



Network-coding-based Cooperative V2V Communication in Vehicular Cloud Networks

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Abstract. We investigate the potential of applying cooperative relaying and network coding techniques to support vehicle-to-vehicle (V2V) communication in vehicular cloud networks (VCN). A reuse-mode MIMO content distribution system with multiple sources, multiple relays, and multiple destinations under Nakagami-m fading is considered. We apply a class of finite field network codes in the relays to achieve high spatial diversity in an efficient manner and derive the system communication error probability that the destinations fail to recover the desired source messages. The results show that our method can improve the performance over conventional data transmission solutions.

Keywords: Vehicular cloud networks · Network coding · Cooperative relaying

1 Introduction

In the past decades, the ever-increasing numbers of vehicles have caused serious problems, such as congestion, accidents and pollution, all over the world. There is a strong desire for an efficient, safe, and clean road traffic system. The concept of intelligent transportation system (ITS) enabled by information and communication technology (ICT) has been accepted as the most promising solution [1]. As a key element in ITS, “smart vehicles” equipped with advanced on-board sensing and computation devices are designed to help reducing accidents caused by human errors, through the advance driving assistance system (ADAS) or even self-driving functions. Google’s self-driving car and Baidu’s Apollo platform are examples of autonomous driving vehicle and developing platform prototypes.

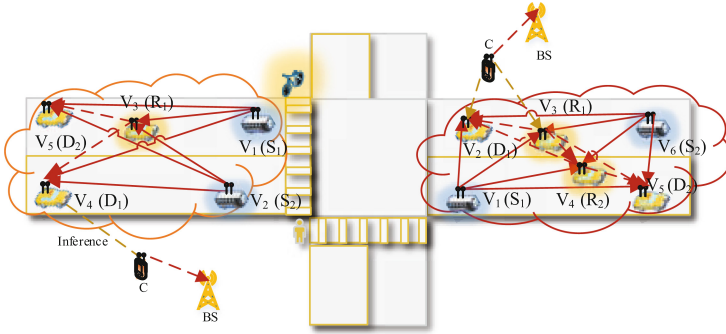


Fig. 1. System model.

One issue with most today's smart vehicle prototypes is that they normally work individually. Even though they have advanced sensors, their sensing range and reliability are relatively limited in complex driving conditions. Allowing vehicles to interact through wireless communications is seen as an effective solution. Since the application scenario is very different from traditional mobile Internet/wireless LAN, a number of wireless technologies dedicated for establishing the Internet of vehicles or V2X (vehicle to everything) communications have been developed in recent years, including e.g., the IEEE 802.11p Dedicated Short Range Communication (DSRC) technology and some LTE-based solutions [2]. More importantly, the current 5G research campaign also considers vehicular communication environment as a key application scenario [3].

With the support of 5G and other advanced V2X technologies, the data exchanged among vehicles and road-side units would not be limited to conventional small-size heart-beat or event-driven messages. Sharing content-rich sensing data will be feasible, which triggers a promising concept *Vehicular Cloud Network* (VCN) [4, 5]. VCN stems from the idea of cloud computing and is envisioned as a framework where multiple vehicles share their sensing, communication, computation, and storage resources to realize functions that each individual vehicle cannot. For example, sharing sensing data allows each vehicle to access the others' sensing resources to extend its own ability of perceiving the surrounding environment. Sharing communication resources (e.g., bandwidth and power) potentially enhances the data exchange capability within the network.

Two example application scenarios of VCN are shown in Fig. 1. The left hand side (LHS) illustrates a VCN with five vehicles conducting cooperative objective detection in complicated driving conditions such as road intersections [6]. V_1 and V_2 have advantageous locations to obtain accurate sensing results regarding their surrounding environment, e.g., the existence, position and movement of obstacles near the intersection corner. Sharing their sensing data with those who relatively far away from the traffic scene (i.e., V_4 and V_5) enables greatly improved sensing range. The right hand side (RHS) of Fig. 1 shows a VCN formed by six autonomous vehicles operating in a cooperative driving scenario

[7]. Now V_1 and V_6 act as sensing information sources and desire to distribute their data to V_2 and V_5 . These illustrate the concept of sensing resource sharing.

