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Adaptive Network Coding based on Node Mobility for Broadcasting in Mobile Ad-hoc Networks

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Abstract

Mobile ad-hoc networks (MANETs) have limited network resources such as node battery capacity and wireless frequency bands. Therefore, to ensure efficient broadcast communication in such networks, it is critical to reduce unnecessary packet transfers and maximize the use of network resources and power. *Network coding* (NC) is a technique for reducing the number of transmitted packets over a network and maximizing the use of devices and network resources. The packet-reduction benefits obtained using NC depend considerably on network topology. In this study, we propose an NC method particularly designed for MANETs. In our approach, the nodes switch the type of transmission between an uncoded transmission (simple broadcast) and a coded transmission (NC) based on the estimated neighboring node's proximity. The effectiveness of the proposed method was evaluated using computer simulations. Our evaluations demonstrated that the proposed method can reduce the number of packets in the network without decreasing the packet delivery rate.

Keywords: Ad-hoc networks, network coding, flooding, broadcast

1 Introduction

Recently, the number of portable devices, such as smartphones and tablets, has increased significantly. Mobile ad-hoc networks (MANETs) can be constructed and easily deployed using mobile devices without a pre-existing network infrastructure. Owing to the movement of the devices in MANETs, the network topology changes dynamically. Because MANETs can operate without existing infrastructure, they are useful in large-scale evacuation and rescue operations during natural disasters. In such applications, broadcast communication is useful for reliable and simultaneous distribution of information to specific points in a MANET. Flooding is a simple and brute-force approach for delivering packets to network points, rendering route construction unnecessary. Flooding can also achieve broadcast communication, even in a highly dynamic MANET with typical patterns of device participation, disappearance, and movement. However, flooding causes significant redundancy in packet transfer, wasting the power and bandwidth of devices. Thus, in flooding-enabled broadcast communication, reducing unnecessary packet forwarding is critical for maximizing network resources and reducing power consumption. Network coding (NC) [1] is a technique that ensures efficient broadcast communication and enables linear operations on received packets at network relay devices to combine them into a single packet before forwarding. This reduces the number of transmissions in the relay devices, and consequently, the total number of packets transmitted over the network.

Various methods for applying NC to ensure efficient communication in MANETs, mainly standard broadcast transmission-only or NC-only methods, have been studied[9]. We propose a method to reduce the number of packets in the network while maintaining the packet delivery rate (PDR) by combining NC and un-encoding. This method is known as adaptive network coding forwarding (ANCF). In ANCF, when relaying a packet, each relay node switches between transmitting coded (NC) or uncoded packets (flooding) based on its neighboring nodes' state and already received packets.

The remainder of this paper is organized as follows. Section 2 describes the NC method. Section 3 presents the proposed node-mobility estimation and the adaptive NC. Section 4 describes the evaluation and results of computer simulations. Finally, Section 5 concludes the paper.

2 NC

The NC method encodes multiple packets and combines them into a single one. Figure 1 shows the sample packet transfer using NC. The relay node receives N multiple packets and encodes them to generate and send a single coded packet (p_{out}) where N is the coding number. A node that generates a single coded packet from N packets reduces the number of transmissions at the relay node.

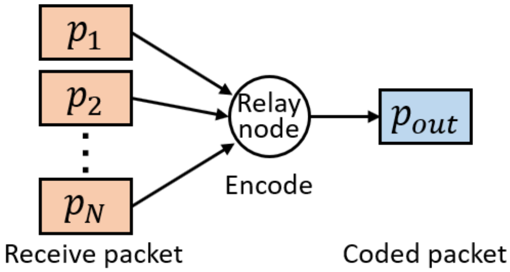


Figure 1: Example of packet relay using NC

Figure 2 illustrates an example of a linear NC. Here, the source node (n_0) transmits packets p_1 and p_2 to nodes n_4 and n_5, respectively. In the absence of NC, the number of n_3 transmissions is doubled owing to the separation of transmissions by p_1 and p_2. When NC is used at node n_3, a coded packet (p_{out}) is generated from p_1 and p_2, resulting in a single n_3 packet transmission. p_{out} is denoted by $p_{out} = (c_1)(p_1) + (c_2)(p_2)$.

Node n_4 was decoded using p_1 and p_{out}. Node n_4 receives p_1 and p_2 after being decoded. A node requires a minimum of N packets to decode the original packets from the coded packets, necessitating a constant number of packets for decoding.

