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A Network-Coding Aided Road-Map of Large-scale Near-capacity Cooperative Communications

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***Abstract*—In the paper, we present a road-map towards a Near-capacity Large-scale Multi-user Cooperative-communications (NLMC) system, where all the evolution paths converge to the construction of the NLMC system. More specifically, we will summarise all relevant schemes appearing on the road-map in the unified frame-work of forward error correction (FEC). Various Network Coding (NC) design paradigms are highlighted for illustrating how the NLMC systems might be designed for meeting diverse design criteria in the context of cooperative and cognitive communications, where the channel capacity of the NLMC systems is used for comparing the different design paradigms.**

I. Introduction and Overview

The design of an attractive channel coding and modulation scheme depends on a range of conflicting factors [1], which are illustrated in Fig. 1. Different solutions accrue when optimising different codec features. For example, in many applications the most important codec parameter is the achievable coding gain, which quantifies the amount of bit-energy reduction attained by a codec at a certain target of Bit Error Ratio (BER) or Frame Error Ratio (FER) [2]. Naturally, attaining a transmit power reduction is extremely important in battery-powered devices [3]. This transmitted power reduction is only achievable at the cost of an increase implementational complexity, which itself typically, increases the power consumption and hence erodes some of the power gain [3]. Viewing this system optimisation problem from a different perspective, it is feasible to transmit at a higher bit rate in a given fixed bandwidth by increasing the number of bits per modulated symbols [4]. However, when aiming for a given BER or FER target, the channel coding (CC) rate has to be reduced in order to increase the transmission integrity. Naturally, this reduces the effective throughput of the system and results in an increased overall system complexity [5].

From the perspective of CC, there are several excellent tutorial papers reviewing the techniques supporting near-capacity

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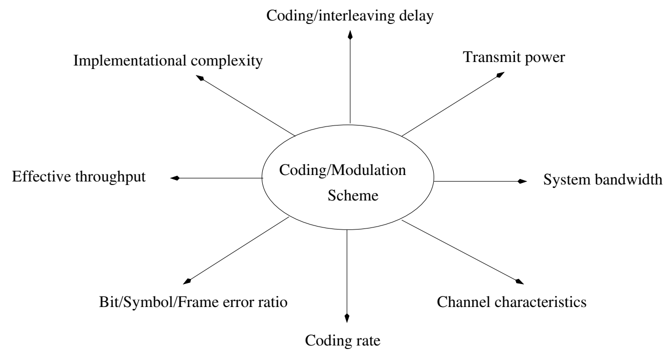

Fig. 1: Factors affecting the design of channel coding and modulation schemes [1].

single-link transmissions conceived for either a single user or a few users [3], [4], [6]–[9], where time-space diversity is created by encoding the entire frame of a single user or by jointly decoding several encoded frames travelling via several users. From the perspective of NC, the goal is to jointly encode the information in the entire network. Given this ambitious objective, the authors of [10] portrayed the history of NC, including related theory. In [11], NC techniques were presented from the perspective of the network architecture, where the diversity order of different NC schemes was compared along with the multiple access types used. NC was also surveyed in the specific context of network tomography [12], where the advantages of NC were detailed. In reference [13], benefits of NC were highlighted in the context of cognitive radio networks (CRN).

Against this background, **we portray NC in the unified framework of FEC, which was employed for diverse CC schemes in [6]. Accordingly, the corresponding channel capacity is used as a benchmarker for the various NC paradigms**. More specifically, we further expand the concept of channel capacity and near-capacity channel coding schemes detailed in [6], in order to cover NC in the context of both cooperative and cognitive communications [14], [15].

In this paper, **we briefly portray an anecdotal research roadmap in Fig. 2, which shows the research-avenues leading to near-capacity multi-user cooperative systems. The central route of our map is illustrated by 'Phy-Cooperation Avenue', which later merged into 'Cooperative Networking Road'. In other words, the route emerged from physical-layer communications, and then culminated in cooperative networking, which is detailed in Fig. 4. This process is also indicated in box 2 of Fig. 3.**

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We set out on our walk through history with the ultimate goal of designing high-throughput wireless communication systems. **When we embark on a historic tour along 'MIMO Avenue', 'Space-Time Coding Street' connects 'MIMO Avenue' with 'Phy-Cooperation Boulevard' heralding the application of STC in cooperative communications. Similarly, as 'MIMO Avenue' approaches 'Next-Generation Place' in Fig. 2, 'Virtual MIMO Street' [16] and 'Multi-user Multi-cell Street' [17]–[19] branch out from the original MIMO techniques and merge with 'Cooperative Networking Road', as detailed in Fig. 4.**

More specifically, as a result of the further development of MIMO-related techniques, single-user cooperative relay aided systems were introduced upon combining the concept of cooperative communications with that of virtual MIMO systems [16]. For example, exploiting the concept of space time coding [20] directly led to 'Cooperative Networking Road' of Fig. 2, which again emerged from 'Phy-Cooperation Boulevard', as further detailed in Fig. 4.

As the cooperation techniques are expanded to multiple cells, 'Multi-user Multi-cell Street' leads to facilitating spectrally-efficient, reliable data transmission between spatially-distributed user nodes and multi-antenna destinations via intermediate multi-antenna relay nodes [19]. Thus, 'Multi-user Multi-cell Street' [17] also merges into 'Cooperative Networking Road' of Fig. 2.

As we travel along 'Coding Parkway' of Fig. 2 and focus our attention on the development of near-capacity codes, since the early 1990s research interests have been focused on Turbo Codes (TC), on Low Density Parity Check (LDPC) codes and on polar codes [21].

Near-capacity performance can be achieved by employing TC [22], which introduces significant delay caused by alternating forward/backward iterations of the classic turbo decoding principle [6]. Fortunately, Maunder's recent parallel decoding approach can be used for reducing the turbo decoding delay [23]. As a result, 'Turbo Street' in Fig. 2 is used for reflecting the development of TC, which emanated from 'Coding Parkway' and later broadened further into 'Phy-Cooperation Boulevard'.

LDPC codes [24] can also support near-capacity operation and a potentially reduced decoding delay. However, both LDPC and TC tend to impose a high complexity and to exhibit error floors. These disadvantages motivated the design of polar codes [25]. Polar codes are also capable of approaching the channel capacity, despite using low-complexity methods for code construction, encoding and decoding. Additionally, polar codes are less prone to error floors [26]. In order to portray these developments in the area of LDPC and Polar codes, we have changed the 'Channel Coding Lane' to 'LDPC-Polar Lane' in Fig. 2.

Then, in the context of cooperative communication [16], Network Coding [27] is cable of exploiting all active nodes in the network in order to provide diversity for Cooperative Networking [28]. Various NCs schemes are presented in Section I.B-2, which can be constructed based on different channel coding schemes, as portrayed in Fig. 6, where Maximum Distance Separable codes constitute a typical example considered in this paper.

Further research along 'Coding Parkway' seen in Fig. 2 has appeared in diverse emerging applications of coding including network coding [27] and quantum communications [29]–[32], just to name a few. As we continue our historic stroll along 'Coding Parkway', we find compelling applications of coding in the emerging contexts of 'Network Coding Street' and 'Quantum Coding Street' seen in Fig. 2. In a nutshell, as we proceed along 'Coding Parkway', new coding schemes continue to emerge for radically evolving communication systems.

Anecdotally speaking, all the roads tend to converge to the "Next-Generation Place" in Fig. 2, where "Quantum Communications Avenue" may be expected to contribute to the landscape of wireless communication systems. Accordingly, TABLE I summarises the important milestones along the road map portrayed in Fig. 2, which are discussed in the order seen in Fig. 3.

As a result, the novel contributions of this paper can be summarised as follows:

- We survey the different routes leading to a Near-capacity Large-scale Multi-user Cooperative communications (NLMC) system by employing near-capacity turbo codes, multi-dimensional modulation, co-located MIMO techniques, distributed and virtual MIMO as well as network coding.
- We focus our attention on the design of network coding in order to construct attractive NLMC systems. More specifically, we detail various techniques employed for improving the diversity versus multiplexing trade-off of large-scale cooperative communication systems invoking network coding.
- We detail our adaptive mechanisms conceived for the top-most network coding layer in order to demonstrate how the multiplexing gain of network coding systems can be further improved.
- In order to provide a complete portrayal of the NC class focused in the paper, we present our approach on the corresponding blind NC, where the network-decoder requires no prior knowledge concerning the encoding process invoked at intermediate nodes.
- We provide discussions and analyses on influential elements of a general NLMC architecture relying on the powerful techniques of multi-layer network coding dispensing with side information network coding, and adaptive network coding, full-diversity network coding, near-capacity channel coding as well as cognitive communications.

In the rest of this section, we first review MDM, which is in a broad sense capable of providing more independently fading dimensions by increasing the dimensionality of the signal space. Typically, the attainable diversity gain may be increased by making use of multiple antennas. Then, by focusing on the diversity aspects, we feature cooperative communications that constitute another solution conceived for enhancing the diversity gain, where single-antenna aided relays cooperate for constructing virtual MIMO antennas. In a nutshell, we harness

Year	*Author*	*Milestone*
1948	Shannon [33]	Shannon's capacity theorem was introduced.
1950	Hamming [34]	Hamming codes were discovered.
1955	Elias [35]	Convolutional codes were introduced.
1957	Prange [36]	Cyclic codes were proclaimed.
1959	Brennan [37]	Three diversity systems, namely selection combining, maximal ratio combining and equal gain combining, were analysed.
1960	Reed and Solomon [38]	Reed Solomon (RS) codes were defined over certain finite Galois fields.
1966	Forney [39]	Concatenated codes were introduced.
1971	van der Meulen [40]	A simple relay channel constituted by a source, a destination and a relay was introduced.
1972	Bahl *et al.* [41]	The Maximum A-Posteriori (MAP) algorithm was invented.
1974	Bahl *et al.* [42]	The symbol based MAP algorithm was proposed.
1977	van der Meulen [43]	The model of [40] was generalised and the transmission efficiency of relays was studied.
1979	Cover and El Gamal [44]	Capacity analysis of the full duplex relay channel was presented.
1993	Berrou *et al.* [45]	Turbo codes were discovered.
1997	Tarokh *et al.* [46]	Space Time Trellis Code (STTC) was introduced.
1996	Foschini *et al.* [47]	Diagonal BLAST was conceived for achieving an MIMO multiplexing gain.
1998	Alamoti *et al.* [48]	Space Time Block Code (STBC) was introduced.
	Sendonaris *et al.* [49]	The relay model was generalised to the system supporting multiple nodes, which are capable of transmitting their own data as well as of serving as relays for others.
1999	Tarokh *et al.* [50]–[52]	Alamouti's scheme of [48] was generalised for supporting systems exploiting more than two transmit antennas.
2000	Ahlswede *et al.* [27]	Widely acknowledged concept of network coding was formally published.
2002	Hanzo, Liew and Yeap [5]	Turbo algorithms were characterised.
2003	Laneman and Wornell [16]	Various cooperative diversity protocols were developed for exploiting spatial diversity in a cooperative scenario.
2004	Laneman *et al.* [53]	Performances of various cooperative diversity protocols, namely of Decode-and-Forward (DF), of Amplify-and-Forward (AF) and of relay selection are compared in terms of their outage behaviours.
	Janani *et al.* [20]	The diversity of coded cooperation was increased by borrowing ideas originated from STCs in conjunction with the application of turbo codes to the proposed relay aided system.
2005	Snessens *et al.* [54]	A soft DF signalling strategy capable of outperforming the conventional DF and AF was proposed.
	Hu and Li *et al.* [55]	Slepian-Wolf cooperation exploiting distributed source coding in wireless cooperative communication was advocated.
2006	Li *et al.* [56]	Soft information relaying applied in a BPSK modulated system employing turbo coding was proposed.
	Hu *et al.* [57]	Wyner-Ziv cooperation relying on the Slepian-Wolf cooperation of [55] in conjunction with a compress-and-forward signalling strategy was proposed.
	Yeung and Cai [58], [59]	Existence of Maximum Distance Separable (MDS) network codes was shown.
	Ho *et al.* [60]	Random Network Coding (RNC) was introduced for a non-coherent network model.
2007	Xiao *et al.* [61]	The concept of network coding was introduced in the context of cooperative communications.
2008	Wang *et al.* [62]	The complex field network coding approach capable of mitigating the throughput loss in conventional cooperative signalling schemes and of attaining full diversity gain was introduced.
2009	Hanzo *et al.* [63]	Low-complexity cooperative MIMOs and distributed turbo codes designed for two users cooperating for the sake of improving their attainable BER performance were presented.
	Ming and Skoglund [64]	A basic example of the applications of MDS network coding was introduced in multi-user relay networks.
	Sadeghi *et al.* [65]	Instantly Decodable Network Coding (IDNC) was introduced for controlling the decoding delay of RNC.
2010	Rebelatto *et al.* [28]	Generalized Distributed Network Coding (GDNC) designed based on RS codes was introduced for cooperative communications.
2011	Rebelatto *et al.* [66], [67]	Adaptive GDNC was introduced in the context of cooperative communications.
2012	Maric *et al.* [68]	Multi-hop network coding based systems relying on an AF mechanism were studied.
	Xiao *et al.* [69]	MDS network codes were investigated in scenarios in the presence or absence of the direct source-base station links and relying on orthogonal/non-orthogonal channels.
2013	Nguyen *et al.* [70]	GDNC is further generalised for incorporating adaptive and full diversity aspects.
	Li *et al.* [71]	Adaptive GDNC is employed for aiding successive relaying in noncoherent cooperation.
	Rayel *et al.* [72]	GDNC is investigated in the context of Nakagami channel.
2014	Moritz *et al.* [73]	GDNC was employed for the uplink transmission, while energy transfer is carried out in the downlink transmission
2015	Chun *et al.* [74]	An adaptive random network coding scheme was proposed for spectrum sharing in cognitive radio networks.
	Chen *et al.* [75]	GDNC was employed in the general context of energy harvesting.
	Liang *et al.* [76]	Distributed GDNC scheme was proposed for Cooperative Cognitive Radio Networks.
2016	Bordon *et al.* [77]	The aspect of energy efficient power allocation was investigated for network-coded cooperative cognitive radio network.
2017	Samadi-Khaftari *et al.* [78]	Coding constructions were conceived for both MDS field-based and for MDS convolutional code in the context of acyclic networks.
	Sundararajan *et al.* [79]	Feedback-based techniques were proposed for controlling the decoding delay of IDNC Schemes.

TABLE I: Milestones related to the research road map presented in Fig. 2.

