Distributed Joint Source-Channel Coding-Based Adaptive Dynamic Network Coding

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ABSTRACT Distributed Source Coding (DSC) schemes rely on separate encoding but joint decoding of statistically dependent sources, which exhibit correlation. More specifically, Distributed Joint Source-Channel coding (DJSC) is associated with the scenario, where the correlated source signals are transmitted through a noisy channel. On one hand, employing DSC or DJSC schemes exploits the existing correlation between sensors resulting in minimising the transmission energy required by the sources, while maintaining reliable communication. On the other hand, Network Coding (NC) is an efficient data transport technique leveraging network efficiency, by allowing Relay Nodes (RNs) in a communication network to combine multiple data packets received via the incoming links before transmitting them to the Destination Node (DN). In this paper, the bandwidth-efficient Distributed Joint Turbo Trellis-Coded Modulation (DJTTCM) aided by both Dynamic Network Coding (DNC) and Adaptive DNC (ADNC)-based cooperative transmission schemes are proposed. Both systems are proposed for supporting correlated source transmissions over hostile channels experiencing both small-scale and large-scale fading in which the RNs dynamically transmit its non-binary linear combinations to the DN. A substantial gain of 19.5 dB was attained at a correlation coefficient of $\rho = 0.8$ over its counterpart dispensing with NC.

INDEX TERMS Distributed source coding, distributed joint source-channel coding, dynamic network coding, Slepian-wolf coding, network coding, joint channel-coding and network-coding, joint channel-coding and network-coding.

LIST OF ABBREVIATIONS

| ADNC  | Adaptive Dynamic Network Coding |
|-------|----------------------------------|
| BER   | Bit Error Ratio                  |
| BP    | Broadcast Phase                  |
| CP    | Cooperative Phase                |
| CSI   | Channel State Information        |
| DJSC  | Distributed Joint Source-Channel coding |
| DJSCN | Distributed Joint Source-Channel coding-aided Network-coding |
| DJTTCM| Distributed Joint Turbo Trellis-Coded Modulation |
| DN    | Destination Node                 |
| DNC   | Dynamic Network Coding           |
| DSC   | Distributed Source Coding        |
| FEC   | Forward Error Correction         |
| FER   | Frame Error Ratio                |
| GF    | Galois Fields                    |
| IFs   | Information Frames               |
| JCN   | Joint Channel-coding and Network-coding |
| MARCs | Multiple Access Relay Channels   |
| MDS   | Maximum Distance Separable       |
| ML    | Maximum Likelihood               |
| MUD   | Multi-User Detector              |
| NC    | Network Coding                   |
| PFs   | Parity Frames                    |
| RNs   | Relay Nodes                      |
| RS    | Reed Solomon                     |
| SD    | Source-to-Destination            |
| SR    | Source-to-Relay                  |
| SDMA  | Space-Division Multiple Access   |
| SNR   | Signal-to-Noise Ratio            |
| SWC   | Slepian-Wolf Coding              |
| WZC   | Wyner-Ziv Coding                 |

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I. INTRODUCTION

Distributed Source Coding (DSC) refers to the problem of compressing several physically separated, but correlated sources, which are unable to communicate with each other by exploiting that the receiver can perform joint decoding of the encoded signals [1]–[3]. However, Distributed Joint Source-Channel coding (DJSC) is specific to the case, when the correlated sources signals are transmitted over noisy channels [3]–[5]. For both DSC and DJSC schemes the ultimate goal is to exploit the existing correlation for the sake of minimising the transmission energy required by the sources, while maintaining reliable communication. The Slepian-Wolf (SW) theorem [1] has laid down the theoretical foundations of DSC through specifying the achievable rate regions of the compressed correlated sources. Let us consider the arrangement of Fig. 1, where both \( \{ b_1 \} \) and \( \{ b_2 \} \) are random sequences of independent and identically distributed (i.i.d) samples, while \( R_1 \) and \( R_2 \) are the transmission rates of 1\(^{st}\) and 2\(^{nd}\) users, respectively. Upon their separate encoding and joint decoding, the SW theorem [1] states the rate region as:

\[
\begin{align*}
R_1 & \geq H(b_1|b_2), \\
R_2 & \geq H(b_2|b_1), \\
R_1 + R_2 & \geq H(b_1, b_2),
\end{align*}
\]

where \( H(b_1|b_2) \) and \( H(b_1, b_2) \) denote the conditional and joint entropies, respectively. Remarkably, and as shown in Fig. 2 this bound is identical regardless of whether joint encoding takes place at the SNs or not. Note that at the corner points shown in Fig. 2, namely \( A \) and \( B \), the Slepian-Wolf Coding (SWC) problem would be reduced to the scenario relying on perfect side-information. Using conventional lossless coding at a rate of \( R_2 = H(b_2) \), for example, will make \( \{ b_2 \} \) available at the joint decoder, thus approaching point \( A \).

Later in 1976, the aforementioned lossless SWC problem of [1] was extended to a lossy source coding problem relying on side-information at the decoder [6], which is widely known as the Wyner-Ziv Coding (WZC) problem [2], [4]. More explicitly, the WZC problem asks the question of how many bits are required for encoding \( \{ b_1 \} \), when the side-information \( \{ b_2 \} \) is perfectly known at the decoder, while maintaining a specific level of distortion concerning \( \{ b_1 \} \) at the receiver. These promising theoretical results have led to intense research activities from both theoretical as well as from practical perspectives.

Both the Network Coding (NC) and DSC schemes have to be carefully designed, when transmitting correlated sources over cooperative networks [7], [8]. More explicitly, the NC would offer multiplexing and/or diversity gains, when communicating over hostile channels, while the DSC scheme would offer source compression by exploiting the correlation between sources. The problem of multi-casting correlated sources over idealised noiseless channel was considered in [9]. Barros et al. generalised the problem to correlated sources communicating in a large-scale NC scenario [7]. Inspired by this theoretical contribution, several practical iterative Joint Channel-coding and Network-coding (JCN) schemes have been proposed in [10]–[12], where the NC was combined with channel coding for the sake of achieving time-diversity. The JCN decoder of the schemes advocated in [10]–[12] was based on exchanging soft information between the channel decoder and the network decoder. More explicitly, the channel coding schemes of [10], [11] invoked turbo decoder, while in [12] a Luby Transform-based decoder was employed.

When considering transmissions over a realistic noisy environment, various Distributed Joint Source-Channel coding-aided Network-coding (DJSCN) schemes were investigated in [13]–[16]. To elaborate further, a linear syndrome-based Slepian-Wolf coding assisted random linear NC was proposed in [13]. An iterative receiver that combines a turbo equalizer, a network decoder and a source decoder was proposed in [14], when both sources are communicating over a frequency-selective Rayleigh fading channel. As a further development, a novel iterative turbo code-based DJSCN schemes were proposed in [15] for communicating over orthogonal block Rayleigh fading Multiple Access Relay Channels (MARCs), where the corresponding outage probability was derived in [16]. In contrast to [14], [15], we opted for dispensing with iterative decoding between the NC decoder and the joint decoder in this contribution. This is because of an extremely high complexity would...
be imposed, if we extended the scheme of [14], [15] for supporting more than two users. More explicitly, the excessive complexity is mainly imposed by the iterative decoding invoked at the receiver. Additionally, the attainable performance gain when activating such decoding iteration would be limited in the block fading channel environment [17], as the channel coding itself cannot considerably improve the Bit Error Ratio (BER) [18]. Recently, two spatially correlated Markov sources based transmission was supported using DJSC scheme in [19]. Additionally, a novel lattice-based coding algorithm was proposed in [20], which shows a robust transmission over noisly channel. A routing algorithm for multi-hop ad hoc networks-aided DJSC scheme was proposed in [21], in which the wireless network has a significant gain by exploiting the correlation among the sources.

Dynamic Network Coding (DNC) concept was introduced in [22], where each of the Relay Nodes (RN)s dynamically transmits its non-binary linear combinations to the Destination Node (DN). To elaborate further, each of the M users broadcast their Information Frames (IF)s to both the DN and to the RNs during their designated Broadcast Phase (BP). Next, after M BPs, each RN sends its Parity Frames (PFs) to the DN within the Cooperative Phase (CP), where each of these PFs is comprised of non-binary linear combinations of the successfully received IFs. In [23], [24], the DNC techniques were extended, where each of the SNs and RNs is allowed to broadcast its IFs and PFs several times during the BPs and CPs rather than just once as in the DNC counterpart scheme of [22]. In [23], [24], the NC problem was formulated as that of designing a linear Forward Error Correction (FEC) block code, where the diversity order achieved was evaluated in order to quantify the expected performance. The upper and lower Frame Error Ratio (FER) bounds as well as the outage probability of the NC systems was derived in [25].