However, due to fast changing network topology and complicated signal propagation environment, the quality of message sharing is often hard to guarantee. In this case, cooperative relaying can serve to significantly improve performance [8]. For example, in the LHS scenario of Fig. 1, V_3 shares its own communication resources with others and serves as a relay to guarantee the sensing data to be delivered from V_1 and V_2 to V_4 and V_5 with low probability of failure. In the RHS scenario, the message sharing can be helped by V_3 and V_4 acting as relays.

The conventional relay forwarding operation is to directly repeat received signals. In multi-source scenarios, such a repetition-coding based relaying strategy does not efficiently use the available channel resources. In this paper, we study applying network coding techniques to handle this issue. Specifically, we consider a reuse-mode multi-source multi-relay multi-destination cooperative MIMO V2V communication scenario in VCN. A class of maximum distance separable finite field network codes (MDS-FFNC) [9–11] is applied in the relays to attain high spatial diversity in an efficient fashion. We derive the system communication error probability, in a Nakagami- m fading environment. It is shown that our method can improve performance over conventional direct transmission and repetition-coding based relaying schemes.

2 System Model

We consider a VCN scenario with a total of U member vehicles V_1, \dots, V_U , among which M vehicles (denoted as sources S_1, \dots, S_M) have attained some sensing data from their own sensors, represented respectively by independent messages I_{S_1}, \dots, I_{S_M} , and intend to share them (i.e., sensing resource sharing) with N other members (denoted as destinations D_1, \dots, D_N). To ensure the quality of the desired message sharing, K vehicles (denoted as relays R_1, \dots, R_K) can serve as cooperative relays (i.e., communication resource sharing). Practical applications abstracted by such a multi-source multi-relay multi-destination content distribution network are illustrated in Fig. 1.

The set of the M source messages to be shared within the VCN is denoted as $\mathcal{I} = \{I_{S_1}, \dots, I_{S_M}\}$. We consider the case that every destination D_i is interested in attaining the whole source message set \mathcal{I} in order to reinforce its own sensing capability. Therefore, the communication in the considered VCN is successful only if all D_1, \dots, D_N correctly recover \mathcal{I} . Otherwise, if any of them is not capable of completely recovering \mathcal{I} , a system communication error is reported.

In addition, in order to efficiently utilize available channel resources, we consider that the V2V transmissions in our VCN can be potentially operated in a reuse mode. In other words, all the aforementioned message delivery process can coexist with the uplink transmission of a certain cellular user, denoted as C . A proper cellular user scheduling strategy is assumed such as that C is chosen to be close to its serving base station. The V2V transmission power is limited, since message sharing in the considered VCN occurs locally in a limited area, to

avoid introducing intolerable interference to the base station. But the reception of each member in the VCN may experience interference from C.

Every node a in the considered system can potentially have $A_a \geq 1$ antennas. All message transmissions are conducted in a narrow-band Nakagami- m slow fading environment. The channel fading matrix between transmitting node a and receiving node b is denoted by an $A_b \times A_a$ matrix $\mathbf{H}_{b,a}$. The element on the j th ($j \in \{1, \dots, A_b\}$) row and i th column ($i \in \{1, \dots, A_a\}$) of $\mathbf{H}_{b,a}$, denoted by h_{bj,a^i} , represents the fading coefficient between the i th antenna of a and j th antenna of b . All the coefficients in $\mathbf{H}_{b,a}$ are modeled by independently and identically distributed (i.i.d.) random variables with absolute values following a Nakagami distribution with parameters $m_{b,a}$ (Nakagami- m fading parameter) and $\hat{\Omega}_{b,a}$ (expected channel power gain) i.e., $|h_{bj,a^i}| \sim \text{Nakagami}(m_{b,a}, \hat{\Omega}_{b,a})$. This means that the channel power gain $|h_{bj,a^i}|^2$ follows a Gamma distribution with shape parameter $\alpha_{b,a} = m_{b,a}$ and rate parameter $\beta_{b,a} = \frac{m_{b,a}}{\hat{\Omega}_{b,a}}$ [12].

