Network-coded cooperative extension of link level FEC in DVB-SH

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In this paper we propose a cooperative ad-hoc networking approach which leverages on network coding (NC) for enhancing coverage in Digital Video Broadcasting - Satellite Handheld (DVB-SH) systems. Our numerical results, based on physical layer abstraction, show that a cooperative relaying system based on network coding can bring important benefits in terms of both throughput and coverage with respect to a system in which nodes receive from satellite only, as well as with respect to a system in which nodes cooperate through a simple relaying scheme.

I. Introduction

In the last decade, several proprietary solutions as well as open standards such as Digital Video Broadcasting - Satellite Handheld (DVB-SH)[1] have been developed to enable data broadcasting via satellite to mobile users. There exist land mobile satellite (LMS) solutions already implemented for maritime and aeronautical communications. Satellite broadcast and relaying capabilities give rise to the possibility of creating mobile broadcast systems over wide geographical areas, which opens large market possibilities for both handheld and vehicular user terminals. Mobile broadcasting is of paramount importance for services such as digital TV or machine-to-machine communication related to road safety and traffic congestion control. However, severe availability problems are endemic in urban and suburban environments, where the concentration of users is high. In the LMS scenario, as described in DVB-SH standard, only users with an adequate channel quality (i.e. Line Of Sight propagation from satellite to user) are able to access services via satellite. Poor channel conditions frequently occur due to the shadowing effect of surrounding environment especially in case of low satellite elevation angles. In absence of a line of sight between terminal and satellite, terrestrial gap fillers and the Link Layer Forward Error Correction (LL-FEC)[2], are employed for complementary coverage. The gap filler solution has two main shortcomings: i)it is a fixed solution which is not able to react quickly to changes in the propagation environment, which may create new dead spots; ii)it is very costly in terms of investment, management, and bandwidth usage. A hybrid satellite-terrestrial networking approach has several advantages with respect to the fixed gap filler solution as we will argue later.

In this paper we propose a hybrid solution based on a cooperative ad-hoc networking approach which leverages on network coding (NC) for message dissemination. NC[3] has shown to achieve significant gains in terms of throughput increase as well as delay and network management complexity reduction in wired and wireless networks, even in the absence of node coordination[4]. In [5] and [6] NC was applied in the

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satellite segment of DVB-SH and DVB-Satellite-Second Generation (DVB-S2) in order to counteract channel impairments in mobile and fixed scenarios. Unlike in these works, in the present paper we propose a scheme where the satellite segment is not modified. In the system we propose land mobile users have both satellite communication and cooperative-networking capabilities. Network coding is merged with the DVB-SH LL-FEC in the terrestrial segment. The proposed ad-hoc cooperative approach based on Network Coding aims at a reduction of the number of fixed gap fillers and, if the target system outage probability is not too restrictive, can lead to a terrestrial gap-filler-less scheme, with a large reduction in the cost of satellite systems. We consider vehicular terminals. Cooperative content dissemination from road side units to vehicular networks based on rateless codes was studied in [7] and [8]. To the best of our knowledge, the proposed approach was not applied before as a cooperative technique to enhance coverage in broadcast satellite transmission. In the present work the IEEE 802.11p standard is adopted for terrestrial communications, while the ETSI DVB-SH standard is considered for the forward (satellite broadcasting) link. We describe the compatibility of the proposed scheme with the existing standards and show with simulations how the proposed scheme enhances the system throughput with respect to a system where simple relaying is used. Simulations are implemented by using state-of-the-art satellite channel models. The simulator interface between the physical channel and the protocol stack at higher layers leverages on Physical Layer Abstraction (PLA), a technique adopted in the standardization process of IEEE 802.16 [9]. The PLA allows to accurately predict the link level performance of a communication system in a computationally simple way. This makes it possible to take into account the physical layer in system level simulations in an accurate and computationally effective manner. The PLA has been widely studied in the last decade, and its higher accuracy with respect to previously proposed methods based on SNR metrics has been shown for a wide range of transmission setups[10],[11].

