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Packet Multicast in Cognitive Radio Ad Hoc Networks: A Method Based on Random Network Coding

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ABSTRACT This paper studies packet multicast technology in cognitive radio ad hoc networks (CRAHNs) by using a random network coding (RNC)-based approach. We first specify the key problem of packet multicast applications in CRAHNs, called multichannel single-hop wireless multicast problem (MCSHWMP), then present the definition of MCSHWMP of its four-element tuple model. Next, we propose a framework for the network coding-based scheme in packet multicast applications of CRAHNs and provide several candidate schemes based on the framework. The proposed schemes have several desirable features: 1) necessary packet transmissions are reduced greatly by exploiting the broadcast nature of wireless transmissions by using RNC; 2) each packet transmission is tried to maximize the packet reception gain of the receivers by considering opportunistic accessibility of wireless channels and heterogeneous packet reception success ratio of different wireless channels; and 3) packet size to be transmitted is effectively shortened by reducing decoding information to be transmitted in the packet. Simulation results show that NC-based schemes decrease packet transmissions significantly comparing with non-NC-based schemes. The advantage of NC-based schemes is more distinctive when packet reception success ratio of wireless links are near but smaller than 1, and in these cases around 50% of packet transmissions could be saved.

INDEX TERMS Random network coding, cognitive radio ad hoc networks, multicast, broadcast, link reliability.

I. INTRODUCTION

Cognitive Radio Ad Hoc Networks (CRAHNs) [1] are wireless multi-hop networks using the cognitive radio technology [2]. CRAHNs can automatically search and utilize the free spectrum to solve the problem of spectrum resource shortage and low utilization rate without impacting licensed users. Efficient information multicasting and broadcasting technologies are the basic technologies of cognitive radio ad hoc network, and they are of great importance to the application and promotion of CRAHNs.

Due to the differences in locations and environments, as well as the changes in the state of nodes in other networks, the data channel sets that can be accessed by different nodes may not be the same. For channels that can be accessed, communication quality may vary across channels because of the impacts of the relative position between the sending and receiving nodes, environment and other factors, and this leads to different transmission rates for different channels [3]. The multicity of channels, the differences in the available channel set of different nodes, and the variability of packet transmission quality in each channel will bring new challenges to the study of multicast and broadcast technology in CRAHNs [4]–[7]. The development of Network Coding (NC) technology [8] provides new ideas and approaches for the researches to overcome the challenges [9], [10]. NC technology combines the main idea of coding and routing [11], and completely changes the network communication mode of store-and-forward. The technology encourages the intermediate nodes to combine the codes of multiple packets into one or more output data packets, and then forward it, so that the destination nodes can obtain the original data by decoding the packet it received. NC technique can make better use of the inherent characteristics of wireless network (e.g. communication broadcast, data redundancy, the nature of space distribution and so on) [12]–[15], and they can significantly enhance the throughput of wireless networks, the reliability, load balance, etc. In RNC technology [16], the encoding coefficient is chosen randomly in Galova region GF(2^q) [17], so that the NC technology can be applied in distributed applications [18], [19].

The existing studies on the application of NC technology in wireless network focus on regular wireless networks. For example, some researchers (see e.g., [20]–[22], etc.) study the NC which is applied to the wireless ad hoc network multicast technology, while Shao *et al.* [21] consider the time-varying wireless network model with the link capacity affected by noises. Based on the time-varying wireless network model, Mohandespour *et al.* [23] utilize a dynamic pressure feedback algorithm to optimize the NC and the routing respectively. Rouayheb *et al.* [24], Nguyen *et al.* [25], Yukun *et al.* [26], Zhenguo *et al.* [27], and Tingting *et al.* [30] study the problem of wireless packet retransmission using the idea of NC, and test the specific implementation of NC at the protocol level of the wireless network.

Nevertheless, there have been very few studies on the applications of NC technology in cognitive wireless network. To the best of our knowledge, the only notable exceptions are [29] and [31]. By analysing the characteristics of NC technology, Bo *et al.* [29] show that the application of NC technique can reduce the probability of collision between licensed and unlicensed users when accessing the wireless channels in cognitive radio network. Zhenguo *et al.* [31] study the problem of error in packet retransmission using NC technology, which can be seen as the improvement and supplement of the Automatic Repeat request (ARQ) protocol at the link layer.

This paper studies the multicast or broadcast transmission technology in CRAHNs. The working assumptions of our study are: (1) all nodes in the CRAHNs support a public wireless control channel and multiple data channels, and the nodes transmit communication control packets through the public wireless communication control channel; (2) data source node controls the information interaction through public control channel, and we use the traditional multicast routing algorithm to build a multicast tree which has a source node as its root, and multicast receiving nodes as its leaves. All the data packets are transmitted along the multicast tree to each receiving node; (3) the control packets are transmitted through the public wireless control channel, while the data packets are delivered via the data channels.

We focus on the data packet multicast algorithm in CRAHNs, and propose an algorithm based on RNC. The algorithm can execute packet multicast tasks in bulk, and allow variant numbers of packets in each bulk. The packets multicast algorithm can be divided into two parts: packet sending algorithm and packet receiving algorithm. Each node has two wireless working threads that run the algorithms respectively. Each node's packet sending algorithm and packet receiving algorithm collaborate to complete the multicast task. The packet sending algorithm consists of two phases: the first phase is called the initial centralized packet sending phase, in which some coded packets are sent intensively according to a strategy; the second phase is called the follow-up discrete packet sending phase, in which each node periodically sends a single message at certain strategy to ensure that the message can be successfully obtained by all downstream nodes. These two phases comprehensively utilize the NC technology and the broadcast characteristic of the wireless communication, decrease the number of the transmitted packets and reduce the demand of the auxiliary information effectively. It also effectively improves the algorithm efficiency, and reduces the overhead of the algorithm. Simulation results show that the algorithm based on NC can save up to 50% of transmitted packets compared with traditional non-network coding algorithm.

Although the packet in multicast is usually transmitted within more than one hop, the transmission process of each one is almost identical. So essentially the packet multicast is one-hop transmission technology. In fact, the nodes on the multicast tree and all its downstream nodes constitute a temporary local single-hop multicast system, and the current node is the packet sending node, while all of its direct downstream nodes are the receiving nodes. We call the basic problem of single hop multicast system as Multi-Channel Single-Hop Wireless Multicast Problem (MCSHWMP). The core of the multicast transmission algorithm proposed in this paper is the solution to MCSHWMP.

The rest of this paper is organized as follows. In Section II, we review the related concept of Multi-Channel Single-Hop Wireless Multicast Problem, and present a 4-element tuple model for the MCSHWMP problem. In Section III, the framework of the packet multicast algorithm in CRAHNs is described, and several multicast algorithms based on the framework are presented. The performance of several proposed algorithms by simulation is tested in Section IV, which shows the advantages of packet multicast technology based on NC in cognitive wireless networks. Section V concludes.