Adaptive Dynamic Network Coding (ADNC) design was proposed in [17], [26], [27], aiming for enhancing the average transmission rate without degrading the diversity gain of the scheme. A channel-quality feedback flag can be used to indicate, whether the IFs received at the DN were successfully or unsuccessfully decoded during the BPs [17], [26], [27]. As a consequence, the multiplexing gain or the transmission rate can be increased because the number of PFs can be reduced. In [17] an ADNC-based near-capacity irregular convolution code scheme supporting multiple users was proposed, which exhibited an excellent performance when communicating over a hostile environment imposing both fast fading (small-scale uncorrelated Rayleigh fading) and slow fading (quasi-static Rayleigh fading). A novel cooperative cognitive radio aided ADNC regime was proposed in [26] where the cognitive users act as RNs that support the primary users that are the SNs in our case.

Against this background, we intrinsically amalgamate the DJSTTCM scheme of [28] with the Dynamic Network Coding (DNC) of [17], [27], [29], resulting in our proposed scheme referred to as DJSTTCM-DNC. Additionally, we have also conceived a novel Adaptive Dynamic Network Coding (ADNC) design of for our DJSTTCM scheme, resulting in the DJSTTCM-ADNC regime, where the RNs would adaptively transmit their corresponding frames depending on whether the signal of the sources have been successfully received at the destination or not. Hence, the scheme’s overall effective throughput could be enhanced, while the decoding complexity and delay associated with extra frames will be reduced. Both systems, namely DJSTTCM-DNC and DJSTTCM-ADNC, are proposed for supporting correlated source transmissions over hostile channels experiencing both small-scale and large-scale fading. Furthermore, in our NC model the RN signals are composed using non-binary linear coefficients based equations, leading to a further scalability in our design. Note that the NC-based cooperative systems proposed in [14], [15] cannot support more than two users, because the RN signals were constructed using a simple bit-wise XOR operator.

The rest of the paper is organised as seen in Fig. 3. Explicitly, The proposed system model is detailed in Section II, in which the physical layer is explained in Section III followed by the illustrations of the NC encoder and decoder in Section IV. The overall system transmission rate as well as the diversity order are also analysed in Section V. Finally, in Section VI the performance of our proposed scheme is quantified. Finally, our conclusions will be offered in Section VII.

II. SYSTEM MODEL

The schematic of our DJSTTCM-ADNC-based cooperative transmission scheme is shown in Fig. 4, where both the

FIGURE 3. Paper structure.

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correlated SNs, namely SN\textsubscript{1} and SN\textsubscript{2} transmit their data to the DN with the aid of the two RNs.\textsuperscript{2} Our communication protocol might be structured into two layers, namely the NC layer and the Forward Error Correction (FEC) layer, where the NC layer is constituted by two transmission sessions, as seen at the upper part of Fig. 4.

More explicitly, the Information Frames (IFs) are broadcast from the corresponding \(M\) number of SNs to \(K\) RNs as well as to the DN during the Broadcast Phase (BP). Next, the DN decodes the IFs received from the SNs, while the RNs decode the same IFs before encoding them into their corresponding Parity Frames (PFs). Then, PFs are transmitted to the DN during the Cooperative Phase (CP). Thus, as illustrated in Fig. 4, the DN receives the IF that contains the original information during the BP, as well as the PF that comprises a non-binary linear combination of the IFs. The key parameters are defined in Table 1.

The BP transmission might be viewed as an Space-Division Multiple Access (SDMA) [31] architecture, where \(M\) SNs transmit their signals to the RNs, with each RN having equipped with \(P\) receive antennas. More specifically, the signal received at the DN via the direct transmission link, namely the Source-to-Destination (SD) link, can be fully characterised using a \((P \times M)\)-element channel matrix \(H_{sd}\) as:

\[
y_d = H_{sd}x_s + n,
\]

where \(y_d = [y_0, y_1, \cdots, y_{P-1}]^T\) and \(n = [n_0, n_1, \cdots, n_{P-1}]^T\) are \((P \times 1)\)-element vectors that denote the received signals and noise elements at the DN, respectively. Note that each element in \(n\) represents the complex-valued AWGN with a variance of \(N_0/2\) per dimension. Additionally, the SNs’ transmitted signal \(x_s = [x_0, x_1, \cdots, x_{M-1}]^T\) is an \((M \times 1)\)-element vector.

This paper considers two main configuration scenarios. The first one is portrayed in the schematic of Fig. 5, where the channel of both phases, namely BP and CP, can be viewed as a \((2 \times 2)\)-elements MIMO MAC. Similar to Equation (4), the signal received at the \(j\)th RN via the Source-to-Relay (SR) link can be written as:

\[
y_{r_j} = H_{sr_j}x_s + n,
\]

where \(j \in K\) and \(K\) is the total number of RNs. Hence, for example, the channel matrix \(H_{sr_1}\) of Scenario A seen in Fig. 4 for the SR link during the BP between both

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\textbf{TABLE 1. List of symbols.}

| Parameters | Description |
|------------|-------------|
| \{b\} | 1\textsuperscript{st} user sequence |
| \{b\} | 2\textsuperscript{nd} user sequence |
| \(R_1\) [BPS] | 1\textsuperscript{st} user transmission rate |
| \(R_2\) [BPS] | 2\textsuperscript{nd} user transmission rate |
| \(H(b_1 b_2)\) | Conditional entropy |
| \(H(b_1 b_2)\) | Joint entropy |
| \(R_{tcm}\) [BPS] | TTTCM coding rate |
| \(R_{p}\) [BPS] | Puncturing rate |
| \(M\) [user] | Number of SNs |
| \(K\) [relay] | Number of RNs |
| \(F\) | Total number of simulated frames |
| \(N\) | Total number of bits per simulated frame |
| \(N_s\) | Total number of symbols per frame |
| \(i\) | SN index |
| \(j\) | RN index |
| \(n_1\) [frame] | # Information Frames (IFs) transmitted per SN during BP within a full transmission cycle |
| \(n_2\) [frame] | # Parity Frames (PFs) transmitted per transmit antenna per RN during CP within a full transmission cycle |
| \(L\) [antenna] | # transmit antennas of RN |
| \(P\) [antenna] | # receive antennas of RN and DN |
| \(G\) | Original transfer matrix that represent the Network Code |
| \(G'\) | Modified transfer matrix that represent the Network Code |
| \(R_{NC}\) [BPS] | Network code information rate |
| \(R_{FEC}\) [BPS] | Channel code information rate |
| \(\eta\) [BPS] | The system overall achievable throughput |
| \(D\) | The diversity order |
| \(\rho\) | Correlation coefficient |
| \(\alpha\) | Path-loss exponent |
For example, assuming a path-loss exponent of two \( \alpha \), albeit, in conjunction with different channel coefficients.

As suggested by Fig. 5, the channel corresponding to geometrical gain [32] experienced by the SN and RD link with respect to the SD link may be calculated, pathloss-induced geometrical gain experienced by the SR link RN\(_1\) between the SD link RD. Thus, we have

\[
G_{SR} = \left( \frac{d_{SR}}{d_{RD}} \right)^2, \quad G_{RD} = \left( \frac{d_{SR}}{d_{RD}} \right)^2,
\]

where \( d_{SR} \) denotes the distance between source nodes SN\(_1\), SN\(_2\) and the DN. The RNs are situated at the mid-point between the SNs and the DN. Thus, we have \( d_{SR} = d_{RD} = \frac{d_{SD}}{2} \), where \( G_{SR} = G_{RD} = 2^\alpha = 4 \).

Without loss of generality, let \( d_{ab} \) represent the distance between node \( a \) and node \( b \). If \( x_a \) is the symbol transmitted from node \( a \) equipped with a single transmit antenna, the received Signal-to-Noise Ratio (SNR) estimated at each receive antenna of node \( b \) can be expressed as [32]:

\[
\text{SNR}_e = \frac{G_{ab} E[|h_{ab}|^2] E[|x_a|^2]}{N_0} = \frac{G_{ab}}{N_0},
\]

where \( E[|h_{ab}|^2] = 1 \) and \( E[|x_a|^2] = 1 \). We define the transmit SNR\(^3\) as a ratio of the power transmitted from node \( a \) to the noise power experienced at the receiver of node \( b \) as:

\[
\text{SNR}_d = \frac{E[|x_a|^2]}{N_0} = \frac{1}{N_0}.
\]

\(^3\) However, the concept of transmit SNR [34] is unconventional, as it relates quantities to each other at two physically different locations, namely the transmit power to the noise power at the receiver.