The message exchange in the considered VCN is conducted in a slotted fashion. Each message is encoded using a capacity-achieving Gaussian random codeword, so that focus of performance analysis can be mainly put on the impact of channel variation. Every codeword is transmitted using a unit-bandwidth time-division-multiple-access (TDMA) time slot. The channel fading coefficients remain unchanged during the whole period of transmission and are known only at the associated receivers. Since transmitter-side channel knowledge is not available, dynamic power control and rate adaptation are not performed. Therefore, all the messages I_{S_1}, \dots, I_{S_M} have the same data rate R bits per codeword. A transmitter a evenly spreads its power P_a across its A_a antennas and applies orthogonal space-time block coding (OSTBC) to broadcast its message.

In the next section, we will elaborate the message transmission process.

3 Message Transmission Process

The complete transmission of the message set \mathcal{I} from the M sources to the N destinations, through the help of K relays, is carried out using $M + K$ individual time slots, each of which is allocated to a transmitting vehicle. Instead of demanding the relays to simply repeat the source messages, we consider applying MDS-FFNC [9–11] at the relays. In particular, each relay R_k ($k \in \{1, \dots, K\}$) is assigned with a set of MDS-FFNC coding coefficients $\omega_k^{[1]}, \dots, \omega_k^{[M]}$. All the coding coefficients within the network are properly constructed in advance to guarantee the transfer matrix $\mathbf{G} = [\mathbf{I}_M \ \mathbf{W}]^T$ to be non-singular, where \mathbf{I}_M is an $M \times M$ identity matrix and \mathbf{W} is the $M \times K$ coefficient matrix whose k th column elements are $\omega_k^{[1]}, \dots, \omega_k^{[M]}$. Therefore, any M elements of the output of the encoding process $\mathbf{G} \cdot [I_{S_1} \ \dots \ I_{S_M}]^T$, where summations are taken in a certain finite grid, are sufficient to recover I_{S_1}, \dots, I_{S_M} . Using these coefficients, if relay R_k correctly attains the complete message set \mathcal{I} , it can re-encode the source messages to a new message using $I_{R_k} = \sum_{i=1}^M \omega_k^{[i]} I_{S_i}$. Knowing any M messages among $I_{S_1}, \dots, I_{S_M}, I_{R_1}, \dots, I_{R_K}$ is sufficient to recover \mathcal{I} .

The detailed message transmission process can be described as follows. The first M time slots are allocated to S_1, \dots, S_M (i.e., during the slot i ($i \in \{1, \dots, M\}$), the source S_i broadcasts its message I_{S_i} to all relays and destinations). After all sources complete transmission, the next K time slots are reserved for the relays R_1, \dots, R_K respectively. All the relays also listen to each other in order to recover the source messages. During time slot $M+k$, if R_k obtains all the messages in \mathcal{I} from its received signals in the previous $M+k-1$ time slots (i.e., it can correctly recover at least M messages among $I_{S_1}, \dots, I_{S_M}, I_{R_1}, \dots, I_{R_{k-1}}$), it re-encodes the source messages into I_{R_k} and forwards it to other relays and the destinations. Otherwise, R_k keeps silent.