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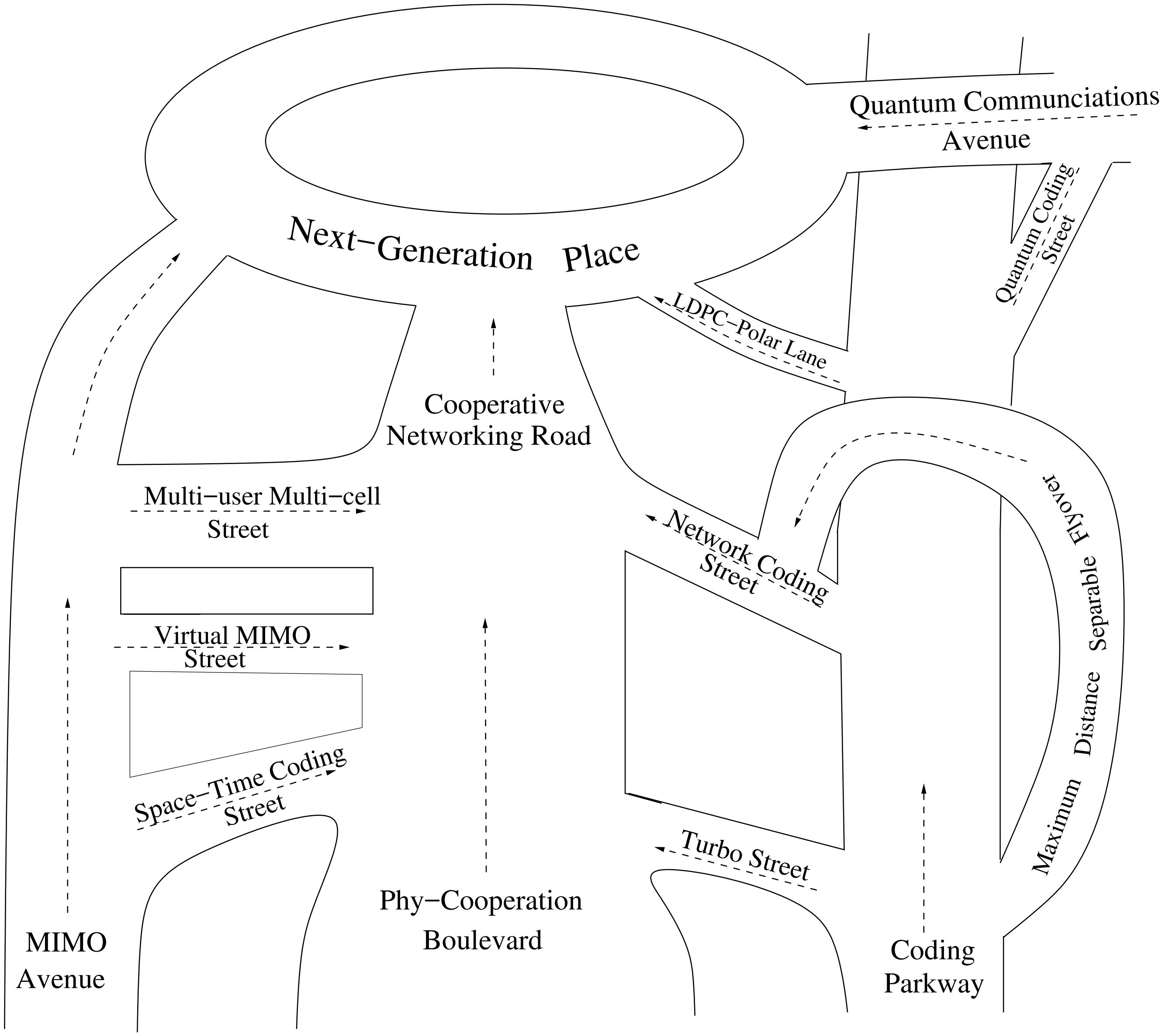

Fig. 2: Stylised Roadmap of Near-capacity Network Coding Aided Cooperative Multi-User Communications.

a general technique of combining the benefits of coding and cooperative communications.

A. Multi-Dimensional Modulation

The idea of MDM was embedded into Shannon's fundamental theorem itself, which relies on increasing the dimensionality of the signal space in order to increase the bandwidth efficiency [80]. Slepian [81] and Ottoson [82] proposed modulation schemes based on equal-energy signals that were defined as M points on a sphere in the N-dimensional Euclidean space.

The motivation for employing MDM may be readily highlighted by referring to the gain achieved with the aid of the classic two-dimensional constellation over the one-dimensional constellation. The implication of this is that upon considering infinitely large constellations, the Signal-to-Noise Ratio (SNR) loss of one-dimensional constellations with respect to two-dimensional constellations is unbounded [83]. Unfortunately, the same reasoning does not hold when this concept is extended from two-dimensional constellations to higher-dimensional constellations. Hence, only the transition from one-dimensional signalling to two-dimensional signalling allows us to double the transmitted information bit rate, provided those signalling schemes are based on the use of an in-phase quadrature-phase carrier [81], [84], [85]. By contrast, a BER performance improvement was reported when evolving from two-dimensional-signalling to four-dimensional-signalling [84], [86], which was not accompanied by a throughput improvement.

Additionally, the seminal paper by Saha and Birdsall [87] suggested that the four-dimensional modulation referred to as

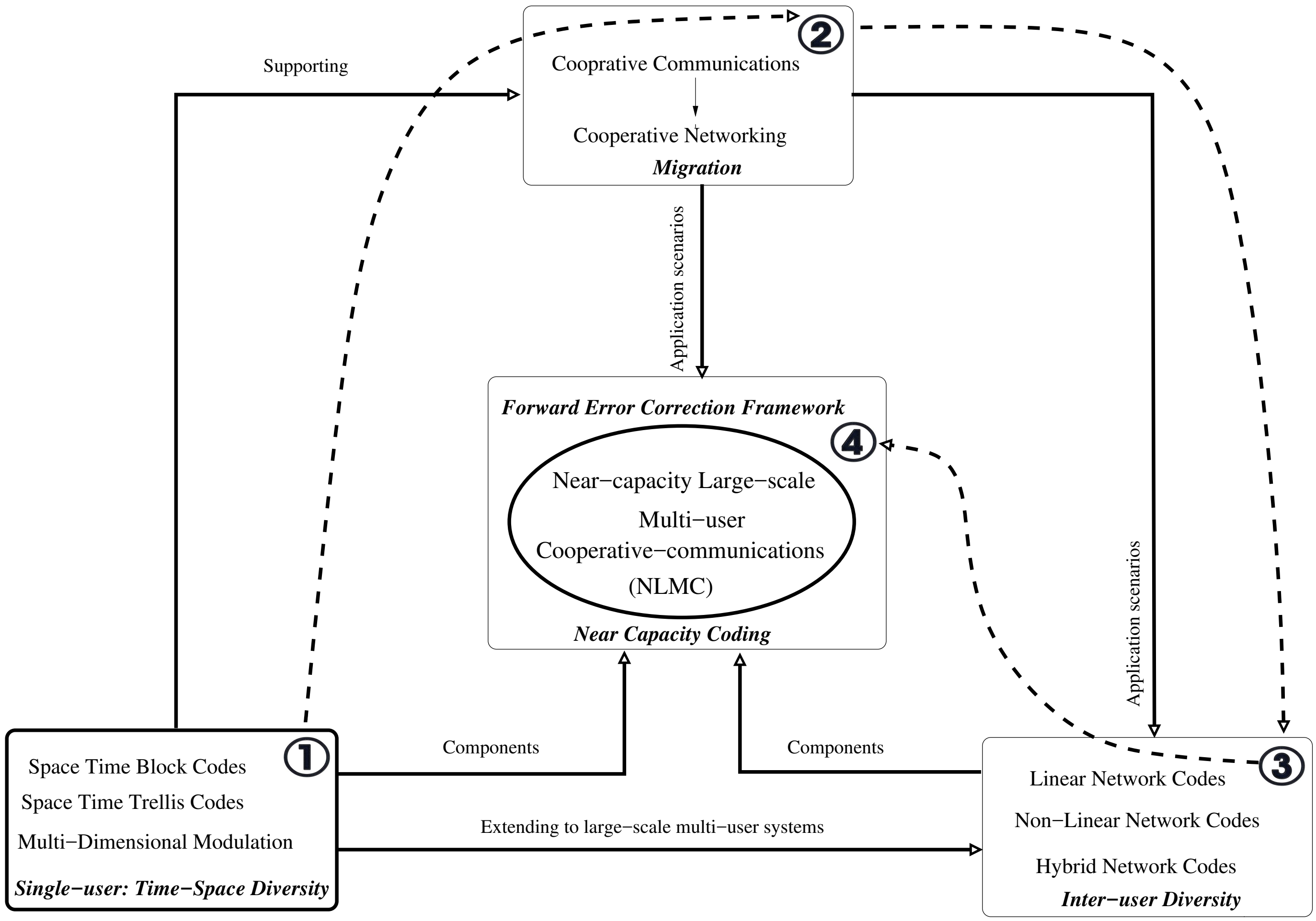

Fig. 3: Presentation structure of the paper.

Quadrature-Quadrature Phase-Shift Keying (Q^2PSK) transmits twice as many bits per second at a given bandwidth compared to that of Quadrature Phase-Shift Keying (QPSK) without any SNR penalty. The evolution from QPSK to Q^2PSK was presented in a way analogous to the transition from BPSK to QPSK. However, the appealing benefits of Q^2PSK eroded after Visintin *et al.* investigated the minimum bandwidth required for each of those modulations [86]. This research clearly showed that the bandwidth efficiency of QPSK and Q^2PSK are, in fact, identical, and that there is no advantage in using Q^2PSK on Additive white Gaussian Noise (AWGN) channels. Visintin also suggested that in order to reap a benefit from using a four-dimensional basis, a channel coded scheme should be used [86].

Following the idea of the coded multi-dimensional scheme, the joint designs between MDM and coding, namely group codes, trellis codes as well as convolutional and block codes were proposed [80], [82], [85], [88], [89]. The MDM concept was also applied to Bit-Interleaved Coded Modulation (BICM) in the context of multi-antenna channels in the form of spatial mapping (mapping across antennas) [90]–[94]. Later, MDM was combined with Space Time Coding (STC) and BICM in the form of coded modulation aided MIMO systems [92]–[95]. In such coded modulation systems, multidimensional bit-to-symbol mapping is used between the channel-coded words and multidimensional constellations.

As regards to channel capacity, advances in channel coding made it feasible to approach Shannon's capacity limit in systems equipped with a single antenna. However, these capacity limits can be further extended with the aid of multiple antennas in MIMO systems, which are capable of providing a linearly increasing capacity as a function of the transmit power, provided that the extra power is assigned to additional antennas [96]. MIMO schemes can be briefly categorised as diversity techniques, multiplexing schemes, multiple access arrangements and beamforming techniques [63]. Typical form of MDM aided diversity techniques are STTC [97], STBC [98] and STBC-Sphere Packing (STBC-SP) [99].

1) Space Time Trellis Code: STTCs [51], [97], [100], [101] were proposed by Tarokh *et al.*, which incorporate jointly designed channel coding, modulation, transmit diversity and optional receiver diversity. The performance of the system employing STTCs is determined upon matrices constructed from pairs of distinct code sequences, while the corresponding diversity gain and coding gain of the codes are determined by the minimum rank and the minimum determinant [97], respectively. The STTCs proposed in [97] strike the best trade-off among the data rate, diversity gain and trellis complexity.

It should be noted that the presence of multiple propagation paths does not decrease the diversity order guaranteed by the design criteria used for constructing the STTCs.

2) Space Time Block Code: STBC concept was conceived by Alamouti in [98] as a simple two-branch transmit diversity scheme. Using two transmit antennas and a single receive antenna, the prevalent scheme provides the same diversity order as maximal-ratio receiver combining with one transmit antenna and two receive antennas, provided that the two antennas experience independent fading. It was also shown in [98] that the scheme can be readily generalised to two transmit antennas and N_r receive antennas for providing a diversity order of $2N_r$.

3) STBC-Sphere Packing: In line with the approach of using channel coded scheme [86], Sphere Packing (SP) modulation was proposed by jointly designing with STBC in [99] for two transmit antennas and for various number of receive antennas. As a result, the scheme is capable of exploiting the benefits of multi-dimensional modulation, where the signals transmitted from two transmit antennas are chosen from L legitimate space-time signals, which are designed over the four-dimensional real-valued Euclidean space $\mathbf{R}^4$. In other words, the L legitimate space-time signals are selected from the four-dimensional real-valued Euclidean space by ensuring that they have the highest possible minimum Euclidean distance from all other $(L-1)$ legitimate signals [63]. The SP-STBC-G2 scheme was also concatenated with other channel coding schemes, namely with Low-Density Parity-Check (LDPC) codes in [102] and with BICM in [103].

Having separately presented the family of transmit diversity techniques including STTC, STBC and SP-STBC, the BER/FER performances of these techniques show that the STTC scheme tends to exhibits a superior BER/FER performance in comparison to the other schemes, namely to G2-STBC and SP-STBC, especially at sufficiently high SNRs. This explains why the STTC scheme is favoured for the further development of MIMO-based solutions, when the BER/FER performance of the systems has a high priority. [104], [105].

B. Cooperative Communications and Network Coding

1) Cooperative Communications: Classically, relays have been used to extend the range of wireless communication systems [44], [106]–[111]. However, in recent years, numerous exciting new applications of relay aided communications have emerged [112]–[120]. The applications of cooperative and relay aided communications involve the Physical Layer (PHY) [113], [118], [119], [121], [122], the Medium Access Control (MAC) [112], [117], [123], the network layer [120] as well as their cross-layer operation [114]–[116], [124], as seen in Fig. 4. One of typical scenarios is to support communications between the source and destination nodes with the aid of cooperative protocols. Such a system is realized by designing sophisticated medium access between the source and relay nodes [125], [126], which is facilitated by appropriate modulation and coding schemes [127], [128]. The system as a whole can be optimized in a centralized or decentralised manner [129], [130]. As a result, the diversity gain of the system can be substantially improved [131]. Moreover, in multi-user systems, different users can also act as cooperating partners or relays in order to share resources and assist each other in their information transmission [132]. Another beneficial application is the exchange of information between multiple users through relay(s). In some cases, the total throughput of these systems can be drastically increased by exploiting the knowledge of one's own transmitted signal [133].

As illustrated in Fig. 2, 3 and 4, cooperative networking exploits the concept of physical-layer cooperation and of cross-layer operation techniques relying on the PHY, MAC and network layers, which has recently received significant research attention [134]–[138]. As seen in Fig. 4, cooperative networking may be classified into the following categories:

- Coding [136], [139]–[146] in the PHY layer;
- Power allocation [147]–[152] in the PHY layer;
- Energy transfer and harvesting [153]–[156] in the PHY layer;
- Cooperative transmission [157]–[160] in the PHY layer;
- Full duplex and two-way relaying [161]–[164] in the PHY layer;
- Relay-selection in the PHY and network layer [165]–[170];
- Service-quality improvement [171]–[173] in cooperative networks;
- Channel access [174]–[178] in the MAC layer;
- Routing [179]–[184] in cooperative networks;
- Scheduling [123], [185], [186] in the MAC layer;
- Topology control [187]–[189] in cooperative networks;
- Resource management [190]–[193] in cooperative networks;
- Cross-layer design [129], [130], [194], [195] in cooperative networks.

Network coding appears in a number of categories within the framework of cooperative networking, namely in coding [139]–[141], power allocation [147], [150], energy harvesting [153], [154], two-way relaying [154], [164], cooperative transmission [157], channel access [177], [178], relay-selection [166], [167] as well as in routing [180], [183], [184] categories, as portrayed in Fig. 4.

2) Network Coding: Network coding is capable of increasing the throughput, while minimising the amount of energy required per packet as well as the delay of packets travelling through the network [196], [197]. This is achieved by allowing intermediate nodes in a communication network to combine multiple data packets received via the incoming links before transmission to the destination [198]. Due to the beneficial merit, the concept of the network coding has been applied in various disciplines, as illustrated in Fig. 5.