Thus, we arrive at:

\[
\text{SNR}_e = \text{SNR}_d \quad G_{ab}, \quad \Gamma_R = \Gamma_T + 10 \log_{10}(G_{ab}) \ [\text{dB}],
\]

where we have \( \Gamma_R = 10 \log_{10}(\text{SNR}_e) \) and \( \Gamma_T = 10 \log_{10}(\text{SNR}_d) \).

As stated previously, both the BP and CP transmission channels are composed of two components, with \( h_i \) and \( h_f \) denoting the uncorrelated fast fading (small-scale Rayleigh fading) and slow fading (quasi-static Rayleigh fading) coefficients, respectively. To elaborate further, each channel coefficient \( h_{1/R}, \) \((1/R)\) of the channel matrix shown in Equation (6) might be expressed as:

\[
h = h_i \cdot h_f,
\]

where \( h_i \) in our simulations is assumed to be constant for all the symbols within a frame, while \( h_f \) fluctuates on a symbol by symbol basis within each frame.

In Scenario B of Fig. 6 both the BP and CP may be viewed as \((2 \times 1)\) and \((1 \times 1)\) SDMA channels, respectively. Thus, the channel matrices encountered during both phases can be evaluated similarly to the analysis of Scenario A.

**III. DJSSTCM ENCODER AND DECODER**

The two correlated sources are encoded using our DJSSTCM [28] encoder and then decoded accordingly. Similar to the source correlation model adopted in [15], [28], [35], [36], the BSC is used for modelling the correlation between the source sequences \( \{b_1\} = \{b_1^1, b_2^1, \ldots, b_i^1, \ldots, b_N^1\} \) and \( \{b_2\} = \{b_2^1, b_2^2, \ldots, b_i^2, \ldots, b_N^2\} \), where \( N \) is the length of each source block. More explicitly, the source sequence \( \{b_1\} \) is generated by an equiprobable binary symmetric i.i.d. source, while \( \{b_2\} \) can be defined as \( b_i^1 = b_i^2 \oplus e_i \), where \( \oplus \) is the modulo-2 addition operation and \( e_i \) is an independent binary random variable assuming the logical value 1 with a cross-over probability of \( p_e \) and 0 with a probability of \( 1 - p_e \).

The achievable compression rate of both sources is bounded by the SW rate region inequalities of Equations (1)-(3). Both source sequences, namely \( \{b_1\} \) and \( \{b_2\} \), are first encoded using TCM encoders having a rate of \( R_{en} = \frac{m}{m+1} \). Then both encoded sequences are mapped onto the corresponding modulated symbols, namely onto
\{x_1\} and \{x_2\}, as illustrated in the lower part of Fig. 4. During the BP, both modulated signals are broadcast to all RNs and the DN through either the (2 x 2) or the (2 x 1)-element MACs according to the used scenario. Consequently, both received signals, namely \(y_r\) and \(y_d\) of Fig. 4 are detected by the Maximum Likelihood (ML)-based Multi-User Detector (MUD) at RN and DN, respectively. Then, both source sequences are estimated by iteratively exchanging their extrinsic information between the MUD and the DJSTTCM decoder.

The sequences estimated at the RN will then be fed into the NC before encoding them using a pair of TTCM encoders, as shown in Fig. 4. These TTCM-encoded streams will be transmitted during the CP. Depending on the specific scenario, different mappers or receivers might be used. More explicitly, in Scenario A of Fig. 5, a pair of TTCM-encoded sequences will mapped into two different QPSK signals. However, in Scenario B of Fig. 6, both coded sequences are combined and mapped onto a 16QAM-SPM signal, since the RN and the DN invokes a single receive antenna, as portrayed in Fig. 6.\(^4\)

Before embarking on our NC investigation, we first have to characterise the attainable performance of our DJSTTCM when communicating over the combined uncorrelated Rayleigh fading and quasi-static Rayleigh fading channels of Equation (11). As shown in both Figures 5 and 6, the transmission phases can be characterised in terms of three different channel combinations. In Scenario A of Fig. 5, we have the SD, SR and RD links. More explicitly, the direct transmission might be characterised as a (2 x 2) MAC regime. Similarly, the SR and SD links of Scenario B of Fig. 6 can be viewed as a (2 x 1) MAC arrangement, while the RD link can be viewed as a (1 x 1) channel. More specifically, the BER performance of the three channels recorded for various source correlation values is shown in Fig. 7, Fig. 8 and Fig. 9 using the simulation parameters of Table 2. Note that the correlation of the pair of sources is represented by \(\rho\), which is given by \(\rho = 1 - 2p_c\), where \(p_c\) is the BSC’s cross-over probability. As all of these three figures suggested, substantial performance degradation is exhibited once our DJSTTCM scheme [28] encounters a slow fading (quasi-static Rayleigh fading) channel. More specifically, fast Rayleigh fading channel provides useful time diversity that can be explored by channel codes, where each symbol would experience a different fading. However, the slow Rayleigh fading channel does not exhibit this time diversity, since all symbols in a frame would experience the same fading in the slow fading channel. From Equation (11), and when the slow fading factor \(|h_s|^2\) is high, the whole frame would enjoy a high receive SNR, where the performance of an uncoded system could be as good as a coded system.

\(^4\)At the RN, although one TTCM would be enough to encode both decoded streams with complexity reduction, we decided to use a couple of TTCM encoders mainly for two reasons. First, to avoid any possible delay when encoding two sequences, second to add further coding flexibility to the design that could be utilised in future works.

However when \(|h_f|^2\) is low, the SNR for the whole frame could be very poor such that no coding would be able to work properly. Hence, channel coding would not work well in the slow fading channel. In the fast + slow fading scenario, the slow fading factor causes the same issue. More explicitly, the corresponding average received SNR is given by

\[
\frac{E[|h_f|^2]}{N_0} = \frac{|h_s|^2}{N_0},
\]

where the expectation of both channel is given as \(E[|h_f|^2] = 1\) and \(E[|h_s|^2] = |h_s|^2\), respectively.

Fortunately, network coding has been invoked to provide some diversity gains when communicating over slow (or fast + slow) fading channel [24], [37]. Since, the network coding is performed across a few frames, which may have different received SNRs [24], [37].

Quantitatively, Fig. 7 shows the BER versus SNR performance of the DJSTTCM-QPSK scheme, when communicating over the (2 x 2) MAC regime. Note that the SNR is be given by:

\[
\text{SNR}[\text{dB}] = E_b/N_0[\text{dB}] + 10\log_{10}(R_{\text{FEC}}),
\]

\[
(12)
\]
attained upon comparing the system having $\rho = 0.8$ to that having $\rho = 0.6$.

As expected, the BER performance was further degraded for the other two channel configurations, namely where the number of the transmit or receive antennas has been reduced to $(2 \times 1)$ and $(1 \times 1)$ channels, as seen in Figures 8 and 9, respectively. To elaborate further, upon analysing Fig. 8 we observe that the DJSTTCM-QPSK scheme requires an excessive transmit power of $\text{SNR} = (19, 22, 24)$ dB for attaining a BER of $10^{-3}$ for $\rho = (0.8, 0.6, 0.4)$ when the correlated sources encounter the $(2 \times 1)$ channel. Additionally, as it is shown in Fig. 9 for the $(1 \times 1)$ channel, even assigning a transmit power of $\text{SNR} = 30$ dB is insufficient for the DJSTTCM-16QAM-SPM scheme to attain a BER $= 10^{-3}$, despite having high correlation value of $\rho = 0.8$. This is not unexpected, because it was pointed out in [18] that in the quasi-static Rayleigh fading channels, the channel coefficients remain constant during the entire transmitted frame, hence for every transmit frame the channel can be viewed as an AWGN channel, albeit, each having different SNR value. More explicitly, the frames associated with low SNRs will dominate the system’s performance during the iterative detection process, hence leading to poor mutual information exchange between the constituent decoders. It was found in [16], [17], [38] that network-coded cooperative transmission constitutes an efficient remedy for such a transmission environment, as the time diversity between the frames will be utilised. Let us now discuss the NC scheme in the following sections.