II. System Model

A. Satellite

1. Satellite Channel

The considered setup is an LMS system with a GEO satellite in L band (or low S band) broadcasting a DVB-SH-B signal to a population of mobile terminals. Propagation conditions change due mainly to building and trees shadowing effect and are classified in Urban, Suburban and Rural. The main cause of channel impairment in Urban and Suburban environments is the long-lasting shadowing of the buildings that causes an intermittent satellite connectivity, while in the Rural propagation scenarios the main source of impairment is tree shadowing. Signal reception in LMS systems is limited by three phenomena:

Path loss at large scale determining very slow fluctuations due to the geometry of the propagation environment. This effect is taken into account in the models by considering a power attenuation in the received signal with respect to the transmitted one which is proportional to d^n, where n can be different from 2 due to the shielding effect of interposed obstacles.

Shadowing at mid-scale determines slow fluctuations in the received signal due to signal scattering on objects (e.g. buildings) nearby the receiver.

Multipath fading at small scale which determines fast fluctuations in the received signal and, in wide band channels, frequency selectivity. Measurements showed that this phenomenon is not significative in DVB-SH for channelization of 1.5 MHz and little significative for 5 MHz channels.

We adopt the Perez-Fontan LMS channel model, based on a three-state Markov chain in which the possible states represent line of sight reception, moderate shadowing reception and deep shadowing reception. In each of the states the signal amplitude is modeled as a Loo process (sum of a Log-normal and a Rayleigh random variables) with different parameters[12]. In Figure 1 the channel amplitude of a 10 second simulation in the Urban Scenario is shown. The time series was generated by a simulator implementing the Perez-Fontan three state channel model.

2. Channel Impairment Countermeasures in DVB-SH

In this section we recall the channel impairment countermeasures foreseen by the DVB-SH.

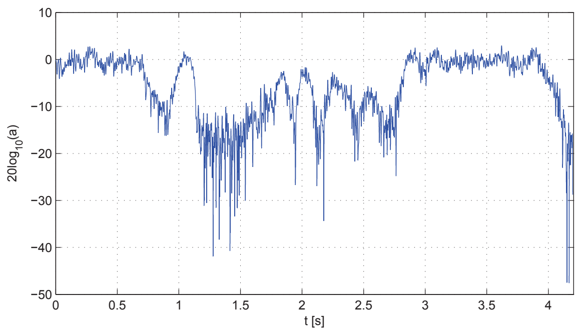

Figure 1. Channel realization in Urban Scenario, satellite elevation angle 40^o, node speed 50 kmph.

Physical Layer The physical layer error protection scheme of the DVB-SH standard is shown in Fig. 2. The main blocks of the scheme are the duobinary turbo code with different rates/word length, the bit

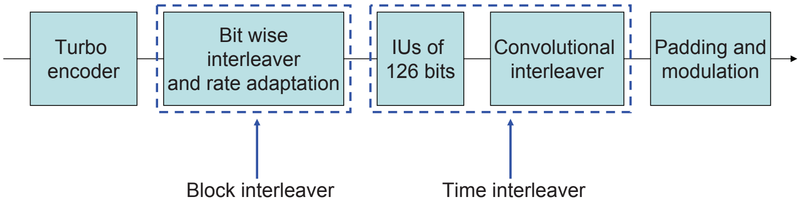

Figure 2. Physical layer error protection in DVB-SH-B. The block interleaver works bit wise, while the time interleaver works on blocks of 126 bits, the interleaving units (IU).

interleaver which works at bit level within a turbo codeword and the time interleaver, the depth of which which spans across more than a codeword and uses interleaving blocks of 126 bits each. This last element is particularly important to counteract long blockage periods, as it can span time intervals in the order of 10 seconds. The drawbacks in using a long time interleaver are the delay in decoding and the memory requirements at mobile terminals, which can be met only in class A nodes.

MPE-IFEC in DVB-SH The Multi Protocol Encapsulation - Inter-burst Forward Error Correction (MPE-IFEC) is a process section introduced in DVB-SH in order to counteract the disturbances in reception and transmission. This can be achieved by applying FEC over multiple bursts. This is contrary to a conventional MPE-FEC for which FEC is applied only within a single time-slice. The long interleaving used in IFEC allows for significant performance enhancements with respect to FEC[2], as it can better counteract long lasting shadowing which are typical of LMS channel.