II. MULTI-CHANNEL SINGLE-HOP WIRELESS MULTICAST PROBLEM

The basic scenario of Multi-Channel Single-Hop Wireless Multicast Problem is as follows: in the cognitive wireless network, a sending node has a packet to broadcast to the receiving nodes, and the receiving nodes are within the transmission range of the sending node which has ability of wireless transmission. Our goal is to find packet transmission strategies to minimize the number of transmitted packets under the premise that each node can receive its message,

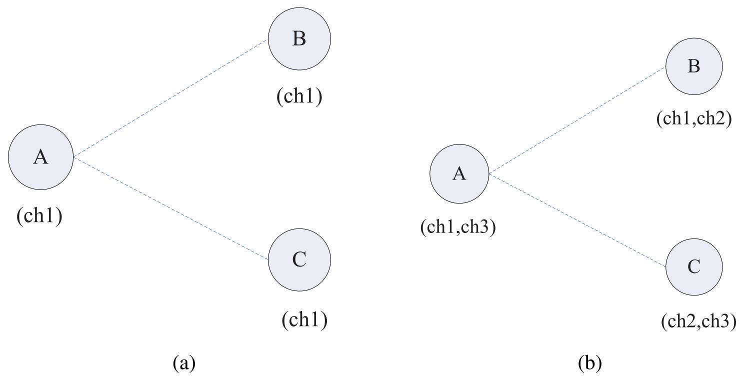

FIGURE 1. Scenario of single-hop broadcast. (a) Traditional Ad Hoc Network. (b) CR Ad Hoc Network.

while taking into account the differences in available channel set of different nodes and the variability of the packet transmission quality in each channel.

To further illustrate the challenges of broadcasting in CR Ad Hoc networks, we consider a single-hop scenario shown in Fig. 1, where node A is the source node.

Definition 1: Multi-Channel Single-Hop Wireless Multicast Problem Multicity of working channels is an appealing feature of multi-channel communication networks (such as CRAHNs) relative to traditional wireless networks, so we call the one-hop wireless broadcast in the CRAHNs as multichannel one-hop wireless multicast problem.

A MCSHWMP problem can be described as follows:

$$\text{MCSHWMP} = \left\{P, R, C, B_{|R|\times|C|}\right\} \tag{1}$$

Where, (1) $P = \{p_i|\forall i \in \{1, \ldots, |P|\}\}$ is the set of packets to be sent to each receiving node by the sending nodes in this problem; (2) $R = \{r_i|\forall i \in \{1, 2, \ldots, |R|\}\}$ is the set of receiving nodes in this problem; (3) $C = \{c_i|\forall i \in \{1, \ldots, |C|\}\}$ is the available channel set for this problem; (4) $B_{|R|\times|C|} = \left\{b_{i,j}\right\}_{|R|\times|C|}$ is the matrix of probabilities that the packet transmission is successful in wireless channels. Each element $b_{i,j}$ of this matrix is the probability of successful packet transmission in the channel c_j between the sending node and the receiving node r_i, and for some impossible channels, $b_{i,j} = 0$.

We calculate the single-hop successful broadcast ratio for the random broadcast scheme. Without loss of generality, in the rest of the paper, the sender and the receiver of the single-hop link is denoted as A and B.We further denote the numbers of available channels for the single-hop communication pair as N_A and N_B, respectively. The number of common channels between A and B is Z_{AB}. Therefore, the probability that the single-hop broadcast is successful in a time slot is

$$p_r = \binom{Z_{AB}}{1}\frac{1}{N_A}\frac{1}{N_B} = \frac{Z_{AB}}{N_A N_B} \tag{2}$$

The goal of MCSHWMP is to find a packet transmission scheme (including NC strategy and channel utilization strategy) and minimize the required number of packets transmitted under the premise of that each node can obtain all packets correctly.

Definition 2: Effective schemes of MCSHWMP problem. If a packet transmission scheme of MCSHWMP problem can ensure that each receiving node can correctly decode the packets of each message in P defined above, then it is an effective scheme for the MCSHWMP problem.

Definition 3: Optimal NC schemes for MCSHWMP problems. The main objective of the MCSHWMP problem is to minimize the number of wireless packets transmitted. Therefore, the NC scheme that has the minimum number of packets is called the optimal NC scheme of MCSHWMP problem.

In this paper, the Galois domain GF (2^q), which is used in NC, is not restricted to the value of q.To simplify exposition, we define $n_{\mathrm{R}} = |R|$, $n_{\mathrm{C}} = |C|$, $n_{\mathrm{P}} = |P|$.

In GF (2^q), of link js inputs, i.e., source processes X_i for which $a(i) = o(j)$ and random processes Y_l for which $d(l) = o(j)$, if any.

For the delay-free case, this is presented by the equation:

$$Y_j = \sum_{\{i:a(i)=o(j)\}} a_{i,j}X_i + \sum_{\{l:d(l)=o(j)\}} f_{l,j}Y_l \tag{3}$$

III. DATA PACKET MULTICAST TRANSMISSION ALGORITHM OF MCSHWMP PROBLEM

The multicast technology based on NC executes the data packet multicast tasks in bulks, and the number of data packets in each bulk is variant. Before the data multicast, the data source node is in the public control channel, and it builds up the multicast tree whose root is the source node, and the leaves are the multicast receiving nodes based on the traditional multicast routing algorithm. After the multicast tree is established completely, source node begins to broadcast data packet along the multicast tree. After the nodes have received the data message, they process and forward the data packets to downstream nodes according to the method proposed in this paper until the leaf nodes have received all the batches of packets, then this batch of data packet multicast tasks is completed successfully. The nodes in the broadcast tree independently decide the time to start conducting the next batch of data packet transmission tasks according to the local information.

A. COMBINED PACKET STRUCTURE

In the packet multicast based on the NC, the receiving nodes require some auxiliary information to decode the packet in addition to the encoding packet. Decoding auxiliary information is generally encapsulated in a combined packet with encoding packet and other information. The real transmitted packet is the combined packet. In this paper, the combined packet includes seven fields as shown in Fig. 2.

FIGURE 2. Structure of the combined packet.

In the figure above, *ID_Src* denotes the number of source nodes; *ID_Batch* marks the batch number of the packet that is currently being processed; *ID_Sender* indicates the sender of the packet; *PktNum_InBatch* indicates the number of packets in the batch of packets; *List_Rcv* indicates the set of downstream receiving nodes of the sending nodes; *Pkt* holds a coded packet, and the encoding vector used to generate the coded packet is actually a random number sequence generated by a public random function using a random number as a seed, while the length of the sequence is *PktNum_InBatch*. The encoding coefficient is considered to be the element in Galois domain GF (2^q), and the field is used to store the corresponding seed of random number.

B. DATA PACKET TRANSMISSION ALGORITHM

The CRAHNs packet multicast algorithm based on the RNC can be divided into two parts: packet sending algorithm and packet receiving algorithm. Each node has an infinite loop working thread of sending algorithm and receiving algorithm, and they conduct the data packet sending task and the data packet receiving task respectively. Each node's packet sending algorithm and packet receiving algorithm collaborate to complete the multicast tasks.

In this paper, we provide the basic framework of the data packet sending algorithm and the receiving algorithm, and different algorithms can be obtained by adjusting some of the steps.