IV. NETWORK CODING

Let us consider the NC transmission example illustrated in Fig. 10, where $M = 2$ SNs aim for transmitting their information to the DN with the aid of $K = 1$ RN. In line with [17], [26], [38], NC typically adopts a TDMA-based access method, where each SN broadcasts $n_1 = 1$ IF during its corresponding BP, while each RN transmits $n_1 = 1$ PF

where $R_{\text{FEC}}$ denotes the effective channel coding rate that can be expressed as:

$$R_{\text{FEC}} = R_{\text{cm}} \cdot R_p \cdot \log_2(M) \cdot M,$$

where $2^{m+1} = M$ denotes the number of PSK/QAM modulation levels, while $M$ is the number of SNs. As portrayed in Fig. 7, there is an approximately 12.0 dB performance degradation, when the DJSTTCM-QPSK scheme operates over the combined channel compared to that when transmitting over uncorrelated fading channels. More explicitly, for $\rho = 0.8$ and at a BER level of $10^{-4}$ an SNR gap of $13 - 0.5 = 12.5$ dB, as seen in Fig. 7. Interestingly, our joint decoder remains capable of exploiting the correlation among the sources, even when communicating over this hostile shadow-faded and fast-faded channel. For example, at a BER of $10^{-4}$ a considerable 3.0 dB improvement can be
within the CP. Thus, a total of \((n_1 \cdot M + n_2 \cdot K) = 4\) transmission phases are required for accomplishing a full transmission cycle. However, in our SDMA based method, each of the SNs broadcasts \(n_1 = 1\) IFs during each BP. Then, during the CP each of the \(L = 2\) transmits antennas of the RN transmit \(n_2 = 1\) PF, as seen in Fig. 10. More explicitly, both PFs are transmitted using twin-antenna-aided RN when Scenario A of Fig. 5 is invoked. However, for Scenario B of Fig. 6 both of the PFs are combined into a super constellation, creating a single SPM signal as illustrated in [28].

A. NETWORK ENCODER

The NC transmission protocol can be fully characterised using a transfer generator matrix \(G\), which is constructed over a Galois Field (GF) \((q)\), where \(q = 2^b\) is the desired alphabet size and \(b\) is a non-zero integer [22], [38]. In our work, we consider two NC systems relying on the generator matrices of \(G_{2 \times 4}\) and \(G_{4 \times 8}\), where both matrices are generated using the software application SAGE [39]. Upon successfully decoding all of the frames during transmission sessions, \(G_{2 \times 4}\) used in our example of Fig. 10 is given by [22], [37], [40]:

\[
G_{2 \times 4} = \begin{bmatrix} 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & 2 \end{bmatrix}.
\] (14)

where the role of the elements is detailed below. Upon comparing the above transfer matrix to Fig. 10, the transmission arrangement can be characterised by:

\[
(BP_1) : SN_1 \xrightarrow{(\cdot 1)} DN, \quad SN_1 \xrightarrow{(\cdot 1)} RN_1 \quad (15)
\]

\[
(BP_2) : SN_2 \xrightarrow{(\cdot 2)} DN, \quad SN_2 \xrightarrow{(\cdot 2)} RN_1 \quad (16)
\]

\[
(CP_1) : RN_1 \xrightarrow{(\cdot 1)} G(I_1) \cdot I_1 \quad DN, \quad RN_1 \xrightarrow{(\cdot 2)} G(I_2) \cdot I_2 \quad DN \quad (17)
\]

\[
RN_2 \xrightarrow{(\cdot 1)} G(I_3) \cdot I_3 \quad DN, \quad RN_2 \xrightarrow{(\cdot 2)} G(I_4) \cdot I_4 \quad DN \quad (18)
\]

as detailed below. As seen in Equation (14), \(G_{2 \times 4}\) can be divided into two main parts. The left-hand identity sub-matrix, having diagonal elements of \(G_{2 \times 4}(i, i) = 1, \ i \in \{1, 2\}\) represents the transmission of the IFs \(I_i\) from the \(i^{th}\) SN to the DN during the BP. This phase can be interpreted using Equation (15) and Equation (16), in which the arrow’s subscript \((= 0 \mid 1)\) indicates the failure or success of decoding the IFs, respectively. Additionally, the PF construction can be gleaned from the right-hand sub-matrix of \(G_{2 \times 4}\) in Equation (14). More explicitly, each of the signal \(\oplus (1)\) and \(\oplus (2)\)\(^5\) that is transmitted from the first and second antennas of RN1 seen in Fig. 10 are generated according to the 3rd and 4th columns of \(G_{2 \times 4}\), respectively, as specified by Equation (18).

Subsequently, a modified transfer matrix, \(G'_{2 \times 4}\), has to be defined at the DN as justified below. As the terminology modified suggests, the entries of \(G'_{2 \times 4}\) are modified according to the success or failure of the transmitted frame. The notation \((= 0)'\) (or \((= 1)'\) beneath the arrows of Equations (15) - (18) indicate, whether the frame was unsuccessfully (or successfully) decoded. Hence, we have \(G'_{2 \times 4} = G_{2 \times 4}\) when all of the transmitted frames were successfully decoded during both phases. More explicitly, the elements \(G'_{2 \times 4}(i, i) = 1, \ i \in \{1, 2\}\) represents the successful decoding of the IFs \(I_i(1)\) transmitted by SN1 at the DN during the BP1. Meanwhile, having \(G'_{2 \times 4}(1, 3) = ‘1’\) or \((G'_{2 \times 4}(2, 4) = ‘2’)\) indicates that the PFs transmitted by the RN during CP1 are successfully decoded at the DN corresponding to linear combining coefficient of the information frame \(I_i(1)\) or \((I_2(2))\). Furthermore, \(G'_{2 \times 4}(2, 3) = ‘1’\) or \((G'_{2 \times 4}(4, 1) = ‘1’)\) signifies that information frame \(I_2(2)\) or \((I_1(1))\) is successfully decoded by RN during BP1, and the PFs transmitted by the RN during the cooperative phase CP1 are successfully decoded at the DN.

To elaborate further, consider the aforementioned system that might experience an actual transmission scenario, where depending on the success or the failure of each specific transmission attempt we arrive at:

\[
(BP_1) : SN_1 \xrightarrow{(\cdot 1)} DN \quad G'_2 \xrightarrow{(I_1(1) = 0)} G'_2 \xrightarrow{(I_1(1) = 1)} DN \quad (19)
\]

\[
SN_1 \xrightarrow{(\cdot 1)} RN_1 \xrightarrow{(\cdot 1)} G'_2 \xrightarrow{(I_2(1) = 0)} G'_2 \xrightarrow{(I_2(1) = 1)} DN \quad (20)
\]

\[
(BP_2) : SN_2 \xrightarrow{(\cdot 2)} DN \quad G'_2 \xrightarrow{(I_2(1) = 0)} G'_2 \xrightarrow{(I_2(1) = 1)} DN \quad (21)
\]

\[
SN_2 \xrightarrow{(\cdot 2)} RN_1 \xrightarrow{(\cdot 1)} G'_2 \xrightarrow{(I_3(1) = 0)} G'_2 \xrightarrow{(I_3(1) = 1)} DN \quad (22)
\]

\[
(CP_1) : RN_1 \xrightarrow{(\cdot 1)} DN \quad G'_2 \xrightarrow{(I_4(1) = 0)} G'_2 \xrightarrow{(I_4(1) = 1)} DN \quad (23)
\]

\[
RN_2 \xrightarrow{(\cdot 1)} DN \quad G'_2 \xrightarrow{(I_2(1) = 0)} G'_2 \xrightarrow{(I_2(1) = 1)} DN \quad (24)
\]

hence, according to the Equations (19) - (24), the modified transfer matrix can be expressed as:

\[
G'_2 = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 2 \end{bmatrix},
\] (25)

Further details and in-depth mathematical description on the construction of the modified matrix construction can be found in [25], [37].

Let us now generalise the above-mentioned \(G_{2 \times 4}\) transfer matrix. Fig. 11 shows the transfer matrix \(G_{M \times (M + (K \times L))}\) or \(G\) for brevity, which consists of two components. The first half is constituted by the identity matrix \(I_{M \times M}\), or \(I\) for short, which models the information frames’ transmission from \(M\) SNs to the DN, and each of its entries is defined as:

\[
I_{i,i} = \begin{cases} 
1 & \text{if } I_{i,i} \text{ successfully recovered,} \\
0 & \text{otherwise,}
\end{cases}
\] (26)

\(^5\oplus\) denotes the non-binary linear combination of the IFs, where all operations are carried out over GF [22].