In the area of communications, network codes may be classified based on different perspectives, for example on the basis of how the information streams are processed at the relays [199], on the construction of network codes [200], on the specific architecture of communication networks employing network coding [201], on the layer in communication networks where the network coding operates [202], just to name a few. As seen in Fig. 6, we may classify network

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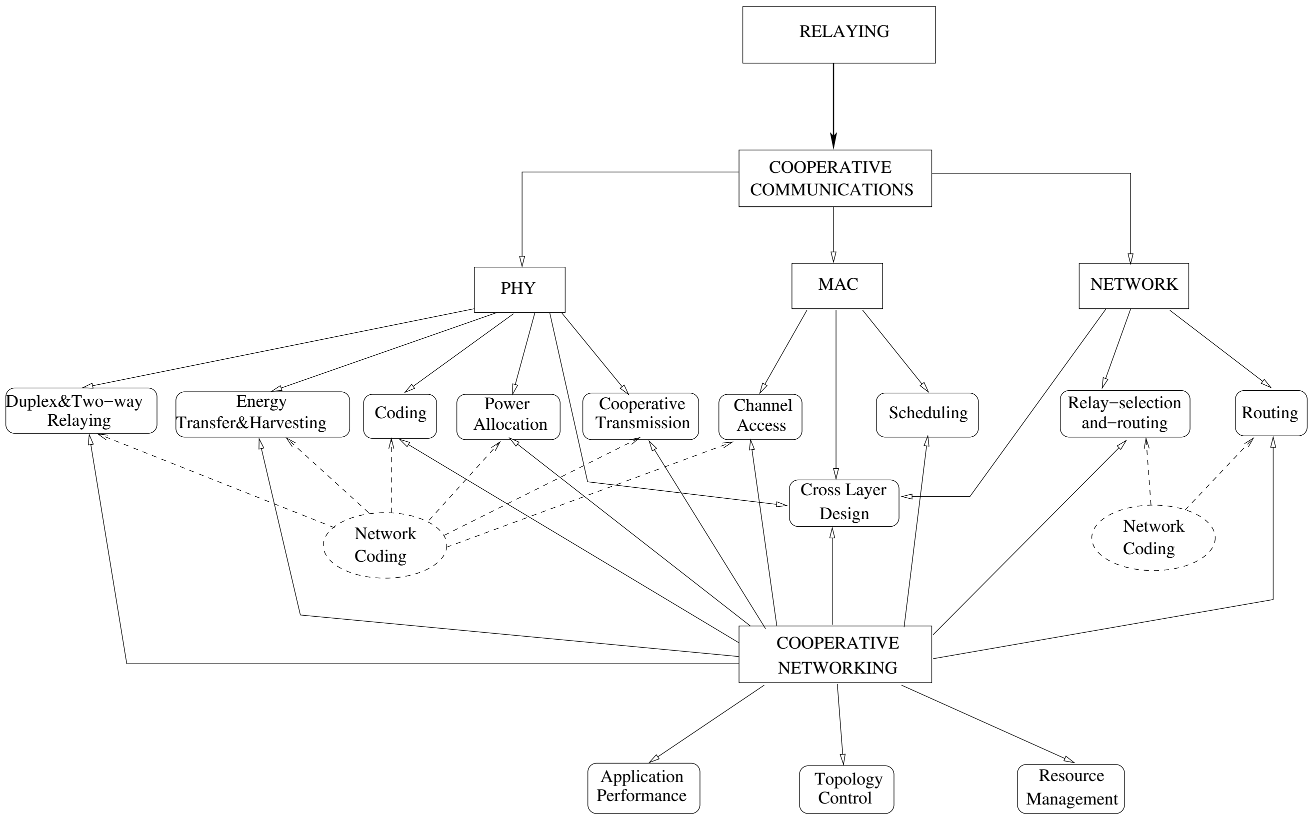

Fig. 4: Migration from physical-layer cooperation to cooperative networking

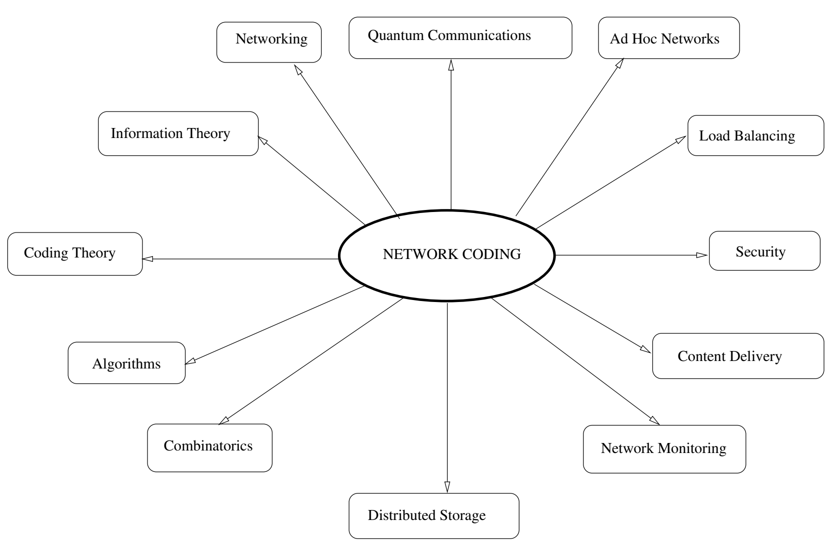

Fig. 5: Network Coding: Connections with other disciplines [199].

codes into three main categories, namely the Linear Network Codes (LNC) [200], [203]–[206], Non-linear Network Codes (NLNC) [207], [208] and the family of so-called Hybrid Network Codes (HNC) [209]–[211][1].

It should be noted that the capacity of single-source multicast communications in a network can be approached by solely using LNC [212], which has many attractive properties. From a theoretical standpoint, linearity is a beneficial algebraic property supported by exact mathematical foundations. From an engineering standpoint, the simplicity of linear approaches leads to relatively low complexity in the encoding and decoding processes, which makes LNC attractive in the area of communication engineering [213]. It is worth noting that the specific categories of the LNC characterised in Fig. 6 are not strictly unrelated to one another.

3) Linear Network Codes: Let us focus our attention on the LNC branch of the network coding taxonomy presented in Fig. 6, where we pay particular attention to Maximum Distance Separable (MDS) network codes and to Random Network Codes (RNC). For the details on Generic Network Codes (GNC), Static Network Codes (SNC) and Convolutional Network Codes (CNC), interested readers might gain insightful details in reference [203]. For the details on Product Codes (PC) seen in Fig. 6, refer to [200], whereas the specifics of Secure Network Codes (SNC) mentioned in Fig. 6 can be found in [204]–[206].

Let us summarise the important milestones in the evolution of MDS network codes and RNCs in TABLE II, where the concept of network coding was introduced by Ahlswede *et al.* in 1998 [214] and was later formally published in 2000 [27].

In 2006, the network coding concept was conceived as a generalisation of classic error correction codes in [58], [59], which also extended bounds employed in classic coding theory, namely the Singleton bound, Hamming bound and Gilbert-Vashamov bound, to the network coding field. Based on the Singleton bound, the existence of Maximum Distance Separable (MDS) network codes was proved. In the same year, RNCs were proposed in [60]. The main benefits of RNC are their decentralised operation and robustness to network changes or link failures, which are considered in the scenario of the non-coherent network model. It was noted that research in network coding theory considered two different network models, namely coherent and non-coherent networks. In the coherent network, the transmitter and receivers are aware of the network characteristics, while in the non-coherent networks the opposite is true. Naturally, the non-coherent network model is more suitable for most practical applications [200].

In 2007, SC was introduced in [215] as a branch of RNC, which was described in more detail in 2008 [216] as a network code capable of correcting various combinations of errors and erasures.

In 2008, the author of [217] proved that the concept of minimum distance plays exactly the same role as it does in classic coding theory in terms of characterising the capability of correcting/detecting errors. This proof simplifies the design of network codes. Hence, the structure of the MDS code family established in classic coding theory may also be applied to network coding.

Relying on the initial work in [64] published in 2009, the application of the MDS network coding in multi-user relay networks was fully characterised in 2011 [218].

In 2011-2012, relying on the initial results of [28] disseminated in 2010, the authors of [67], [219] formally introduced GDNC relying on employing the construction of Reed Solomon (RS) codes, which belong to the family of MDS codes.

In 2012-2013, the concept of GDNC systems was further developed for incorporating near-capacity channel coding schemes into the GDNC systems, in order to conceive a family of multi-user, multi-layer, multi-mode cooperative systems[2]

During 2014-2017, the GDNC based system was further investigated in the context of energy transfer [73], energy harvesting [75] and cognitive radio networks [74], [77]. Furthermore, beneficial coding constructions were conceived for both MDS field-based and MDS convolutional coded acyclic networks [78].

The rest of the paper is organised according to Fig. 3 as follows. We first discuss the overall architecture of NLMC systems in Section II before focusing on detailing two prominent layers, namely Network Coding 1 in Section III and Network Coding 2 in Section IV, respectively. The principles and examples of the NLMC system design are presented in Section V, before offering our design guidelines and conclusions in Section VI.

II. General architecture of the NLMC system

The general architecture of the NLMC system shown in Fig. 7 can be structured into three coding layers, namely CC, Network Coding 1 (NC1) and Network Coding 2 (NC2). In the triple-layer coding architecture, H consecutive frames of a user's information are processed in NC2 by using either the fixed mode or the rate adaptive mode, before feeding the Θ number of resultant encoded frames to NC1, as seen in Fig. 7. Details of the encoding and decoding processes at the NC2 layer are discussed in Section IV.

At the NC1 layer, the NLMC system can be activated for operating either in a centralised or in a distributed topology. If the centralised topology is opted for, the M users cooperatively transmit Mk_1 Information Frames (IFs) to the same destination node (also known as Base Station (BS)) during a transmission session, where k_1 is the number of IFs transmitted by each of the M users during the transmission session. Once the frames to be transmitted have been constructed according to the processes performed at NC1 and NC2, each frame is encoded by the channel coding scheme, as shown in Fig. 7. By contrast, the distributed topology may be used for the scenario, where M users communicating with a BS via N relay nodes, which apply network-coding

[1]We use the term 'hybrid network codes' for the network codes that do not entirely belong to either the linear network coding or non-linear network coding classes

[2]It is observed by the authors of [212] that in the area of network coding research, the gradual shift from more theoretical investigations to more practical concerns has demonstrated that network coding research has reached a level of maturity. As a result, recent research in network coding is more focused on its practical challenges, implications and implementations [212].

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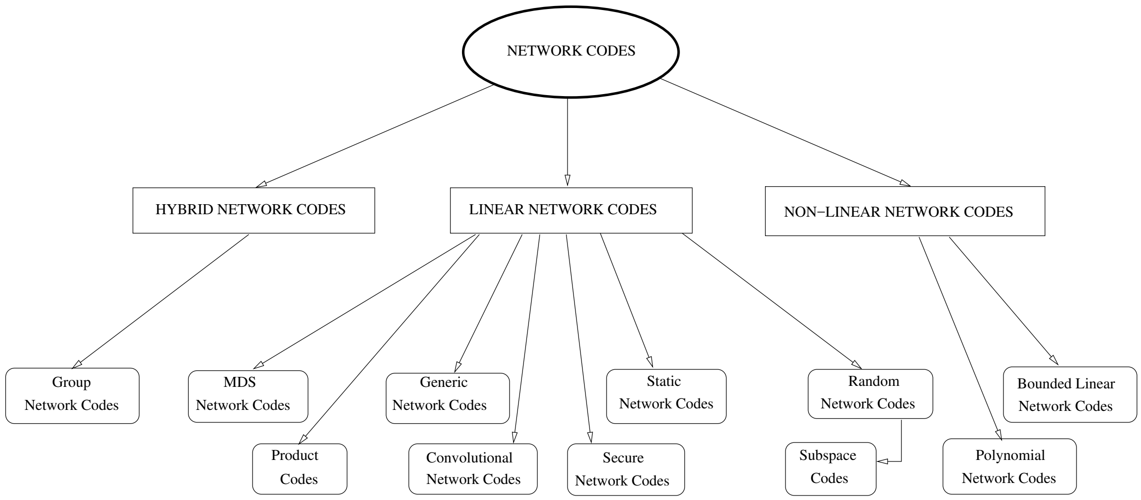

Fig. 6: A rough classification of network codes

Year	*Author*	*Milestone*
1998	Ahlswede *et al.* [214]	Seminal work on the network coding field introducing the concept of processing information frames at intermediate nodes rather than simply forwarding them.
2000	Ahlswede *et al.* [27]	Widely acknowledged concept of the network coding was formally published.
2006	Yeung and Cai [58], [59]	Existence of Maximum Distance Separable (MDS) network codes was proved for paving the way applying classic code theory to network coding.
	Ho *et al.* [60]	Random Network Coding (RNC) was introduced for non-coherent network model, which is more suitable for most practical applications.
2007	Koetter *et al.* [215], [216]	Subspace Codes (SC) was proposed as a branch of RNC family, which is capable of correcting various combinations of errors and erasures.
	Xiao *et al.* [61]	The concept of network coding was introduced in the context of relay aided communications.
2008	Zhang [217]	Concept of minimum distance in LNC was proved to be the same as that in classic coding theory, when characterising the capability in correcting/detecting errors.
2009	Ming and Skoglund [64]	A basic example on the applications of MDS network coding in multi-user relay networks was introduced.
2010	Rebelatto *et al.* [28]	Generalized Distributed Network Coding (GDNC) was introduced, which is generalised from the basic model of [64] by allowing each user to transmit multiple frames during broadcast and cooperative phases according to a transfer matrix constructed from generating matrices of RS codes.
2011	Chao *et al.* [218]	Applications of MDS network coding in multi-user relay networks was fully introduced along with analyses on Diversity Multiplexing Trade-off (DMT).
	Rebelatto *et al.* [66], [67]	Adaptive GDNC was introduced by allowing each user in the GDNC system to transmit fewer parity frames based on the feedback from transmission during the broadcast phases
2012	Rebelatto *et al.* [219]	GDNC systems was formally introduced.
	Maric *et al.* [68]	Multi-hop network coding based systems relying on an AF mechanism were studied.
	Xiao *et al.* [69]	MDS network codes were investigated in scenarios in the presenceor absence of the direct source-BS links and relying on orthogonal/non-orthogonal channels.
2013	Nguyen *et al.* [70]	GDNC was further generalised for incorporating adaptive and full diversity aspects.
	Li *et al.* [71]	Adaptive GDNC was employed for aiding successive relaying in noncoherent cooperation.
	Rayel *et al.* [72]	GDNC was investigated in the context of Nakagami channel
2014	Moritz *et al.* [73]	GDNC was employed for the uplink transmission, while energy transfer is carried out in the downlink transmission.
2015	Chun *et al.* [74]	An adaptive random network coding scheme was proposed for spectrum sharing in cognitive radio networks.
	Chen *et al.* [75]	GDNC was employed in the general context of energy harvesting
	Liang *et al.* [76]	Distributed GDNC scheme was proposed for Cooperative Cognitive Radio Networks
2016	Bordon *et al.* [77]	Energy Efficient Power Allocation aspect was investigated for Network-Coded Cooperative Cognitive Radio Network.
2017	Samadi-Khaftari *et al.* [78]	Coding constructions were conceived for both MDS field-based and for MDS convolutional code assisted acyclic networks.

TABLE II: Milestones in network coding (2000-2017) with regard to the development and applications of the Maximum Distance Separable (MDS) based network coding.

to the IFs received from the M users in order to generate PFs for transmission to the BS. Moreover, the NC1 layer can be configured for operating in various modes chosen from two groups of appropriate modes, namely using the combined modes and the single modes.

At the CC layer featured in Fig. 7, the NLMC system can be programmed for functioning in different modulation modes that are concatenated with diverse coding schemes. Then, the most appropriate coded modulation scheme can be activated for supporting the cognitive radio functionality, while the diversity between transmission frames can be improved by exploiting the most suitable sub-frame transmission mechanism. More specifically, all the links in the system are supported by near-capacity schemes that comprise a powerful channel coding scheme and a modulator [6], [8], [70], [104], [220]. The channel coding scheme is capable of providing either a fixed coding rate [70] or an adaptive coding rate [76] that can be amalgamated with either a single antenna system [70], [220] or multiple antenna system [221]. The modulator can be configured for a coherent regime [220] or a non-coherent regime [70]. For further details of how the near-capacity schemes are designed, consult [6]–[8]. For the sake of brevity, refer the interested readers to the above-mentioned references for further details relating to the near-capacity channel coding design, while in this paper, we focus our attention on characterising the NC1 and NC2 layers.

