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BNNC: Improving Performance of Multipath Transmission in Heterogeneous Vehicular Networks

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ABSTRACT Nowadays, multipath transmission scheme in heterogeneous vehicular networks has become an emerging topic. It is a great challenge to overcome the unreliability of heterogeneous wireless network in vehicle-to-ground multipath communication. Many multipath transmission schemes were proposed. However, most schemes do not consider the unreliability of wireless networks and are difficult to deploy in vehicle-to-ground communications. Even though part of the multipath transmission schemes consider the unreliability of wireless networks, their overhead is too large to be deployed in vehicle-to-ground multipath communication. Therefore, we propose a **B**ig**N**um **N**etwork **C**oding (BNNC) scheme for vehicle-to-ground multipath communication. Compared with the Opportunistic Routing (OR) scheme, BNNC's network resource overhead is smaller. Compared with other network coding schemes, it is a better trade-off between coding flexibility and codec efficiency. In this paper, we propose a brand-new mathematical model for network coding which can effectively improve the reliability of the vehicular networks. Secondly, based on the mathematical model, we design BNNC multipath transmission scheme. Compared with the current network coding scheme, the BNNC scheme considers coding flexibility and codec efficiency while ensuring multipath transmission reliability. Thirdly, we compare BNNC scheme with many current multipath transmission schemes through lots of simulations and real tests. The results show that the BNNC scheme is significantly superior to the other network coding schemes in terms of computational performance. And in terms of the network performance, the BNNC scheme can overcome the unreliability of wireless networks in multipath transmission and it has lower overhead than OR scheme.

INDEX TERMS Vehicular networks, multipath transmission, reliability, network coding.

I. INTRODUCTION

Vehicle-to-ground communication is an important part of the Vehicular Networks [1], [2]. As more devices are added to support greater automation, and multimedia systems entertain us and provide vision, therefore the vehicle-to-ground communication is coming under increasing pressure [3]. Providing a high performance and reliable vehicle-to-ground communication network for on-board users and devices is a challenging task [4]–[6].

Studies have shown that the use of heterogeneous wireless networks between vehicles and ground can establish a high performance and reliable vehicle-to-ground communication network [7], [8]. Early studies such as Information Raining [9], MAR [10], and these studies focused on how to access heterogeneous networks. In recent years, studies have

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focused on how to comprehensively utilize heterogeneous network resources in mobile scenario to improve overall performance [11], [12].

However, vehicle-to-ground multipath communication faces many challenges, the most serious challenge is the unreliability of heterogeneous wireless networks [13], [14]. In order to improve the reliability of multipath transmission, there have been many works dedicating on it, for example [15]–[17] and [18]. These works can be divided into two categories, one is Opportunistic Routing (OR) and the other is Network Coding (NC) [19]. The essence of the OR scheme is to send each packet to the peer through all available links to improve the reliability [20], [21]. However, the network resource overhead of OR scheme is enormous.

With the same network resource overhead, NC can improve the reliability of vehicle-to-ground communication more effectively than other schemes. The essence of NC scheme is to improve the reliability of multipath transmission by adding some redundancy [22]. During the sending process, the coding algorithm groups the packets and increases redundancy. During the receiving process, a sufficient number of packets, rather than all packets, are received to recover the original packets. The network resource overhead of the NC scheme is less than the OR scheme [23], [24]. However, the current NC schemes only consider improving the reliability of the system, instead of the trade-off between coding flexibility and codec efficiency.

In this paper, we propose a **B**ig**N**um **N**etwork **C**oding (BNNC) scheme for vehicular networks. Bignum means a very large integer. It is usually larger than the largest integer that a byte can represent (2^{64}). The essence of the BNNC scheme is to consider a packet as a bignum. The encoding and decoding processes are transformed into an integer linear operation. Therefore, the BNNC scheme can work in the set of integers instead of the Galois Field [25] to improve the efficiency of encoding and decoding. The processes of encoding and decoding in BNNC scheme use the Independent Matrix (IM) that we propose. The IM is a $n \times k$ matrix that any k rows are independent. In the encoding process, the BNNC encodes k packets and obtains n packets through the IM. In the decoding process, the original k packets can be recovered as long as any k packets are received. Through this encoding and decoding process, the BNNC scheme can effectively improve the reliability of multipath transmission. Moreover, because all the elements in the matrix are integers, its codec efficiency is much higher than that of Galois Field arithmetic. Therefore, the BNNC scheme considers coding flexibility and codec efficiency while ensuring reliability of multipath transmission.

Our contributions in this paper are summarized as follow. Firstly, we propose a mathematical model for network coding based on Bignum. It can significantly improve the reliability of vehicle-to-ground multipath communication. Secondly, based on the mathematical model, we design a multipath transmission scheme based on Bignum network coding. Compared with the current network coding scheme, the BNNC scheme considers coding flexibility and codec efficiency while ensuring multipath transmission reliability. Thirdly, we verified the efficiency and reliability of the network coding scheme through a lot of simulations and practical tests.

The structure of the paper is organized as follows. Section II reviews some related works about multipath transmission in vehicular networks and network coding schemes. In Section III, we give an overview of BNNC scheme. In Section IV, we introduce the mathematical model of BNNC scheme. In Section V, we introduce the implementation of BNNC scheme. In Section VI and VII, we verify the performance of the BNNC scheme through simulations and real tests. In Section VIII, we conclude the paper.

II. RELATED WORK

In this section, we focus on multipath transmission schemes and reliable transmission schemes. Regarding the works of the multipath transmission schemes, we divide them by layer, focusing on the transport layer schemes and the network layer schemes. Regarding the works of improving the reliability of wireless networks, we focus on the OR schemes and NC schemes.

A. MULTIPATH TRANSMISSION RESEARCH

At the transport layer, SCTP and MPTCP are two typical schemes to take advantage of heterogeneous networks. A standard SCTP is a general-purpose and connection-oriented protocol and provides multipath and redundant path to increase reliability [26]. The standard SCTP does not support multipath transmission simultaneously, and a large number of extensions based on the standard SCTP, such as SCTP-CMT [27] and SCTP-MAN [28] support multipath transmission simultaneously. However, SCTP does not consider compatibility with traditional devices at the beginning of design, and a large number of deployed commercial network devices do not support SCTP. This makes the SCTP protocol and its extensions difficult to deploy in real scenarios. MPTCP is a widely studied multipath transmission protocol at transport layer which is evolved on the basis of TCP [29]. It is very compatible with the TCP protocol. Based on the standard MPTCP, lots of extensions were proposed, such as BLEST [30] and BBP [31]. Earliest Completion First (ECF) [32] is a current multipath scheduling scheme in MPTCP. According to the design of the ECF, the ECF selects the path with the shortest delay for each packet. It can make full use of heterogeneous wireless networks to obtain higher bandwidth for vehicular networks. However, it has two shortcomings. Firstly, it is primarily designed to achieve bandwidth aggregation without considering the unreliability of wireless link. In some scenarios with high packet loss, the performance of ECF deteriorates. Secondly, MPTCP including its extension is an end-to-end communication protocol. It requires both ends to the communication to support the same version of the MPTCP protocol [33]. This makes a large number of current smart devices and servers needs to update the communication protocol stack in the real deployment process, which is costly. The BNNC scheme in this paper is designed with these two points in mind, therefore, it can improve the performance of vehicle-to-ground multipath communication.

At the network layer, there are mainly two types of schemes, NAT and IP-in-IP encapsulation, to realize multipath communication [13]. OSCAR [34] is a typical scheme for multipath transmission through NAT. It has a NAT module at both parties to communication. It uses the NAT module to modify the IP address and port of the raw packet to achieve multipath communication. However, when the original packets are encrypted by IPsec, NAT will not be able to achieve multiplexing. Dong *et al.* [35] proposed a transparent transmission scheme in heterogeneous vehicular wireless networks. This scheme establishes a virtual tunnel through IP-in-IP encapsulation that can take advantage of heterogeneous wireless networks between on-board smart devices and ground-based servers. The IP-in-IP encapsulation scheme adds a pair of proxy at both parties of the communication. In order to achieve multipath transmission, it encapsulates the raw data packets by new IP packets which has Strong compatibility with other multipath transmission schemes. In this paper, the network topology of BNNC scheme is a variant of the IP-in-IP encapsulation.

B. WIRELESS LINK RELIABILITY RESEARCH

OR and NC are two promising schemes that have been proposed for vehicle-to-ground multipath communication.