\(^6\)Here we assume single BP and CP, i.e. \(n_1 = n_2 = 1\). However, the more general representation \(G_{n_1 M \times (n_1 M + n_2 (K \times L))}\) would involve further concatenation of the matrix \(G_{M \times (M + (K \times L))}\) seen in Fig. 11.
where we have $i \in \{1, \ldots, M\}$. The second component of $G$ is the parity matrix $P_{M \times (K \times L)}$, or $P$ for short, which illustrates the PFs construction process formulated as:

$$\Pi(j) = \oplus p(j,i)I(i),$$

where we have $j \in \{1, \ldots, (K \times L)\}$. Again, $K$ and $L$ denotes the number of the RNs and transmit antennas employed by each RN, respectively. Here, $\oplus$ denotes the non-binary linear combination of the IFs over finite Galois Fields (GF) [22] which can be replaced with simple modulo-2 addition operation $\oplus$ when considering binary combination. Additionally, at the $j^{th}$ RN, the modified version of the parity matrix, namely $P'_{M \times (K \times L)}$, represents the IFs status of being recovered or not according to:

$$P'_{i,j} = \begin{cases} p(i,j) & \text{if } I_{i,j} \text{ successfully recovered at RN}_j, \\ 0 & \text{otherwise.} \end{cases}$$

In a nutshell, the modified matrix $G'$ is constructed by modifying the entries of the original matrix $G$ according to Equation (26) and Equation (28).

**B. NETWORK DECODER**

Following our discussions on the NC encoder, this section considers at the NC decoder briefly. The motivated readers might like to refer to [25], and to the references therein for more details. Let us consider the NC-based $G_{4 \times 8}$ scheme depicted in Fig. 12 relaying on the transfer matrix of Equation (55). Let us assume that the full transmission resulted in a modified matrix of:

$$G'_{4 \times 8} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 7 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 6 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 3 & 2 \end{bmatrix}.$$  

As suggested by Fig. 11, The modified transfer matrix $G'_{4 \times 8}$ can be partitioned into:

$$I'_{4 \times 8} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix},$$

$$P'_{4 \times 8} = \begin{bmatrix} 0 & 0 & 3 & 0 \\ 0 & 0 & 7 & 0 \\ 0 & 0 & 6 & 1 \\ 0 & 0 & 3 & 2 \end{bmatrix}.$$  

Let us now denote the IFs transmitted from both SNs of Fig. 12 during the two BPs as $X_{4 \times 8} = \{I_1^{(1)}, I_1^{(2)}, I_3^{(2)}, I_2^{(2)}\}$, which can be illustrated in matrix format using:

$$X_{4 \times 8} = \begin{bmatrix} I_1^{(1)} & 0 & 0 & 0 \\ 0 & I_2^{(1)} & 0 & 0 \\ 0 & 0 & I_3^{(2)} & 0 \\ 0 & 0 & 0 & I_2^{(2)} \end{bmatrix}.$$  

Then the signals received at the DN during the BPs and CPs are denoted by $Z'_{4 \times 8}$ and $Z_{4 \times 8}$, respectively and are formulated as:

$$Z'_{4 \times 8} = X_{4 \times 8}I'_{4 \times 8},$$

$$Z_{4 \times 8} = X_{4 \times 8}P'_{4 \times 8}.$$  

Since the DN knows $G'_{4 \times 8}$, both $Z'_{4 \times 8}$ and $Z_{4 \times 8}$ can be estimated according to Equation (33) and Equation (34) as:

$$Z'_{4 \times 8} = \begin{bmatrix} 0 & 0 & 3 & 0 \end{bmatrix},$$

$$Z_{4 \times 8} = \begin{bmatrix} 0 & 0 & 47 & 11 \end{bmatrix}.$$  

More explicitly, the entries of the vector in Equation (35) are calculated as:

$$0 \cdot I_1^{(1)} + 0 \cdot I_2^{(1)} + 1 \cdot I_3^{(2)} + 0 \cdot I_2^{(2)} = 3 \Rightarrow I_3^{(2)} = 3.$$  

Similarly, the entries of the vector in Equation (36) can be expressed as:

$$3 \cdot I_1^{(1)} + 7 \cdot I_2^{(1)} + 6 \cdot I_3^{(2)} + 3 \cdot I_2^{(2)} = 47,$$

$$0 \cdot I_1^{(1)} + 0 \cdot I_2^{(1)} + 1 \cdot I_3^{(2)} + 2 \cdot I_2^{(2)} = 11.$$  

Substituting the results of Equation (37) into both Equation (38) and Equation (39), we arrive at:

$$3 \cdot I_1^{(1)} + 7 \cdot I_2^{(1)} + 3 \cdot I_3^{(2)} = 29,$$

$$2 \cdot I_2^{(2)} = 8 \Rightarrow I_2^{(2)} = 4.$$  

Upon substituting Equation (41) into Equation (40), we arrive at:

$$3 \cdot I_1^{(1)} + 7 \cdot I_2^{(1)} + 3 \cdot I_3^{(2)} = 29,$$

$$3 \cdot I_1^{(1)} + 7 \cdot I_2^{(1)} = 17.$$  

Observe in Equation (43) that we only have a single equation, but two unknown variables. Hence, out of the four transmitted IFs, only two IFs namely $I_3^{(2)}$ and $I_4^{(2)}$ can be recovered based on Equation (37) and Equation (41), respectively.

To generalise, let us assume that $X'$ denotes the IFs transmitted by the SNs to both the RNs and the DN during the BP, while $X'$ represents the PFs transmitted from the RNs to the DN during the CP. This PF matrix is constructed using Equation (27). Then, upon using the modified matrices,
$P'$ and $I'$, the frames that are successfully received at the DN can be written as [25]:

$$Z_{I'} = X' I', \quad (44)$$

$$Z_{P'} = X' P', \quad (45)$$

where the matrices $Z_{I'}$ and $Z_{P'}$ denote the IFs and PFs that are successfully received at the DN during the BP and CP, respectively. Let us now assume that the DN can successfully recover a set $X_{I'}'$ that is a correct subset of $X'$ and since the DN knows $G'$ [17], [24], [38], i.e. the DN is aware of how each PF was constructed, $X_{I'}'$ is a subset of $X'$. Thus, from Equation (44), we arrive at:

$$X_{I'}' = Z_{I'} = Z_{P'}'. \quad (46)$$

Then, upon substituting Equation (46) into Equation (45) we arrive at [25]:

$$(X' - X_{I'}') P' = Z_{P'} - X_{I'}' P'. \quad (47)$$

Therefore, a set $X_{I'}'$ of IFs may then be extracted from Equation (47) with the aid of the Gaussian elimination algorithm [38]. Consequently, the entire set of the recorded IFs at the DN may be expressed as $X_{I'}' \cup X_{I'}$ out of the full set $X'$ of IFs.

**V. TRANSMISSION RATE AND DIVERSITY ORDER**

Before detailing our adaptive scheme, let us remind the readers of our scenarios. Fig. 5 and Fig. 6 defined Scenario A and Scenario B, respectively. The main simulation parameters of both scenarios were listed in Table 3.

Again, the transmission structure employed can be divided into two layers, namely the FEC and NC layers. This section will discuss the transmission layer’s rate as well as the overall system throughput.

**A. TRANSMISSION RATE**

Let us commence with the NC rate, which is directly related to the multiplexing versus diversity capability and it might be expressed as:

$$R_{DNC} = \frac{E \cdot [\# \text{ IFs from SNs}]}{E \cdot [\# \text{ IFs from SNs} + \# \text{ PFs -from RNs}]} \cdot (48)$$

where $E[\ ]$ represents the expectation operation over the total number of simulated frames.

Naturally, when designing any cooperative scheme, we have to aim for reducing the number of PFs transmitted from the RNs during the CPs [38], without any performance degradation. As a further benefit of this reduction, the resources required, such as the time, bandwidth and power, for accomplishing a full transmission cycle might be reduced. Hence, for the same amount of available resources, the system might be able to admit more users or to transmit more IFs of the same number of users to the DN. One of the efficient techniques is to adaptively adjust the number of PFs depending on the prevalent to the channel quality. For the simplest non-adaptive case, the rate of Dynamic Network Coding (DNC) is given by:

$$R_{DNC} = \frac{n_1 \cdot M}{n_1 \cdot M + n_2 \cdot K \cdot L} \quad (49)$$

where $M$ is the number of SNs and $K$ is the number of RNs, while $n_1$ and $n_2$ represent the number of IFs and PFs, respectively. Recall that the parameters used in this paper are defined in Table 1, while the simulation parameters are listed in Table 3. When considering a single relay-aided Scenario A transmission, for example, the $R_{DNC} = 1/2$ BPS, where we have $M = 2$ SNs and $K = 1 \text{ RN-aided} \ L = 2 \text{ transmit antennas}$. Regarding the FEC layer used for direct transmission, without relaying, the effective FEC transmission rate $R_{FEC}$ can be conventionally estimated using Equation (13). By contrast, the overall throughput of the relaying-aided DNC can be expressed as the number of information bits transmitted delivered by the number of modulated symbols transmitted during both phases [26]. More explicitly, the overall throughput of cooperative DNC can be formulated as:

$$\eta_{DNC} = \frac{n_1 \cdot M \cdot N_i}{n_1 \cdot M \cdot N_{BP} + n_2 \cdot K \cdot L \cdot N_{CP}}, \quad (50)$$

where $N_i$ is the number of information bits per frame transmitted within a duration of $(N_{BP} + N_{CP})$ symbol periods and $M$ denotes the number of users. Furthermore, $N_{BP}$ is the number of modulated symbols per frame transmitted from the SNs during the BP, while $N_{CP}$ is the number of modulated symbols per frame transmitted from the RNs during the CP. We have $N_{BP} = \frac{N_i}{R_{SN}}$ and $N_{CP} = \frac{N_i}{R_{RN}}$, where $R_{SN}$ and $R_{RN}$ denote the effective FEC transmission rates of the SN and RN, that can