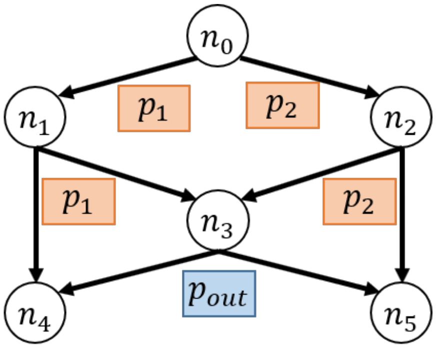


Figure 2: Example of linear NC in a network ($N = 2$)

2.1 Coding and Decoding Method

In this study, we used the linear NC method[6], which employs linear operations. In linear NC, packets are considered Galois field elements. First, we consider the case of generating p_{out} using an NC with N. Assume that a node receives a set of N packets $p_i (i = 1, 2, ..., N)$ and that the coding vector c_i, p_{out} is derived using Equation 1, where c_i and source packets p_i are elements of the Galois field $\mathbf{GF}(2^m)$ of order $m(2^m \geq N \wedge m \forall \mathbb{N})$.

$$p_{out} = \sum_{i=1}^{N} c_i p_i \tag{1}$$

Next, we consider the case of decoding encoded packets using NC with N. Assuming that a node receives encoded packets $r_j (j = 1, 2, ..., N)$, they are collectively represented by $R = (r_1, r_2, ..., r_j)$. If the coding vector of r_j is $\boldsymbol{c}_j = (c_{j,1}, c_{j,2}, ..., c_{j,i})^{\mathrm{T}}$, it is collectively represented by $\boldsymbol{C} = (c_1, c_2, ..., c_j)$. Additionally, if the received packets R are encoded from the original packets $O = (o_1, o_2, ..., o_i)$, then the received packets R are represented by Equation 2.

$$\begin{aligned} R &= \boldsymbol{C}O \\ &= \begin{pmatrix} c_{1,1} & c_{2,1} & \cdots & c_{j,1} \\ c_{1,2} & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ c_{1,i} & \cdots & \cdots & c_{j,i} \end{pmatrix} \begin{pmatrix} o_1 & o_2 & ... & o_i \end{pmatrix} \end{aligned} \tag{2}$$

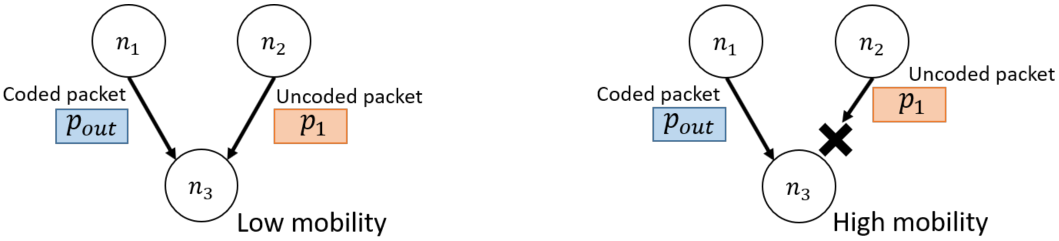
In this case, if the inverse matrix $\boldsymbol{C}^{-1}$ of $\boldsymbol{C}$ is present, the original packet O can be decoded. The decoding operation can be expressed using Equation 3.

$$O = R\boldsymbol{C}^{-1} \tag{3}$$

In such a linear NC, although $\boldsymbol{C}$ is allocated to each node in advance, it is necessary to set the appropriate coding vectors according to the network. Therefore, a random NC method was used to solve this problem. A random NC automatically and randomly selects the coding vector from the Galois field. In a random NC, the node must share the coding vector information for decoding because it does not have the other nodes' coding vector information. In this study, coding vector information was included in the packet header. However, the coding vector can be unrolled if it becomes linearly dependent. To solve this problem, we can reduce the possibility of decoding by increasing the size of the Galois field to select the coding vector.

2.2 Drawbacks of NC

Network topologies impact NC performance. NC is effective in static topologies but not in dynamic topologies because it is difficult for receivers to collect the minimum N coded packets necessary for the decoding process. In other words, when one coded packet with coding number N cannot be decoded, N uncoded packets are lost because of this failure. Conversely, packet flooding is effective against frequent topology changes owing to redundant transmission. Therefore, in a MANET with frequent topology changes, switching between NC and un-encoding is convenient. Figure 3 (a) shows an example of successful decoding of a coded packet p_{out} generated by combining p_1 and p_2 (coding number = 2). n_3 is a node with low mobility that can collect p_1. p_1 must decode a coded packet received from $n_1(p_{out})$. In contrast, Figure 3 (b) shows an example of decoding failure owing to node mobility. In this example, node n_3 has high mobility; therefore, even if it receives the coded packet p_{out} from n_1, it cannot decode the packet because the necessary p_1 packet is missing. This results in the loss of packets p_1 and p_2 inside the coded packet p_{out}.



(a) Decoding success (b) Decoding failure

Figure 3: Decoding example

2.3 Related Research

Broadcast storms are a possible phenomenon when flooding is used in a MANET[8]. To alleviate this problem, a broadcasting method[7] that uses random NC[3] has been proposed. However, this method is vulnerable to bit error. Another study achieved multicast communication using NC; the proposed protocol decreased packet arrival delay while maintaining throughput by performing dynamic coding control and autonomous retransmission control[4]. A real-world implementation of ad-hoc multicasting with NC on Android devices has also been presented[9].