As an idea to improve the performance of wireless links, OR has been widely studied by scholars. Many schemes are proposed based on OR idea. Kim *et al.* [36] combines OR with multipath transmission to improve the reliability of overall communication. Different from the traditional end-to-end communication, the packet can only select one fixed link to send at a time, and the OR broadcasts the packet to all possible next hops, and simultaneously transmits the packet through multiple links. For each packet, at the sender, the OR copies the packet into multiple packets and sends them from all possible links. At the receiver, any copy of the packet received is regarded as valid reception of the packet. Give a simple example. Assuming that the packet loss rate of each link is p, the overall packet loss rate of the n links is $1-(1-p)^n$. It can be seen that this idea effectively improves the reliability of the entire system. However, the drawbacks of this idea are also very obvious. For an n links, each time a valid packet is sent, it means that $n-1$ redundant packets need to be sent simultaneously. It has a large cost on network resources. In the real communication process, the receiver receives a large number of redundant data packets and discards them [37], [38].

In order to reduce the overhead of OR scheme, scholars study the NC scheme. NC scheme was firstly proposed by Ahlswede *et al.* [39]. It is designed for multicast rather than multipath transmission. FMTCP is added network coding scheme based on MPTCP [18]. By adding certain redundant packets, FMTCP can effectively improve the reliability of multipath transmission. FMTCP uses Fountain Codes for encoding. The encoded packets are obtained by bitwise XOR operation of the original packets and Fountain Codes. However, the result of bitwise XOR operation is only 0 or 1, therefore its encoding flexibility is far less than the BNNC scheme proposed in this paper. The use of Galois Field arithmetic instead of XOR operations to achieve network coding can effectively increase coding flexibility. CMT-NC [23] and MPTCP-PNC [24] are network coding schemes working in Galois Field. In the following paper, we collectively refer to these two schemes as the GF scheme. However, in the CMT-NC, the coefficients of encoding matrix are randomly chosen from the Galois Field, and this process needs spend extra time to check the linear independence among the row vectors in the encoding matrix. In the MPTCP-PNC, it does not give a concrete encoding matrix, although it mentions the encoding matrix. In addition, the computational complexity of Galois Field arithmetic far exceeds the integer arithmetic [40]. In section IV, the time complexity of GF network coding and Bignum network coding to complete an encoding and decoding process is described in detail.

TABLE 1. Summary of important symbols.

Symbol	Description
k	Number of packets before encoding
n	Number of packets after encoding
B	Bignum matrix
E	Encoding matrix
C	Coefficient matrix
D	Matrix to be decoded
IM	Linearly independent matrix
I	Identity matrix
RM	Redundant matrix
$O(\cdot)$	Time complexity
$\mathbb{P}$	Probability of successful packet reception
L	Average length of packets

III. THE BNNC SCHEME OVERVIEW

In this section, we briefly introduce the Bignum Network Coding scheme from three aspects: network topology, system model and core algorithm. The process of communication is symmetrical. In the following of this paper, we introduce the BNNC scheme by taking the uplink traffic from the on-board users' devices to the server as an example. Before the introduction, we summarize the symbols that appeared in this paper in the Table 1.

A. THE NETWORK TOPOLOGY OF VEHICLE-TO-GROUND MULTIPATH COMMUNICATION

Fig. 1 shows the network topology of the BNNC scheme deployed in vehicle-to-ground multipath communication. This network topology allows a large number of deployed on-board network devices to support vehicle-to-ground multipath communication.

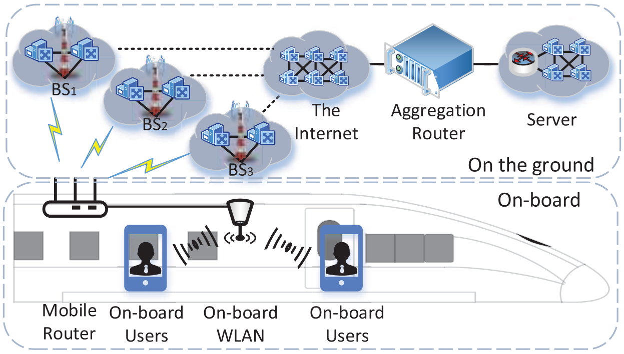


FIGURE 1. Vehicle-to-ground multipath transmission topology.

The BNNC scheme deploys in the Mobile Router (MR) and Aggregation Router (AR). MR is a router that is deployed on a vehicle to provide multipath access for on-board users' smart devices. Data is forwarded to the MR via the on-board WLAN. There are multiple wireless network adaptors on the MR, which can simultaneously access heterogeneous wireless networks of different operators. MR uses these wireless network adaptors to send data to the Internet through heterogeneous wireless networks. This data is eventually aggregated and forwarded to the server in AR.

B. THE PRINCIPLE OF BNNC SCHEME

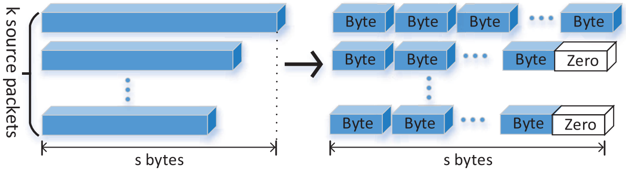
At a macro level, the core of the network topology is MR and AR. In MR and AR, the BNNC scheme combines the unreliable wireless links between vehicles and ground into a reliable link and establishes a reliable transparent transmission tunnel between the user and the server. In the process of communication, the user and the server completely do not feel the existence of MR and AR.

At a micro level, the packets generated by smart devices are mapped to a bignum after reaching the MR. A series of consecutive k bignums constitutes the original bignum matrix $\mathbf{B}$. The matrix $\mathbf{B}$ is multiplied by the coding matrix $\mathbf{IM}$ to obtain a coded bignum matrix $\mathbf{E}$. The n coded packets are obtained by inverse mapping the n bignums in the matrix $\mathbf{E}$. Packet loss is inevitable as packets travel through heterogeneous wireless networks. As long as the AR receives the k encoded packets in the same group, the original k packets can be recovered.

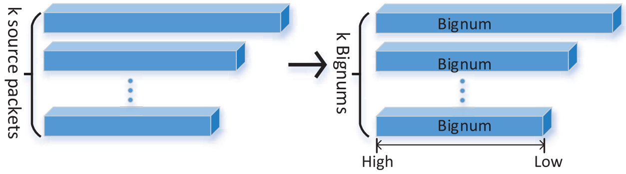
IV. THE MATHEMATICAL MODEL OF BNNC SCHEME

A. BIGNUM MAPPING

In the process of encoding packets, the BNNC scheme first needs to map the bit information into a bignum. As shown in Fig. 2(a), the current NC schemes use the Galois field for coding and decoding. Galois Field is a field that contains a finite number of elements [25]. In computer science, it is generally uses $GF = 2^8$. It maps packet byte by byte. When the packet lengths in the same group are inconsistent, the shorter packets need to be padded with zeros. The process of zero padding has a certain amount of overhead. The BNNC scheme that we propose does not need to pad zero.



(a) Galois Field Mapping



(b) Bignum Mapping

FIGURE 2. Different mapping schemes in network coding.

As shown in Fig. 2(b), the BNNC scheme regard each packet as a binary number. The first bit of the packet represents the high-order of the binary number. The last bit of the packet represents the low-order of the binary number. The encoding and decoding process of the BNNC scheme is the mathematical operation of the number.

B. ENCODING/DECODING MODEL OF BNNC SCHEME

The encoding and decoding model of the BNNC scheme is shown in the Fig. 3. When the packets from smart devices reach the sender, it divides the original consecutive packets into different groups. Each group has k packets and the length of the packet can be different. Each packet is seen as a bignum b_i. Consecutive k bignums constitute matrix $B = [b_1, b_2, \cdots b_k]^T$.

$$E^{n\times 1} = IM^{n\times k} \times B^{k\times 1} = \begin{bmatrix} e_1 & e_2 & \cdots & e_n \end{bmatrix}^T \; (n \geq k) \tag{1}$$

The mathematical model of the encoding process is shown in the formula (1). Multiply encoding matrix $IM^{n\times k}$ and matrix $B^{k\times 1}$ to obtain encoding result matrix $E^{n\times 1}$. The encoding redundancy is n/k. The key is how to design encoding matrix IM. In order to ensure that any k bignums in the matrix $\mathbf{E}$ can be decoded, matrix IM should satisfy any k row vectors are independent. In other words, the k-squared matrix composed of the k row vectors is a invertible matrix. In the next subsection, we will introduce how to design matrix IM.