Clearly, during each of the $M+K$ time slots, if a transmitting vehicle a ($a \in \{S_1, \dots, S_M, R_1, \dots, R_K\}$) is actually activated as being scheduled, the received signal at any receiving vehicle b ($b \in \{R_1, \dots, R_K, D_1, \dots, D_N\}$) can be expressed as the following general form:

$$\mathbf{y}_{b,a} = \sqrt{\frac{P_a}{A_a}} \mathbf{H}_{b,a} \mathbf{x}_a + \sqrt{\frac{P_C}{A_C}} \mathbf{H}_{b,C} \mathbf{x}_C + \mathbf{n}_b, \quad (1)$$

where $\mathbf{y}_{b,a}$ is the A_b -dimensional received signal, \mathbf{x}_a is the transmitted signal from a , \mathbf{x}_C denotes the co-channel interference from cellular user C , and \mathbf{n}_b represents additive white Gaussian noise with total power N_0 .

Since each vehicle uses OSTBC to transmit its message in the VCN, the received signal-to-interference-plus-noise-ratio (SINR) can be expressed as [13]

$$\gamma_{b,a} = \frac{\|\mathbf{H}_{b,a}\|_F^2 \cdot \rho_a}{\|\mathbf{H}_{b,C}\|_F^2 \cdot \rho_C + 1}, \quad (2)$$

where $\|\cdot\|_F$ represents the Frobenius norm, and $\rho_a = \frac{P_a}{A_a N_0}$ and $\rho_C = \frac{P_C}{A_C N_0}$ represent transmitter-side signal-to-noise ratio (SNR).

As we mentioned earlier, The probability of occurring system communication error event can be expressed as

$$P_{\text{err}} = P_r \{D_i \text{ cannot recover } \mathcal{I}, \exists i \in \{1, \dots, N\}\}. \quad (3)$$

We will provide the method to derive P_{err} in the following section.

4 System Error Performance Analysis

Due to the facts that the probability of activation of each relay depends on the other relays that are scheduled before it, and that the decoding events at different destinations are related (in fact, they are conditionally independent given the decoding set of the relays), the derivation of P_{err} is actually quite involved. In this paper, we decouple the calculation of P_{err} into three elementary probability expressions that would be easier to tackle.

The first is the link decoding probability $\mathcal{P}_{b,a}^L$ that, during each time slot, a receiving vehicle b correctly decodes the transmit signal of the activated vehicle

a. We consider Gaussian random coding so that this probability can be found by the probability that the SINR expressed by (2) is larger than the message data rate R , i.e., $\mathcal{P}_{b,a}^L = P_r\{\log_2(1 + \gamma_{b,a}) > R\}$.

The second elementary probability is the probability that a particular set of activated relays occurs. Let us use $\Delta = [\delta_1, \dots, \delta_K]$ to denote the activation behaviors of the K relays after the scheduled $M + K$ time slots, where $\delta_k = 1$ denotes R_k is able to recover \mathcal{I} from its received signals and $\delta_k = 0$ denotes the opposite situation. The second elementary probability is denoted by \mathcal{P}_Δ .

The third, $\mathcal{P}_{D_n|\Delta}$ ($n \in \{1, \dots, N\}$), is the conditional probability that the destination D_n can fully recover all the source messages given a particular relay activation behavior Δ . Since the destinations' decoding capabilities are conditionally independent, the system's error probability P_{err} can be calculated by

$$P_{\text{err}} = 1 - \sum_{\Delta} \left(\mathcal{P}_\Delta \prod_{n=1}^N \mathcal{P}_{D_n|\Delta} \right), \tag{4}$$

where the summation is taken for all $\delta_k \in \{0, 1\}, k \in \{1, \dots, K\}$, and both \mathcal{P}_Δ and $\mathcal{P}_{D_n|\Delta}$ are functions of $\mathcal{P}_{b,a}^L$.