It should be noted that at the NC1, NC2 and CC layers, there are a number of operational modes that may be activated according to the specific system requirements. The CC layer is used for providing time diversity within a transmission frame, while the NC1 layer is capable of gleaning spatial diversity from all M users involved in a transmission session. When the time diversity between the different transmission sessions further improves the system performance attained, the NC2 layer may be activated. Accordingly, the modes of the layers are described in the corresponding layers presented in Section III and Section IV.

III. NETWORK CODING 1: MULTI-USER COOPERATIVE COMMUNICATION

In the Dynamic Network Codes (DNCs) scheme proposed by Xiao and Skoglund [64], each of the M users also acts as a relay for the other users. In the scheme, each user broadcasts a single IF of its own both to the BS and to the other users during the first Time Slot (TS). Then, during the 2^{nd} to the $(M)^{th}$ TS, each user transmits $(M-1)$ Parity Frames (PFs) to the BS. Each of these PFs consists of nonbinary linear combinations of the IFs that it could successfully decode.

By contrast, GDNCs adopted as conventional mode (C mode) at NC1 layer were proposed in [28], [219] by interpreting the scenario as being equivalent to that of operations of linear block codes defined over GF(q) for erasure correction. The authors of [28], [219] extended the original Dynamic Network Coding (DNC) concept by allowing each user to broadcast several (as opposed to a single) IFs of its own during the Broadcast Phase (BP), as well as to transmit several nonbinary linear combinations, which are also considered as PFs, during the Cooperative Phase (CP). A transmission session of GDNC comprises two phases, namely the BP and the CP.

A. Network Coding 1: Conventional Mode employing Generalised Dynamic-Network Codes

1) System Model: In the cooperative multiple-user system employing GDNC having M users cooperatively communicating with a common BS, a transmission session of the system is conducted in two groups of phases, the BPs and the CPs. Let us detail an example of such the GDNC system that has $M = 2$ users communicating with a BS [64]. In a transmission session, each user transmits $k_1 = 1$ IF during the BP and $k_2 = 1$ PF during the CP. The details of transmission phases are illustrated in Fig. 8 and summarised as follows

$$\begin{aligned}
&\underline{\text{Broadcast phases}}\\
&(B_1)\ \text{Broadcast phase 1 : User 1} \xrightarrow{I_1(1)} BS \text{ and User 2},\\
&(B_2)\ \text{Broadcast phase 2 : User 2} \xrightarrow{I_2(2)} BS \text{ and User 1},\\
&\underline{\text{Cooperative phases}}\\
&(C_1)\ \text{Cooperative phase 1 : User 1} \xrightarrow{\boxplus 1(1)=I_1(1)+I_2(2)} BS,\\
&(C_2)\ \text{Cooperative phase 2 : User 2} \xrightarrow{\boxplus 2(2)=I_1(1)+2I_2(2)} BS.
\end{aligned}$$

If all the frames transmitted within the session are successfully decoded, the transmission session can be equivalently represented by the matrix $\boldsymbol{G}_{2\times 4}$ [28], [219]

$$\boldsymbol{G}_{2\times 4} = \begin{bmatrix} 1 & 0 & | & 1 & 1 \\ 0 & 1 & | & 1 & 2 \end{bmatrix}, \tag{1}$$

where $\boldsymbol{G}_{2\times 4}(i,i) = 1, i = [1,2]$ represents the successful decoding of the IFs $I_i(i)$ at the BS, which was transmitted by User i during the BP B_i. Having $\boldsymbol{G}_{2\times 4}(1,3) =$ "1" or $\boldsymbol{G}_{2\times 4}(2,4) =$ "2" means that the PF transmitted by User 1 or User 2 during the CP C_1 or C_2 is successfully decoded at the BS, and the linear combining coefficient of the IF $I_1(1)$ or $I_2(2)$ in this PF has a value of "1" or "2", respectively. Note that having $\boldsymbol{G}_{2\times 4}(2,3) =$ "1" or $\boldsymbol{G}_{2\times 4}(1,4) =$ "1" indicates that IF $I_2(2)$ or $I_1(1)$ is successfully decoded by User 1 or User 2, and the PF transmitted by User 1 or User 2 during the CP C_1 or C_2 is successfully decoded at the BS, provided that the linear combining coefficient of the IF $I_1(1)$ or $I_2(2)$ in this PF has a value of "1" or "1", respectively.

To elaborate further, the system might experience an actual transmission session containing $(k_1M + k_2M) = 4$ phases depending on the success or failure of a specific transmission

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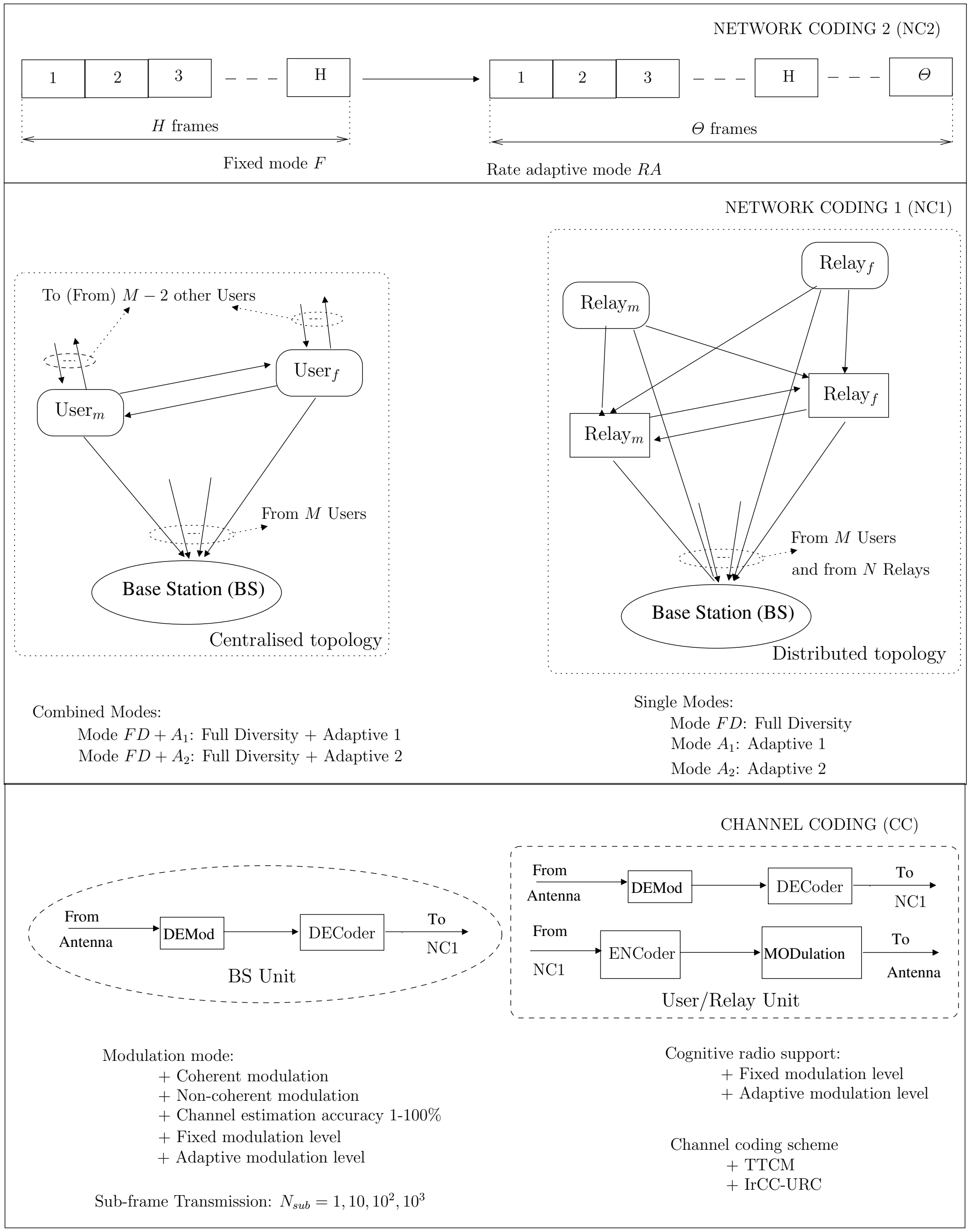

Fig. 7: The general architecture of the Generalised Near-Capacity Multi-user Network-coding system.

attempt as follows

Broadcast phases

(B_1) $\quad \boldsymbol{G}'_{2\times4}(1,3) = \boldsymbol{G}_{2\times4}(1,3),$

$[\text{User } 1 \xrightarrow{=0} BS] : \boldsymbol{G}'_{2\times4}(1,1) = 0,$

$[\text{User } 1 \xrightarrow{=1} \text{User } 2] : \boldsymbol{G}'_{2\times4}(2,4) = \boldsymbol{G}_{2\times4}(2,4),$

(B_2) $\quad \boldsymbol{G}'_{2\times4}(2,4) = \boldsymbol{G}_{2\times4}(2,4),$

$[\text{User } 2 \xrightarrow{=0} BS] : \boldsymbol{G}'_{2\times4}(2,2) = 0,$

$[\text{User } 2 \xrightarrow{=1} \text{User } 1] : \boldsymbol{G}'_{2\times4}(1,4) = \boldsymbol{G}_{2\times4}(1,4),$

Cooperative phases

(C_1) $\quad [\text{User } 1 \xrightarrow{=0} BS] : \boldsymbol{G}'_{2\times4}(i,3) = 0, i = 1,2,$

(C_2) $\quad [\text{User } 2 \xrightarrow{=0} BS] :,$

where $' \rightarrow '$ represents the transmission direction, while $' = 1'/' = 0'$ means that the frame is successfully/unsuccessfully recovered at the destination, respectively. The matrix $\boldsymbol{G}'_{2\times4}$ is defined as the corresponding 'modified' transfer matrix, where the terminology 'modified' implies that the entries of $\boldsymbol{G}'_{2\times4}$ are modified from those of the original transfer matrix $\boldsymbol{G}_{2\times4}$ of Eq. (1) according to the actual transmission session detailed in Eq. (2). As a result, $\boldsymbol{G}'_{2\times4}$ is formed as

$$\boldsymbol{G}'_{2\times4} = \left[\begin{array}{cc|cc} 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 2 \end{array} \right], \tag{2}$$

where the diagonal elements '1' at the left of Eq. (1) be-

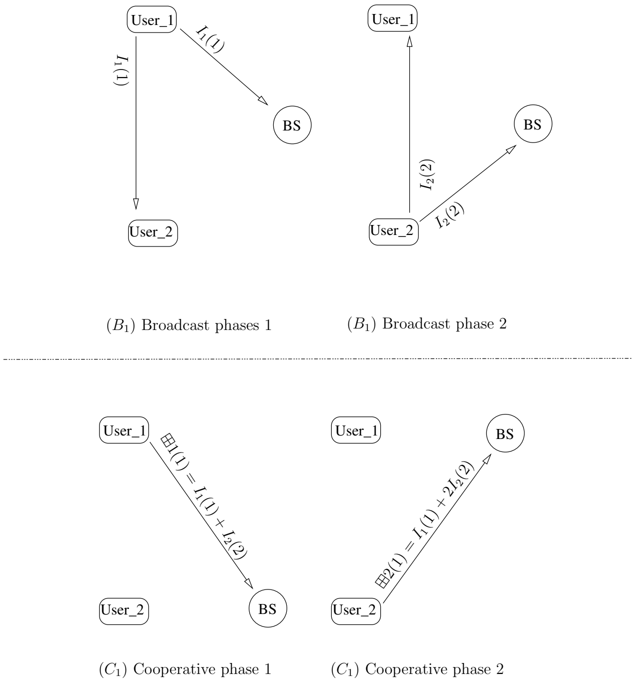

Fig. 8: The model of the system supporting $M = 2$ users, where each user transmits $k_1 = 1$ IFs and $k_2 = 1$ PFs [220].

come '0' owing to the unsuccessful [User 1 $\xrightarrow{=0}$ BS] and [User 2 $\xrightarrow{=0}$ BS] transmissions in $(2B_1)$ and $(2B_2)$. The '0' elements in the third column of Eq. (2) indicate the unsuccessful [User 1 $\xrightarrow{=0}$ BS] transmission in $(2C_1)$.

In the generalised system model, the transfer matrix $\boldsymbol{G}_{k_1M\times k_1M+k_2M}$ (or $\boldsymbol{G}$ for shorthand) comprising the identity matrix $\boldsymbol{I}_{k_1M\times k_1M}$ (or $\boldsymbol{I}$ for shorthand) and the parity matrix $\boldsymbol{P}_{k_1M\times k_2M}$ (or $\boldsymbol{P}$ for shorthand) represents a transmission session of the system, where all the frames transmitted during that session are successfully decoded [219]. In fact, there may be unsuccessful frame transmission occurring during the transmission session, then the transfer matrix is modified for reflecting the transmission session to become the modified transfer matrix $\boldsymbol{G}^{'}$. The formula representing how the $\boldsymbol{G}^{'}$ is calculated from $\boldsymbol{G}$ is detailed in [220], [222].

The decoding process is carried out at the BS by employing the modified transfer matrix $\boldsymbol{G}^{'}$. To characterize the FER-performance of the GDNC based system, a method referred to as Purely Rank-Based Method (PRBM) is used in the study presented in [28], [219]. Later, a method coined as Pragmatic Algebraic Linear Equation Method (PALEM) is proposed in [220]. The method is capable of providing more accurate FER results for the characterisation of network codes than those provided by PRBM. The PALEM facilitates the investigation of the FER-performance bounds of GDNC based systems [222], which allows to estimate FER-performance of large-scale GDNC based systems.

2) Performance Bounds and Diversity Order of the GDNC system: In the GDNC system, each of the M users broadcasts the k_1 IFs to the other $M-1$ users during BPs. Then, during CPs each of M users transmits the k_2 IFs to the BS. If all the inter-user transmissions are successful, all the PFs formed by a user are linearly independent combination of the IFs, which were successfully received during BPs. As a result, an IF is conveyed to the BS by (Mk_2+1) independent paths, which leads to the diversity order of (Mk_2+1).

By contrast, the unsuccessful inter-channel transmissions may lead to the case where some of the PFs transmitted by a user are not linearly independent combinations of the IFs. The worst case is when each of the other $(M-1)$ user is able to produce only a single linearly independent combination (PF), while the user itself is always capable of constructing k_2 linearly independent combinations. As a result of such worst case, there are $(M+k_2)$ independent paths for carrying the IF to the BS, which induces the diversity order of $(M+k_2)$.

In line with the above-mentioned analysis, it was proved in [219], [223] that the diversity order D of the system is bounded by

$$M + k_2 \leq D \leq Mk_2 + 1. \tag{3}$$

The authors of [222] formulated the diversity order D of the GDNC based system mentioned in Eq. (3) as follows

$$D = \lim_{SNR\to\infty} \frac{-\log_2 P_o}{\log_2 SNR}\ , \tag{4}$$

where SNR is the signal to noise power ratio, while P_o was estimated on the basis of the best case P_o^{Lower} and worst case P_o^{Upper} instead of using exact value of P_o. Then, by using the most influential terms of P_o^{Upper} and P_o^{Lower} instead of exact value of P_o in Eq. (4), it is observed in [222] that the upper and lower bounds of the probability P_o are in harmony with the estimated diversity order given by Eq. (3).