The essence of the decoding process is solving the linear equations. During decoding process, as long as any k bignums in the matrix $\mathbf{E}$ are received, the k bignums can be multiplied with the decoding matrix to obtain the original k continuous packets. Then, we give the mathematical model of the decoding process. Firstly, we introduce notation $D^{k\times 1}$ for the matrix of receiving k bignums. Secondly, we introduce $C_d^{k\times k}$ for a k-square matrix. The k-square matrix is composed of the k row vectors in matrix IM corresponding to the k bignums. The mathematical model of the decoding process is shown

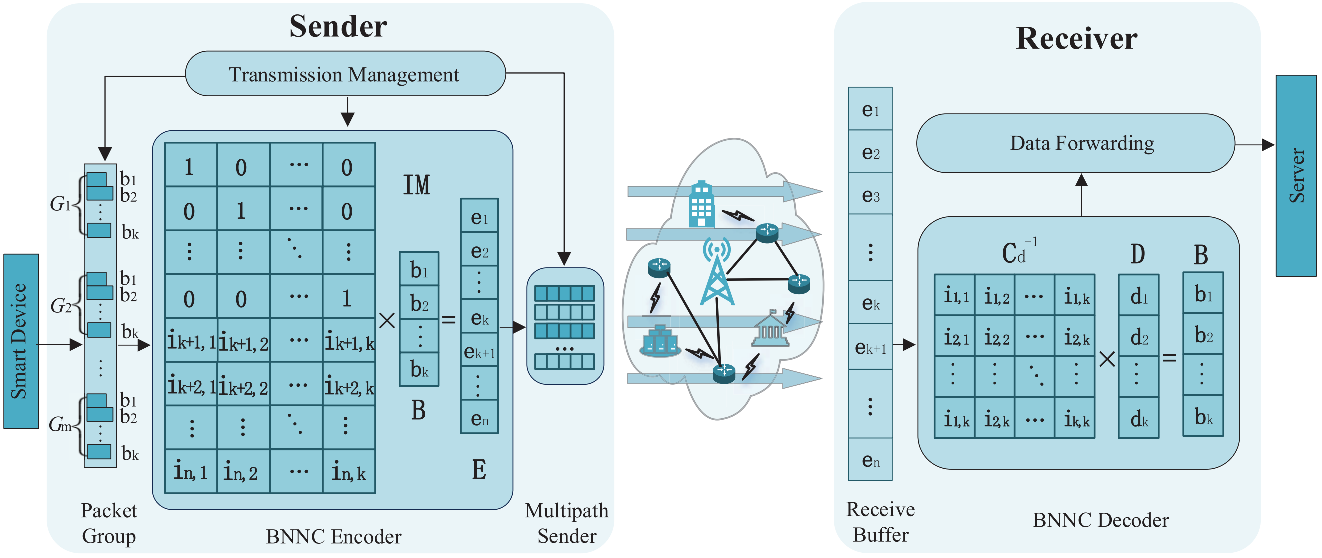


FIGURE 3. Encoding and decoding details.

in formula (2)

$$B^{k\times 1} = (C_d^{k\times k})^{-1} \times D^{k\times 1} \tag{2}$$

Since the entire encoding and decoding processes work in $\mathbb{Z}$, we need to introduce the determinant and adjoint of matrix to represent the inverse of the matrix. We denote the determinant of matrix A by $detA$. And we also denote the adjoint of matrix A by $(adjA)$. Where,

$$A^{-1} = \frac{1}{detA}(adjA) \tag{3}$$

especially, if $A \in \mathbb{Z}^{n\times n}$, we have the relation $detA \in \mathbb{Z}$, $(adjA) \in \mathbb{Z}^{n\times n}$.

According to formula (3), we have the equation $C_d^{-1} = (adjC_d)/detC_d$. Therefore, the decoding process is,

$$B = \frac{1}{detC_d}(adjC_d) \times D \tag{4}$$

Finally, the consecutive k packets are forwarded to the server.

C. NUMERICAL ANALYSIS

Compared with current vehicle-to-ground multipath communication schemes, the BNNC scheme has significantly improved both overall reliability and codec efficiency. In this subsection, we analyze the BNNC scheme by numerical analysis.

First of all, we ignore the impact of the multipath scheduling scheme on the overall reliability, and theoretically analyze the improvement of the overall reliability by encoding and decoding model of BNNC scheme. Assume that the vehicle-to-ground multipath communication network consists of three links, and the packet loss rate of each link is p. Then, the packet loss rate in the encoding and decoding model of BNNC scheme is

$$\mathbb{P}_{BNNC}(k,n) = \sum_{m=0}^{m=k-1} \binom{n}{m} p^{n-m}(1-p)^{m}. \tag{5}$$

In the same scenario, the packet loss rate of OR scheme is

$$\mathbb{P}_{OR} = 1-(1-p)^{k}. \tag{6}$$

Let us take $k = 3$ as an example, and compare the different schemes to improve the overall reliability. The results show in Fig. 4. For the convenience of observation, we show the results through a logarithmic coordinate system. The abscissa is the link set packet loss rate, and the ordinate is the multipath transmission schemes' theoretical packet loss rate. The yellow line is the effect of the OR scheme transmitting through three links. The remaining lines represent the results of the BNNC scheme at $k = 3$ and n equal to 4 to 9. For the OR scheme, transmission over three links means that its redundancy is the same as the redundancy of the BNNC scheme at $k = 3$, $n = 9$. It can be seen that with the same redundancy, the BNNC scheme can better improve the overall reliability compared to the OR scheme. When the two schemes have similar improvements to overall reliability, the BNNC scheme requires fewer redundant packets.

Next, we analyze the efficiency of the encoding and decoding processes. Let us take the encoding and decoding process of a group packets as an example to illustrate the advantages of the BNNC scheme over the GF scheme. We assume that the encoding and decoding process is a process in which k packets encode n packets and then recover into k packets. The average length of the data packet is L bytes, and the coefficient length of the coding matrix is s bits $s \ll L \times 8$.

First we analyze the time complexity of the basic operation. According to the Reference [40], we get a complex

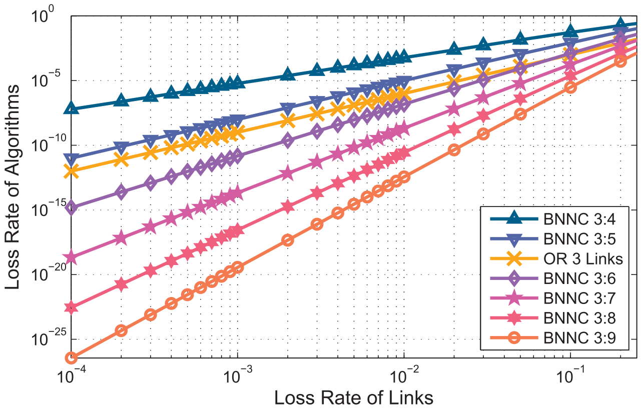


FIGURE 4. Different schemes loss rate.

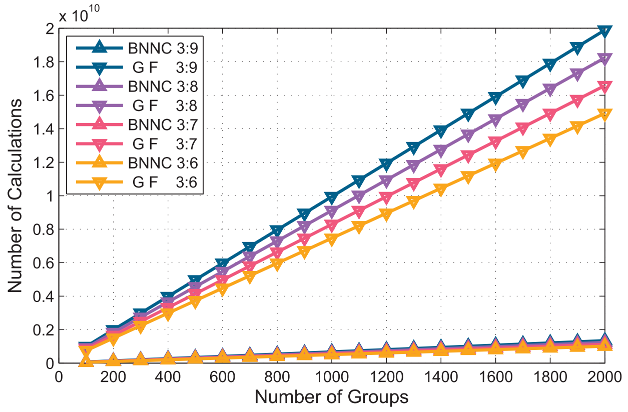


FIGURE 5. Different schemes time complexity.

TABLE 2. Computational complexity of different operations.

Operaion	Bignum	Galois Field
Add	$O(q)$	$O(q)$
q bits $\times$ q bits	$O(q \log q)$	$O(3q^2)$
q bits $\times$ s	$O(q)$	$O(3q^2)$

TABLE 3. Number of calculation for different processes.