The encoding is made over several datagram bursts, that generally contain more than one IP datagrams of variable length. Let us consider a datagram entering the MPE-IFEC process. The datagram is reshaped in a matrix of T by C bytes called Applicsation Data Sub-Table (ADST) illustrated in Fig. 3[2] . The columns of the ADST are then distributed in a round robin fashion among B of the M Application Data Tables (ADT). An ADT is a T by K matrix. The FEC, always systematic, is applied on the ADT producing a T by N parity matrix, called IFEC Data Table (iFDT), with $K = C \times EP$. EP is the Encoding Period, and determines the number of datagram bursts over which the parity is calculated. The ADT and the iFDT together form an *encoding matrix*. It takes $B \times EP$ bursts to fill up a single ADT. Once an ADT is full (this happens to B ADT at the same time) the iFDT is calculated. As soon as the B iFDTs are calculated an *IFEC burst* is generated by taking groups of columns from S different iFDTs. An IFEC burst is made up of several IFEC sections. Each section is comprised of a header, a payload containing g columns from the same iFDT and a cyclic redundancy check (CRC). The k-th IFEC burst is merged with the $(k - D)$-th datagram burst (and eventual MPE-FEC redundancy) to form a *time-slice burst*. The time slice burst is then multiplexed on MPEG2-TS frames and passed down to lower layers.

Depending on the FEC technique applied, different values of EP, B and S are adopted. When a Reed-Solomon code is used, EP is set to 1, while B and S are generally greater than 1. In case a Raptor code is

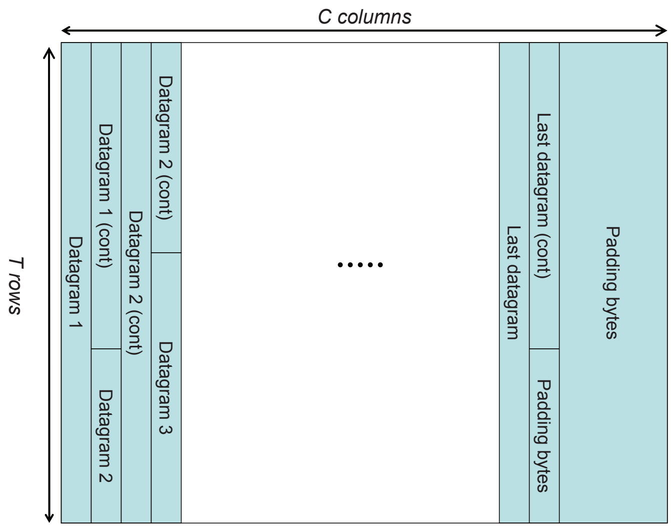

Figure 3. ADST reshaping of a datagram burst.

used EP is generally greater than 1, while $B = S = 1$. This is because Raptor codes are capable of handling large source matrixes (i.e. ADT), that can span several datagram burst. Reed-Solomon codes, instead, are more suited for smaller source matrices, and an interleaver is used so that parts of several datagram bursts are encoded within the same encoding matrix (i.e. the same datagram burst is distributed among several encoding matrixes)[13].

RAPTOR CODES IN DVB-SH The Raptor code adopted for the DVB-SH is the same as in the DVB-H[2]. Its description can be found in[14]. A source block in [14] corresponds to an ADT and a source symbol is a column of the ADT. Thus a source block has K symbols of T bytes each. The Raptor encoder is applied independently to each source block, each of which is identified by a Source Block Number (SBN). The encoding produces K systematic symbols (the ADT matrix) and N *repair* (parity) symbols. Systematic and repair symbols are called *encoding symbols*. Each symbol is identified by an Encoding Symbol Identifier (ESI). Values from 0 to $K-1$ are assigned to the systematic symbols, while values from K to $N+K-1$ identify repair symbols. The encoding procedure consists of two parts. In the first part L *intermediate symbols* are produced starting from the K source symbols, while in the second part $K+N$ encoding symbols are generated starting from the L intermediate symbols.

The L intermediate symbols are generated starting from K source symbols. The intermediate symbols from 0 to $K-1$ are systematic (i.e. are the source symbols). The S intermediate symbols from K to $K+S-1$ are generated using an LDPC encoder while the last H symbols from $K+S$ to L are called *Half Symbols* and are produced by a binary reflected Gray encoder[2].