As a further benefit of the performance bounds, one can invoke the performance bounds derived in [222] for the sake of exploring the GDNC system's FER-performance in order to find the most appropriate network code. More specifically, it may be gleaned from the formula of P_o^{Lower} in [222] that the performance of the system approaches its lower bound more closely, when the SNR value increases. Hence, we can use the lower bound of the system performance for estimating its capacity, when large transfer matrices are employed for building the GDNC system.

For example, as seen in Fig. 9 that presents further comparison of the system detailed in [70], along with the increase of the size of the transfer matrix from $\boldsymbol{G}_{2\times4}$ to $\boldsymbol{G}_{4\times8}$, $\boldsymbol{G}_{6\times12}$, $\boldsymbol{G}_{20\times40}$, $\boldsymbol{G}_{200\times400}$, $\boldsymbol{G}_{1000\times2000}$, $\boldsymbol{G}_{10000\times20000}$ and $\boldsymbol{G}_{12000\times24000}$, the distance from the GDNC system capacity having a network coding rate of $R_{info} = 1/2$ is reduced to 1.7 dB from 24.8 dB, where a further marginal improvement is exhibited when employing a transfer matrix having a larger size than the matrix $\boldsymbol{G}_{12000\times24000}$. From another perspective, when a network code relying on a larger transfer matrix, say $\boldsymbol{G}_{12000\times24000}$ is used, a maximum improvement of approximately 44 dB may be expected for the system investigated in Fig. 9.

B. Network Coding 1: Full Diversity Mode

The Full Diversity (FD) principle is first proposed in [224] and later generalised in [70] for the NLMC system, in

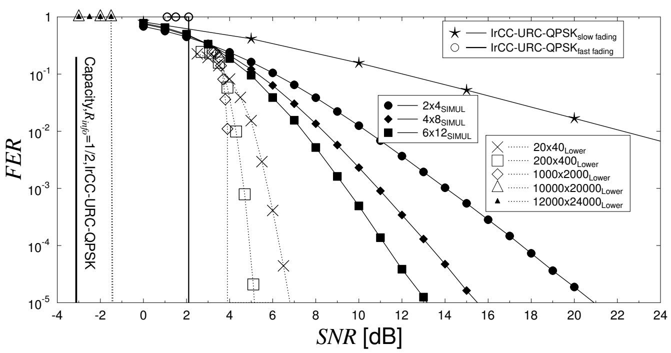

Fig. 9: The FER performance of network coding based systems having $R_{info} = 1/2$ and employing the realistic IrCC-URC-QPSK channel coding scheme [6], [70], when communicating over wireless channels influenced by both the fast Rayleigh and block Rayleigh fadings.

order to provide more diversity to the C mode described in Section III-A. In the FD mode, the NLMC system is capable of exploiting the inter-user transmissions during CPs, for improving inter-user transmissions in BPs. More specifically, if each user in the system is equipped with a network-coding decoder, which is identical to the network-coding decoder used at the BS, the user can decode all the IFs and PFs that were successfully received, in order to improve its knowledge about IFs transmitted by the other users. Then, the improved knowledge is exploited for constructing the subsequent PFs transmitted by the user. The process of decode-and-update is repeatedly kicked off, as soon as the user receives a PF transmitted by another user in the system. The decode-and-update process at a certain user is no longer required, as soon as all IFs transmitted by the other users during the BPs are comprehensively known by the user.

In the C mode, the system is potentially capable of approaching the full diversity that corresponds to the maximum diversity order of $D = Mk_2 + 1$, however this is not guaranteed in all scenarios. Thus, the FD mode is employed for broadening scenarios, where the maximum diversity order is achieved. These scenarios would emerge when a user has a full knowledge of the IFs transmitted by the other users in the system. Therefore, having a full knowledge of the IFs of all the other users is the best scenario created by the FD mode. This best scenario is equivalent to the case, where all of the inter-user transmissions carried out during the BPs are successful. If this condition holds, the system always achieves its maximum diversity order given in [224] as:

$$D_{NLMC}^{Max} = Mk_2 + 1. \quad (5)$$

Hence, the system's performance associated with the idealised simplifying assumption of having perfect inter-user channels, where the inter-user channels are error free, sets a limit for the maximum attainable diversity gain of the near-full-diversity process.

C. Network Coding 1: Adaptive Mode

1) Operating mechanism: The inter-operation of channel- and network-coding may be exploited for providing an improved performance [67]. The inter-operation advocates an adaptive mechanism, which relies on a feedback flag directly reflecting the performance of the network coding scheme. This feedback flag can be employed to control the channel coding scheme, and vice versa, the feedback flag provided by the channel coding scheme may be utilised for controlling the operation of network coding. The authors of [67] applied this adaptive flag-controlled mechanism under the idealised simplifying assumption of using an ideal/perfect channel code. The authors of [70], [76], [220] further generalised this adaptive feedback flag based solution for the NLMC system, where the adaptive mechanism can be used with the FD mode described in Section III-B, while the flag-controlled mechanism operates upon realistic near-capacity channel codes.

In the adaptive mechanism, each users transmit a changeable number of PFs, which is decided upon feedback flags sent from the BS. The feedback flags indicate successful/unsuccessful transmission of the IFs received at the BS. As a result, the multiplexing gain of NC1 is increased due to the reduction on the number of transmitted PFs. In line with [67], the authors of [70], [76], [220] assume that the BS is capable of sending back to the users a modest amount of information containing feedback flags. Accordingly, let us denote the number of PFs transmitted by User j in a transmission session by $k_{2,j}$. In order to increase the achievable multiplexing gain, the value of $k_{2,j}$ has to be adaptively adjusted for each transmission session according to two potential approaches referred to as two adaptive modes, namely (A_1) and (A_2) [67].

In the *first adaptive* (A_1) mode, the diversity gain remains unaltered, while the value of $k_{2,j}$ is adaptively adjusted based on a feedback flag, which is an acknowledgement bit sent by the BS to indicate the successful/unsuccessful reception of all the Mk_1 IFs transmitted by all the M users during their BPs. In the *second adaptive* (A_2) mode, the value of $k_{2,j}$ is adaptively adjusted upon a feedback flag, which is an acknowledgement bit sent by the BS to indicate the successful/unsuccessful reception of all the k_1 IFs transmitted by User j during his/her BPs. Hence, by the end of a transmission session, in the (A_1) mode there is a single acknowledgement bit sent by the BS, while in the (A_2) mode the BS needs to send M acknowledgement bits during a transmission session.

Accordingly, the average adaptive network code rate corresponding to the two adaptive modes, namely the A_1 mode and the A_2 mode can be calculated upon given values of k_1, k_2, M and P_e. It should be noted that P_e is the outage probability of a single link in the system, which reflects the FER-performance of the link [67]. As a result of having improved average network code rates, namely the R_{info,A_1} and the R_{info,A_2}, we accordingly have the associated average multiplexing gain defined as: $\Omega_1 = \frac{R_{info,A_1}}{R_{info}}$ and $\Omega_2 = \frac{R_{info,A_2}}{R_{info}}$, where R_{info} is the network coding rate in the C mode, which can be can be calculated by $R_{info} = \frac{k_1}{k_1+k_2}$. Moreover, it is observed in [67], [70] that the average network coding rates R_{info,A_1} and R_{info,A_2} increase when the outage probability P_e decreases. Since we have the outage probability $1 \geq P_e \geq 0$, the adaptive network coding rates can reach its maximum value, when the

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outage probability approaches zero $P_e = 0$. In other words, having the average adaptive network coding rate reached its maximum value of 1 corresponds to the scenario where PFs are no longer required to be transmitted to the BS.

The maximum value of the average multiplexing gain associated with the adaptive modes A_1 and A_2 may be characterised by the maximum value of the E_b/N_0-improvement obtained by employing the adaptive feedback-flag based mechanism, which may be formulated as

$$\begin{aligned} \varrho &= \text{Max}\left\{10\log\left(\varOmega_1\right)\right\}[\text{dB}], \\ &= \text{Max}\left\{10\log\left(\varOmega_2\right)\right\}[\text{dB}], \\ &= 10\log\left(\frac{k_1+k_2}{k_1}\right)[\text{dB}], \end{aligned} \tag{6}$$

which merely depends on the values of the number of transmitted IFs k_1 and the number of PFs k_2.

2) Adaptive Network Coding: Multiplexing Gain versus Diversity Gain: In order to feature the relationship between the multiplexing aspect and the diversity aspect of the GDNC system, which may appear when activating an individual mode or a combination of available modes in the NC1 layer, which are described separately in Section III-B and Section III-C. It should be noted that in order to have a fair comparison, the gains have to be compared by the same basis, for example SNR value of the system.

Let us recall the multiplexing gains, namely $\varOmega_1$ and $\varOmega_2$, where its maximum value is determined by Eq. (6). If the matrix $G_{2\times4}$, the matrix $G_{4\times8}$ or the matrix $G_{6\times12}$ is used at the NC1, we have $k_1 = k_2 = 1$, $k_1 = k_2 = 2$ or $k_1 = k_2 = 3$, respectively [219]. As a result of substituting the specific values of k_1 and k_2 into Eq. (6), we may obtain the maximum value of the multiplexing gain as

$$\begin{aligned} \varOmega_{1,2}^{\max} &= 10\log\left(\frac{k_1+k_2}{k_1}\right)[\text{dB}], \\ &= 3[\text{dB}]. \end{aligned} \tag{7}$$

Hence, it is expected that the multiplexing gains, namely $\varOmega_1$ and $\varOmega_2$, increasingly approach the $\varOmega_{1,2}^{\max} = 3$ dB, when increasing the SNR value used in the NLMC system employing the matrix $G_{2\times4}$, the matrix $G_{4\times8}$ or the matrix $G_{6\times12}$. Fig. 10a shows various gains affecting the performance of the system relying on the IrCC-URC-QPSK scheme when activating the A_1 mode or the A_2 mode. Both multiplexing gains, $\varOmega_1$ and $\varOmega_2$ increase along with the increase of the SNR value. The $\varOmega_{1,2}^{\max} = 3$ dB sets an upper bound for both multiplexing gains.

It is observed that the diversity gain can be represented by changes in FER-versus-SNR performance of the system, when a particular regime is employed in the system. The regime can be set by activating FD mode for approaching the system's full-diversity presented in Section III-B, or by applying the adaptive mechanism (A_1 mode or A_2 mode) described in Section III-C or by employing a combination of the adaptive mechanism and the full-diversity modes. More specifically, when the adaptive mechanism is applied to the system employing NC1, the changes in FER-performance of the system associated with a given SNR value reflects the effect of changing the number of PFs transmitted within transmission sessions on the FER-performance of the system. Hence, the attainable diversity gain can be characterised by the FER-versus-SNR performance of the system, when the adaptive mode is employed. Therefore, let us define the diversity gain $\varPhi_1$ and $\varPhi_2$ achieved in the system by applying the A_1 and A_2 mode, respectively:

$$\varPhi_1 = SNR_C - SNR_{A_1}, \tag{8}$$

$$\varPhi_2 = SNR_C - SNR_{A_2}, \tag{9}$$

where SNR_C, SNR_{A_1} and SNR_{A_2} denotes the SNR value required by the system using the C mode, A_1 mode and A_2 mode, respectively.

In the system supported by the A_1 mode, none of the PFs are transmitted, when the BS already recovered all the IFs [67], [70], [76], [220]. As a result, the FER-versus-SNR performance of the system remains unchanged at a given SNR value, when the A_1 mode is applied. Hence, the diversity gain $\varPhi_1$ corresponding to the system exploiting the A_1 mode is $\varPhi_1 = 0$, as seen in Fig. 10. Let us consider the total-gain $\varSigma_1 = \varOmega_1 + \varPhi_1$ as the sum of the diversity gain and multiplexing gain in the case of employing the A_1 mode. As a result of having a diversity gain of $\varPhi_1 = 0$ for the A_1 mode, the total-gain $\varSigma_1$ is equal to the multiplexing gain $\varOmega_1$, as also seen in Fig. 10.

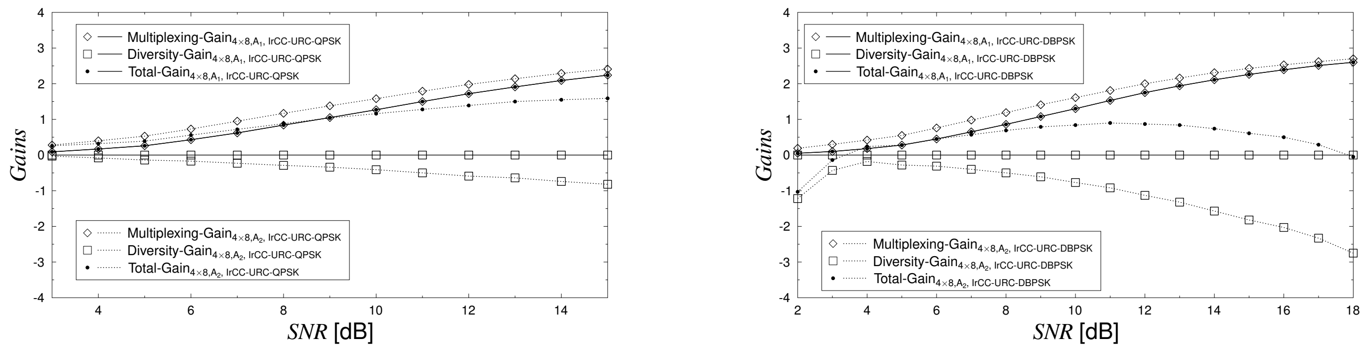
By contrast, having more levels for adjusting the number k_2 of PFs, the A_2 mode is capable of supporting the improved multiplexing gain $\varOmega_2$ seen in Fig. 10 in comparison to that associated with the A_1 mode. It is also shown by Fig. 10 that although the system supported by the A_2 mode has the higher multiplexing gain of $\varOmega_2$, the overwhelming degradation[3] of the related diversity gain $\varPhi_2$ results in an inferior total gain of $\varSigma_2 = \varOmega_2 + \varPhi_2$. Hence, it is expected that the system employing the A_1 mode outperforms the system invoking the A_2 mode.

D. Network Coding 1: Dispensing with side information

In all existing contribution on GNDN [67], [219], the BS (or destination) is assumed to have full knowledge of the side-information concerning the encoding process at the intermediate nodes. Hence, an imposed overhead containing the side information about the instantaneous formation of each PF has to be transmitted over an error-free channel or a well-protected channel to achieve error-free transmission. In this section, we introduce our approach on the so-called No-side-Information based GDNC (NI-GDNC) scheme that requires no prior knowledge of how the PFs were formed. In order to characterise the performance of the NI-GDNC based system, we compare the performance of GDNC systems in the following scenarios:

- GDNC with perfect side information (BS is aware of the formation of PFs);
- NI-GDNC without any side information at the BS;
- GDNC with different amount of imperfect side information, where the overhead is contaminated by realistic error-prone channels.

[3]The degradation in diversity gain $\varPhi_2$ is caused by introducing 0, 1 or k_2 PFs in the A_2 mode, rather than employing 0 or k_2 PFs in the A_1 mode [67].



(a) Coherent IrCC-URC-QPSK scheme [70]

(b) Non-coherent IrCC-URC-DBPSK scheme [220]

Fig. 10: The diversity-versus-multiplexing gain breakdown of the $\boldsymbol{G}_{4\times 8}$ based systems of Fig. 7 relying the NC1 and CC layers, when considering both the A_1 mode and the A_2 mode at NC1 layer and activating the IrCC-URC-QPSK [70] and IrCC-URC-DBPSK [220] at the CC layer. Both the block Rayleigh fading and the fast Rayleigh fading are considered, when a frame is transmitted in the $N_{sub} = 1$ subframe regime [6] over the wireless channel. For the sake of brevity, the SNR-performance used for characterising the diversity gains in the A_1 and A_2 modes is presented in Section III-C2.