(1) *Link decoding probability $\mathcal{P}_{b,a}^L$:*

The link decoding probability $\mathcal{P}_{b,a}^L$ can also be written as $P_r\{\gamma_{b,a} > 2^R - 1\}$. To simplify presentation, we define equivalent received SNR $\hat{\gamma}_{b,a} = \|\mathbf{H}_{b,a}\|_F^2 \cdot \rho_a$, $\hat{\gamma}_{b,C} = \|\mathbf{H}_{b,C}\|_F^2 \cdot \rho_C$, and $\gamma_{th} = 2^R - 1$. Now $\mathcal{P}_{b,a}^L = P_r\left\{\frac{\hat{\gamma}_{b,a}}{\hat{\gamma}_{b,C} + 1} > \gamma_{th}\right\}$.

It is easy to see that $\|\mathbf{H}_{b,a}\|_F^2$ (resp. $\|\mathbf{H}_{b,C}\|_F^2$) is the sum of $A_b \times A_a$ (resp. $A_b \times A_C$) i.i.d. Gamma random variables with shape parameter $m_{b,a}$ and rate parameter $\frac{m_{b,a}}{\hat{\Omega}_{b,a}}$ (resp. $m_{b,C}$ and $\frac{m_{b,C}}{\hat{\Omega}_{b,C}}$) [13]. The sum of n i.i.d. Gamma random variables with shape parameter α and rate parameter β is Gamma distributed with parameters $n\alpha$ and β . Thus the pdf of $\hat{\gamma}_{b,a}$ is

$$f_{\hat{\gamma}_{b,a}}(x) = \left(\frac{m_{b,a}}{\rho_a \hat{\Omega}_{b,a}}\right)^{m_{b,a} A_b A_a} \cdot \frac{x^{m_{b,a} A_b A_a - 1}}{\Gamma(m_{b,a} A_b A_a)} \cdot \exp\left(-\frac{m_{b,a} x}{\rho_a \hat{\Omega}_{b,a}}\right). \tag{5}$$

The pdf of $\hat{\gamma}_{b,C}$ can be expressed similarly, by replacing $m_{b,a}, A_a, \hat{\Omega}_{b,a}, \rho_a$ with $m_{b,C}, A_C, \hat{\Omega}_{b,C}, \rho_C$ respectively. As a result, we can derive $\mathcal{P}_{b,a}^L$ as

$$\mathcal{P}_{b,a}^L = \left\{ \frac{\hat{\gamma}_{b,a}}{\hat{\gamma}_{b,C} + 1} \geq \gamma_{th} \right\} = \int_0^\infty P_r\{\hat{\gamma}_{b,a} \geq \gamma_{th}(x + 1)\} f_{\hat{\gamma}_{b,C}}(x) dx. \tag{6}$$

Denote $\Omega_{b,a} = \rho_a \hat{\Omega}_{b,a}$ and $\Omega_{b,C} = \rho_C \hat{\Omega}_{b,C}$. Using the CDF of Gamma distribution, we have

$$P_r\{\hat{\gamma}_{b,a} \geq \gamma_{th}(x + 1)\} = \exp\left(-\frac{m_{b,a} \gamma_{th}(x + 1)}{\Omega_{b,a}}\right) \sum_{k=0}^{m_{b,a} A_b A_a - 1} \frac{1}{k!} \left(\frac{m_{b,a} \gamma_{th}}{\Omega_{b,a}}(x + 1)\right)^k \tag{7}$$