The encoding symbols are generated applying an LT encoder to the L intermediate symbols. The LT encoder operates a bit-wise XOR of intermediate symbols chosen according to a certain degree distribution. Each of the encoding symbols is transmitted together with its ESI and a triple (d, a, b) where d is the symbol degree and a and b are integers from the sets $1, \ldots, L''-1$ and $0, \ldots, L''-1$ respectively, $L''-1$ being the smallest prime integer greater than or equal to L. At the end of the encoding process, K systematic symbols plus N parity symbols are produced. The parity symbols are linear combinations of systematic symbols in $GF(2)$. The encoding symbol triple together with the ESI and the value K allows the decoder to determine which intermediate symbols (and thus which source symbols) were combined to form each of the encoding symbols.

B. Ground

1. *Terminal Types*

We consider high class terminals as defined in [15]. High class terminals are not energy constrained and have relatively high computation capabilities and memory [15]. This is the case of vehicular terminals, which are powered by rechargeable batteries and can host computation units of high speed, thanks to the relative low impact in terms of cost, space and weight. We assume that each terminal has both satellite and ad-hoc networking capabilities.

2. Terrestrial Channel

Two different classifications of the Vehicle-to-Vehicle (VtoV) communication channel can be made. The first one is based on tx-rx distance and leads to divide propagation scenarios into Large Spatial Scale (LSS, more than 1 Km) Moderate Spatial Scale (MSS, between 300 m and 1 Km) and Small Spatial Scale (SSS, less than 300 m). Generally LSS and MSS scenarios are suitable for broadcasting and geocasting (i.e. geographic broadcasting), while SSS can be suitable also for unicast communications. Another type of classification for VtoV scenarios is based on roadside environments such as buildings, trees and bridges. In this case the propagation scenarios are categorized as urban canyon, suburban street and expressway. Signal propagation in the two cases has been studied in [16],[17] and [18]. In case of flat fading channels Rayleigh and Ricean statistical models are often adopted for their mathematical tractability. However when LOS component intermittently disappears, fading can become more severe than Rayleigh due to high channel fluctuations. This kind of fading is called severe fading and the amplitude PDF can be modeled as a Weibull distribution[16].

In order to include the VtoV channel in the simulator we define a transmission range for each transmitter, within which a node can correctly decode the transmitter's message. Collisions are taken into account, as they constitute an important throughput-limiting and delay-increasing factors in ad-hoc wireless networks [19]. In[20] a measurements campaign made on the 5.9 GHz frequency is presented. The measurements in the paper were done using a Dedicated Short Range Communication (DSRC)/IEEE 802.11p prototype radio. In the paper it is shown how the signal strength in Suburban scenario falls below the receiver sensibility around 100 meters, which can be taken as a good value for the communication range. Communication within range can, however, be unsuccessful due to shadowing and fading.

In order to characterize the packet losses within the transmission range we adopt a Weibull distribution of the amplitude in our simulator. The packet (iFEC symbol) is correctly received if the signal power is above a certain threshold. The signal power is the product of a shadowing process, a Weibull fading process and the free space attenuation with a given path loss which depends on the distance. The parameters of shadowing and Weibull processes as well as the path loss exponent were taken from[21], where a modeling of the 5 GHz vehicular channel was presented based on measurement.

III. Network-Coded Cooperation for DVB-SH

In the following we describe the cooperation scheme we propose for coverage enhancement in the forward link. Let us consider a satellite broadcasting a DVB-SH-B signal with MPE-IFEC protection to a population of vehicle terminals with IEEE 802.11p radio interfaces. During a time window $(0, t)$ the satellite transmits $K + N$ IFEC symbols obtained from an (ADT). Terrestrial and satellite communications take place in orthogonal frequency bands. Due to long-lasting shadowing caused by urban propagation conditions, it can happen that a user decodes a number of symbols equal to $M < K$ during the interval $(0, t)$. In this case the user cannot decode the entire source data block. In order to enhance satellite coverage each node re-encodes the received packets (either received directly from satellite or from other terminals) and broadcasts them to nodes within its transmission range. In the following sections we describe the encoding procedure at land mobile nodes.