The different-accuracy imperfect side information is reflected by the BER $Q_u = \{10^{-1} : 10^{-6}\}$ of the signalling channels that convey the side information. In the GDNC system operating in different-BER signalling channels, if the signalling channel provides reliable side information, the GDNC system is switched to the perfect-side-information mode, namely to GDNC. Otherwise a blind search algorithm S_b is activated for exhaustively searching in the predefined network coding search-space defined by the transfer matrix $\boldsymbol{G}$ used for constructing the network coding codec, in order to recover IFs transmitted by the users of the system.

To demonstrate the benefits of GDNC systems when no side information is available, we use the simplest GDNC configuration relying on the $\boldsymbol{G}_{2\times 4}$ matrix of [67], [219], [222], where a similar idealised channel coding scheme operating at the CCMC capacity is employed for the sake of comparison to existing benchmarkers [67], [219].

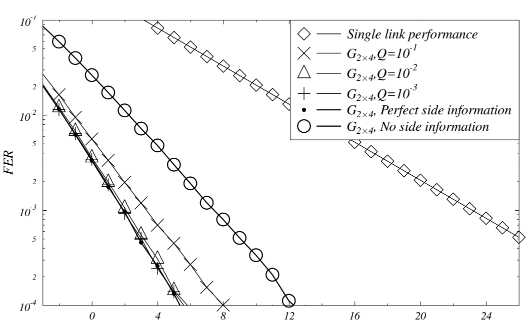


Fig. 11: Comparison of GDNC system's performance in different scenarios, namely perfect side information available at the BS, no side information available at the BS and erroneous signalling channels used for conveying the side information.

As elucidated by Fig. 11, when no side information is available at the BS, the GDNC system is still capable of providing a significant improvement of $18\ dB$ compared to that of the direct link transmission. The GNDC system requires $Q_u = 10^{-3}$ guaranteed by the signalling channels in order to support a performance similar to that exhibited in the perfect side information based scenario.

IV. NETWORK CODING 2: EXPANDING TIME DIVERSITY AMONG TRANSMISSION SESSIONS

In order to enhance the reliability of NLMC system by provisioning time diversity between transmission sessions occurring at the NC1, NC2 may be activated in order to form the triple-layer coding architecture [70]. When in use, a random network code [60] at the NC2 layer is applied across the H IFs, namely across $I_1, ...I_H$, in order to generate the Θ network-coded frames of $Z_1, ..., Z_\Theta$, where $\Theta \geq H$. It should be noted that Θ network-coded frames are then allocated into transmission sessions at the NC1. As a result, a linear combination of the H IFs having a length of N bits/frame forms a network-coded frame Z_j, $Z_j = \sum_{i=1}^{H} \alpha_{ij} I_i$, where scalars α_{ij} ($i \in [i, ..., H]$ and $j \in [1, ..., \Theta]$) may be chosen randomly and uniformly from a $GF(2^q)$. If the $GF(2^q)$ is sufficiently large, the expected number of successfully received frames required by the BS for successfully decoding the H IFs is approximately H [60], [225]. Hence, it can be deemed that the reception of H network-coded frames at the BS is sufficient for the BS to recover H corresponding IFs [60], [70]. An outage is declared, when the number of frames received at the BS is less than H, and this outage occurs with the probability:

$$P_o^{NC2} = \sum_{i=0}^{H-1} \binom{\Theta}{i} (1-P_o)^i P_o^{\Theta-i}, \qquad (10)$$

where P_o is the outage probability of the system when NC2 is not in operation. In practice, the outage probability P_o is represented by the FER-performance of the system without activation of NC2 [70].

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Accordingly, the conventional information rate of NC2 may be defined as:

$$R_{info2} \quad = \quad \frac{H}{\Theta} \, . \tag{11}$$

Bearing in mind information rate R_c, R_{info} characterizing the channel coding scheme at the CC layer and network coding scheme at the NC1 layer and the network code rate R_{info} of NC2, the aggregate code rate of the NLMC system becomes

$$R_{NLMC} \quad = \quad R_c \times R_{info} \times R_{info2} \, . \tag{12}$$

It should be noted that when the delay due to the encoding and decoding process becomes a critical criterion, the variants detailed in [65], [79], [226] may be favoured. However, our unified framework used in this paper can still be applied to cover those variants.

A. Design and Benefits of NC2

As mentioned both in [225], [227], the scalar of α_{ij} ($i \in [i, ..., H]$) used in NC2 can be chosen from random coefficients defined over $GF(2^8)$, which is sufficiently large for providing the Θ number of virtually unlimited sets of α_{ij}, where the resultant Θ sets of α_{ij} form Θ vectors that are linearly independent of each other. Accordingly, the coefficients α_{ij} may be obtained by obeying the constraints imposed by the specific structure of the Vandermonde matrix [227], [228]. Then, the coefficient matrix may be pre-generated and be stored by the users as well as by the BS for encoding and decoding. Hence, the users only need to transmit the indices of the coefficient sets employed for encoding the IFs to be transmitted to the other users or the BS, as part of the session set-up information, before transmitting actual data. As a result, no overhead pertaining to the random coefficients is transmitted during the actual communication session.

In order to simply demonstrate the benefit of the NC2 in the context of NLMC system, let us consider $\Theta = 20$, $H = 18$ that leads to the fixed coding rate $R_{info2} = N/\Theta$ according to Eq. (11). Once NC2 is activated, the time diversity across $H = 18$ frames is exploited by scattering over $\Theta = 20$ encoded frames at the output of the NC2, in order to improve the system's performance. More specifically, as shown in Fig. 12a, a significant FER versus E_b/N_0-performance improvement of approximately 34 dB can be achieved at an FER of 10^{-4} by activating the most appropriate modes of the triple-layer coding scheme presented in Fig. 7. It should be noted that the $(FD + A2)$ mode is the most appropriate mode that supports the best performance of the system used in our illustration, as readily seen in Fig. 12b. It should be noted that the appropriate mode supporting the best performance of the system may be selected by determining the operating region of the NC1 [70].

In order to study the factor deciding the operating region of the NC1 layer as well as to investigate the most appropriate value of R_{info2} associated with the highest improvement of the system's performance, let us consider the performance associated with the NC2 configurations that are reflected by different values of R_{info2}, as presented in Fig. 13. As a result of reducing the network coding rate R_{info2} at the NC2 layer, the system's performance characterised in Fig. 13 is improved. However, when the rate R_{info2} falls below the point corresponding to $R_{info2} = 10/20 = 1/2$, the performance of the system degrades, as seen in Fig. 13. This may be interpreted by assuming that the point having $R_{info2} = 10/20 = 1/2$ is a threshold, where the gain provided by activating the NC2 reaches its maximum value. Thus, reducing the coding rate achieves no further network coding gain, while the multiplexing gain represented by R_{NLMC} of Eq. (12) is reduced.

For further study, once the hardware capability of the NLMC system allows us to support a higher value of H in the NC2, we may extend our scope for finding the optimal parameters of the NC2, namely the optimal value of H and Θ, in order to attain the best possible performance of the system, provided that the parameters of the CC and NC1 layers are given. For example, it is suggested by Fig. 13 that the rate of $R_{info2} = 1/2$ is the optimal network coding rate in the scenario considered and that given $R_{info2} = 1/2$, the performance associated with higher values of the parameter Θ, say $\Theta = 200$, is better than that associated with the smaller value of $\Theta = 20$, when comparing Fig. 13a and Fig. 13b. Hence, it may be desirable to examine the optimal value of H and Θ, provided that the network coding rate $R_{info2} = 1/2$ remains unaltered.

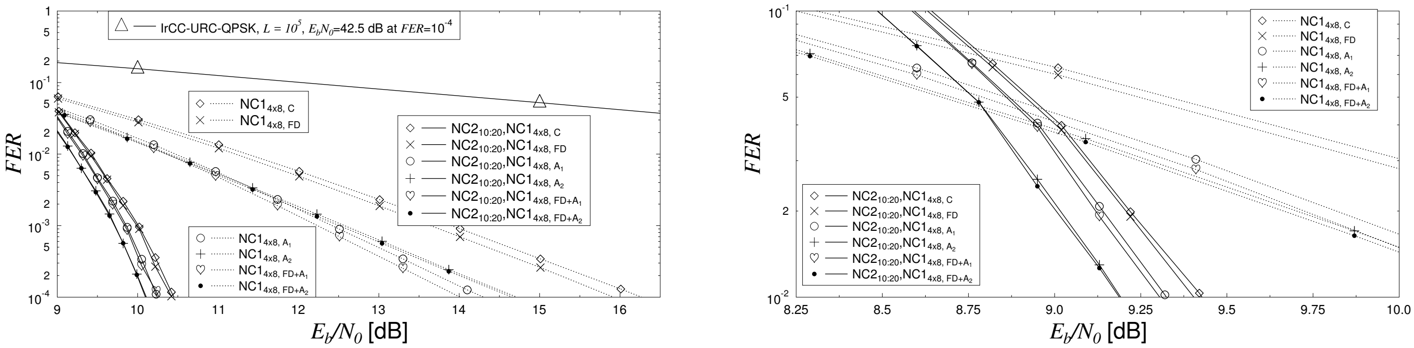
In order to address the issue regarding the optimal value of the parameter H and Θ in the NC2 layer, we activate one of the modes in the NC1 relying on the matrix $\mathbf{G}_{4\times8}$, namely mode C, and employ the IrCC-URC-QPSK scheme in the CC layer relying on the sub-frame transmission associated with $N_{sub} = 1$ [6], [70]. Then, the performance of the system is investigated for different values of Θ, namely for $\Theta = 2, 20, 2\times10^2, 2\times10^3, 2\times10^4, 2\times10^5$. Note that we fix the network coding rate to $R_{info2} = 1/2$ and assume that the parameter Θ and H are related by Eq. (11) as

$$R_{info2} \quad = \quad \frac{H}{\Theta} \, . \tag{13}$$

Thus, we have to investigate different values of Θ, in order to determine the optimal value of Θ and H associated with the best FER-versus-E_b/N_0 performance. It can be readily seen in Fig. 14 that when the value of Θ increases from $\Theta = 2$ to $\Theta = 2\times10^4$, the E_b/N_0-versus-FER performance of the system is improved. However, when the value of Θ becomes higher than $\Theta = 2\times10^4$, no further performance improvement is exhibited. Hence, we may deem $\Theta = 2\times10^4$ to be the optimal value for the system under investigation. As for the general case, the issue of finding the optimal value of Θ, provided that the other parameters of the system are given, is set aside for future work.

V. System Design: Approaching Near-capacity Performance

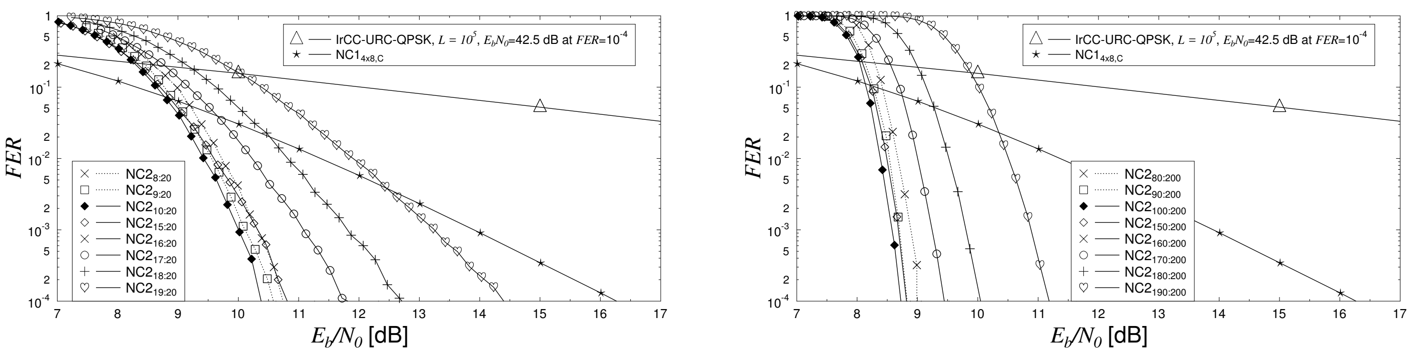
In this section, we consider our examples of the system configurations to illustrate how the DCMC capacity can be used as a benchmarker for the near-capacity performance of the system, in order to design near-capacity NLMC system. We begin performance comparison of the system supported



(a) Large range performance, namely FER values in a range from 10^{-4} to 1 and E_b/N_0 values in a range from 9 dB to 16.5 dB

(b) Performance in low E_b/N_0 region, namely FER values in a range from 10^{-2} to 10^{-1} and E_b/N_0 values in a range from 8.25 dB to 10.00 dB

Fig. 12: The benefit of employing the NC2 ($H = 10$ and $\Theta = 20$) in the NLMC system portrayed in Fig. 7, relying on the NC2, NC1 and CC layers when the matrix $\boldsymbol{G}_{4\times 8}$ is employed at the NC1 layer, while the IrCC-URC-QPSK [6], [70] activated at the CC layer for the $N_{sub} = 1$ sub-frame transmission [6] over the wireless channel influenced by both the block Rayleigh and the fast Rayleigh fadings.



(a) NC2: $\Theta = 20$

(b) NC2: $\Theta = 200$

Fig. 13: The performance of the NLMC system portrayed in Fig. 7, relying on the NC2, NC1 and CC layers, when employing different values of R_{info2} at the NC2, while the matrix $\boldsymbol{G}_{4\times 8}$ is selected for operating in the C mode at the NC1 layer, whereas the IrCC-URC-QPSK scheme [6], [70] is used for transmitting in the $N_{sub} = 1$ sub-frame regime [6] over wireless channels influenced by both fast Rayleigh and block Rayleigh fadings.

by a realistic channel coding scheme, for example the IrCC-URC-QPSK scheme detailed in [70], to that of the system relying on the ideal/perfect coding scheme operating exactly at the DCMC capacity detailed in [6], when activating various configurations at the NC1 and NC2 layer, as listed Fig. 7. Then, again the method detailed in [6] can be used as a basis for determining the capacity of the NLMC system, in order to lead to measures that might be invoked for approaching the capacity.

A. Achievable Capacity of the Ideal/Perfect Coding Scheme

Let us consider Fig. 15, where the E_b/N_0-versus-FER performance of the system employing the IrCC-URC-QPSK scheme [70] is plotted along with that of the system relying on the ideal/perfect channel coding scheme operating at the DCMC capacity [6]. At the NC1 layer of Fig. 7, all the available modes, namely the C, A_1, A_2, $FD + A_1$ and $FD + A_2$ modes, are investigated, while the network coding rate $R_{info2} = 1/2$ is set at the NC2 layer of Fig. 7. It can be seen in Fig. 15 that in all the studied cases, the performance curves associated with the IrCC-URC-QPSK scheme are approximately 1.0 dB apart from their corresponding performance curve supported by the ideal/perfect coding scheme at $FER = 10^{-4}$. In other words, the FER-performance of the NLMC system employing the IrCC-URC-QPSK scheme is approximately 1.0 dB within its capacity, which is the performance of the NLMC system assumingly relying on the ideal/perfect coding scheme operating at the DCMC capacity.

