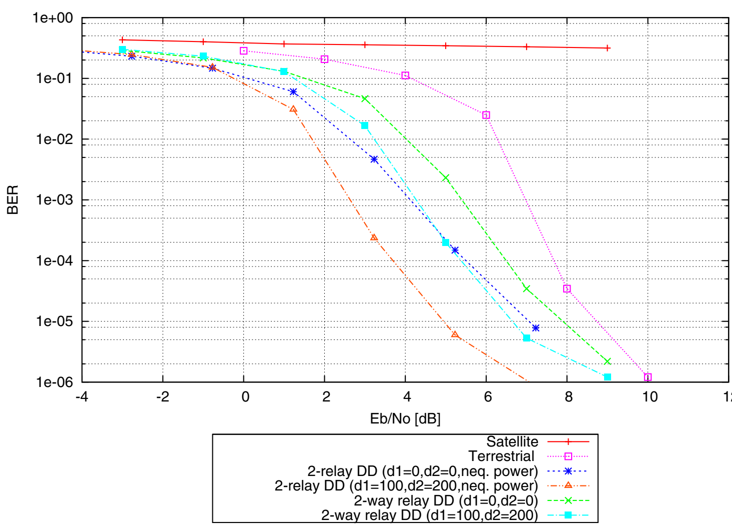


**Fig. 6.** Performance comparison of DVB-SH system among: satellite-only, terrestrial-only, N-Relay Cooperative DD and N-Way Relay Cooperative DD, with $N = 2$ in City environment

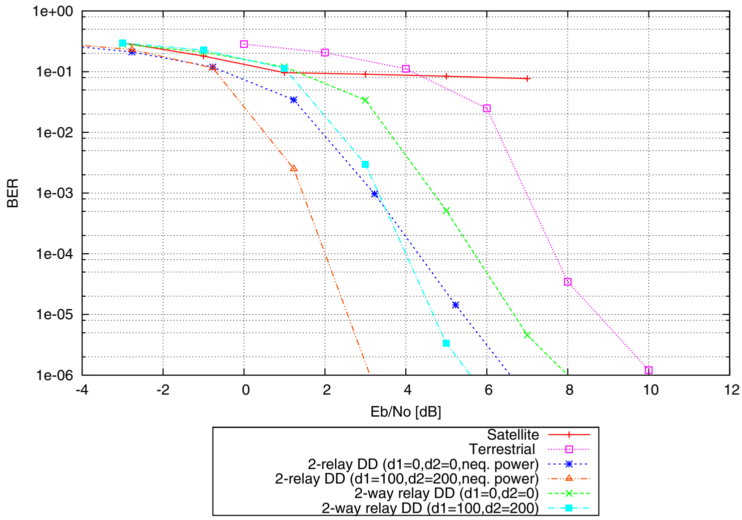


**Fig. 7.** Performance comparison of DVB-SH system among: satellite-only, terrestrial-only, N-Relay Cooperative DD and N-Way Relay Cooperative DD, with $N = 2$ in Highway environment

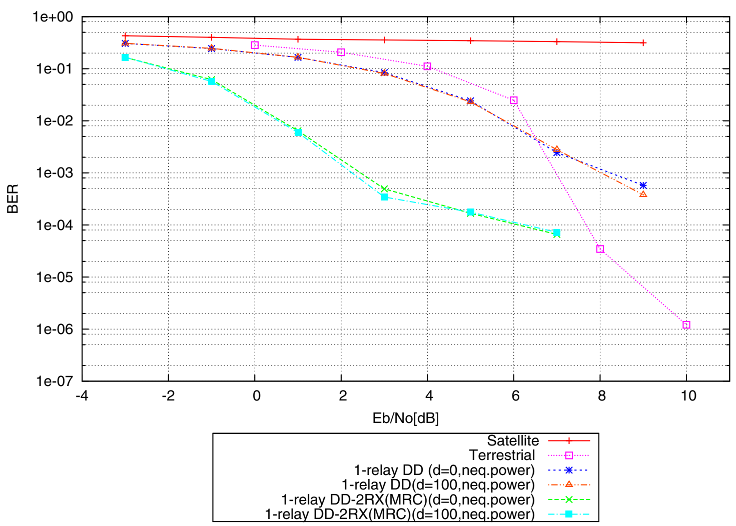


**Fig. 8.** Performance comparison of DVB-SH system among: satellite-only, terrestrial-only, N-Relay Cooperative DD and N-Relay Cooperative DD combined with MRC, with $N = 1$ in City environment