The data packet sending process includes two stages: the initial sending phase and the subsequent discrete packet transmission phase. The initial centralized packet transmission phase cannot guarantee that all nodes receive sufficient information to decode the packet and obtain all packets in the current multicast batch. And subsequent discrete message sending node is to ensure that packet transmission task can be successfully completed. The nodes in subsequent discrete packet transmission transmit only one combined packet at a time, and the channel used for transmitting the packet is determined along the selection strategy for the discrete packet channel selection. The frame chart of sending algorithm for data packet is shown in Fig. 3, which is described below.

Framework flow of sending algorithm for data packet is as follows:

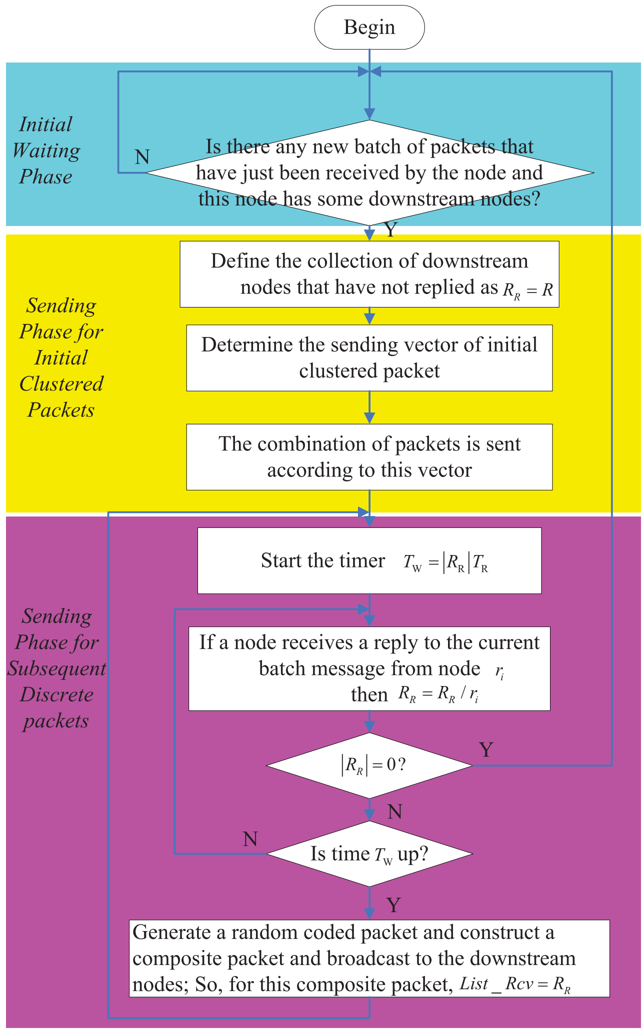

FIGURE 3. The framework flowchart of the sending algorithm for data packet in CRAHNs.

Step 1. If the node has a new batch of data packet that has been received and is going to be transmitted to the downstream nodes, and the current node has downstream nodes, then it goes to step 2; Otherwise it keeps waiting;

Step 2. The sending node generates the initial packet allocation vector $V_{Init} = \{x_1, x_2, \ldots, x_{|C|}\}$ based on the strategy that determines an initial packet allocation vector. The vector element x_j means that the sending node needs to transmit x_j combined packets on channel c_j at the initial packet sending phase.

Step 3. Transmit x_j combined messages in turn on channel c_j according to the initial packet allocation vector; for $(j = 1, j < n_C, j++)$

if $x_j = 0$, then continue next loop;

if $x_j < 0$, then do it as follows:

- Inform each receiving node $r \in \{r_i | b_{ij} > 0\}$through the public control information exchange channel to transfer the receiving channel to channel c_j;
- Construct $x_j$coded packets:

$$p_{Y,j} = \boldsymbol{m_i} \cdot \boldsymbol{P}_X \left(i = \{1, 2, \ldots, x_j\}\right) \tag{4}$$

In which the coding coefficient vector $\boldsymbol{m}_i$ is generated by random number seed s_j;

- Construct the combined message $P_{Z,j} = [ID\_Src, ID\_Batch, ID\_Sender, PktNum\_InBatch, List\_Rcv, s_j, p_{Y,j}]$, in which $List\_Rcv = R_R$;
- Broadcast all $x_j$combined packets $P_{Z,j}$on channel c_j;

Step 4. Start the timer T_W, and the timer will end at $t_W = |R_R| \cdot T_R$. (T_R is a parameter, and its value is larger than the time required to receive a reply packet.) During this period, we are waiting for the response packet of each receiving node.

Step 5. If we get a reply packet from node r_i for the current batch of data packet, it indicates that this node has correctly obtained all of its required packets, $R_R = R_R / r_i$;

Step 6. The timer T_W is over. If $R_R = \emptyset$, return to step 1.

Step 7. Construct one coded packet:

$$p_Y = \boldsymbol{m} \cdot \boldsymbol{P}_X \left(i = \left\{1, 2, \ldots, x_j\right\}\right) \quad (5)$$

In which the coding coefficient vector $\boldsymbol{m}$ is generated by the random number seed s_j; and $\boldsymbol{P}_X = \{p_1, p_2, \ldots, p_n\}$;

Step 8. Construct one combined packet: $P_Z = \{ID\_Src, ID\_Batch, ID\_Sender, PktNum\_InBatch, List\_Rcv, s_j, p_Y\}$, in which $List\_Rcv = R_R$, and broadcast it on channel $c_j = \arg\max_{c_j \in C} \left(\sum_{r_i \in R_R} b_{i,j} \right)$. After completing the packet transmission, go to step 4;

The flow of receiving algorithm for data packet in the data packet multicast algorithm is shown in Fig. 4, which is described as follows:

The framework flow of the data packet receiving algorithm is as follows:

Step 1. If a new batch of data are received, then it goes to step 2; Otherwise, wait for the new batch of packets;

Step 2. Initialize the decoding matrix M_D of new batch of packets as null, and initialize the column vector of coding packet in new batch of packets P_Y as null;

Step 3. Suppose that the received data packet is p. Using the $p.Info$ as a random number seed, recover the coding vector by the same method used in the generation of encoding matrix and label it as v; Take out the packet $p.Pkt$ in the combined packet p, and label it as p_R, i.e. $p_R = p.Pkt$;

Step 4. According to equation (6), the row vector v is attached to the decoding matrix M_D as its tail;

$$M_D = \begin{bmatrix} M_D \\ v \end{bmatrix} \quad (6)$$

Step 5. Let $p_R = p.pkt$, and add p_R to the tail of p_Y according to equation (7);

$$P_Y = \begin{bmatrix} P_Y \\ p_R \end{bmatrix} \quad (7)$$

Step 6. The rank $rank\,(M_D)$ of decoding matrix M_D is calculated on the domain GF (2^q);

Step 7. If $rank\,(M_D) < n$, then wait for the new combined packet to be received, and go to step 3;