A. Encoding at Land Mobile Nodes

Let us assume that a node is able to decode some of the encoding symbols directly from the satellite. Each of them carries an ESI and a triple (d, a, b). As described in Section 2 the node can use this information to find out which of the source symbols were combined together to form that symbol. We propose to apply a network encoding scheme at land mobile nodes using source symbols of iFEC as source symbols of the network code. In other words, nodes exchange linear combinations of encoding symbols in some finite field, with the aim of decoding all of them.

B. Terrestrial Channel Usage

If a node decodes a whole source block, it broadcasts linear combinations of source symbols over an extended Galois Field $GF(2^b)$, where b is the number of bits needed to represent a symbol in the field. If node could not decode the whole block, but simply has received a certain number of encoding symbols, it can still help other nodes. Each encoding symbol received is interpreted as a linear combination of intermediate symbols with coefficients 0 or 1 in $GF(2^b)$. So the node can just apply the normal network coding procedure keeping track of which source symbols have been encoded in each received encoding symbol (that can be derived from symbol's ESI and triple (d, a, b)) in the encoding vector of the outgoing packet.

The probability to access the channel in each slot is determined by the parameter *cooperation level* which we indicate with ζ, $\zeta \geq 0$. In each slot, if a node has a number of stored linearly independent packets which is greater than the number of transmitted packets for the current generation, it creates a linear combination of all the stored packets and tries to access the channel with probability ζ. If $\zeta > 1$ two cases must be considered. In case the number of transmissions made by the node is lower than the number of linearly independent received packets, then the node tries to access the channel with probability 1. If the node has a number of stored packets which is lower than or equal to the number of those transmitted, instead, it tries to access the channel with probability $1 - \zeta$.

At the receiver side, when a node receives a packet from another node, it checks whether it is linearly independent with the stored packets and, if this is the case, the new packet is stored. If the received packet is not linearly independent with those stored, it is discarded.

Another possible relaying choice is to have nodes simply forward received symbols without combining them. We call this scheme *simple relaying* (SR) and use it as a benchmark. It is described in detail in Section V.

C. Implementation Aspects

We consider a source symbol size of 1024 Bytes each. Each source symbol is divided into n subsymbols, each of which containing $\frac{1}{n}10^3$ bytes. Each of these subsymbols is multiplied by a randomly chosen coefficient in a field with 2^n elements The coefficient is the same for all subsymbols within a packet. In this way the complexity of the network enoder/decoder can be kept at a reasonably level[22]. Field size of 2^8 or 2^{16} (one or two bytes) may constitute a valid choice. The NC is applied as in[22], adding the encoding vector at the end of each packet. Thus for a K symbols generation, a header with $K \times n$ bits is appended to each symbol. The loss in spectral efficiency then $(Kn)/8192$. Assuming coefficients of 1 byte are used, the loss becomes $K/1024$. In order to keep the loss at a reasonable value we should limit the size of the generation. For instance, if generations of $K = 100$ are used, the loss is below 10%. The adoption of small generation sizes has the drawback that the code efficiency is reduced. For example, it is known that the efficiency of the Raptor code increases with the source block. There is, however, advantages in using small blocks. Actually, if a short interleaver is used together with blocks of small size, the data is readily available to the upper layer sooner than in the case of large blocks, i.e., the delay decreases.

IV. Interaction of Physical Layer and Upper Layers

In order to evaluate the performance of the proposed methods at system level, the simulator must be capable of taking into account the channel impairments at physical layer. In order to do this physical layer simulations should be run for each of the nodes taking into account the channel characteristics and the error correction capabilities of the considered PHY layer standards. Such approach is, however, extremely time consuming, which makes it unfit for a system level simulation. A valid alternative is given by PLA, which significantly decreases the required computational power and at the same time being able to take into account the physical layer such as the effect of coding and modulation, interleaver and interference.

A. Physical-Layer Abstraction

The use of PLA allows to take into account the effects of physical layer at system level in a computational efficient way. This is particularly useful in case of time-selective channels, in which the channel gain changes within the duration of a codeword. A method used in the past to obtain instantaneous link performances was the average SINR mapping, which consisted in calculating the arithmetic (or geometric) average SINR experienced by the channel symbols of a codeword and map such average on the FER curve in AWGN for the considered code and modulation. This technique shows in general an optimistic behavior of the channel, as high SINR experienced in some parts of the codeword would distort the results.