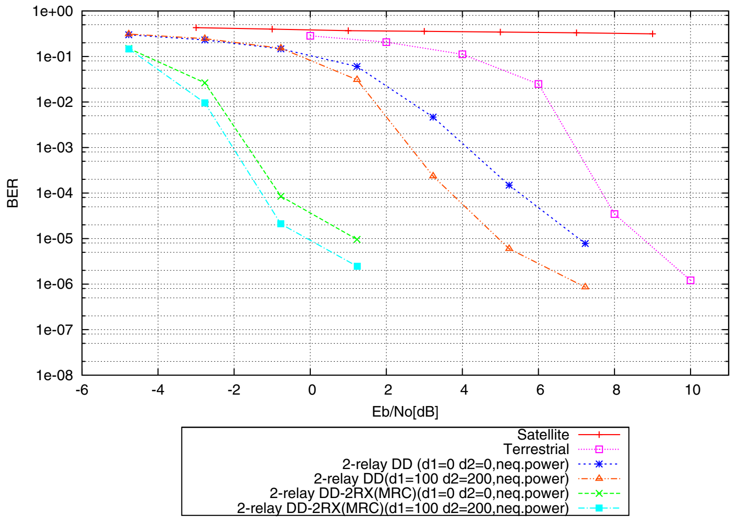


**Fig. 9.** Performance comparison of DVB-SH system among: satellite-only, terrestrial-only, N-Relay Cooperative DD and N-Relay Cooperative DD combined with MRC, with $N = 2$ in City environment

and the CGC is assumed (not equal power): particularly, the copies of the signals coming from the CGCs (all types) are characterised by a higher level of power with respect to the signal directly transmitted from the satellite.

In order to highlight the BER-performance of the *N-Relay Cooperative DD system* with only CGC-GFs, the $N = 1$ and $N = 2$ cases are depicted in Fig.4, where the two cooperative relaying schemes are compared in the City environment. In particular the 2-relay system gains 4-5dB ($\delta$-depending) for BER=$10^{-3}$ over the 1-relay system. Therefore the presence of more than one relay, increasing the frequency selectivity of the channel transfer function, permits to achieve a performance improvement in term of bit error rate.

In Fig.5 two versions of the *N-Relay Cooperative DD system* with $N = 2$ are compared: the 2-relay-case characterized by the presence of two CGC-GFs and the 2-relay modified-case, in which the two relays are represented by one CGC-GF and one CGC-TX. In particular the 2-Relay modified system gains 1-2dB ($\delta$-depending) for BER=$10^{-4}$ over the 2-Relay system. These results are justified by the fact that the CGC-TX transmits an exact copy of the original signal.

In Fig.6 and in Fig.7 the *N-Relay Cooperative DD system* and the *N-Way Relay Cooperative DD system* (with the $N = 2$) are compared in City and Highway setting respectively. In particular the N-Relay system gains 1-1.8dB and 1.5-2dB ($\delta$-depending) for BER=$10^{-4}$ over the N-Way Relay system in City and Highway environment respectively, validating the effectiveness of the first scheme.

Finally, in order to highlight the effect of the cooperative DD technique combined with the MRC receive diversity scheme, we analyse the BER performance of the 1-relay (Fig.8) and 2-relay (Fig.9) systems in the City setting, assuming a double-antenna equipped receiver. The combination of the cooperative DD technique with the MRC receive diversity algorithm makes the 1-relay DD-2RX system gains 6dB for BER=$10^{-3}$ over the 1-relay DD scheme and the 2-relay DD-2RX system gains 5-6dB for BER=$10^{-4}$ over the 2-relay DD scheme.

## 8 Conclusions

Simple and feasible cooperative relaying strategies based on the *Delay Diversity* (DD) technique have been proposed for a DVB-SH compliant hybrid satellite/terrestrial network in order to reduce the impairments caused by the NLOS condition in the satellite propagation channel. Besides the combination between the cooperative DD system and the MRC diversity scheme has been investigated.

The proposed cooperative schemes are characterized by a significant gain with respect to the satellite system and therefore represent a promising solution to guarantee communication in public emergency situations, particularly, in the first response phase of a disaster, without any additional complexity requirement.

Simulation results show that combining the cooperative DD technique with the MRC receive diversity scheme permits to achieve interesting BER-performance overcoming the performance of a terrestrial system through the exploitation of the channel propagation features and the spatial diversity gain.

Moreover the double-use (communication and navigation purpose) of the cooperative DD algorithm in a SFN DVB-SH system has been discussed, highlighting the NAV/COM capabilities and therefore the suitability of these schemes in emergency situation management.

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