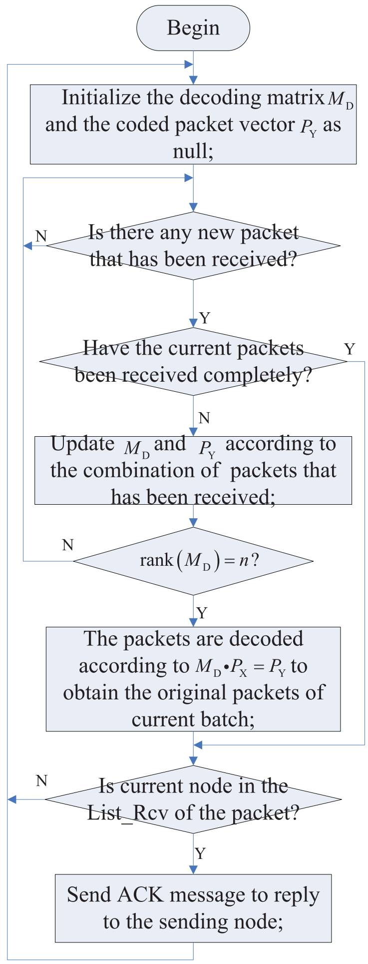

FIGURE 4. **The framework flowchart of the receiving algorithm for data packet in CRAHNs.**

Step 8. If $rank\,(M_D) = n$, decode the equation (8) using Gaussian Jordan elimination method to obtain all packets needed;

$$M_D \cdot P_X = P_Y \quad (8)$$

Step 9. If the current node ID is in the *List_Rcv* field of the packet, the ACK reply packet is sent to the sending node to inform the sender that it has received the current batch of all packets;

Step 10. Go to step 1.

C. DETERMINATION STRATEGY OF INITIAL CENTRALIZED PACKET SENDING VECTOR

In the packet sending algorithm described above, the combined packets need to be sent in accordance with the initial packet allocation vector in the initial packet sending stage. The initial packet allocation vector has a decisive influence on the time delay of the algorithm, and also has great influence on the number of packets transmitted. If the packet allocation vector identifies too many packets to send, although it can reduce the completion time of 1 hop packet multicast task, in initial stage it may send large amount of packets information that already satisfies even more than the need of each node, leading to heavy packet transmission, which will increase the energy consumption. If the number of packets is too small in the initial stage, it may be required to send more packets in the subsequent discrete packet transmission stage, which will increase the completion time of 1 hop packet multicast task, and also cannot significantly reduce the total number of packet transmitted. Thus it is very important to find a proper initial packet allocation vector to save the number of packets and reduce the completion time of the packet multicast task.

This paper presents three strategies and compares the performance of these three strategies through simulation. These three strategies are labeled as INIT_RAND1, INIT_LINK100, INIT_ LINKRATIO. Obviously, the number of packets sent in the initial phase of these three strategies is increasing in turn.

INIT_RAND1 strategy

In the INIT_RAND1 strategy, the initial packet allocation vector is randomly determined, but it has to satisfy $\sum_{j=1}^{n_C} x_j = 1$, that is, a combined packet should be conveyed on a randomly selected channel.

INIT_LINKRATIO strategy

The goal of INIT_LINKRATIO strategy is to find the optimal NC scheme of MCSHWMP problem under the desired state that each node can obtain enough information to get the original packets in the expected stage, and try to find a scheme in which the number of the packets transmitted is the least, and then take the solution of the scheme as the initial packet allocation vector. The analysis shows that the original packet allocation vector in INIT_LINKRATIO strategy is the solution vector of integer linear programming problems as shown in equation (9).

$$\begin{aligned} &\min \sum_{j=1}^{n_C} x_j \\ &\text{s.t.:} \sum_{j=1}^{n_C} (x_j \cdot b_{i,j}) \geq n_P \quad \forall i \in \{1, 2, \ldots, n_R\}; \\ &\qquad x_j \in \{0, 1,2, \ldots\} \quad \forall j \in \{1, 2, \ldots, n_C\}; \end{aligned} \tag{9}$$

In equation (9), the integer programming variable is x_j, which indicates that the sending node needs to send x_j coded packets via the channel c_j.

The meaning of each constraint in equation (9) is as follows. The first constraint is to ensure that the sum of the expected number of coded packets received by $r_i$from each channel is greater than or equal to the number of required packets $n_P = |P|$. The second constraint is that $x_j$can only take non-negative integers.

INIT_LINK100 strategy

The goal of INIT_LINK100 strategy is to find the optimal NC scheme in all the available links (namely the links that satisfied $b_{i,j} > 0$) in the case of that the success rate of packet transmission is 100%, that is assuming the success rate of packet transmission in the links as 100%, then each node can find the scheme that acquires the least transmitted packets and take the solution of the scheme as the original packet allocation vector under the premise of that each node can get enough information to decode and obtain the original packets. The analysis shows that the original packet allocation vector in INIT_LINK100 strategy is the solution vector of integer linear programming problem as shown in equation (10).

$$\begin{aligned} &\min \sum_{j=1}^{n_C} x_j \\ &\text{s.t.:} \sum_{j=1}^{n_C} (x_j \cdot ceil(b_{i,j})) \geq n_P \quad \forall i \in \{1, 2, \ldots, n_R\}; \\ &\qquad x_j \in \{0, 1,2, \ldots\} \quad \forall j \in \{1, 2, \ldots, n_C\}; \end{aligned} \tag{10}$$

The integer programming variable in equation (10) is x_j, which indicates that the sending node needs to send x_j coded packets on the channel c_j.

The meaning of the constraint conditions in equation (10) is as follows. First constraint ensures that, under the premise of that the success rate of packet transmission in all the available links is 100%, and the sum of the number of coded packets that received correctly by receiving node $r_i$from each channel is greater than or equal to the number of the packets required $n_p = |P|$, in which the *ceil* (x) indicates the upward integer of variables x, that is to set all the packet transmission rate of each available link as 100%; The second constraint means that x_j can only take non-negative integers.

INIT_LINK100's initial packet allocation vector is equivalent to the scheme that has the minimum number of transmitted packets in an ideal state.

IV. SIMULATION TEST

A. THE ALGORITHM TO BE TESTED

The performance of the data packet multicast algorithm of MCSHWMP problem is tested by simulation using Matlab. In this paper, we compare the performance of the three determination strategies for initial centralized packet delivery vector: INIT_RAND1, INIT_LINK100 and INIT_LINKRATIO, and the algorithms using these three initial strategies are recorded as Rand1, Link100 and LinkRatio algorithm, respectively.

In addition, in order to evaluate the performance of the algorithm based on NC comparing with the traditional non-network coding algorithm, the analysis shows that for the MCSHWMP problem, the transmission scheme that has the minimum number of packets transmitted for the traditional non-network coding algorithm can be converted into the integer linear programming problem as equation (11) in the expected case, and the solution of the planning problem can be directly converted into the non-network coding scheme for MCSHWMP problem. We call this algorithm as NoNCExpOpt, and use it as a benchmark to evaluate each algorithm.

The integer programming variable in equation (11) is $x_{j,k}$, which represents the number of retransmitted packets p_k via the channel c_j.