**TABLE 3. Simulation parameters for both Scenario A and Scenario B**

where the notations are defined in Table 1, while the rates corresponding to the $K = 1$ and $K = 2 \text{ RN/RNs scenarios are summarised in Tables 4– 7, respectively.**
be estimated using Equation (13), respectively. Additionally, we assume having an identical number of BPs and CPs, i.e. \( n_1 = n_2 \). Thus, Equation (50) can be further simplified as:

\[
\eta_{DNC} = \frac{M \cdot R_{SN}^f \cdot R_{RN}^f}{M \cdot R_{SN}^f + R_{RN}^f \cdot K \cdot L},
\]

hence, we have \( \eta_{DNC} = 1 \) BPS, when considering a single relay-aided Scenario A transmission associated with \( M = 2 \) SNs, \( K = 1 \) RN-aided \( L = 2 \) transmit antennas and FEC transmission rates of \( R_{SN}^f = R_{RN}^f = 2 \) BPS.

**B. ADAPTIVE DYNAMIC NETWORK CODING**

As suggested in the previous section, DNC-aided adaptive transmission is capable of enhancing the overall multiplexing or diversity gains. Similarly to the system proposed in [17], [26], in our ADNC system we assume that the DN has the capability of sending a feedback flag \( F_g \) back to the NC encoder of the RNs, as portrayed in Fig. 4. This flag requests the transmission of further PFs from the RNs during the BP according to the channel quality encountered. Intuitively, if the IFs were received correctly at the DN, then there is no need for any PF transmission. More explicitly, if the RNs received \( F_g = 1 \), this indicates that all IFs have been successfully decoded at the DN and hence the RNs become inactive. This adaptive operation may be formulated as:

\[
(K_{AD} \cdot L) = \begin{cases} 
0 & \text{if } F_g = 1, \\
(K \cdot L) & \text{otherwise},
\end{cases}
\]

(52)

where \( K_{AD} \) denotes the number of RNs used, while \( n_2 \) represents the number of the PFs sent from each RN. The corresponding adaptive NC rate might be expressed as:

\[
R_{ADNC} = \frac{n_1 \cdot M}{n_1 \cdot M + E [n_2 \cdot K_{AD} \cdot L]},
\]

(53)

where again, the expectation \( E [\cdot] \) is evaluated over the number of simulated frames. Upon comparing Equations (52) with (53). For the case, when the number of SNs equals to that of NC the RNs, \( M = K \), the adaptive NC rate of \( R_{ADNC} \) has to approach \( \frac{n_1 \cdot M}{n_1 \cdot M + K \cdot L} = 1 \) for the sake of attaining the maximum achievable rate. Hence, in the high SNR region, i.e. when encountering a high channel quality or in highly correlated source scenarios, where the IFs can be recovered correctly during the BP, the term \( K_{AD} \cdot L \) has to be adaptively adjusted towards 0. For example, according to Equation (53) \( R_{ADNC} \) will assume two different values of \( R_{ADNC} = 1 \) BPS or \( R_{ADNC} = 1/2 \) BPS if the feedback flag received \( F_g = 1 \) or (otherwise), when considering a single relay-aided Scenario A transmission associated with \( M = 2 \) SNs, \( K = 1 \) RN-aided \( L = 2 \). Upon assuming \( n_1 = n_2 \), similarly to Equation (51), the overall throughput of our adaptive scheme can be expressed as:

\[
\eta_{ADNC} = \frac{M \cdot R_{SN}^f \cdot R_{RN}^f}{M \cdot R_{SN}^f + R_{RN}^f \cdot E [K_{AD} \cdot L]},
\]

(54)

Similarly, \( \eta_{ADNC} = 2 \) BPS or \( \eta_{ADNC} = 1 \) BPS according to whether the \( F_g = 1 \) or (otherwise), when considering a single relay-aided Scenario A transmission associated with \( M = 2 \) SNs, \( K = 1 \) RN-aided \( L = 2 \) transmit antennas and FEC transmission rates of \( R_{SN}^f = R_{RN}^f = 2 \) BPS.

**C. DIVERSITY ORDER AND COMPLEXITY**

In order to emphasise the scalability of our system, we consider a higher order transfer matrix of \( G_{4 \times 8} \) that is constructed over GF(8), as follows [23], [24]:

\[
G_{4 \times 8} = \begin{bmatrix}
1 & 0 & 0 & 0 & 3 & 7 & 3 & 6 \\
0 & 1 & 0 & 0 & 5 & 7 & 7 & 4 \\
0 & 0 & 1 & 0 & 2 & 4 & 6 & 1 \\
0 & 0 & 0 & 1 & 5 & 5 & 3 & 2
\end{bmatrix}.
\]

(55)

As portrayed in Fig. 11, the NC transfer matrix \( G \) is comprised of two sub-matrices, namely the identity matrix \( I \) and the parity matrix \( P \). The sub-matrices of \( G_{4 \times 8} \) in Equation (55) have two more columns and rows compared to those of \( G_{2 \times 4} \) in Equation (14). Intuitively, this expansion can be exploited either by adding a pair of SNs and RNs, or by doubling the number of the BPs and CPs, respectively.

![Fig. 12. Schematic of the NC-based \( G_{4 \times 8} \)-based system having \( M = 2 \) SNs each transmitting \( n_1 = 2 \) IFs, while the \( K = 1 \) RN is equipped with \( L = 2 \) antennas that transmits \( n_1 = 2 \) IFs. The PFs transmitted during CPs, namely \( \oplus 1(1), \oplus 2(1), \oplus 1(2) \) and \( \oplus 2(2) \) are generated according to the 3rd, 4th, 5th and 6th columns of \( G_{4 \times 8} \), respectively, as specified in Equation (55). Table 1 defines the main system parameters.](image)
to the upper part of Fig. 12, while the CPs can be characterised with the aid of the parity matrix of Equation (55) that is portrayed in the lower part of Fig. 12. The number of transmitted IFs and PFs is identical in $G_{2\times 4}$-based and the $G_{4\times 8}$-based scheme, i.e. we have $n_1 = n_2$. Hence, their NC rate will be the same as shown in Equation (49) Equation (53). However, the diversity order $D_{NC}$ of the $G_{4\times 8}$-based scheme will be higher than that of its $G_{2\times 4}$-based counterpart [24]. Thus the diversity order $D$ of the Dynamic Network Coding (DNC)-based system is bounded by [22], [24], [25], [37], [38]:

$$D_{DNC} = \lim_{\text{SNR} \to \infty} -\log_2 P_o,$$

(57)

where $K$ is the number of RNs and $L$ is the number of transmit antennas per RN, while we have $n_1 = 1$ or $n_2 = 2$ for the $G_{2\times 4}$ or $G_{4\times 8}$ based schemes, respectively. Naturally, a higher diversity order implies having a better Frame Error Rate (FER) performance, since a higher diversity leads to an improved signal detection reliability. We considered a number of scenarios, each of which invoked either $K = 1$ RN or $K = 2$ RNs. The authors of [22], [24], [25], [37], [38] inferred the diversity order $D_{DNC}$ in Equation (56) can be found using the following formula:

$$D_{DNC} = \frac{(K \cdot L) + n_2 \leq D_{DNC} \leq (K \cdot L) \cdot n_2 + 1}{(K \cdot L) + n_2 \leq D_{DNC} \leq (K \cdot L) \cdot n_2 + 1},$$

(56)

where $n_2$ is the number of the RNs is $K = 1$ RN or $K = 2$ RNs. The authors of [22], [24], [25], [37], [38] inferred the diversity order $D_{DNC}$ in Equation (56) can be found using the following formula:

$$D_{DNC} = \lim_{\text{SNR} \to \infty} -\log_2 P_o,$$

(57)

where the SNR is the signal to noise ratio, and $P_o$ is the probability of erroneous frames that cannot be recovered at the DN. $P_o$ can be approximated using $P_o = 1 - e^{(-1-2\cdot L)\text{SNR}}$ and it has upper $P^{\text{Upper}}_o$ and lower $P^{\text{Lower}}_o$ outage bounds [38]. It was found in [25], [38], that the most influential variables in both $P^{\text{Upper}}_o$ is $P_o^{(K \cdot L) \cdot n_2 + 1}$, and in $P^{\text{Lower}}_o$ is $P_o^{(K \cdot L) \cdot n_2}$, respectively. Thus, both upper and lower bounds are in-lined with the Equation (56). Note that the full derivation of $P^{\text{Upper}}_o$ and $P^{\text{Lower}}_o$ can be found in Equation (24) and Equation (28) of [25], respectively.