Process	Add	q bits $\times$ q bits	q bits $\times$ s
BNNC Encoding	$n(k-1)$	0	nk
BNNC Decoding	$k(k-1)$	0	k^2
GF Encoding	$Ln(k-1)$	Lnk	0
GF Decoding	$Lk(k-1)$	Lk^2	0

comparison of the q bits length numbers in different operation. The results are shown in Table 2 and we give a simple explanation. The time complexity of q bits integer addition is $O(\log n + \sqrt{(2+o(1))\log n})$. In order to facilitate the calculation, we represent it with $O(n)$, which is bigger than $O(\log n + \sqrt{(2+o(1))\log n})$. q bits $\times$ q bits means q bits length numbers multiply by q bits length numbers. q bits $\times$ s means q bits length numbers multiply by a s bits length number $s \ll q$. The time complexity of q bits $\times$ q bits by bignum operation is

$$n \log n 2^{\log^* n}, \tag{7}$$

Here $\log^* n$ is a vary slowly growing function defined by

$$\lfloor \log \ldots \log n \rfloor = 1. \tag{8}$$

When we calculate time complexity of q bits $\times$ s by Galois Field operation, we need replace s to a q bits number in Galois Field. Therefore, the time complexity of q bits $\times$ s is same as q bits $\times$ q bits by bignum operation.

Next, we calculate the number of operations of the network coding and decoding process performed by the two network coding schemes. The result shows in Table 3 and we give a simple explanation. When decoding, only the first k packets of each group need to be decoded, so the decoding efficiency is better than the coding efficiency. In the BNNC scheme, there is no bignum multiply by bignum, so the results of q bits $\times$ q bits are 0. In the GF scheme, we need replace coefficient of coding matrix to a q bits number, so the results of q bits $\times$ s are 0. Considering that the GF scheme operates in bytes, so $q = 8$. The time complexity of the GF scheme to complete an encoding and decoding process is

$$O(8L(25nk + 25k^2 - n - k)). \tag{9}$$

The time complexity of the BNNC scheme to complete an encoding and decoding process is

$$O(8L(2nk + 2k^2 - n - k)). \tag{10}$$

The time complexity of the BNNC scheme is significantly smaller than the GF scheme.

Further, we take the average packet length of 1400 bytes as an example to clearly show the improvement of computing performance by the BNNC scheme through Fig. 5. The abscissa is the number of coding groups. The ordinate is the number of calculations required to codec all groups of packets. We can see that as the number of groups increases, the advantages of the BNNC scheme over the GF scheme become more and more obvious.

V. THE IMPLEMENTATION OF BNNC SCHEME

A. DESIGN OF ENCODING MATRIX

The design of the encoding matrix must satisfy two conditions:

1) linear independence;
2) reducing encoding time as much as possible.

Firstly, as shown in formula (2), the essence of the decoding process in BNNC scheme is solving linear equations. The linear equations have one solution if and only if matrix C_d is an invertible matrix. Since matrix C_d is composed of any k rows of matrix IM, any k rows in matrix IM are linearly independent. Secondly, since the encoded packet that uses a certain row in the identity matrix as a coding coefficient can be directly decoded and it can be immediately forwarded. The first k rows of the matrix IM should be a identity matrix.

Therefore, the encoding coefficient matrix is designed as formula (11). The first k rows from **IM** is identity matrix and the last $n-k$ rows from **IM** is Redundant Matrix (**RM**).

$$IM = \begin{bmatrix} I \\ RM \end{bmatrix} = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \\ i_{k+1,1} & i_{k+1,2} & \cdots & i_{k+1,k} \\ i_{k+2,1} & i_{k+2,2} & \cdots & i_{k+2,k} \\ \vdots & \vdots & \ddots & \vdots \\ i_{n,1} & i_{n,2} & \cdots & i_{n,k} \end{bmatrix} \tag{11}$$

where **RM** is composed of a series of Toeplize Matrix T_i.

$$RM = \begin{bmatrix} T_1 \\ T_2 \\ \vdots \end{bmatrix}, T_i = \begin{bmatrix} 1^i & 2^i & \cdots & k^i \\ k^i & 1^i & \cdots & (k-1)^i \\ \vdots & \vdots & \ddots & \vdots \\ 2^i & 3^i & \cdots & 1^i \end{bmatrix} \tag{12}$$

Next, we will prove that the k-order square matrix composed of any k rows in IM is reversible. In general, we complete the proof in two steps with the characteristic of Permutation Group.

First, we prove that matrix T_i is reversible.

Let $\beta = [1^m, 2^m, 3^m, \ldots, k^m]$. Define a linear transformation α for β,

$$\begin{aligned} &\alpha(1^i) = k^i, \alpha(k^i) = (k-1)^i, \\ &\alpha((k-1)^i) = (k-2)^i, \ldots, \alpha(3^i) = 1^i, \alpha(2^i) = 1^i. \end{aligned}$$

Then this permutation group can be denoted as,

$$\begin{aligned} \begin{bmatrix} \beta \\ \alpha(\beta) \end{bmatrix} &= \begin{bmatrix} 1^i & 2^i & \cdots & k^i \\ \alpha(1^i) & alpha(2^i) & \cdots & alpha(k^i) \end{bmatrix} \\ &= \begin{bmatrix} 1^i & 2^i & \cdots & k^i \\ k^i & 1^i & \cdots & (k-1)^i \end{bmatrix} \end{aligned} \tag{13}$$

Therefore, the elements of matrix T_i have the form

$$\begin{bmatrix} \beta \\ \alpha(\beta) \\ \alpha^2(\beta) \\ \vdots \\ \alpha^{k-2}(\beta) \\ \alpha^{k-1}(\beta) \end{bmatrix} \tag{14}$$

$\alpha^k(\beta) = \beta$ and $\forall i \ll k, \alpha^i(\beta) \neq \beta$, so that $\alpha^k = e$, e is identity mapping. The order of T_i is k. That is, the rank of matrix T_i is k and matrix T_i is reversible.

Second, we prove the linear independence between the permutation group.

We redefine the $\beta = [1, 2, 3, \ldots, k-1, k]$. Linear transformation does not change α. ω is Hadamard multiplication. That is,

$$\begin{aligned} \omega(\beta) &= \beta, \\ \omega^2(\beta) &= \beta^2 = [1^2, 2^2, 3^2, \ldots, k^m], \\ \omega^m(\beta) &= \beta^m = [1^m, 2^m, 3^m, \ldots, k^m]. \end{aligned}$$

Algorithm 1 BNNC Scheme: Sender

```
while ReadPacet() do
    Grouping();
    if group.isNotEnough then
        continue;
    BignumList = EncodeGroup();
    while BignumList! = NULL do
        GetFastLink();
        SendBN();
```

Algorithm 2 BNNC Scheme: Receiver

```
while ReadPacet() do
    Add2Group();
    if group.isNotEnough then
        continue;
    BignumList = DecodeGroup();
    InOrderPackets = Add2RecvBuffer();
    while InOrderPackets! = NULL do
        ForwardPackets();
```

Then, $\forall k$ rows in **IM** are,

$$\begin{bmatrix} \alpha^{n_1}(\beta^{m_1}) \\ \alpha^{n_2}(\beta^{m_2}) \\ \vdots \\ \alpha^{n_{k-1}}(\beta^{m_{k-1}}) \\ \alpha^{n_k}(\beta^{m_k}) \end{bmatrix} = \begin{bmatrix} \alpha^{n_1}\omega^{m_1}(\beta) \\ \alpha^{n_2}\omega^{m_2}(\beta) \\ \vdots \\ \alpha^{n_{k-1}}\omega^{m_{k-1}}(\beta) \\ \alpha^{n_k}\omega^{m_k}(\beta) \end{bmatrix} \tag{15}$$

According to the definition of ω,

$$\begin{aligned} |\omega| &= \infty \\ |\alpha^i\omega^j| &\geq max\{|\alpha^i|, |\omega^j|\} = \infty \end{aligned} \tag{16}$$

Therefore, $\forall k$ rows in **IM** are linearly independent.

B. DESIGN OF TRANSMISSION PROTOCOL

The sending algorithm of the BNNC scheme is as shown in Algorithm 1. The sender listens for packets from the on-board users at all times. Each group has consecutive k packets. After encoding, n packets to be transmitted are obtained. For each packet to be sent, the sender calculates the time that the packet is sent from all available links in real time, and selects the link with the shortest time to send. The receiving algorithm of the BNNC scheme is as shown in Algorithm 2. The receiver receives the encoded packets from the sender. When the same group of packets receives k, the group of packets is decoded. The decoded packets are sent to the receive buffer for sorting and forwarded to the server.