The meaning of each constraint in equation (11) is as follows. The first constraint requires that, in the expected case, the number of that the packets p_k to be correctly received by receiving node r_i from each channel should be greater than or equal to 1; The second constraint indicates that $x_{j,k}$ can only take non-negative integers.

$$\begin{aligned} \min \quad & \sum_{j=1}^{n_C} \sum_{k=1}^{n_P} x_{j,k} \\ \text{s. t.:} \quad & \sum_{j=1}^{n_C} (x_{j,k} \cdot b_{i,j}) - 1 \geq 0 \qquad \forall i \in \{1, 2, \ldots, n_R\}, \\ & x_{j,k} \in \{0, 1, 2, \ldots\} \qquad \forall j \in \{1, 2, \ldots, n_C\}, \\ & \qquad \qquad \forall k \in \{1, 2, \ldots, n_P\}; \end{aligned} \tag{11}$$

To sum up, the algorithms to be tested in the simulation include the following: Rand1, Link100, LinkRatio and NoNCExpOpt. In these algorithms, some integer linear programming problems need to be addressed, and to solve these planning problems in the simulation we adopt the algorithm of progressive integer determination proposed by Zhu [12].

B. PERFORMANCE METRICS

1) TOTAL NUMBER OF PACKETS TRANSMITTED

This metric denotes the total number of combined packets that need to be sent from sending node for completely transmitting a batch of packets, including the packets sent in the initial centralized packet transmission phase and the packets sent in the subsequent discrete packets transmission phase. This metric mainly reflects the performance of the algorithm in decreasing the number of packets.

2) THE NUMBER OF DISCRETE MESSAGE TRANSMITTED

This metric denotes the number of packets sent by the sending node in the subsequent discrete packet transmission phase of the MCSHWMP problem. This metric can partially characterize the time delay of the algorithm.

3) RELATIVE VALUE OF TOTAL NUMBER OF THE PACKETS TRANSMITTED

Relative value of total number of the packets transmitted is defined as the ratio between the total numbers of packets transmitted using different algorithms. For example, Link100/NoNCExpOpt indicates the ratio of the number of packets transmitted by Link100 to that transmitted by NoNExpOpt.

4) THE NUMBER OF CHANNEL SWITCHING

Channel switching will increase energy consumption, delay and other overhead costs, so the average channel switching times of nodes is also used as a performance metric. In some solutions, if the node needs to work in n different channels, the number of channel switching is recorded as n. For a MCSHWMP problem, the average number of channel switching of a sending node and all its receiving nodes are referred as the metric for the number of channel switching of the scheme.

C. SIMULATION CONFIGURATION

The parameters of MCSHWMP $\{P, R, C, B\}$ in simulation include packets number $|P|$, receiving node number $|R|$, the number of channels $|C|$, channel dispersion c_{Level}, and base value of success rate for channel packet transmission *LinkSuc_Base*. A combination of $\{|P|, |R|, |C|, c_{\text{Level}}$, *LinkSuc_Base*$\}$ is called as a simulation configuration.

For one simulation configuration, 100 problem instances are generated repeatedly. For each instance, every test algorithm is used to deal with the problem, and their corresponding metrics are recorded respectively. The average value of simulation result of 100 instances is calculated as the final result, and the 95% confidence interval of the average value is calculated as well.

Each instance is expressed by the successful transmission rate matrix M_B whose size is $|R| \times |C|$. The element $a_{i,j}$ of the M_B is determined as follows: choose a random number in the (0,1) interval $x = rand\,()$.

if $x < c_{\text{Level}}$:

$$a_{i,j} = LinkSuc\_Base + (1 - LinkSuc\_Base) * rand\,() \tag{12}$$

and it indicates that the packet successful transmission rate between the sending node and the receiving node r_i via the channel c_j is $a_{i,j}$; Otherwise, if $x \geq c_{\text{Level}}$, then $a_{i,j} = 0$. c_{Level} is only used to control the distribution of the available channels for each node in the simulation, and the larger the value is, the more available channels it has.

D. SIMULATION RESULTS

In this paper, the performance of the multicast algorithm is tested by extensive simulations. Partial simulation results will be given in this section.

1) INFLUENCE OF CHANNEL NUMBER AND *LINKSUC_BASE* ON PERFORMANCE

We fix $|P| = 5$, $|R| = 5$, $c_{\text{Level}} = 0.5$, and coding digits $q = 8$ when $|C| \in [2, 10]$ and the base value of success rate of packet transmission in channels $LinkSuc\_Base \in [0.1, 1]$. The changes of the performance metrics are shown in Fig. 5.

The changes of the total number of packets transmitted are shown in Fig. 5(a), while in Fig. 5(b), the changes of the relative value of total number of packets transmitted are described. The results show that the number of channels has little influence on the performance of each algorithm compared to NoNCExpOpt, while *LinkSuc_Base* has a great influence on the performance for each algorithm. As *LinkSuc_Base* decreases from 1 to 0.1, the relative value of number of packets transmitted decreases first and then increases, and the relative value of number of packets transmitted would achieve the lowest when the *LinkSuc_Base* is