Now we can substitute (5) and (7) into (6) and take integration

$$\begin{aligned}
 \mathcal{P}_{b,a}^L &= \exp\left(-\frac{m_{b,a}\gamma th}{\Omega_{b,a}}\right) \left(\frac{m_{b,C}}{\Omega_{b,C}}\right)^{A_b A_C m_{b,C}} \frac{1}{\Gamma(A_b A_C m_{b,C})} \sum_{k=0}^{A_b A_a m_{b,a}-1} \sum_{n=0}^k \binom{k}{n} \frac{1}{k!} \\
 &\quad \cdot \left(\frac{m_{b,a}\gamma th}{\Omega_{b,a}}\right)^k \cdot \int_0^\infty \exp\left(-\left(\frac{m_{b,a}\gamma th}{\Omega_{b,a}} + \frac{m_{b,C}}{\Omega_{b,C}}\right)x\right) x^{n+A_b A_C m_{b,C}-1} dx \\
 &= \exp\left(-\frac{m_{b,a}\gamma th}{\Omega_{b,a}}\right) \left(\frac{m_{b,C}}{\Omega_{b,C}}\right)^{A_b A_C m_{b,C}} \frac{1}{\Gamma(A_b A_C m_{b,C})} \cdot \sum_{k=0}^{m_{b,a} A_b A_a - 1} \sum_{n=0}^k \binom{k}{n} \frac{1}{k!} \\
 &\quad \cdot \left(\frac{m_{b,a}\gamma th}{\Omega_{b,a}}\right)^k \left(\frac{m_{b,a}\gamma th}{\Omega_{b,a}} + \frac{m_{b,C}}{\Omega_{b,C}}\right)^{-(n+A_b A_C m_{b,C})} \cdot (n + A_b A_C m_{b,C} - 1)! \quad (8)
 \end{aligned}$$

(2) *Relay activation probability* \mathcal{P}_Δ :

$\mathcal{P}_\Delta = P_r\{\delta_1, \dots, \delta_K\}$ denotes the probability that a particular relay activation sequence occurs. Whether a relay can be activated is related to the activities of those relays scheduled prior to it. Hence we can decompose \mathcal{P}_Δ using the chain rule $\mathcal{P}_\Delta = P_r\{\delta_1\}P_r\{\delta_2|\delta_1\}P_r\{\delta_3|\delta_1, \delta_2\} \cdots P_r\{\delta_K|\delta_1, \dots, \delta_{K-1}\}$. In what follows, we will focus on two expressions $P_r\{\delta_1\}$ and $P_r\{\delta_k|\delta_1, \dots, \delta_{k-1}\}$.

First, $P_r\{\delta_1 = 1\}$ denotes the probability that R_1 can fully recover \mathcal{I} . This event happens only if R_1 successfully decodes the signals transmitted from all the sources. Using the link decoding probability $\mathcal{P}_{b,a}^L$ (8), we can directly have

$$P_r\{\delta_1 = 1\} = \prod_{s=1}^M \mathcal{P}_{R_1, S_s}^L \quad \text{and} \quad P_r\{\delta_1 = 0\} = 1 - \prod_{s=1}^M \mathcal{P}_{R_1, S_s}^L. \quad (9)$$

To derive $P_r\{\delta_k|\delta_1, \dots, \delta_{k-1}\}$, we define a decoding relay set \mathcal{R}_{k-1} after the $(M + k - 1)$ th time slot. This set contains the relays corresponding to $\delta_i = 1$ among R_1, \dots, R_{k-1} , and therefore has size $\sum_{i=1}^{k-1} \delta_i$. Thus $P_r\{\delta_k = 1|\delta_1, \dots, \delta_{k-1}\}$ is the probability that R_k can correctly decode at least M out of the $M + \sum_{i=1}^{k-1} \delta_i$ signals it received from the M sources and the $\sum_{i=1}^{k-1} \delta_i$ relays in \mathcal{R}_{k-1} . We further define an $(M + \sum_{i=1}^{k-1} \delta_i) \times 1$ indicator vector $\kappa^{[k-1]} = [\kappa_1^{[k-1]}, \dots, \kappa_{M+\sum_{i=1}^{k-1} \delta_i}^{[k-1]}]$, where each element $\kappa_j^{[k-1]} \in \{0, 1\}$ denotes whether R_k can decode the j th node in $\mathcal{S} \cup \mathcal{R}_{k-1}$, and \mathcal{S} is the set of all sources. Now

$$P_r\{\delta_k = 1|\delta_1, \dots, \delta_{k-1}\} = \sum_{\sum_j \kappa_j^{[k-1]} \geq M} \left(\prod_{a_i \in \mathcal{S} \cup \mathcal{R}_{k-1}} (\mathcal{P}_{R_k, a_i}^L)^{\kappa_i^{[k-1]}} (1 - \mathcal{P}_{R_k, a_i}^L)^{1 - \kappa_i^{[k-1]}} \right) \quad (10)$$