In PLA the instantaneous symbol SINR vector is compressed in a single SINR value, the effective SINR ($SINR_{eff}$). Such approach is called *effective SNIR mapping* (ESM). Several ESM PHY abstraction have been proposed in the literature based on mean instantaneous capacity, exponential-effective SINR mapping and Mutual Information Effective SINR Mapping (MIESM). A more detail description as well as more references for these methods can be found in[9].

The $SINR_{eff}$ in ESM methods is obtained as follows:

$$SINR_{eff} = \Phi^{-1}\left(\frac{1}{N}\sum_{n=1}^{N}\Phi(SINR_n)\right) \quad (1)$$

where $\Phi(x)$ is an invertible function that depends on the specific ESM method. In MIESM such function can be related to the mutual information per received coded bit. This approach is called *received bit mutual information rate* (RBIR). The function $\Phi(x)$ is provided by the so called *modulation-channel model* through a function obtained by normalizing the modulation constrained symbol mutual information (SI) vs SNR function. Once $SINR_{eff}$ is obtained, it can be used to determine the FER using curves for the considered channel code in AWGN. Note that $SINR_{eff}$ is referred to the coded symbol, which means that modulation order and coding rate must be taken into account before using it in the FER curves. If for instance E_b/N_o FER curves are used, the $SINR_{eff}$ must be multiplied by a factor $\frac{1}{\log_2(M)R}$, M and R being the modulation order and the coding rate, respectively.

B. Simulator Validation

We have applied the PLA methodology to the DVB-SH standard taking into account the physical layer protection of the standard, which is described in Section 2. We made a validation by comparing the FER curve obtained with our simulator with the actual FER curve obtained from the physical layer simulation in the same scenario. The following scenario was considered:

Table 1. Physical layer abstraction validation scenario.

Environment	ITS
Carrier frequency	2.2 GHz
Terminal speed	50 km/h
Elevation angle	40°
Convolutional Interleaver Delay	200 ms

Figure 4 shows the comparison of the FER curves obtained with the two methods for the considered E_s/N_o. We see how they almost coincide, indicating the validity of the PLA approach.

V. Simulation Setup

The simulator models a satellite to land mobile broadcast transmission that uses DVB-SH-B standard (TDMA satellite waveform). 150 nodes were randomly placed on a urban grid of one square kilometer with 12 intersecting roads. The distance between two parallel road is 110 m. Nodes can communicate with each other and have network coding capabilities. Communication can take place between two nodes only if they are in the same road, or in proximity of the same crossroad, and within a radius of 100 m. A number $N_{block} = 20$ of IFEC blocks of 10 IFEC symbols each is transmitted at each trial. In the following we will use interchangeably the terms "IFEC block" and "generation", a term which is typically used in the context of network coding. Each block contains K source symbols of 1024 bytes each. The total number of coded symbols transmitted for a single generation is K/R_{IFEC}, where R_{IFEC} is the rate of the Raptor encoder.

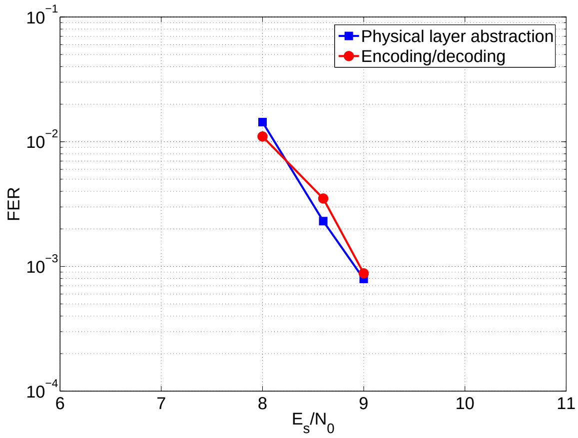

Figure 4. Physical layer abstraction validation.