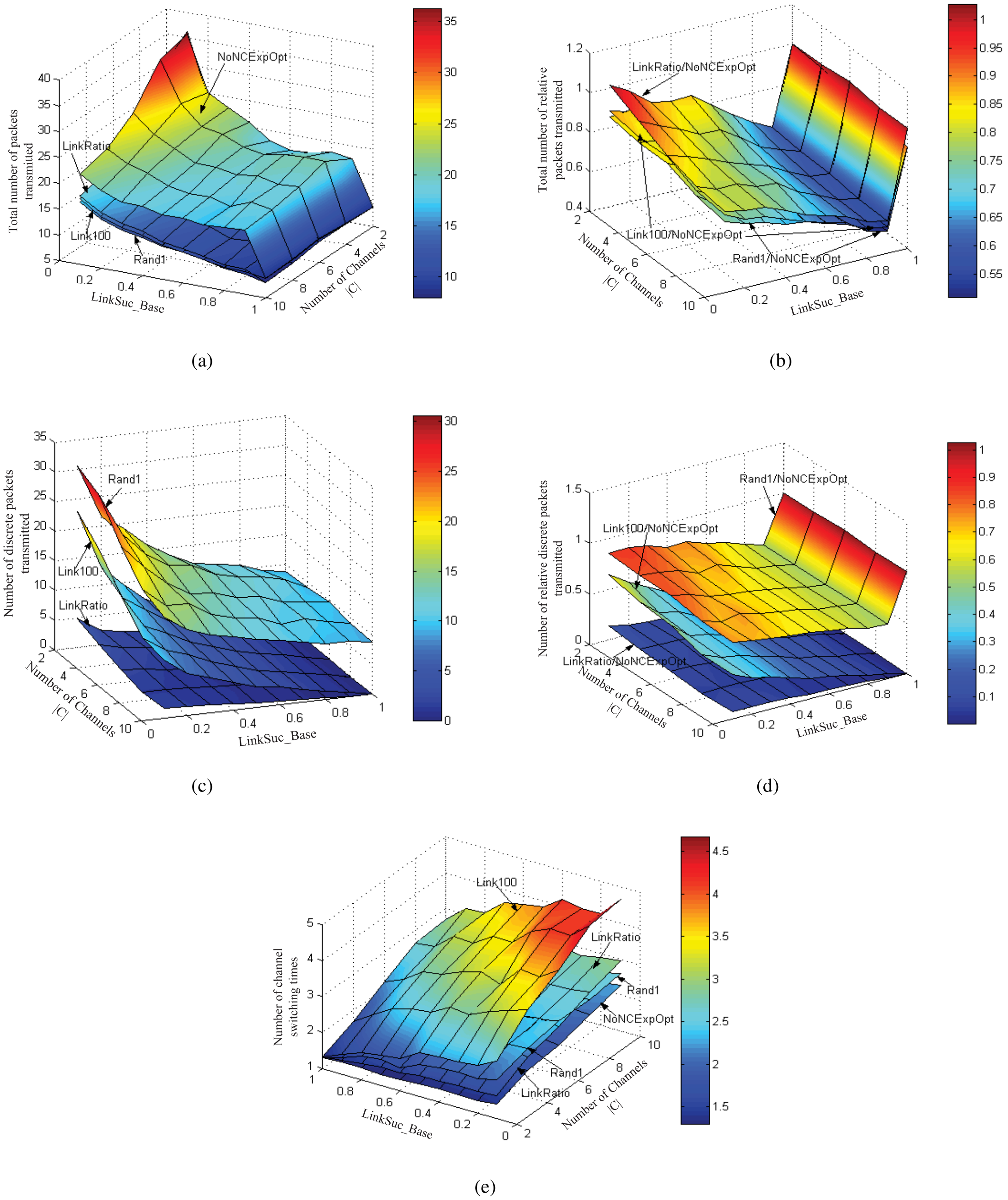

FIGURE 5. Impact of the number of channels and *LinkSuc_Base* on performance of each scheme ([$R = 5$; $P = 5$; $q = 8$; $c_{\text{Level}} = 0.5$]. (a) Total number of the packets transmitted. (b) Relative value of total number of packets transmitted. (c) Number of discrete packets transmitted. (d) Relative value of number of discrete packets transmitted. (e) Number of channel switching times.)

about 0.9, namely obtain the greatest advantage of the algorithm based on NC. When $LinkSuc\_Base = 0.9$, compared to NoNCExpOpt, Link100 and Rand1 can reduce nearly 50% of packets to be transmitted. This result can be explained as follows. Because each planning variable can only take an integer, and in order to satisfy the constraint conditions, the variable can only round up to an integer. When the *LinkSuc_Base* is close to 1, the corresponding linear programming solution gained after the cancellation of the integer restrictions may be slightly larger than an integer. Rounding up to an integer will result in a larger amplitude of the increase, while the network coding can integrate the packets, and reduce the negative impact of the rounding up, so that the algorithm based on NC is more optimal than the network non-coding algorithm. In this case, the maximum advantage can be achieved when *LinkSuc_Base*

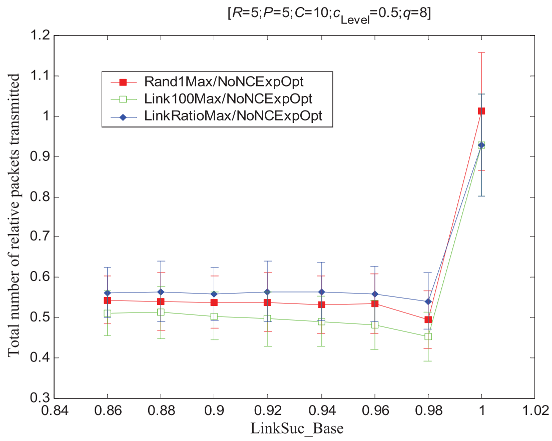

FIGURE 6. Impact of ***LinkSuc_Base*** on performance of each scheme.

is about 0.9. Although the relative value of total number of packets transmitted of LinkRatio is slightly larger than that of Link100 and Rand1when *LinkSuc_Base* is about 0.9, the packets transmitted it can reduced is still about 45% of the packets, so the three kinds of algorithms based on NC technique can all greatly reduce the number of packets transmitted. As shown in Fig. 6, the further simulation results around $LinkSuc\_Base = 0.9$ indicate that the relative value of the number of packets transferred will decrease with the increase of *LinkSuc_Base* when $LinkSuc\_Base = [0.9, 1]$. Until $LinkSuc\_Base = 1$, it increases to nearly 1.

Fig. 5(c) illustrates the changes of the number of discrete packets transmitted, and the changes of the metric for the relative value of number of discrete packets transmitted are presented in Fig. 5(d). Both graphs show that the number of discrete packets transmitted in LinkRatio algorithm is very small, indicating that the number of concentrated packets transmitted is larger. The more the number of discrete packets is transmitted, the longer time the completion of algorithm will take, that is the longer the delay will be.

In Fig. 5(e), we show that LinkRatio algorithm and NoNCExpOpt have the minimum number of channel switching. The analysis of algorithm process shows that, in each phase of the sending algorithm, the working channel will not switch to the original working channel, so the frequency of channel switching will not exceed $|C|$. Since the channel switching times of the two stages have the superposition effect, the allocation of the messages in two stages will have a crucial influence on the number of channel switching. Link100 algorithm sends more packets in both of phases, so the metric of channel switching frequency is the largest. And for Rand1 and LinkRatio, packets are mainly transmitted in the second stage or the first phase, so the channel switching times of the two algorithms are smaller. The NoNCExpOpt algorithm is the optimal solution for solving integer linear programming problem, so its metric is the lowest.

2) IMPACT OF TOTAL NUMBER OF PACKETS AND NUMBER OF RECEIVING NODES ON PERFORMANCE

We fix $|C| = 5$, $c_{\text{Level}} = 0.5$, coding coefficient digits $q = 8$, $LinkSuc\_Base = 0.9$, when $|R| \in [2, 10]$and $|P| \in [2, 10]$. The changes of the algorithm performance metric are shown in Fig. 7.

From Fig. 7(a) we can see the changes of the total number of packets transmitted, and the changes of the relative value of total number of the packet transmitted in each algorithm compared to the NoNCExpOpt algorithm are shown in Fig. 7(b). These results show that the relative value of total number of packet transferred in Link100 is impacted little by the number of receiving nodes $|R|$ and the number of batches of packets $|P|$, and the value of its influence is about 0.5, which indicates that compared with packet multicast algorithm based on traditional non-network coding technique, the algorithm presented in this paper can decrease nearly 50% of the packets transmitted. The relative performance metric of Link100 increases slightly when $|R|$ increases, and when $|R|$ increases from 2 to 10, the metric increases from 50% to 53%. The relative value of total number of packet transmitted in Rand1 also increases slightly with increasing of $|R|$, but it increases slightly faster. When $|R|$ increases from 2 to 10, the metric increases from 50% to 54%. In general, $|P|$ and $|R|$ have little impact on Link100 and Rand1. $|P|$ has a great influence on LinkRatio. When $|P|$ increases from 2 to 10, the relative value of total number of packet transmitted reduces from 0.75 to 0.54, correspondingly, the number of packets decreases from 25% to 46%.

From Fig. 7(c), we can see the changes of the number of discrete packet transmitted, and Fig. 7(d) show the changes of the quantity metric of relative value of discrete packets. Results show that the LinkRatio sends the least packets in the second phase of the algorithm, and Link100 sends a bit more packets in the second phase of the algorithm, while Rand1 sends the most packets in the second phase of the algorithm, so that the former two algorithms have shorter delay time and the last one has longer delay time. All of Rand1's data packets can be seen as transmitted in the second phase. Fig. 7(e) show the variation in the number of channel switching times.