In order to achieve the above process, we have designed a new header. Fig. 6 shows the BNNC scheme packet header. In the case of not using the extended field, the header consists of 11 fields with a total length of 16 bytes. Group Seq is

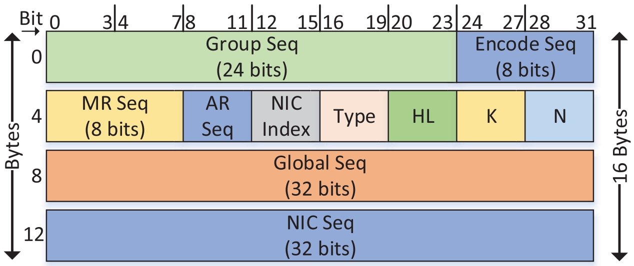


FIGURE 6. BNNC scheme packet header.

a group sequence number field, which is 24 bits long and records the packet group sequence. The group number starts from 0. After 2^{24}, it returns to zero. Encode Seq is the code sequence number, 8 bits in length, indicating the line in the coding matrix. The MR Seq field is 8 bits in length. An AR supports multiple MRs at the same time. This field is used to distinguish different MRs that are connected to the AR at the same time. The AR Seq field is 4 bits long and is used to support one MR at the same time to access multiple ARs at the same time. The NIC Index indicates that the packet is sent from the physical physical network card of the MR. Type indicates the protocol number and will support more protocols in the future. HL is the length of the header, and the length of the header is equal to the HL value multiplied by 4. There is no extension field by default, which means the default value is 0x04. k and n represent the length and redundancy of the packet when the packet is encoded, that is, k packets are encoded to obtain n packets. Since the grouping of the process will cause the queue header to block, the k field is 4 bits long and the n field is 8 bits long. The Global Seq records the number of packets sent by the MR, and the NIC Seq indicates the number of packets sent by the NIC index corresponding to the NIC in the MR.

VI. PERFORMANCE OF SIMULATION

The simulations in this paper are based on NS3. NS3 is a discrete event-driven network simulation tool. In the NS3, the delay is only related to the network status. Therefore, in the NS3, even if the time complexity of the algorithm is high, it does not affect the performance of the network operation. GF network coding scheme is only suitable for performance comparison in the simulation environment due to its high time complexity. In real test, communication performance is affected by computational performance limitations. In addition, NS3 can simulate a variety of network status in different scenarios. Therefore, simulation can be used to more fully verify the performance of different algorithms.

A. SIMULATION TOPOLOGY

The simulation topology is shown in Fig. 7. We use 4 nodes to form a minimum heterogeneous network simulation topology. Among them, node 1 simulates the user's device on the vehicle, node 2 simulates the MR on the vehicle, node 3 simulates the AR on the ground, and node 4 simulates the server. Node 2 and node 3 are connected to different base stations through a wired link, and there are three wireless links, link 1, link 2 and link 3 between the base stations. Simulation used these three wireless links to simulate heterogeneous wireless networks. In the simulation process, TCP and UDP communication is performed between node 1 and node 4, and data packets are transmitted in parallel between nodes 2 and 3. We set different link parameters for links 2, 3 and 4 to simulate different scenarios.

TABLE 4. Paths parameters.

Paths	Loss	Bandwidth	RTT
Path 1	1%	22 Mbps	44 ms
Path 2	0.5%	15 Mbps	30 ms
Path 3	0.1%	20 Mbps	40 ms

B. THROUGHPUT IN HETEROGENEOUS NETWORKS

Next, we verify the throughput of the BNNC scheme under a typical heterogeneous networks. Based on previous real tests data, we select a set of link parameters to simulate a mobile scenario. The parameters of the three paths are shown in Table 4. First we get the real-time throughput of the simulated heterogeneous network through TCP. We generate three TCP streams at node 1 and send them to node 4. After the TCP streams arrive at node 2, they are sent from path 2, 3, and 4 to node 3. The real-time throughput of the three TCP streams is shown in Fig 8(a), the abscissa is the running time, and the ordinate is the real-time throughput. Through Fig. 8(a), the real-time throughput of the TCP stream in each path can be clearly seen.

Keeping the paths parameters fixed, we verify the throughput advantage of the BNNC scheme over other schemes. We deploy different mulitpath transmission schemes on Node 2 and Node 3, respectively: BNNC, ECF, GF, OR. Node 1 sends a TCP stream to node 4. Fig. 8(b) is a comparison of real-time throughput of different multipath transmission schemes in heterogeneous networks. Because the ECF scheme does not tackle the link loss and the TCP stream is sensitive to link loss, the ECF scheme performs poorly in this scenario. Comparing Fig. 8(a) with Fig. 8(b), the performance of the OR scheme is consistent with the current optimal path. However, due to the essence of OR scheme, it cannot exceed the optimal path at the current time and achieve bandwidth aggregation in a certain sense. The two NC schemes add some redundancy through network coding, which can effectively tolerate link loss. In addition, the performance of the GFNC scheme is close to the BNNC scheme because the computational performance is not considered in the simulation. However, due to the advantages of packet mapping and encoding, in the heterogeneous network, the average throughput of the BNNC scheme is 20 Mbps, and the GF scheme is 19.8 Mbps. The performance of the BNNC scheme is slightly higher than the GF scheme.

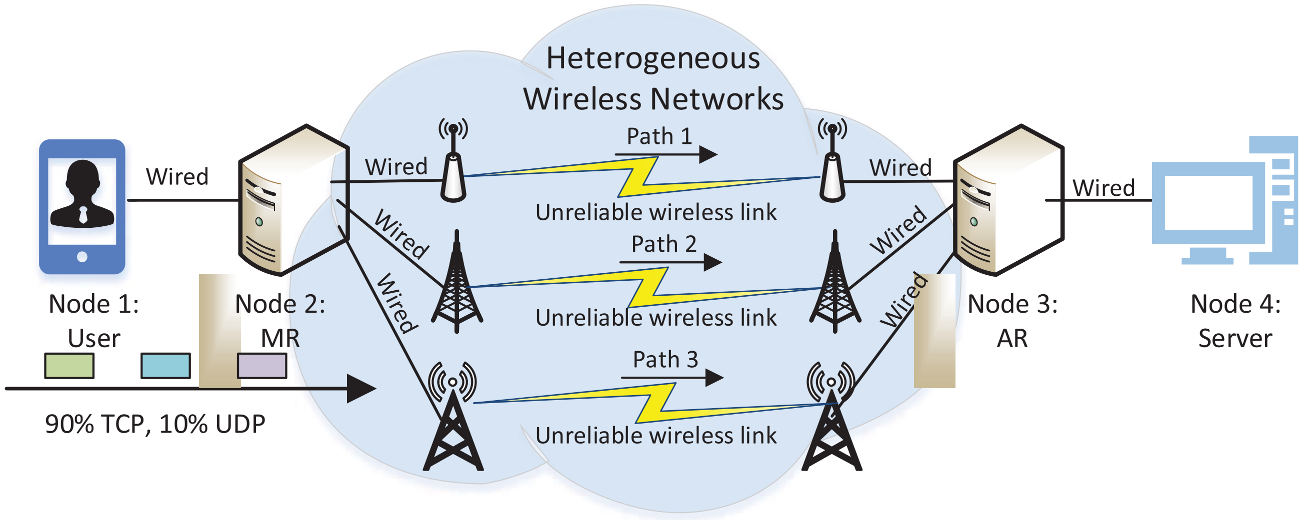
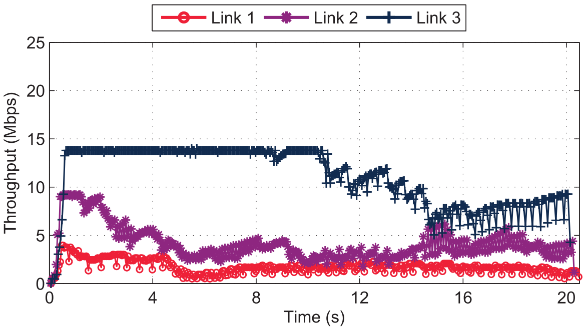
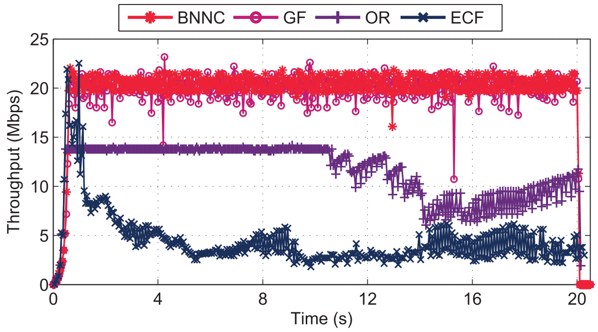


FIGURE 7. Simulation network topology.