The Raptor encoder is the one indicated in [2] and described in[14]. Each IFEC symbol is encapsulated in an MPEG2 TS packet and sent to the channel encoder. The channel encoder is the 3GPP2 turbo encoder specified in[23]. Each source message of the channel encoder has a fixed length of 12288 bits, which means that about one and a half IFEC symbols fit within one Turbo source message. Once encoded with a rate R_{turbo} the IFEC symbols are interleaved with the bit interleaver and successively with the time interleaver, which provides time diversity to the signal. In the simulator we implemented two of the time interleavers described in[15], namely the *short uniform* interleaver and the *long uniform* interleaver. The former has a depth on the order of 200 milliseconds while the latter has a depth on the order of 10 seconds. After time interleaving, the bits are QPSK modulated and transmitted with roll off factor 0.35. Each of the mobile nodes sees a channel generated using a channel series generator implementing a three state Perez-Fontan LMS channel model. The correctness of the reception of each turbo codeword is evaluated using PLA as described in Section A, taking into account data rate, channel interleaver, channel code rate, and other relevant parameters. The link budget adopted is the one in[1], Table 11.28. Table 2 summarizes the main simulation parameters.

Table 2. Simulation parameters.

Environment	Urban
Carrier frequency	2.2 GHz
Terminal speed	50 km/h
Satellite elevation angle	40°
Time interleaver type	Short Uniform - Long Uniform
Modulation	QPSK
Roll-off factor	0.35
Bandwidth	5 MHz
Number of LL-FEC bloks	20 ($\sim$ 200 kB of data)
Rate Turbo Code	1/2 - 1/4
Rate Raptor Code	1/2
Number of nodes	150
Node type	Vehicular
Scenario surface	1 sq. km

Depending on the sequence of correctly decoded codewords, the IFEC symbols which were correctly decoded can be determined. Nodes exchange IFEC messages using DSRC/IEEE 802.11p interfaces. The transmission rate in the ground segment is set high enough so that an IFEC symbol can be transmitted before the next one is received on the satellite channel. The medium access control (MAC) mechanism in the terrestrial segment is CSMA as in 802.11p. Nodes are set in *promiscuous mode* so that each node can receive the transmissions of any other node.

We compare two different relay methods. One is based on NC, as described in Section III. The other is simple relaying, introduced in Section III. Unlike in the scheme with NC, in SR nodes do not combine packets, they just transmit the oldest non transmitted packet. If all the received packets have already been transmitted, then, if $\zeta > 1$, a node transmits (with probability $1 - \zeta$) a randomly chosen packet.

The throughput is measured at the interface of the IFEC and the upper layers, as indicated in Fig. 5, considering the IFEC block as a fundamental data unit. The reason for this choice is that the variable-length IP datagrams coming from the upper layers are reshaped in the ADST's. Thus receiving one or more IFEC symbols, even if systematic, may not provide any useful data to higher layers, as they can be made up of partial datagrams. Thus when we refer to *decoded data* we talk about decoded IFEC blocks. We assume that the decoding is possible if and only if a number of linearly independent IFEC coded symbols equal to the number of IFEC source symbols is correctly received. This is possible as each of the IFEC coded symbols embeds information about which source symbols were combined to form it, and thus common matrix manipulation techniques can be used to retrieve the source symbols.

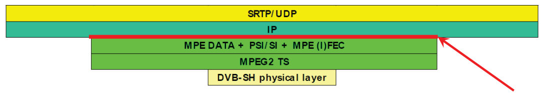

Figure 5. Throughput is measured at the interface of the IFEC and the upper layers.

VI. Numerical Results

In this section we compare the performance of three system. One is the network-coded system described in Section III, one is a system in which the nodes can receive only from the satellite (i.e. no cooperation) and the last one is the SR system described in Section V, which is our benchmark. Our performance metrics are the *coverage* and the *normalized throughput*. We define the coverage as the average percentage of nodes that can decode all the transmitted IFEC blocks. The normalized throughput is defined as the average number of IFEC blocks that can be correctly decoded by a node, normalized by the total number of IFEC blocks transmitted. The two metrics are evaluated for different values of ζ in the range $[0.2, 2]$. Note that the system with satellite only reception corresponds to a cooperative system with $\zeta = 0$. Considering different values of ζ we can evaluate the performance gain of the cooperative methods with respect to the non cooperative system as a function of the terrestrial channel utilization. In Fig. 6 the normalized throughput is plotted. The NC-scheme outperforms the non cooperative system by up to 15% in case the long interleaver and the turbo code with rate 1/4 are used, and by up to about 20% in case the configuration with short interleaver and rate 1/2 is adopted. This last configuration is particularly interesting as, apart from doubling the data rate for a fixed bandwidth, it notably simplifies the transmitter with respect to the case with a long interleaver. This would allow, for example, handheld terminals to receive packets broadcasted by the vehicular terminals, which would not be possible if a long interleaver is uses due to handheld terminal limitations. The relay system shows little improvement with respect to the non cooperative system. Similar considerations can be made for the coverage, which is plotted in Fig. 7. It can be seen how the network-coded system achieves more than 20% gain in coverage with respect to the non cooperative system if the configuration with short interleaver and turbo rate 1/2 is adopted. A notable fact that emerges from the plots is that the best performances are achieved for values of ζ lower than 2. This may be due to the fact that, beyond a certain value of ζ, the terrestrial channel saturates, as the collisions become more and more frequent. This guess will be evaluated in our future work.