B. Approaching the NLMC capacity

Let us continue by employing the approach detailed in [6] for determining the NLMC system's capacity. Accordingly, the

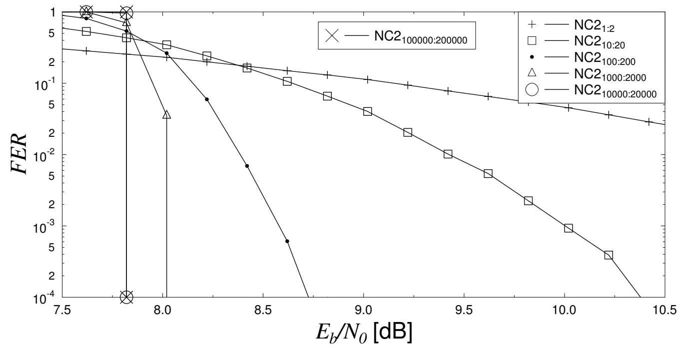


Fig. 14: The performance of the NLMC system portrayed in Fig. 7, relying on the NC2, NC1 and CC layers, corresponding to different values of Θ at the NC2 layer, namely $\Theta = 2, 20, 2 \times 10^2, 2 \times 10^3, 2 \times 10^4, 2 \times 10^5$, when the matrix $\mathbf{G}_{4\times 8}$ along with the C mode is used at the NC1, while the IrCC-URC-QPSK [6], [70] is employed at the CC layer for supporting the $N_{sub} = 1$ sub-frame [6] transmission over wireless channels influenced by both fast Rayleigh and block Rayleigh fadings.

Parameters	CC layer	
	Coherent	**Non-coherent**
R[BPS]	1.0(QPSK)	1.0(DQPSK)
R_c	0.5	0.5
N_{sub} [bit]	$1, 10, 10^2, 10^3$	$1, 10, 10^2, 10^3$
Parameters	**NC1 layer**	
Mode	C, FD, A_1, A_2, $FD + A_1$, $FD + A_2$	
$\boldsymbol{G}$	$\boldsymbol{G}_{2\times 4}$, $\boldsymbol{G}_{4\times 8}$, $\boldsymbol{G}_{6\times 12}$	
M [user]	2	
k_1 [frame]	1($\boldsymbol{G}_{2\times 4}$), 2 ($\boldsymbol{G}_{4\times 8}$), 3 ($\boldsymbol{G}_{6\times 12}$)	
k_2 [frame]	1($\boldsymbol{G}_{2\times 4}$), 2 ($\boldsymbol{G}_{4\times 8}$), 3 ($\boldsymbol{G}_{6\times 12}$)	
R_{info}	0.5	
D_{NLMC}	$D_{2\times 4} = 3$, $4 \leq D_{4\times 8} \leq 5$, $5 \leq D_{6\times 12} \leq 7$	
Parameters	**NC2 layer**	
H	10	
Θ	20	
R_{info2}	1/2	

TABLE III: Parameters for an example of the NLMC system portrayed in Fig. 7.

capacity of the NLMC based systems can be characterised by the transmission links capacity spamming from a certain user supported by the system to the BS. This link in the NLMC based systems may be viewed as an equivalent single-link model, where the equivalent transmission rate R_e of the user-to-BS link in the NLMC system can be formulated as

$$R_e = R_{info2} R_{info} R \ , \tag{14}$$

where R is the information rate of a single link in the NLMC system, while the network-coding scheme's rate R_{info} of the NC1 and the network-coding arrangement's rate R_{info2} of the NC2 are described in TABLE III. Then, the equivalent transmission rate R_e of Eq. (14) may be used for determining the capacity of the channel in the case of the DCMC capacity [70] and D-DCMC capacity [220], respectively.

Let us invoke the numerical example in TABLE III, in order to illustrate the method employed for determining the capacity of the NLMC system. Accordingly, the network-coding's information rate of NC1 is $R_{info} = 0.5$. This system employs a channel coding scheme characterised by an information rate of $R = 0.5$ and by a coding rate of $R_c = 0.5$. The configuration of the system in this example results in the number of modulated bits expressed as follows:

$$\mu \ = \ \frac{R}{R_c} = \frac{1.0}{0.5} = 2 \ . \tag{15}$$

Having μ =2 BPS means that the coherent (non-coherent) modulation scheme of QPSK (DQPSK) may be employed at the CC layer. Similar to the method invoked in [6] for determining the receive SNR value (SNR_r) corresponding to a given throughput R, which is also considered as the information rate in this context, the capacity of the above-mentioned NLMC system may be equivalently determined by identifying the corresponding value of SNR_r.

For the convenience of presentation, we define $SNR_e|_{R_e}$ as the equivalent SNR_r value corresponding to a given throughput of R_e. According to Eq. (14), the value of $R_e = 0.25$ in the numerical example can be determined by using $R_{info} = 0.5$,$R_{info2} = 0.5$ and $R = 1.0$ given in TABLE III. Then, the SNR value can be determined based on the DCMC capacity curve $SNR_e|_{R_e} = -6.9$ dB [70] or on the D-DCMC capacity curve $SNR_e|_{R_e} = -2.73$ [220]. These $SNR_e|_{R_e}$ values can be benchmarked as the achievable capacity of the system in the configurations considered.

It should be noted that the value of the system's capacity is determined on an SNR basis. By contrast, when considering it on an E_b/N_0 basis, the equivalent coding rate $R_e = 0.25$ must be taken into account, in order to infer to the corresponding equivalent E_b/N_0 value in ratio as

$$E_b/N_0^R|_{R_e} \ = \ \frac{SNR_e^R|_{R_e}}{R_e}, \tag{16}$$

which leads to the corresponding $E_b/N_0^R|_{R_e} = -0.88$ dB in the DCMC scenario $E_b/N_0|_{R_e} = 3.29$ dB in the D-DCMC scenario.

Having calculated the capacity of the NLMC system, we can now proceed to evaluate the distance between the FER-performance curve of a NLMC system and its capacity. It is worth noting that the distance must be measured at a vanishingly low value of FER, e.g. an $FER = 10^{-4}$. For example, Fig. 16 characterises the distance between the system's capacity and the E_b/N_0-versus-FER performance of the system employing $R_{info2} = 1/2$ at the NC2 and invoking the matrix $\boldsymbol{G}_{6\times 12}$ at the NC1 activating the C as well as the FD modes and relying on the IrCC-URC-QPSK scheme at the CC layer supported by $N_{sub} = 1$ frame transmission. Note that the value of $E_b/N_0 = -0.88$ dB is the system's E_b/N_0 limit. Accordingly, a relatively large gap of approximately 11 dB is exhibited at an $FER = 10^{-4}$. This leads to a question regarding which particular solution may be employed for reducing the 11 dB-gap.

In order to address the above-mentioned issue, let us recall the NLMC system's architecture presented in Fig. 7, which comprise three layers, namely CC, NC1 and NC2 layers. A

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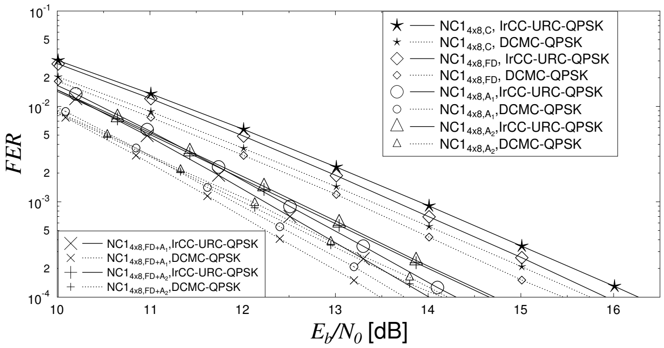
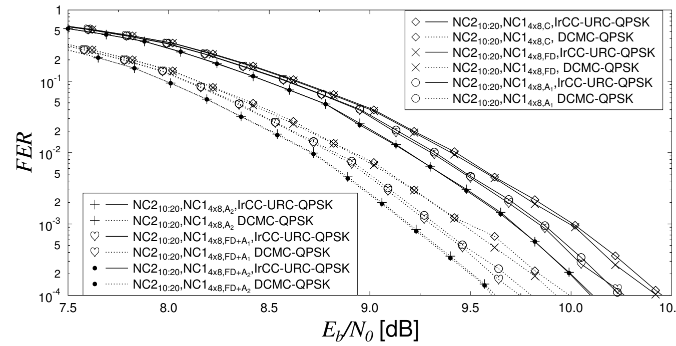


(a) Two layer architecture



(b) Three layer architecture

Fig. 15: The performance of the NLMC systems portrayed in Fig. 7 comprising the NC2, NC1 and CC layers, when comparing the two scenarios at the CC layer, namely that employing the coding IrCC-URC-URC-QPSK scheme [70] and that employing the corresponding ideal/perfect coding scheme operating at the DCMC capacity [6]. The performance is recorded in various modes of the NC1 relying on the matrix $\boldsymbol{G}_{4\times8}$, namely the C , A_1, A_2, $FD + A_1$ and $FD + A_2$ modes, while the R_{info2} at the NC2 is fixed at the optimal value of $R_{info2} = 1/2$, as determined in Section IV-A. A transmission frame is transmitted in the $N_{sub} = 1$ subframe regime [6] over the wireless channel.

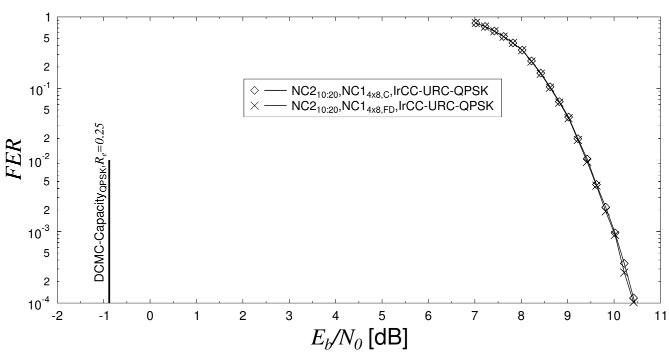


Fig. 16: The E_b/N_0-versus-FER performance of the NLMC system portrayed in Fig. 7, which comprises the NC2, NC1 and CC layers and has all parameters listed in TABLE III. The system employs $R_{info2} = 1/2$ at the NC2, invokes the $\boldsymbol{G}_{6\times12}$ matrix at the NC1 layer operating in the C and FD modes and relies on the IrCC-URC-QPSK scheme at the CC layer supported by $N_{sub} = 1$ frame transmission.

straightforward approach is to optimise each individual layer in a scenario, when the parameters of the other layers are given. More specifically:

- At the CC: The employment of sub-frames and the near-capacity coding design can be utilised for improving the system's performance;
- At the NC1: Selecting the appropriate transfer matrices, as suggested in Section III-A2, has the potential to enhance the system's performance. Additionally, activating a suitable mode of the available ones, namely of the C, FD, A_1, A_2, $FD{+}A_1$ and $FD{+}A_2$ modes, may improve the system's performance;
- At the NC2: Applying the optimal network coding rate R_{info2} can help improve the system's performance.

Hence, in the following sections, the above-mentioned optimization issues at each layer are discussed in detail.

C. Solutions at Channel Coding Layer

Let us continue to employ the IrCC-URC-QPSK scheme [6], [70] to demonstrate the benefits of the sub-frame transmission regime at the CC depicted in Fig. 7. As a remedy, the sub-frame transmission regime detailed in [6] may be invoked at the CC layer for improving the system's performance. It can be seen in Fig. 17 that the higher the number of sub-frames (N_{sub}) per transmission frame, the better the system's performance becomes. Particularly, if the system is designed to allow a transmission frame partitioned into $N_{sub} \geq 10^4$ sub-frames, the performance of the system supported by the IrCC-URC-QPSK scheme is capable of operating at a mere 0.5 dB from the corresponding DCMC capacity. It should be emphasised that when N_{sub} is higher than $N_{sub} = 10^4$, no further improvements are observed. It may be further inferred that once the system is permitted to partition a transmission frame into $N_{sub} = 10^4$ sub-frames, there is no need for employing the NC1 and NC2. If the NC1 and NC2 are still activated, the performance of the system would be degraded. This is because the FER-versus-SNR performance is no longer improved, but the multiplexing gain is reduced. However, in order to make the system capable of automatically adjusting its operational mode, the adaptive modes at both the NC1 and NC2 have to be activated. We will further discuss this issue later in Section V-D and Section V-E

Furthermore, in order to approach the near-instantaneous channel capacity that varies according to the status of each transmission link in the NLMC systems, the most appropriate adaptive modulation regime has to be applied during each transmission. Hence, the CC layer of the NLMC system of Fig. 7 can be designed for having a beneficial BER/FER-performance improvement over a fixed bandwidth. Alterna-

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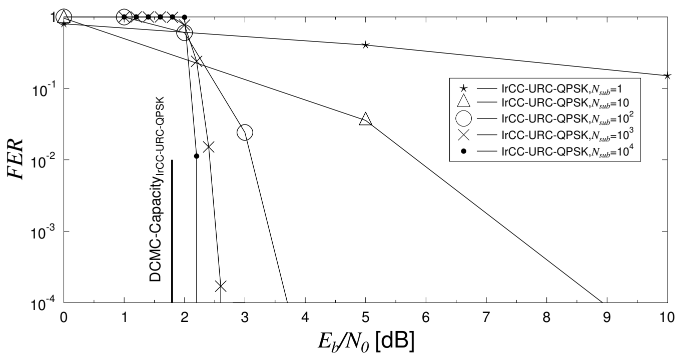


Fig. 17: The benefit of employing different the sub-frames, namely $N_{sub} = 1, 10, 10^2, 10^3, 10^4$, in performance of the IrCC-URC-QPSK scheme [6], [70], when communicating over a wireless channel influenced by both the fast Rayleigh and block Rayleigh fadings.

tively, it can be used for achieving an improved throughput for a given BER/FER performance, or for reducing the usage of the bandwidth while maintaining the required target throughput and BER/FER performance [76].

D. Solutions at the Network Coding 1 Layer

As discussed in Section V-C, there is no need to employ the NC1, when the number of sub-frames used for conveying a transmission frame becomes as high as $N_{sub} = 10^4$. However, invoking a large number of sub-frames N_{sub} may result in an unaffordable delay incurred by a user. For example, a frame in the Long Term Evolution-Advanced (LTE-Advanced) standard is of 10ms duration [229], [230]. Let us consider a scenario, in which the number of subframes is set to $N_{sub} = 10^4$ at the CC layer for transmitting a single transmission frame, while the fading coefficients remain constant during the time period of a frame length and vary independently frame by frame. In order to have a beneficial time diversity, each of the 10^4 sub-frames must be mapped to a single LTE-Advanced frame having a length of 10ms [229], [230]. In other words, 10^4 LTE-Advanced frames are used for conveying a single transmission frame, which is divided into $N_{sub} = 10^4$ sub-frames. Consequently, a transmission frame incurs a delay of $10^4 \times$ 10ms=100s, which is too long for interactive or delay-sensitive applications. Hence, let us now consider a scenario employing $N_{sub} = 10$ sub-frames per transmission frame, which leads to a moderate delay of $10 \times$ 10ms=100ms. It should be noted that the employment of network coding can also lead to an additional delay, which is as much as k_1 frame lengths. For example, if the matrix $\boldsymbol{G}_{6\times12}$ is employed at the NC1, the delay becomes $k_1 = 3$ times of the delay for a transmission frame, which is equal to $3 \times 100 = 300$ms.

Having opted for $N_{sub} = 10$, let us now investigate the benefit of employing the NC1. As seen in Fig. 18, the network coding significantly improves the attainable system performance. More specifically, the more powerful the network coding, the better performance in comparison to that of the system relying solely on sub-frame transmission, as seen in Fig. 18b. At an $FER = 10^{-4}$, the distance to the E_b/N_0 value corresponding to the system's capacity having $R_e = 0.5$ from the performance curve of the system employing the $\boldsymbol{G}_{4\times8}$ and $\boldsymbol{G}_{6\times12}$ matrices is as low as 2.0 dB and 2.7 dB, respectively, as seen in Fig. 18b. By contrast, that of the system solely supported by the $N_{sub} = 10$-based transmission regime is approximately 7 dB, as seen in Fig. 17. Hence, a gain of (7-2.0=5 dB) and (7-2.7=4.3 dB) may be achieved by employing the $\boldsymbol{G}_{4\times8}$ and $\boldsymbol{G}_{6\times12}$ matrices at the NC1 layer, respectively. Note that Fig. 18a characterises the SNR-versus-FER performance of the system relying on the $\boldsymbol{G}_{4\times8}$ and $\boldsymbol{G}_{6\times12}$ matrices at the NC1 layer operating in the FD, $FD + A_1$ and $FD + A_2$ modes of Fig. 7.