(a) TCP performance in different paths.

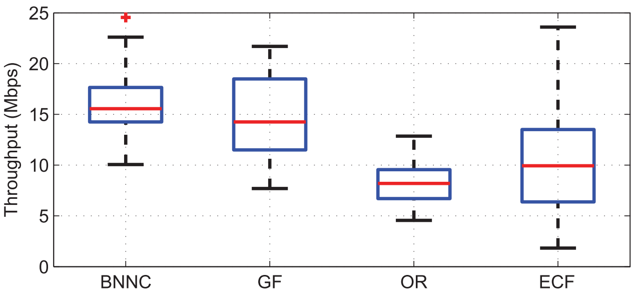


(b) The performance of multipath transmission schemes in heterogeneous networks.

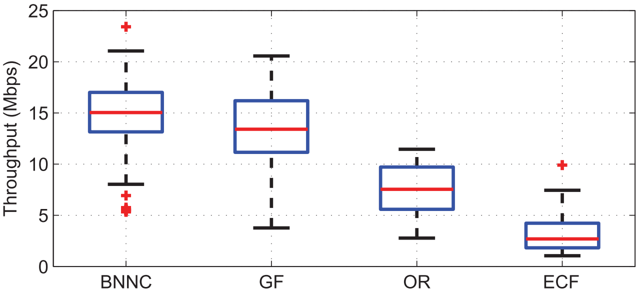
FIGURE 8. The performance of different schemes in heterogeneous networks.

C. DIVERSITY SCENARIOS

Further, we verify the performance of different multipath transmission schemes at different packet loss rates. During the simulation process, we randomly selected the path parameters within a certain range and generated 2000 sets of heterogeneous networks, thus simulating diversity scenarios that fully verify the performance of different algorithms.



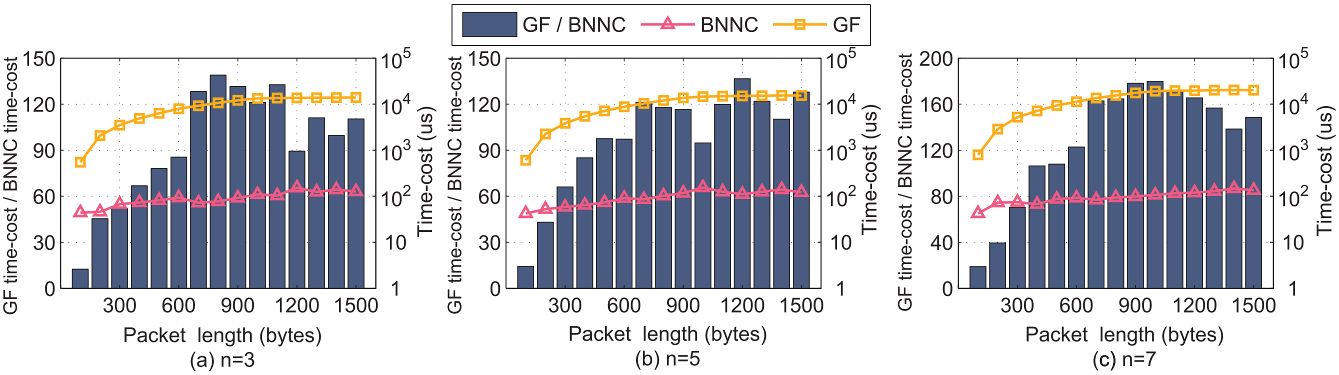
(a) GF Mapping



(b) BNNC Mapping

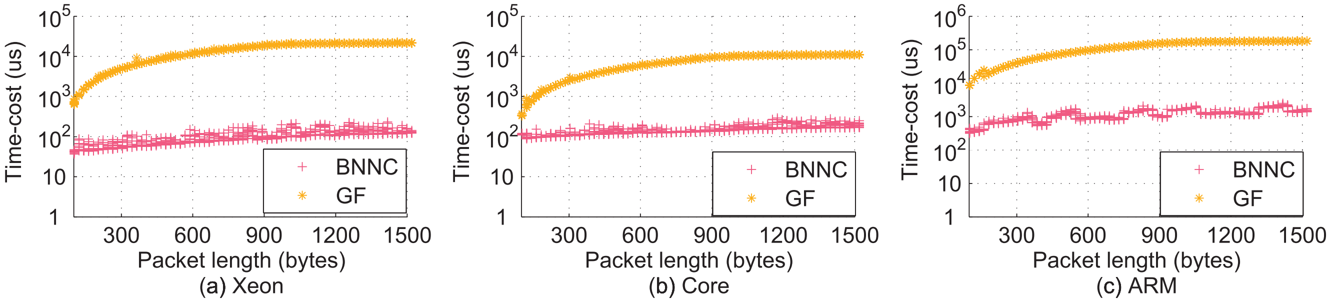
FIGURE 9. Different mapping scheme.

These 2000 heterogeneous networks are divided into low packet loss rate set and high packet loss rate set based on different packet loss rates. The path parameters setting range of the low packet loss rate set is 0.01% to 0.5%, and the average value is 0.25%. The path parameters setting of the high packet loss rate set ranges from 0.5% to 1.5% with an average of 1%. In Fig. 9(a) and Fig. 9(b), the abscissa corresponds to different multipath transmission schemes, and the ordinate corresponds to throughput. Analysis of Fig. 9(a) and Fig. 9(b) separately shows that in a network with low packet loss rate, the network coding schemes are better than OR and ECF.



(a) n=3 (b) n=5 (c) n=7

FIGURE 10. The time-cost of encoding and decoding processes for different network coding schemes.



(a) Xeon (b) Core (c) ARM

FIGURE 11. The time-cost distribution of encoding and decoding processes for different network coding schemes.

The BNNC scheme is slightly higher than the GF scheme. The OR scheme and the ECF scheme are close to each other, but the ECF scheme is susceptible to packet loss, and the range of variation is relatively large and relatively unstable. In a network with high packet loss rate, the network coding scheme is better than OR and ECF. The BNNC scheme is slightly higher than the GF scheme. The ECF scheme is greatly affected by packet loss and has the lowest throughput performance. A comprehensive analysis of Fig. 9(a) and Fig. 9(b) shows that network coding has a strong tolerance to packet loss rate. As the packet loss rate increases, the performance of network coding decreases little. The ECF scheme is very sensitive to the packet loss rate. As the link loss rate increases, the overall performance decreases significantly.

VII. PERFORMANCE OF REAL TESTS

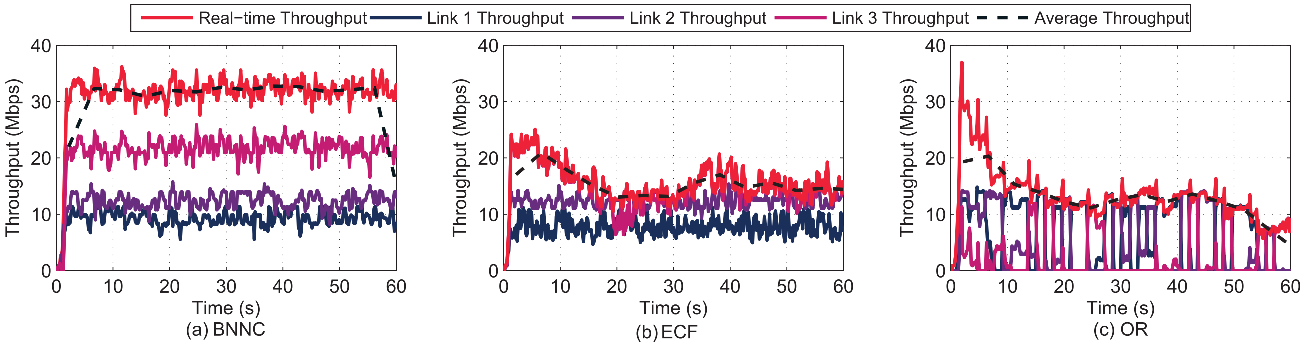
In this section, we fully verify the performance of the BNNC scheme through different hardware platforms and different real test scenarios. First, we choose different hardware platforms to verify the advantages of the BNNC scheme over other network coding scheme in terms of codec efficiency. Next, we verify the advantages of the BNNC scheme over other multipath transmission schemes in different mobile scenarios.

A. CODEC EFFICIENCY OF DIFFERENT NETWORK CODING SCHEMES

In this subsection, we analyze the codec efficiency of different network coding schemes on real deployment. In order to verify that this influence is universal, we chose three types of CPUs with different properties and we did a lot of tests to verify the generality of the conclusion. In the real deployment process, two network coding schemes were deployed in the Ubuntu 16.04 operating system and compiled with g++ 5.4.0.