The corresponding rates and diversity orders are summarised according to the specific transfer matrix used in Tables 4–7. It can be clearly seen that, employing DNC schemes will increase the diversity order leading to a substantial performance improvement.

8A gain of 19.0 dB was attained after employing our DNC scheme when compared against its non-cooperative counterparts as illustrated in Fig. 14.
TABLE 6. Rates and diversity orders of the systems based on the transfer matrices $G_{2 \times 4}$ and $G_{4 \times 8}$, when employing Scenario A of Fig. 5, while the number of RNs is $K = 2$. Note that the terminologies are defined in Table 1, while the main parameters are listed in Table 3.

| Parameters [BPS] | Equation | Scenario A, $G_{2 \times 4}$ | Scenario A, $G_{4 \times 8}$ |
|------------------|----------|-----------------------------|-----------------------------|
| $R_{\text{BC}}$  | (13)     | 2                           | 2                           |
| $R_{\text{DNC}}$ | (49)     | $1/3$                        | $1/3$                        |
| $R_{\text{ADNC}}$| (53)     | $\begin{cases} 1 \text{ if } F_0 = 1, \\ 1/3 \text{ otherwise} \end{cases}$ | $\begin{cases} 1 \text{ if } F_0 = 1, \\ 1/3 \text{ otherwise} \end{cases}$ |
| $\eta_{\text{DNC}}$| (50)     | $2/3$                        | $2/3$                        |
| $\eta_{\text{ADNC}}$| (54)     | $\begin{cases} 2 \text{ if } F_0 = 1, \\ 2/3 \text{ otherwise} \end{cases}$ | $\begin{cases} 2 \text{ if } F_0 = 1, \\ 2/3 \text{ otherwise} \end{cases}$ |
| $D_{\text{DNC}}$  | (56)     | $5 \leq D_{\text{DNC}} < 5$ | $6 \leq D_{\text{DNC}} < 9$ |
| $D_{\text{ADNC}}$| (56)     | $\begin{cases} 1 \text{ if } F_0 = 1, \\ D_{\text{DNC}} \text{ otherwise} \end{cases}$ | $\begin{cases} 1 \text{ if } F_0 = 1, \\ D_{\text{DNC}} \text{ otherwise} \end{cases}$ |
| $n_1$ [frame]    | --       | 1                           | 2                           |
| $n_2$ [frame]    | --       | 1                           | 2                           |
| $M$ [user]       | --       | 2                           | 2                           |

TABLE 7. Rates and diversity orders of the systems based on the transfer matrices $G_{2 \times 4}$ and $G_{4 \times 8}$, when employing Scenario B of Fig. 6 and the number of RNs is $K = 2$. Note that the terminologies are defined in Table 1, while the main parameters are listed in Table 3.

| Parameters [BPS] | Equation | Scenario B, $G_{2 \times 4}$ | Scenario B, $G_{4 \times 8}$ |
|------------------|----------|-----------------------------|-----------------------------|
| $R_{\text{BC}}$  | (13)     | 3                           | 3                           |
| $R_{\text{DNC}}$ | (49)     | $1/3$                        | $1/3$                        |
| $R_{\text{ADNC}}$| (53)     | $\begin{cases} 1 \text{ if } F_0 = 1, \\ 1/3 \text{ otherwise} \end{cases}$ | $\begin{cases} 1 \text{ if } F_0 = 1, \\ 1/3 \text{ otherwise} \end{cases}$ |
| $\eta_{\text{DNC}}$| (50)     | 0.86                        | 0.86                        |
| $\eta_{\text{ADNC}}$| (54)     | $\begin{cases} 2 \text{ if } F_0 = 1, \\ 0.86 \text{ otherwise} \end{cases}$ | $\begin{cases} 2 \text{ if } F_0 = 1, \\ 0.86 \text{ otherwise} \end{cases}$ |
| $D_{\text{DNC}}$  | (56)     | $5 \leq D_{\text{DNC}} < 5$ | $6 \leq D_{\text{DNC}} < 9$ |
| $D_{\text{ADNC}}$| (56)     | $\begin{cases} 1 \text{ if } F_0 = 1, \\ D_{\text{DNC}} \text{ otherwise} \end{cases}$ | $\begin{cases} 1 \text{ if } F_0 = 1, \\ D_{\text{DNC}} \text{ otherwise} \end{cases}$ |
| $n_1$ [frame]    | --       | 1                           | 2                           |
| $n_2$ [frame]    | --       | 1                           | 2                           |
| $M$ [user]       | --       | 2                           | 2                           |

VI. PERFORMANCE RESULTS

The following two sections will discuss the performance results of Scenario A of Fig. 5 and Scenario B of Fig. 6, respectively. The main simulation parameters of both scenarios were listed in Table 3.

A. PERFORMANCE RESULTS OF SCENARIO A

The FER performance of the proposed DJSTTCM-aided DNC and ADNC schemes invoked in Scenario A is characterised in Fig. 13 and Fig. 14. It can be observed from all these FER performance results that our NC-aided schemes always perform better than the non-cooperative schemes, regardless of the correlation coefficient values. To elaborate further, Fig. 13 portrays the FER performance of Scenario A, when only a single RN ($K = 1$) is used, where the DJSTTCM-aided DNC/ADNC schemes are constructed using the transfer matrix $G_{2 \times 4}$ of Equation (14). As the figure shows, a substantial performance enhancement can be obtained, when employing our NC schemes benchmarked against its non-cooperative counterparts. More explicitly, at a FER level of $10^{-3}$ the DJSTTCM-ADNC scheme outperforms the DJSTTCM scheme by $\frac{E_b}{N_0} \approx 18.0$ dB for $\rho = 0.8$. This gain drops to $\frac{E_b}{N_0} \approx 14.7$ dB, when using the non-adaptive DJSTTCM-DNC scheme, as seen in Fig. 13.

Fig. 14 portrays the FER performance of our DJSTTCM-aided DNC/ADNC scheme of Fig. 4 using $K = 2$ RNs based on the transfer matrix $G_{2 \times 4}$ of Equation (14). As the figure shows, a substantial performance enhancement can be obtained, when employing our NC schemes benchmarked against its non-cooperative counterparts. More explicitly, at a FER level of $10^{-3}$ the DJSTTCM-ADNC scheme outperforms the DJSTTCM scheme by $\frac{E_b}{N_0} = 19.5 - 1.5 = 18.0$ dB for $\rho = 0.8$. This gain drops to $\frac{E_b}{N_0} \approx 14.7$ dB, when using the non-adaptive DJSTTCM-DNC scheme, as seen in Fig. 13. The adaptive feedback-flag based technique of Section V-B contributed a considerable $\frac{E_b}{N_0}$-performance improvement in comparison to that of the system operating without the adaptive mechanism. For example, an $\frac{E_b}{N_0}$-performance improvement of about $1.5$ dB is recorded at an FER of $10^{-3}$, when applying the adaptive feedback-flag based mechanism in the context of the DJSTTCM-ADNC for the $G_{2 \times 4}$-based scheme relying on $\rho = 0.8$, as seen in Fig. 13.