Again, $P_r\{\delta_k = 0|\delta_1, \dots, \delta_{k-1}\} = 1 - P_r\{\delta_k = 1|\delta_1, \dots, \delta_{k-1}\}$. Now, for each $\Delta = [\delta_1, \dots, \delta_K]$, we substitute (9) and (10) into the chain rule to attain \mathcal{P}_Δ .

(3) *Destination conditional decoding probability* $\mathcal{P}_{D_n|\Delta}$:

We follow the logic presented in the above subsection to calculate $\mathcal{P}_{D_n|\Delta}$. In particular, define \mathcal{R}_K to be the decoding relay set after all the relays finish forwarding source messages. This set contains the relays corresponding to $\delta_i = 1$ among R_1, \dots, R_K , and has size $\sum_{i=1}^K \delta_i$. Thus $\mathcal{P}_{D_n|\Delta}$ is the probability that D_n can correctly decode at least M out of the $M + \sum_{i=1}^K \delta_i$ signals it received from the M sources and all activated relays. Again, we define an $(M + \sum_{i=1}^K \delta_i) \times 1$ indicator vector $\pi^{[n]} = [\pi_1^{[n]}, \dots, \pi_{M+\sum_{i=1}^K \delta_i}^{[n]}]$, where each element $\pi_i^{[n]} \in \{0, 1\}$ denotes whether D_n can decode the i th node in $\mathcal{S} \cup \mathcal{R}_K$. We have

$$\mathcal{P}_{D_n|\Delta} = \sum_{\sum_j \pi_j^{[n]} \geq M} \left(\prod_{a_i \in \mathcal{S} \cup \mathcal{R}_K} (\mathcal{P}_{D_n, a_i}^L)^{\pi_i^{[n]}} (1 - \mathcal{P}_{D_n, a_i}^L)^{1 - \pi_i^{[n]}} \right). \quad (11)$$

Substituting (10) and (11) into (4) leads to the system error probability.

Remark: The above derivation is complicated because the large-scale path loss, transmit power and antenna numbers can be different for different V2V links, which makes the decoding probability of each link unique. If the considered VCN system has the same fading and path loss factors for all V2V links (i.e., $m_{b,a} = m$ and $\Omega_{b,a} = \Omega$), and that between C and vehicles ($m_{b,C} = m_C$ and $\Omega_{b,C} = \Omega_C$), and has the same transmit power and antennas at each vehicle (i.e., $P_a = P_V$ and $A_a = A$), we have the same link decoding probability $\mathcal{P}_{b,a}^L$ for all V2V pairs, which can be denoted by \mathcal{P}^L . We have simplified expressions

$$P_r\{\delta_k = 1 | \delta_1, \dots, \delta_{k-1}\} = \sum_{j=M}^{M+\sum_{i=1}^{k-1} \delta_i} \binom{M+\sum_{i=1}^{k-1} \delta_i}{j} (\mathcal{P}^L)^j (1 - \mathcal{P}^L)^{M+\sum_{i=1}^{k-1} \delta_i - j}$$

$$\mathcal{P}_{D_n|\Delta} = \sum_{j=M}^{M+\sum_{i=1}^K \delta_i} \binom{M+\sum_{i=1}^K \delta_i}{j} (\mathcal{P}^L)^j (1 - \mathcal{P}^L)^{M+\sum_{i=1}^K \delta_i - j}.$$