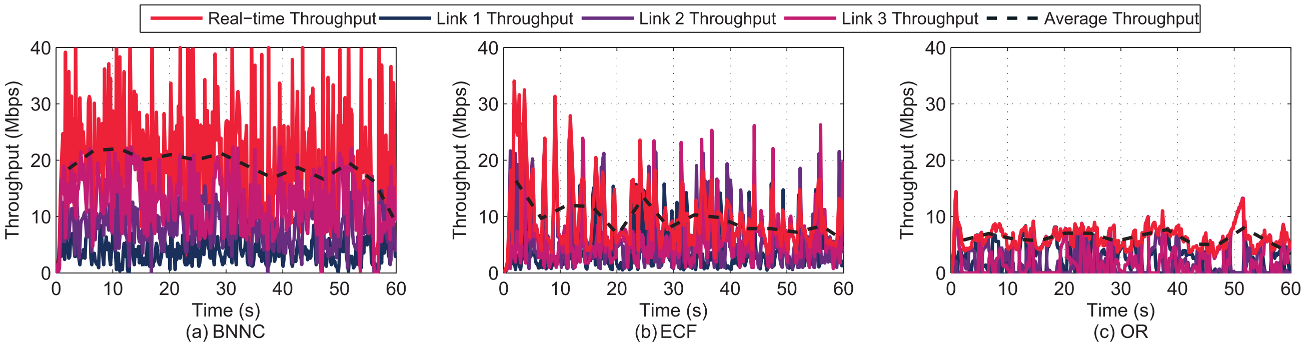
Fig. 10 shows the results of time-cost for different network coding schemes. The abscissa indicates the average length of the packet. The ordinate of the line chart is the time-cost by different network coding schemes to complete one encoding and decoding process under different coding redundancy which is located on the right side of each figure. The ordinate of the histogram is the encoding and decoding processes time ratio of the two network coding schemes which is located on the left side of each figure. As the length of the packet increases and the encoding redundancy increases, the time for BNNC scheme to complete an encoding and decoding processes are basically in the hundreds of microseconds order of magnitude. However, the time for the GF schemes to complete one encoding and decoding process gradually increases. And the encoding and decoding processes times are several tens of times than that of the BNNC scheme. According to the previous theoretical analysis, since the bignum arithmetic has a mathematically fast calculation algorithm, the BNNC scheme has a higher coding and decoding efficiency than the GF schemes.

Next, we analyze the generality of the above conclusions. We chose three typical network devices to test the two network coding schemes. The three typical network devices are



(a) BNNC (b) ECF (c) OR

FIGURE 12. **The performance of different multipath transmission schemes in static scenario.**



(a) BNNC (b) ECF (c) OR

FIGURE 13. **The Performance of different multipath transmission schemes in high-speed mobile scenario.**

TABLE 5. **CPU configurations in real tests.**

Device	CPU model	Core frequency
Laptop	Core i7-6700k	4GHz
Server	Xeon E5-2680	2.5GHz
Embedded device	ARM Cortex-A7	900MHz

laptops, commercial servers, and embedded devices respectively. The CPU configurations of three devices are shown in the Table 5. As shown in Fig. 11, the abscissa indicates the average length of the packet. The ordinate is the time-cost by different network coding schemes to complete one encoding and decoding process under different CPUs. The time-cost for the BNNC scheme to complete one encoding and decoding process is basically in the hundreds of microseconds order of magnitude. However, for GF schemes, in the server, the time to complete one encoding and decoding process is basically in the one millisecond order of magnitude. In the embedded device, the time to complete one encoding and decoding process is basically in the ten milliseconds order of magnitude.

B. TCP PERFORMANCE OF DIFFERENT MULTIPATH TRANSMISSION SCHEME IN DIFFERENT SCENARIOS

Further, in the real tests, we deploy the BNNC scheme and compare it with several current multipath transmission schemes to verify the performance of the BNNC scheme. The real test network topology is deployed according to the network topology shown in Fig. 1. MR simultaneously accesses the cellular networks of three different operators: China Telecom, CMCC and China Unicom. In terms of hardware selection, we chose the Core I7 CPU-based MR to minimize the impact of computing performance on scheme throughput performance. In the comparison scheme, we choose ECF and OR, the two current multipath transmission schemes. In the test scenario, we selected a static scenario with a good network on campus and a high-speed mobile scenario with complex network conditions on high-speed railway.

The test results are shown in Fig. 12 and Fig. 13. Fig. 12 is a comparison of real-time throughput of three different schemes in static scenario. Fig. 13 is a comparison of real-time throughput of three different schemes in high-speed mobile scenario. In each of the figures, the abscissa represents the time and the ordinate represents the throughput. Among them, the solid red line represents the real-time throughput of the scheme, and the black dashed line traces the trend of throughput variation of the scheme over a period of time. The remaining three solid lines represent the real-time throughput of the three vendors.

Fig. 12 shows the performance of different multipath transmission scheme in static scenario. The ECF scheme does not consider the unreliability of the link. It can be seen from Fig. 12 (c) that the scheme performs well when initially running, but the performance degradation is severe after some packets are inevitably lost. The OR scheme improves link loss to a limit extent. It can be seen from the Fig. 12 (b) that the scheme basically realizes selecting the current optimal path in real time, but the overhead of this scheme is too large, resulting in low overall throughput. The BNNC scheme improves the packet loss with less overhead. As shown in Fig. 12 (a), in static scenario, the BNNC scheme has higher throughput and stable performance.

As shown in Fig. 13, in high-speed mobile scenario, a single vendor cannot provide a stable path, and the real-time throughput of the three multipath transmission schemes is reduced to a limit extent. However, in term of horizontal comparison, we observe the overall trend of the three multipath transmission schemes. The throughput of the BNNC scheme is significantly higher than the other two and is relatively stable. In terms of vertical comparison, the BNNC scheme is less affected by network fluctuations than other multipath transmission schemes. In a complex network scenario, a relatively stable network access can be provided by BNNC scheme.

VIII. CONCLUSION

In this paper, we propose the BNNC scheme for vehicle-to-ground multipath communication. It can guarantee the reliability and improve the performance of multipath transmission in vehicle networks. We proposed a brand-new mathematical model for network coding which can significantly improve the reliability and performance of vehicle-to-ground multipath communication. Based on this mathematical model, we proposed BNNC scheme. The scheme uses integer arithmetic instead of Galois Field arithmetic to achieve trade-off between coding flexibility and codec efficiency. In addition, we propose an Independent Matrix to further improved codec efficiency. Finally, we did a large number of simulations and tests. The results show that the BNNC scheme is significantly superior to other multipath transmission schemes, especially in term of improving reliability and bandwidth aggregation. In the future, we will combine reinforcement learning with BNNC scheme to further enhance the performance of vehicle-to-ground multipath communication in complex mobile scenario.

REFERENCES

[1] Y. Zhang, P. Dong, Y. Yu, X. Du, H. Luo, T. Zheng, and M. Guizani, "A bignum network coding scheme for multipath transmission in vehicular networks," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2018, pp. 206–212.

[2] Y. Zhang, P. Dong, S. Yu, H. Luo, T. Zheng, and H. Zhang, "An adaptive multipath algorithm to overcome the unpredictability of heterogeneous wireless networks for high-speed railway," *IEEE Trans. Veh. Technol.*, vol. 67, no. 12, pp. 11332–11344, Dec. 2018.

[3] P. Dong, T. Zheng, X. Du, H. Zhang, and M. Guizani, "SVCC-HSR: Providing secure vehicular cloud computing for intelligent high-speed rail," *IEEE Netw.*, vol. 32, no. 3, pp. 64–71, May/Jun. 2018.

[4] J. Zhao, Q. Li, Y. Gong, and K. Zhang, "Computation offloading and resource allocation for cloud assisted mobile edge computing in vehicular networks," *IEEE Trans. Veh. Technol.*, vol. 68, no. 8, pp. 7944–7956, Aug. 2019.

[5] Z. Guan, Y. Zhang, L. Zhu, L. Wu, and S. Yu, "EFFECT: An efficient flexible privacy-preserving data aggregation scheme with authentication in smart grid," *Sci. China Inf. Sci.*, vol. 62, no. 3, pp. 1–14, Mar. 2019.