The numerical results just shown suggest that a cooperative relaying system based on network coding may bring important benefits in terms of throughput and coverage with respect to a system in which nodes receive from satellite only, as well as with respect to a simple relay system, which shows poor performance in the considered scenario.

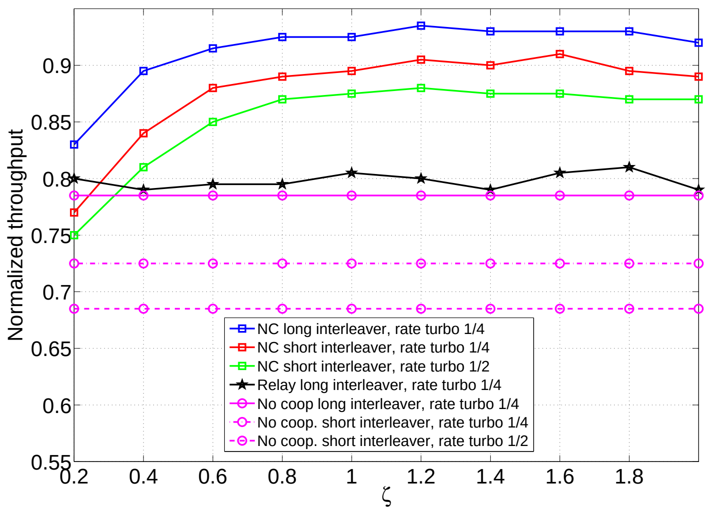

Figure 6. Normalized throughput (average number of decoded generations per node) plotted against cooperation level.

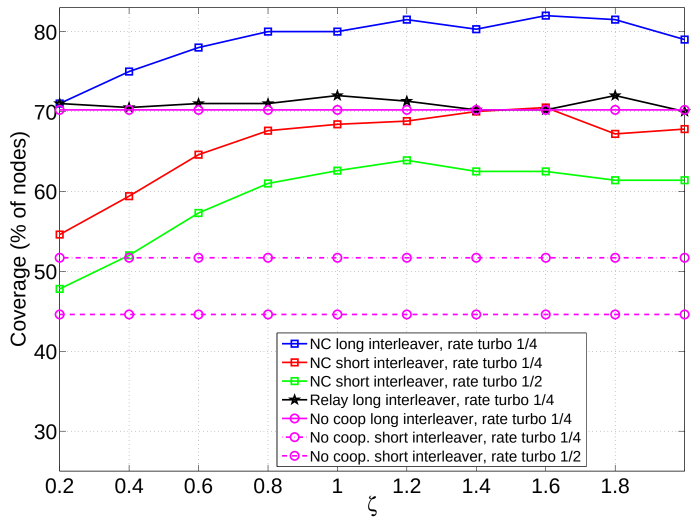

Figure 7. Average percentage of nodes that decode all generations plotted against the cooperation level.

VII. Conclusion

We proposed a cooperative ad-hoc networking approach which leverages on network coding NC for enhancing coverage and throughput in DVB-SH-B. Our numerical results, based on physical layer abstraction, showed that a cooperative relaying system based on network coding can bring important benefits in terms of both throughput and coverage with respect to a system in which nodes receive from satellite only, as well as with respect to a system in which nodes do not combine messages.

As future work we plan to include gap fillers in the considered scenario, in order to compare the performance of a system with and without gap fillers and evaluate the impact that cooperation may have in reducing their number.

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