3) THE INFLUENCE OF c_{Level} AND *LinkSuc_Base* ON PERFORMANCE

We fix $|P| = 5$, $|C| = 8$, $|R| = 5$, coding digits $q = 8$, when the channel distribution probability $c_{\text{Level}} \in [0.1, 1]$ and the base value of success rate for packet transmission in channels $LinkSuc\_Base \in [0.1, 1]$. The changes in the performance of these schemes are shown in Fig. 8.

In Fig. 8(a), the changes of the total number of packets transmitted are shown, and in Fig. 8(b) the changes of the relative value of total number of packets transmitted of each algorithm compared to the NoNCExpOpt algorithm are shown. c_{Level} has small effect on the relative performance of these algorithms, while it has large effect on the

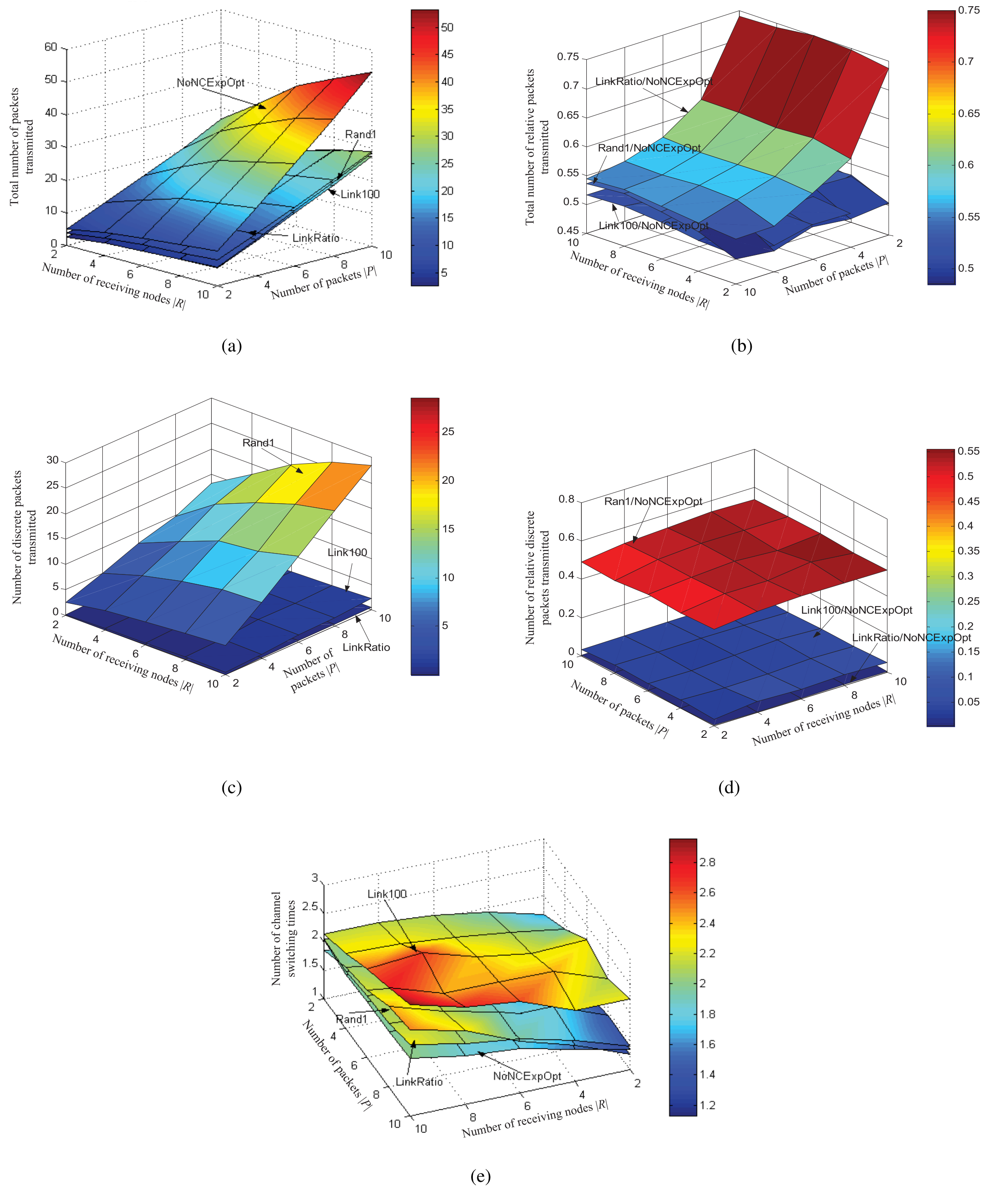

FIGURE 7. **Impact of total number of packets and total number of receiving nodes on performance of each scheme ([$C = 5$; $c_{\text{Level}} = 0.5$; *LinkSuc_Base* $= 0.9$; $q = 8$]). (a) Total number of the packets transmitted. (b) Relative value of total number of packets transmitted. (c) Number of discrete packets transmitted. (d) Relative value of number of discrete packets transmitted. (e) Number of channel switching times.**

total number of packets transmitted. This pattern is easy to explain because the greater the c_{Level} is, the more likely for the receiving nodes to share the channels, which will cause the total number of packets transmitted to be small. *LinkSuc_Base* has a significant impact on the two metrics of each algorithm. Each algorithm can save up to 47% of the packets when *LinkSuc_Base* $= 0.9$. And it is consistent with the simulation results in Section 4.4.1. When *LinkSuc_Base* decreases from 0.9 to 0.1, the number of packets saved in Rand1 and Link100 decreases linearly to about 15%. When *LinkSuc_Base* $= 1$, the relative value of total number of packets transmitted in each algorithm is about 1, indicating that the application of NC technology cannot reduce the number of packets transmitted.