It should be noted that when the A_1 and A_2 modes are activated at the NC1 layer of Fig. 7, the performance of the system may be improved beyond the SNR value associated with the capacity having $R_e = 0.25$ and approaches that associated with the capacity having $R_e = 0.5$, as seen in Fig. 18b. This can be interpreted by recalling Eq. (14), where we can see that once the adaptive mechanism is employed, the coding rate R_{info} becomes $R_{info,A}$. Accordingly, when a sufficiently high E_b/N_0 value is encountered, the value of $R_{info,A}$ may approach its maximum of $R_{info,A} = 1$. As a result, the maximum value of R_e can be calculated as

$$R_{e,max} = \underbrace{\text{Max}\{R_{info,A}\}}_{=1} R = R \ . \qquad (17)$$

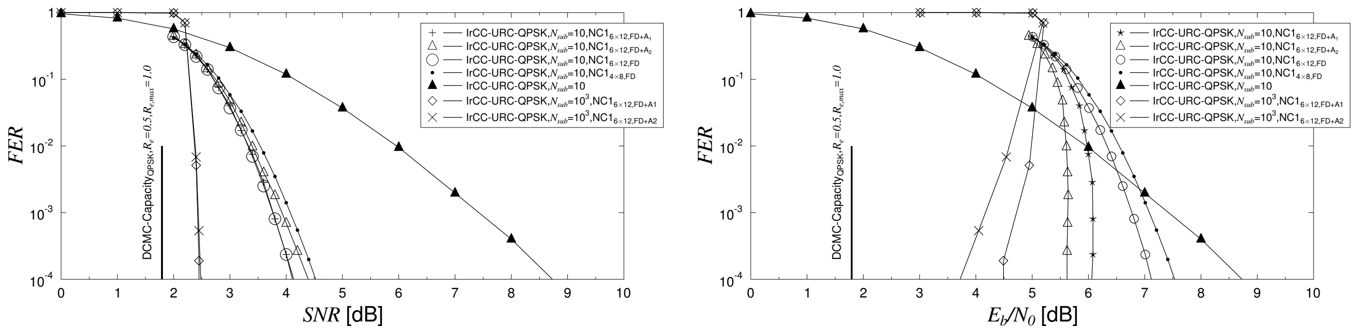
This leads to obtaining the corresponding $E_b/N_0|_{R_e,max} = 1.78$ dB.

Moreover, as a result of having an increased adaptive network coding rate $R_{info,A}$ upon increasing the transmit power, the system experiences an increased multiplexing gain. Note that the multiplexing gain has no effect on the FER-versus-SNR performance of the system, as seen in Fig. 18a. However, a substantially increased multiplexing gain ultimately leads to a considerably improved FER-versus-E_b/N_0 performance, as seen in Fig. 18b, since the beneficial multiplexing gain increase outweighs the detrimental SNR increase. As a result, reduced E_b/N_0 values might actually be associated with a fixed or even increased SNR value owing to the changes in the coding rate, which potentially allows the system to provide an improved FER-versus-E_b/N_0 performance.

E. Solutions at the Network Coding 2 Layer

As demonstrated in Section IV-A, the NC2 layer of Fig. 7 has the potential of further improving the system performance in some scenarios. In a delay-tolerant system that allows us to have a delay as high as N frame durations, NC2 is capable of approaching the achievable capacity determined in Section V-A.

Let us illustrate the above-mentioned issue by considering the NLMC system of Fig. 7 relying on the IrCC-URC-QPSK scheme [6], [70] and on the basis of $N_{sub} = 10$ sub-frame transmission determined in Section V-C, while the $\boldsymbol{G}_{6\times12}$ matrix is employed at the NC1, where the $FD + A_1$ and $FD + A_2$ modes at the CC layer of Fig. 7 may be used for



(a) SNR-versus-FER performance

(b) E_b/N_0-versus-FER performance

Fig. 18: The benefit of employing the NC1 in the NLMC system pictured in Fig. 7. The system consists of the NC1 and CC layers having all the parameters listed in TABLE III, where the $\mathbf{G}_{4\times8}$ and $\mathbf{G}_{6\times12}$ matrices are employed at the NC1 layer, while the IrCC-URC-QPSK scheme is activated at the CC layer for supporting the $N_{sub} = 10, 10^3$ sub-frame transmission regimes over wireless channels influenced by both the fast Rayleigh and block Rayleigh fadings.

the sake of supporting the best attainable performance. Then, we investigate the benefit of employing the NC2 for the sake of approaching the capacity of the NLMC system, which is characterised by parameters listed in TABLE IV.

Parameters	CC layer	
	Coherent	
R[BPS]	1.0(QPSK)	
R_c	0.5	
N [bit]	10^6	
N_{sub} [bit]	10	
Parameters	**NC1 layer**	
Mode	FD, $FD + A_1$, $FD + A_2$	
G	$\boldsymbol{G}_{2\times4}$, $\boldsymbol{G}_{4\times8}$, $\boldsymbol{G}_{6\times12}$	
M [user]	2	
k_1 [frame]	3($\boldsymbol{G}_{6\times12}$)	
k_2 [frame]	3($\boldsymbol{G}_{6\times12}$)	
R_{info}	0.5	
D_{NLMC}	$5 \leq D_{6\times12} \leq 7$	
Parameters	**NC2 layer**	
H	10	
Θ	20	
R_{info2}	1/2	
Mode	*Adaptive* (*Fixed*)	

TABLE IV: Parameters for an example of a NLMC system used for illustrating the benefit of NC2.

It should be noted that the NC2 layer in Fig. 7 is capable of operating in two modes. More specifically:

- The *Fixed* mode is configured for having a fixed rate for the network codec at the NC2 layer. In other words, in the fixed mode, we always have $R_{info2} = H/\Theta$, which is equal to $R_{info2} = 1/2$, as listed in TABLE IV.
- The *Rate adaptive* mode may be activated, when the system can afford the delay of acquiring the feed-back information acknowledging the number of frames that are correctly recovered at the BS. Upon receiving the feed-back information from the BS, the users supported by the system may decide to refrain from transmitting the rest of the Θ encoded frames. Hence, the adaptive rate at the NC2 may be expressed by:

$$R_{info2,A} = \frac{\Theta}{E[\text{Number of frames transmitted}]}. \quad (18)$$

Hence, in the high SNR region, we may have $\text{Max}\{R_{info2,A}\} = 1$.

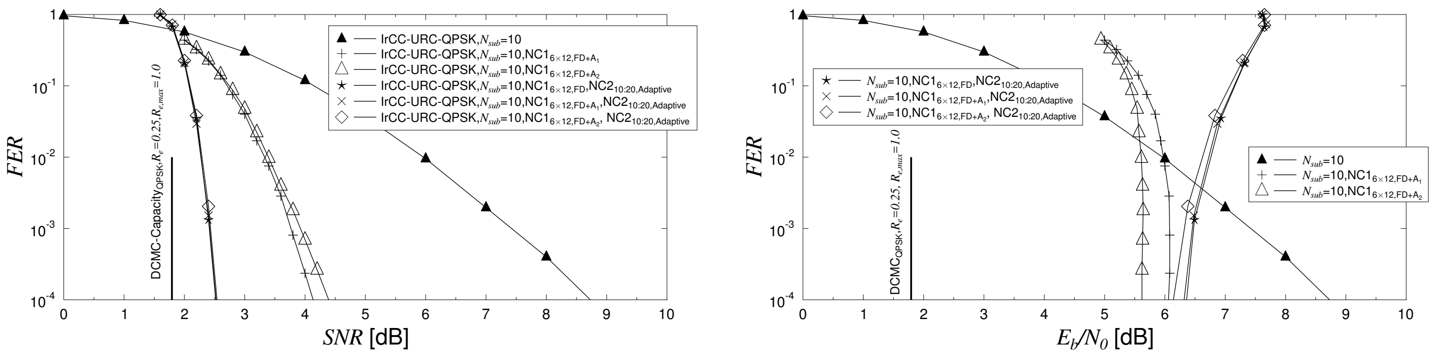
As seen in Fig. 19, when the adaptive mode is activated at NC2, the performance of the system relying on the $G_{6\times12}$ matrix at the NC1 operating in the C mode tends to approach its capacity within a distance of 1.5 dB at an $FER = 10^{-4}$. If we activate the adaptive mode at both the NC1 and NC2, namely the $FD + A_1$ and $FD + A_2$ modes at the NC1 layer and the adaptive mode at the NC2 layer, it is expected that the performance curves closely approach their corresponding capacity, which is the one associated with the $R_e = 0.5$, as seen in Fig. 19b. However, there is a distance of approximately 4.4 dB seen in Fig. 19b, when we compare the capacity associated with $R_e = 0.5$ and the performance curve of the system employing the NC1 activating the $FD + A_1$ mode and the NC2 operating in the adaptive mode. We set aside for future study the issue of optimising the parameters in order to match the two adaptive modes at both the NC1 and NC2.

It can be seen in Fig. 19b that the increased aggregate multiplexing gain of both NC1 and NC2 requires reduced E_b/N_0 values for maintaining a fixed FER value. Again, this is due to the fact that the beneficial effect of the improved multiplexing gain outweighs the detrimental effect of requiring an increased SNR value. It should be noted that the increased multiplexing gain has no impact on the FER-versus-SNR performance, where the effect of the adaptive mechanism employed at NC1 is excluded, as seen in Fig. 19a.

VI. Design Guidelines and Conclusions

To summarise, the design process of the NLMC may obey the following phases.

Phase 1 is used for interpreting the details of the design requirements, which may encompass two groups of parameters. The first group contains parameters characterising the NLMC



(a) SNR-versus-FER performance

(b) E_b/N_0-versus-FER performance

Fig. 19: The benefit of employing the NC2 in the NLMC system pictured in Fig. 7. The system comprises NC2, NC1 and CC layers having all the parameter listed in TABLE IV, where $H = 10$ and $\Theta = 20$ are employed at the NC2 layer operating in both the fixed and adaptive modes, while the $\mathbf{G}_{4\times8}$ and $\mathbf{G}_{6\times12}$ matrices are employed at the NC1 layer, whereas the IrCC-URC-QPSK scheme is activated at the CC layer for supporting the $N_{sub} = 10$ sub-frame transmission regime over wireless channels influenced by both the fast Rayleigh and block Rayleigh fadings.

system as a whole, including the number of users and their configurations, the number of relays and their configurations, as well as the BER/FER target performance, the tolerable delay, the affordable complexity, etc. The configuration of the users or relays determines the transmission modes as well as the corresponding maximum/minimum code rates (throughput) in the NC2, NC1 and CC layers of the NLMC system. The second group comprises parameters that can be used for defining requirements of a single link's transmissions in the NLMC system, hence they are mainly related to the CC layers, namely to the BER or FER performance, to the available coded modulation schemes, the available transmission modes, etc.

In phase 2, we need to construct the overall system architecture from the first group of parameter as well as to determine the system's configuration based on the constraints and requirements given. Then, we can quantify the equivalent capacity of the NLMC system, as detailed in Section V-A and exemplified in Section V-B. Accordingly, the corresponding capacity is employed as a reference point for carrying out the three layer design, as demonstrated in Section V-C, Section V-D and Section V-E.

In phase 3, the layer-design results are further calibrated for matching to the stipulated design requirements on the system's overall performance in order to conceive various operating regimes for the LMNC system.

In a nutshell, we have portrayed the road map leading to the formation NLMC systems relying on multiple layers, namely CC layer, NC1 layer and NC2. The techniques proposed for these layers have been analysed with the objective of facilitating near-capacity cooperative and cognitive communications.

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	LIST of ACRONYMS and SYMBOLS
xPSK	x level Phase Shift Keying
ADNC	Adaptive Dynamic Network Coding
AF	Amplify-and-Forward
ATTCM	Adaptive Trellis Turbo Coded Modulation
BER	Bit Error Ratio
BP	Broadcast Phase
BPSK	Binary Phase Shift Keying
BS	Base Station
CC	Channel Coding
CCR	Cooperative Cognitive Radio
CP	Cooperative Phase
CR	Cognitive Radio
CU	Cognitive User
DF	Decode-and-Forward
FER	Frame Error Ratio
FEC	Forward Error Correction
GDNC	Generalized Distributed Network Coding
GNC	Generic Network Codes
HNC	Hybrid Network Codes
IF	Information Frame
IrCC-URC-QPSK	Irregular Convolutional Coded Unity Rate Coded Quaradture Phase Shift Keying
IDNC	Instantly Decodable Network Coding
LNC	Linear Network Codes
LDPC	Low Density Parity Check
NLMC	Large-scale Near-capacity Multi-user Cooperative communications
MAC	Medium Access Control
MDS	Maximum Distance Separable
MIMO	Multiple Input Multiple Output
NC1	Network Coding 1
NC2	Network Coding 2
NI-GDNC	No-side-Information GDNC
NLNC	Non-linear Network Codes
PALEM	Pragmatic Algebraic Linear Equation Method
PC	Product Codes
PF	Parity Frame
PHY	Physical Layer
PRBM	Purely Rank-Based Method
PU	Primary User
Q^2PSK	Quadrature-Quadrature Phase-Shift Keying
QAM	Quadrature Amplitude Modulation
RDRPR	Reduced-Distance-Related-Pathloss-Reduction
RNC	Random Network Coding
RNC	Random Network Codes
RN	Relay Node
SN	Source Node
SNC	Static Network Codes
SNC	Secure Network Codes
SP	Set Partition
STBC	Space Time Block Code
STC	Space Time Coding
STTC	Space Time Trellis Code
TCM	Turbo Coded Modulation
TS	Time Slot
M	Number of users
BPS	Number of bits per symbol
k_1	Number of information frames transmitted by a user
k_2	Number of parity frames transmitted by a user/relay
C	Conventional mode at the NC1 layer
FD	Full diversity mode at the NC1 layer
A_1	Adaptive mode 1 at the NC1 layer
A_2	Adaptive mode 2 at the NC1 layer
$G_{a\times b}$	Transfer matrix
$G^{'}_{a\times b}$	Modified transfer matrix
D	Diversity order
R_{info}	Network coding rate at NC1
R_{info2}	Network coding rate at NC2
Ω	Multiplexing gain

LIST of ACRONYMS and SYMBOLS	
Φ	Diversity gain
Q_u	Quality of the channel conveying the side information
P_o	Outage probability
d_{sr}	Distance from the source node to the relay node
d_{sd}	Distance from the source node to the destination node
d_{rd}	Distance from the relay node to the destination node
G_{xx}	Reduced-Distance-Related-Pathloss-Reduction (or Geographical gain)
R_{tran}	Effective throughput of an adaptive transmission link
γ_i	Switching threshold
$ADNC-M1$	Adaptive mode 1 at the NC1 layer in the cognitive scenario
$ADNC-M2$	Adaptive mode 2 at the NC1 layer in the cognitive scenario
E_b/N_0	Power per transmitted bit
N_{sub}	Number of sub-frames per transmission frame

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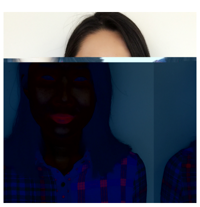

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