5 Numerical Results

In what follows, we use numerical results to demonstrate the advantage of the proposed scheme. We consider an example network with $M = 2$ sources, $K = 2$ relays and $N = 2$ or $N = 10$ destinations. Each node has 2 antennas. We demand all the vehicles to transmit with the same power P_a . The relationship between P_a and P_C is set to be $\frac{P_a}{P_C} = \tau P_a^\theta = P_a^{0.8}$, so that we can scale them together by changing P_a . The system bandwidth is set as $W = 100$ kHz, and the noise density is -174 dBm/Hz. The Nakagami fading parameters are set to $m_{b,a} = 2$, $m_{b,C} = 4$. $\Omega_{b,a}$ and $\Omega_{b,C}$ take into account the path loss as $\Omega_{b,a} = \frac{10^{0.1 \cdot (101 \log_{10}(1000 P_a) - PL(d_{b,a}))}}{1000 N_0 A_a}$, $\Omega_{b,C} = \frac{10^{0.1 \cdot (101 \log_{10}(1000 P_C) - PL(d_{b,C}))}}{1000 N_0 A_C}$, $PL(d_{b,a}) = 103.4 + 24.2 \log_{10} d_{b,a}$ and $PL(d_{b,C}) = 127 + 30 \log_{10} d_{b,C}$, where $d_{b,a}$ denotes the distances between a V2V pair a and b , $d_{b,C}$ denotes that between C

and b , and the path loss setting follows [14] for V2V and C2V communication environments. All distances $d_{b,a}$ ($d_{b,c}$) are generated from Gaussian distribution with mean 50 m (200 m) and standard deviation 2 m (5 m).

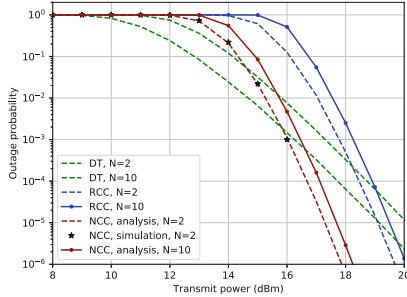


Fig. 2. System error performance comparison

In addition to our scheme (termed NCC, networking coding cooperation), we also consider the direct transmission (DT) and the repetition-coding based cooperation (RCC) scheme. For fair comparison, we define the average transmission rate of each scheme to be $\bar{R} = 0.1$ bps/Hz. Figure 2 shows that the analytical error performance of our NCC scheme is in line with results attained through simulation. This demonstrates the accuracy of our derivation. The DT scheme ($R = \bar{R}MW$ bits) has lower diversity gain due to the lack of the assistance of relays (i.e., communication resource sharing in VCN) to combat fading and interference. Higher power has to be consumed to guarantee sufficiently good performance. The RCC scheme attains the same diversity as NCC. But since it has to use a high data rate ($R = \bar{R}M(K+1)W$ bits) to compensate inefficient channel usage, which causes difficulties in the decoding process at the relays and destinations, especially when the received SNR is relative low. Hence the advantages of cooperative transmission emerge only when the transmit power of each node is sufficiently large. Finally, our NCC ($R = \bar{R}(M+K)W$ bits) scheme adopts the efficient network coding concept and properly chooses the coding structure suitable for multi-source multi-relay networks. Although it uses more time slots than the DT scheme to conduct transmissions, the increase in channel consumption is limited. This fact balances the decoding errors due to fading and high data rate. The situation will become severe if more information sources and destinations are involved in the VCN, because it is easier to make errors. But high diversity still remains. These clearly show the benefits of our scheme.

6 Conclusion

We have studied applying cooperative relaying and network coding techniques to support V2V communication in VCN. We have considered a reuse-mode MIMO multi-sources, multi-relay, and multi-destination network under Nakagami-m

fading. A class of MDS-FFNC is applied and the closed-form system error probability has been derived. Our results have demonstrated the potential of combining relaying and network coding techniques in future VCN.

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