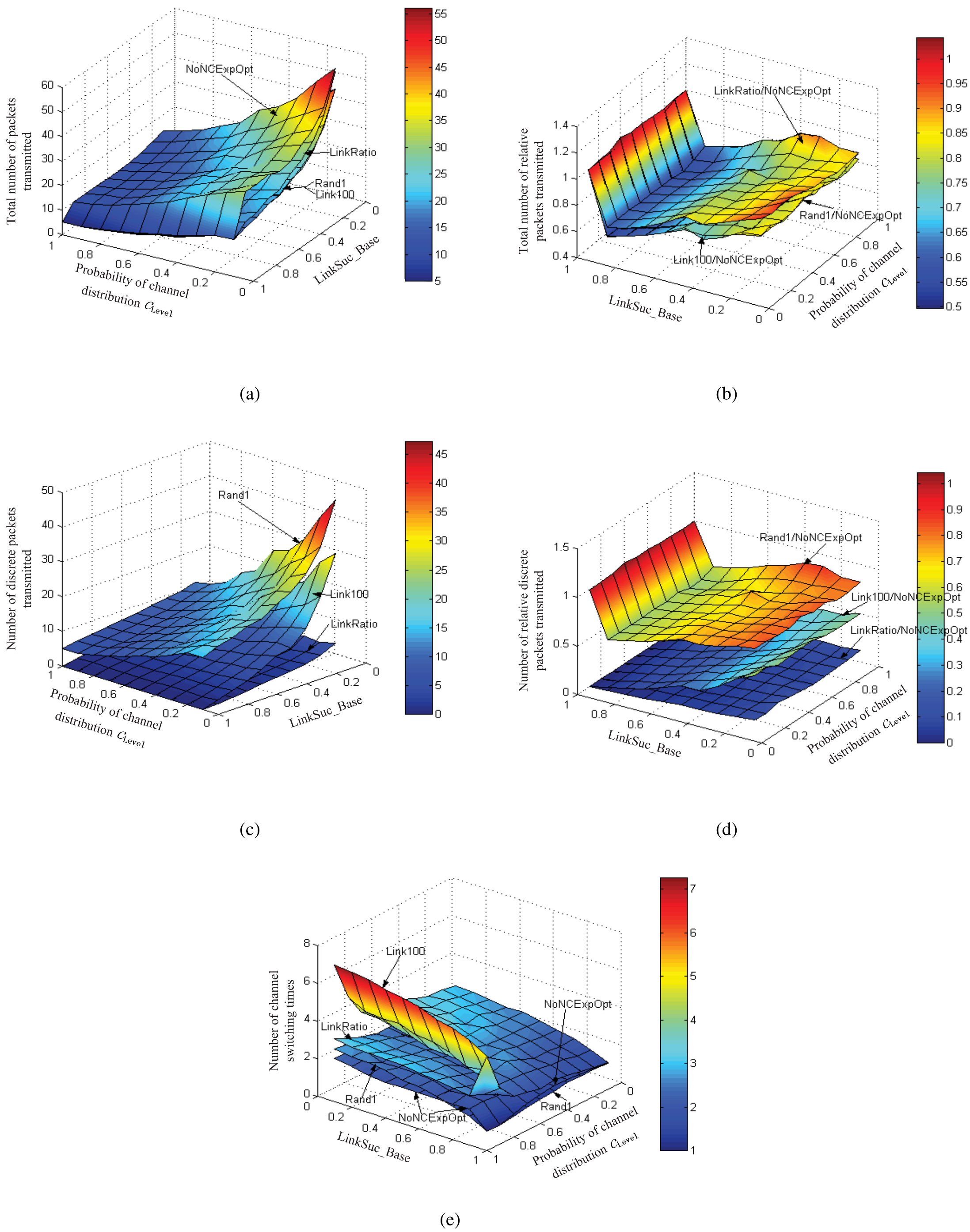

FIGURE 8. Impact of *LinkSuc_Base* and c_{Level} on performance of each scheme([$R = 5$; $P = 5$; $C = 5$; ; $q = 8$]).(a) Total number of the packets transmitted. (b) Relative value of total number of packets transmitted. (c) Number of discrete packets transmitted. (d) Relative value of number of discrete packets transmitted. (e) Number of channel switching times.

In Fig. 8(c), it is shown that the changes of the number of discrete packets transmitted, and the changes of the quantity metric of relative value of discrete packets transmitted are shown in Fig. 8(d). The results show that the LinkRatio sends the least packets in the second phase of the algorithm, and although the parameter changes more slowly, Link100 sends more packets in the second phase. And Rand1 sends the most packets in the second phase of the algorithm, which indicates the former two algorithms have short delay time, while the last has a long delay time.

The variation of the number of channel switching are shown in Fig. 8(e). The analysis of algorithm process shows that in each phase of the sending algorithm, the working channel will not switch to the original working channel, so the frequency of channel switching will not exceed $|C|$. The channel switching times of the two phases have the superposition effect, so the allocation of the packets sent in both phases will have an important influence on the number of channel switching. Link100 algorithm sends more packets in both phases, so the channel switching frequency metric is the largest. But Rand1 and LinkRatio mainly send packets in the second phase or the first phase, so the channel switching times of two algorithms are smaller. The NoNCExpOpt algorithm is an ideal solution for solving integer linear programming, so its metric is generally the lowest. When $c_{\text{Level}} = 1$, the channel switching times is larger than that in other circumstances, which may be caused by the asymptotic integral solution method of integer linear programming. Because when $c_{\text{Level}} = 1$, each variable in the linear optimization solution is almost the same, the variables in the asymptotic solution process are easier to be affected by the computer data accuracy error, etc, which will cause the setting variables to be selected more randomly and make the channel switching times close to the number of the channels.

The simulation results in this section show that Link100 has better comprehensive performance. Link100 is obviously better than Rand1 because the delay of the former is shorter and the total number of packets sent is roughly the same, even the number of packets in Link100 is smaller. Both Link100 and LinkRatio have their advantages and disadvantages, while the former has less packets transmitted and the latter has shorter delay time. However, the number of discrete packets decreases with the increase of *LinkSuc_Base*. *LinkSuc_Base* is not too small in the existing wireless network, so the number of discrete packets of Link100 algorithm is not too large, so that the Link100 algorithm outperforms others.

4) LINK100 AND LINKRATIO HYBRID ALGORITHM

We can use Link100 and LinkRatio as the basis to get a hybrid algorithm LinkHybrid. The initial packet allocation vector of this algorithm is defined by (13).

$$V_{\text{Hybrid}} = V_{\text{Link100}} + f(\max(V_{\text{LinkRatio}} - V_{\text{Link100}}, 0), k_{\text{Coef}}) \tag{13}$$

In equation (13), (1) V_{link100} and $V_{\text{linkRatio}}$ respectively represents the initial packet allocation vector of Link100 and LinkRatio algorithm; (2) k_{coef} denotes the coefficient of mix, $k_{\text{coef}} \in [0, 1]$; (3) $\max(v, 0)$ represents a vector that is generated according to v. If an element of $v$is less than 0, then the corresponding element of $\max(v, 0)$ is 0, otherwise the corresponding element of $\max(v, 0)$ is equal to the corresponding element of v; (3) we can use function $f(v, k)$ to generate a non-complex integer vector according to the vector v and k, and the sum of each element of the vector is equal to $fix(k \cdot \text{sum}(v))$, and each element of $f(v, k)$ is smaller than the corresponding element of v.

V. CONCLUSION

In this paper we studied the packet multicast technique in CRAHNs, presented the framework of the multicast algorithm based on the NC technology, and provided several multicast algorithms based on the framework. By introducing RNC technology, this algorithm made full use of the broadcast nature of wireless channel to reduce the number of packets transmitted. We fully considered access authority of the transport nodes to different channel and packet transmission quality for the purpose of maximizing the earnings of the trailing nodes at each packet transmission in upstream nodes and improve the effect of packet multicast and broadcast. This algorithm effectively saved the additional information used to decode the coded packets in the combined packets, and reduced the length of the combined packet.

The simulation results showed that: (1) the network coding technology can significantly reduce the number of packets transmitted in the multicast of the CRAHNs; (2) When successful transmission rate of links is higher and less than 1, the algorithm applying NC network technique outperforms that of algorithms applying non-network coding, and it can decrease the number of packets transmitted up to 50%. An implication of our simulation is that the NC technology has better application prospect in CRAHNs.

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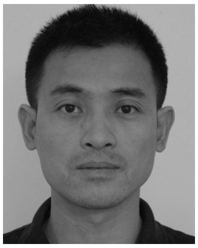

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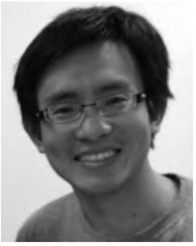

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