[6] S. Yu, M. Liu, W. Dou, X. Liu, and S. Zhou, "Networking for big data: A survey," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 1, pp. 531–549, 1st Quart., 2016.

[7] L. Li, K. Xu, T. Li, K. Zheng, C. Peng, D. Wang, X. Wang, M. Shen, and R. Mijumbi, "A measurement study on multi-path TCP with multiple cellular carriers on high speed rails," in *Proc. Conf. ACM Special Interest Group Data Commun. (SIGCOMM)*, Aug. 2018, pp. 161–175.

[8] Y. Zhang, T. Zheng, P. Dong, H. Luo, and Z. Pang, "Comprehensive analysis on heterogeneous wireless network in high-speed scenarios," *Wireless Commun. Mobile Comput.*, vol. 2018, May 2018, Art. no. 4259510.

[9] D. Huang, P. Fan, and K. Ben Letaief, "An optimal antenna assignment strategy for information raining," *IEEE Trans. Wireless Commun.*, vol. 7, no. 4, pp. 1134–1139, Apr. 2008.

[10] P. Rodriguez, R. Chakravorty, J. Chesterfield, I. Pratt, and S. Banerjee, "MAR: A commuter router infrastructure for the mobile Internet," in *Proc. 2nd Int. Conf. Mobile Syst., Appl., Services*, Jun. 2004, pp. 217–230.

[11] X. Yan, P. Dong, X. Du, T. Zheng, H. Zhang, and M. Guizani, "Congestion game with link failures for network selection in high-speed vehicular networks," *IEEE Access*, vol. 6, pp. 76165–76175, 2018.

[12] Q. Li, J. Zhao, and Y. Gong, "Computation offloading and resource allocation for mobile edge computing with multiple access points," *IET Commun.*, vol. 13, no. 17, pp. 2668–2677, Oct. 2019.

[13] M. Li, A. Lukyanenko, Z. Ou, A. Ylä-Jääski, S. Tarkoma, M. Coudron, and S. Secci, "Multipath transmission for the Internet: A survey," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 4, pp. 2887–2925, 4th Quart., 2016.

[14] Y. Xiao, X. Du, J. Zhang, F. Hu, and S. Guizani, "Internet protocol television (IPTV): The killer application for the next-generation Internet," *IEEE Commun. Mag.*, vol. 45, no. 11, pp. 126–134, Nov. 2007.

[15] X. Du, Y. Xiao, M. Guizani, and H.-H. Chen, "An effective key management scheme for heterogeneous sensor networks," *Ad Hoc Netw.*, vol. 5, no. 1, pp. 24–34, 2007.

[16] X. Ma, J. Zhao, Y. Gong, and X. Sun, "Carrier sense multiple access with collision avoidance-aware connectivity quality of downlink broadcast in vehicular relay networks," *IET Commun.*, vol. 13, no. 8, pp. 1096–1103, Jul. 2019.

[17] X. Du, Y. Xiao, M. Guizani, and H.-H. Chen, "Transactions papers a routing-driven elliptic curve cryptography based key management scheme for heterogeneous sensor networks," *IEEE Trans. Wireless Commun.*, vol. 8, no. 3, pp. 1223–1229, Mar. 2009.

[18] Y. Cui, L. Wang, X. Wang, H. Wang, and Y. Wang, "FMTCP: A fountain code-based multipath transmission control protocol," *IEEE/ACM Trans. Netw.*, vol. 23, no. 2, pp. 465–478, Apr. 2015.

[19] C. Zhang, C. Li, and Y. Chen, "Joint opportunistic routing and intra-flow network coding in multi-hop wireless networks: A survey," *IEEE Netw.*, vol. 33, no. 1, pp. 113–119, Jan./Feb. 2018.

[20] S. Kafaie, Y. Chen, O. A. Dobre, and M. H. Ahmed, "Joint inter-flow network coding and opportunistic routing in multi-hop wireless mesh networks: A comprehensive survey," *IEEE Trans. Surveys Tuts.*, vol. 20, no. 2, pp. 1014–1035, 2nd Quart., 2018.

[21] N. Chakchouk, "A survey on opportunistic routing in wireless communication networks," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 2214–2241, Mar. 2015.

[22] X. Zhang and B. Li, "Optimized multipath network coding in lossy wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 27, no. 5, pp. 622–634, Jun. 2009.

[23] C. Xu, Z. Li, L. Zhong, H. Zhang, and G. M. Muntean, "CMT-NC: Improving the concurrent multipath transfer performance using network coding in wireless networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 3, pp. 1735–1751, Mar. 2016.

[24] C. Xu, P. Wang, C. Xiong, X. Wei, and G. Muntean, "Pipeline network coding-based multipath data transfer in heterogeneous wireless networks," *IEEE Trans. Broadcast.*, vol. 63, no. 2, pp. 376–390, Jun. 2016.

[25] L. E. Dickson, *Linear Groups: With an Exposition of the Galois Field 8 Theory*. New York, NY, USA: Courier Corporation, 2003.

[26] R. Stewart, Q. Xie, K. Morneault, C. Sharp, H. Schwarzbauer, T. Taylor, I. Rytina, M. Kalla, L. Zhang, and V. Paxson, *Stream Control Transmission Protocol (SCTP)*, document RFC 4960, IETF, Sep. 2007, pp. 1–152.

[27] J. R. Iyengar, P. D. Amer, and R. Stewart, "Concurrent multipath transfer using SCTP multihoming over independent end-to-end paths," *IEEE/ACM Trans. Netw.*, vol. 14, no. 5, pp. 951–964, Oct. 2006.

[28] Y. Yuan, D. Zhang, L. Tian, and J. Shi, "Research on the extension of SCTP protocol on the heterogeneous wireless network," *Int. J. Interdiscipl. Telecommun. Netw. (IJITN)*, vol. 8, no. 2, pp. 69–87, Apr. 2016.

[29] M. Scharf and A. Ford, *Multipath TCP (MPTCP) Application Interface Considerations*, document RFC 6897, Mar. 2013.

[30] S. Ferlin, Ö. Alay, O. Mehani, and R. Boreli, "BLEST: Blocking estimation-based MPTCP scheduler for heterogeneous networks," in *Proc. IFIP Netw. Conf. (IFIP Netw.) Workshops*, Jun. 2016, pp. 431–439.

[31] B. Oh and J. Lee, "Feedback-based path failure detection and buffer blocking protection for MPTCP," *IEEE/ACM Trans. Netw.*, vol. 24, no. 6, pp. 3450–3461, Dec. 2016.

[32] Y.-S. Lim, E. M. Nahum, D. Towsley, and R. J. Gibbens, "ECF: An MPTCP path scheduler to manage heterogeneous paths," in *Proc. ACM SIGMETRICS/Int. Conf. Meas. Modeling Comput. Syst.*, Jun. 2017, pp. 33–34.

[33] B. Feng, H. Zhang, H. Zhou, and S. Yu, "Locator/identifier split networking: A promising future Internet architecture," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 4, pp. 2927–2948, 4th Quart., 2017.

[34] K. Habak, K. A. Harras, and M. Youssef, "OSCAR: A collaborative bandwidth aggregation system," 2014, *arXiv:1401.1258*. [Online]. Available: https://arxiv.org/abs/1401.1258

[35] P. Dong, B. Song, H. Zhang, and X. Du, "Improving onboard Internet services for high-speed vehicles by multipath transmission in heterogeneous wireless networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 12, pp. 9493–9507, Dec. 2016.

[36] S. Kim, H. Cho, T. Yang, C. Kim, and S.-H. Kim, "Low-cost multipath routing protocol by adapting opportunistic routing in wireless sensor networks," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Mar. 2017, pp. 1–6.

[37] S. Biswas and R. Morris, "Opportunistic routing in multi-hop wireless networks," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 34, no. 1, pp. 69–74, Jan. 2004.

[38] N. Li, J.-F. Martinez-Ortega, V. H. Diaz, and J. A. S. Fernandez, "Probability prediction-based reliable and efficient opportunistic routing algorithm for VANETs," *IEEE/ACM Trans. Netw. (TON)*, vol. 26, no. 4, pp. 1933–1947, Aug. 2018.

[39] R. Ahlswede, N. Cai, S.-Y. R. Li, and R. W. Yeung, "Network information flow," *IEEE Trans. Inf. Theory*, vol. 46, no. 4, pp. 1204–1216, Jul. 2000.

[40] S. B. Gashkov and I. S. Sergeev, "Complexity of computation in finite fields," *J. Math. Sci.*, vol. 191, no. 5, pp. 661–685, Jun. 2013.

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