Fig. 14 portrays the FER performance of our DJSTTCM-aided DNC/ADNC scheme of Fig. 4 using $K = 2$ RNs based...
TABLE 8. System performance of the proposed DJSTTCM-DNC/ADNC scheme of Fig. 4 in Scenario A of Fig. 5 using simulation parameters of Table 3. The results are extracted from Fig. 13 and Fig. 14 at a FER level of $10^{-3}$.

| Scheme             | $p_c$ | $\rho$ | Gain (dB) |
|--------------------|-------|--------|----------|
| DJSTTCM-DNC $G_{2\times4}$ Fig. 13 | 0.10  | 0.80   | 14.7     |
|                    | 0.20  | 0.60   | 14.6     |
|                    | 0.40  | 0.20   | 16.5     |
| DJSTTCM-ADNC $G_{2\times4}$ Fig. 13 | 0.10  | 0.80   | 18.0     |
|                    | 0.20  | 0.60   | 17.4     |
|                    | 0.40  | 0.20   | 19.0     |
| DJSTTCM-DNC $G_{4\times8}$ Fig. 14 | 0.10  | 0.80   | 17.5     |
|                    | 0.20  | 0.60   | 16.6     |
|                    | 0.40  | 0.20   | 18.0     |
| DJSTTCM-ADNC $G_{4\times8}$ Fig. 14 | 0.10  | 0.80   | 19.5     |
|                    | 0.20  | 0.60   | 18.6     |
|                    | 0.40  | 0.20   | 20.0     |

As expected, employing a higher order transfer matrix improves the attainable performance further. For example, an impressive gain of about 19.5 dB is achieved when comparing the DJSTTCM-ADNC scheme to the DJSTTCM benchmark scheme for a correlation coefficient of $\rho = 0.8$. This performance improvement is an explicit benefit of the higher diversity gain offered by the $G_{4\times8}$-based arrangements over their $G_{2\times4}$-based counterparts. Similarly, applying our ADNC mechanism is expected to provide the scheme with a further $[E_b/N_0]_t$ gain. To elaborate, our adaptive DJSTTCM-ADNC schemes approach a FER = $10^{-3}$ at 2 dB lower power than its non-adaptive DJSTTCM-DNC counterparts, as seen in Fig. 14. Table 8 summarises the attainable performance gains of our proposed schemes, namely of the DJSTTCM-DNC and DJSTTCM-ADNC, for Scenario A in comparison to the benchmark scheme dispensing with NC at an integrity requirement of FER = $10^{-3}$.

Fig. 15 quantifies the schemes’ effective per user throughput against SNR, for our DJSTTCM-ADNC scheme, when employing $K = 1$ RN and $K = 2$ RNs. According to Equation (50) the non-adaptive schemes have an effective per user throughput of $\eta_{DNC} = 0.5$ [BPS], when a single RN is used. However this throughput is reduced to $\eta_{DNC} = 1/3$ [BPS], when adding one more RN, as shown in Fig.15(a) and Fig.15(b), respectively. As expected, upon invoking the ADNC scheme the overall normalised throughput, $\eta_{ADNC}$, increases when SNR increases. Hence, in the high-SNR region, more IFs may be recovered at the DN directly from the SNs, in which case $E[K_{AD}]$ of Equation (54) tends to zero. This implies that less PFs are required as SNR increases, where $\eta_{ADNC}$ might asymptotically reach 1 BPS, which simply corresponds to the direct link’s rate computed from Equation (13). Note that, this would have a direct delay and decoding complexity reduction, as the number of number of PFs during the cooperative phase will be decreased. Therefore, Equation (54) implies that the effective throughput of the adaptive scheme, namely $\eta_{ADNC}$, exhibits a near-instantaneously time-variant nature, depending on the SNR of each transmission session.
When aiming for a fair comparison, using the SNR $t$ might be not suitable for a FER performance comparison. Thus, we have considered the transmit SNR per information bit $[E_b/N_0]_{[dB]} = \text{SNR}_t[\text{dB}] - 10 \log_{10}(\eta_{\text{ADNC}})$, where the effect of the rate fluctuation has been eliminated.

**TABLE 9.** System performance of the proposed DJSTTCM-DNC/ADNC scheme of Fig. 4 when employing Scenario B of Fig. 6 and simulation parameters of Table 3 are used. The results are extracted from Fig. 16 and Fig. 17 when aiming for FER level of $10^{-3}$.

| Scheme          | $p_c$ | $p$  | Gain (dB) |
|-----------------|-------|------|-----------|
| DJSTTCM-DNC $G_{2 \times 4}$ Fig. 16 | 0.10  | 0.80 | 23.7      |
|                 | 0.20  | 0.60 | 23.5      |
|                 | 0.40  | 0.20 | 24.5      |
| DJSTTCM-ADNC $G_{2 \times 4}$ Fig. 16 | 0.10  | 0.80 | 26.5      |
|                 | 0.20  | 0.60 | 25.2      |
|                 | 0.40  | 0.20 | 26.5      |
| DJSTTCM-DNC $G_{4 \times 8}$ Fig. 17 | 0.10  | 0.80 | 26.0      |
|                 | 0.20  | 0.60 | 25.5      |
|                 | 0.40  | 0.20 | 25.5      |
| DJSTTCM-ADNC $G_{4 \times 8}$ Fig. 17 | 0.10  | 0.80 | 27.4      |
|                 | 0.20  | 0.60 | 27.0      |
|                 | 0.40  | 0.20 | 27.2      |

When aiming for a fair comparison, using the SNR $t$ might be not suitable for a FER performance comparison. Thus, we have considered the transmit SNR per information bit $[E_b/N_0]_{[dB]} = \text{SNR}_t[\text{dB}] - 10 \log_{10}(\eta_{\text{ADNC}})$, where the effect of the rate fluctuation has been eliminated.

**B. PERFORMANCE RESULTS OF SCENARIO B**

As the schematic of Fig. 6 shows, each node of our Scenario B arrangement, namely the SNs, RNs and the DN are equipped with a single transmit and/or receive antenna. This structure
constitutes an attractive scheme, especially when aiming for a reduced-complexity design, where each of the RNs combines both of the received IFs during the BP into a SPM signal [28].

Similar to Section VI-A, we will first discuss the FER performance of Scenario B, followed by its achievable throughput. As expected, the FER performance of Scenario A is better than that of Scenario B, since the MIMO structure of the former improves the system performance at the cost of a higher hardware complexity. However, our proposed scheme is still capable of outperforming the non-cooperative scheme for all the correlation values considered, as shown in Fig. 16 and Fig. 17. More quantitatively, our proposed DJSTTCM-ADNC-aided $G_{2\times4}$ scheme of Fig. 4 requires only $[E_b/N_0]_t = 5.0$ dB to attain a FER $= 10^{-3}$, while the DJSTTCM dispensing with NC requires $[E_b/N_0]_t = 31.5$ dB at $\rho = 0.8$, as seen in Fig. 16. However, upon adding one more RN the proposed DJSTTCM-ADNC-aided $G_{4\times8}$ only as 4.1 dB to achieve FER $= 10^{-3}$, as shown in Fig. 17. To summarise, Table 9 listed the FER performance of the DJSTTCM-DNC/ADNC schemes performance for Scenario B of Fig. 6.

Fig. 18 shows that the effective per user throughput increases as the SNR increases, when the adaptive scheme is activated. In contrast to Scenario A, the DJSTTCM-ADNC using $G_{2\times4}$ requires almost SNR$_t = 14$ dB for asymptotically approaching a throughput of 1 BPS, as shown in Fig. 18(a). Otherwise similar trends prevail to those discussed in Section VI-B.

![FIGURE 19. The reduction of the transmitted PFs during the cooperative phase when the Scenario B with $K = 2$ RN for $\rho = 0.8$ and $\rho = 0.8$ is invoked.](image)

In order to investigate the decoding complexity reduction, we have analysed the complexity associated with the “DJSTTCM-ADNC” scheme for Scenario B with $K = 2$ RN, as shown in Fig. 19. Here the complexity reduction is quantified by determining the number of error-free IFs that can be recovered at the DN directly from the SNs. Hence, the RNs will avoid transmitting extra PFs that would be associated with significant decoding complexity. As Fig. 19 suggested, upon increasing SNR$_t$ values the complexity reduced considerably as at SNR$_t = 10$ dB only 20% and 5% of the PFs are transmitted for $\rho = 0.2$ and $\rho = 0.8$, respectively.

**VII. CONCLUSIONS**

In this work the transmission of correlated source signals was assisted by two different NC schemes, which exhibited a robust performance for transmission over hostile channels. The BER performance of our cooperative arrangements was characterised when subjected to both uncorrelated Rayleigh fading and a quasi-static Rayleigh fading channels. A significant performance degradation was exhibited for transmission over quasi-static Rayleigh fading channels.

As a counter-measure, the use of both DNC and ADNC were conceived, where the time diversity between the frames will be further exploited. A substantial gain of 19.5 dB was attained at a correlation coefficient $\rho = 0.8$ over its counterpart dispensing with NC, as evidenced by Fig. 14.

Furthermore, according to the resources availability, two scenarios were considered. In Scenario A each of the RNs and the DN were equipped with two antennas, while in Scenario B, all RNs and the DN had a single antenna. Despite having only a single antenna in Scenario B, a robust performance was attained. Quantitatively, our DJSTTCM-ADNC scheme only requires $E_b/N_0 = 5.0$ dB and $E_b/N_0 = 4.1$ dB for achieving a FER of $10^{-3}$ by the $G_{2\times4}$ and $G_{4\times8}$ schemes, respectively, as evidenced by Fig. 16 and Fig. 17.

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