In [11], a node that performs NC was selected based on the neighboring node's link state, and packets were concentrated on the NC node using a directional antenna. However, directional antennas are not installed in popular devices such as smartphones, and they are difficult to apply. AdapCode[5] is an existing study on adaptive NC methods. This study adaptively changes the coding number based on the number of neighboring nodes whose link state is stable in the sensor network. The appropriate coding number was determined based on previous experiments. However, the change in the number of neighboring nodes in the sensor network is smaller than that in MANET; therefore, applying it to MANET is not optimal. Network coding performs packet operations on the nodes. This requires more power than uncoded packet transmission. Another study[10] compared the power consumption of a node between the cases of uncoded transmission and NC. According to this study, in NC, the power consumption can be reduced compared with uncoded transmission. Generally, sending a packet requires significantly more power than encoding a packet.

Our previous work [13] estimated the mobility of neighbor nodes based on the packet reception history and proposed an adaptive NC method. The nodes' mobility estimation in this study was based only on layer 3 information. However, it was difficult to accurately estimate the mobility of the neighboring nodes using only layer 3 information. Setting the appropriate parameters was also difficult. Therefore, we propose estimating the mobility of neighboring nodes using both layers 2 and 3 information[12]. The neighboring nodes' packet flow direction was estimated from layer 3 information, and the neighboring node mobility was estimated from layer 2 information. Therefore, our proposed approach can provide more accurate mobility estimates and improve adaptive NC operation. However, the accuracy of packet flow estimation is poor in this method, and there are some network situations in which appropriate packet flow direction estimation is impossible.

3 Adaptive Network Coding Forwarding

In this study, we propose a method to estimate the proximity of neighboring nodes and switch the transmission type between uncoded and NC based on the estimated proximity. The proposed method consists of four steps:

1. **Neighboring nodes' packet flow direction estimation.** Depending on whether the information received from neighboring nodes is classified as first-time reception, each node classifies it as an upstream or downstream node.
2. **Proximity estimation.** Each node estimates the proximity of its downstream neighboring nodes based on the received signal strength between itself and the downstream nodes.
3. **Packet transmission type selection.** The packet transmission type (coded or uncoded) is selected according to the estimated proximity in the previous step.
4. **Packet transmission procedure.** The packet is sent using the transmission type selected in the previous step.

3.1 Packet flow direction estimation

In this step, each node classifies its neighboring nodes into upstream or downstream nodes according to their packet flow. Packet flow estimation uses only uncoded packets because coded packets may contain a combination of packets received previously or for the first time. This property renders the use of coded packets for flow estimation unfeasible. Each node maintains a temporary record of each unique uncoded packet received (using its ID), its originator node, trigger node, and received time to estimate neighboring nodes' packet flow.

Figure 4 shows an example of an originator and a trigger node. First, a packet is transmitted from node A to node B. Second, node B is transmitted to node C. After receiving the packet from node A, node B overrides the packet format, with the originator node as its ID and the trigger node as the node ID, one hop before node B. Node B then forwards the packet. When node C receives a packet, it can determine the packet's forwarding node (originator node) and the forwarding node one hop ahead (trigger node).

When each node receives a packet, it checks its ID. When an ID is received for the first time, the packet trigger node is added to the upstream trigger node list. Simultaneously, the packet's originator node is classified as an upstream node. When the packet ID is received for the second or subsequent time, the node checks for the trigger node in the packet. If the trigger node included in the packet exists in its upstream trigger node list, the packet's originator node is classified as an upstream node. In other cases, the packet's originator node is classified as a downstream node. Figure 5 illustrates the procedure from packet reception to flow estimation.

Figure 6 shows an example of the flow estimation in node C. In this example, we focus on node C. First, node A transmits a packet (ID = 1) to nodes B and E. Second, node B relays the packet and node C receives it. Third, the packet (ID = 1) is the first reception for node C, registers the trigger node included in the packet in its upstream trigger node list and classifies node B as an upstream

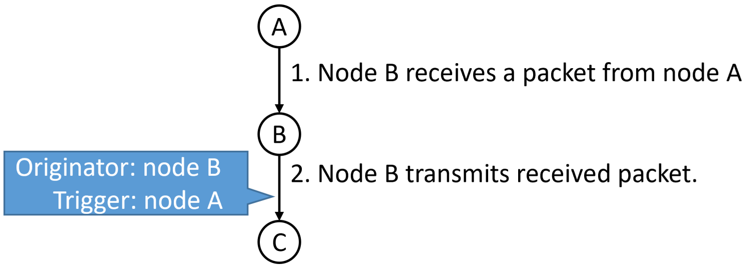


Figure 4: Originator and trigger node

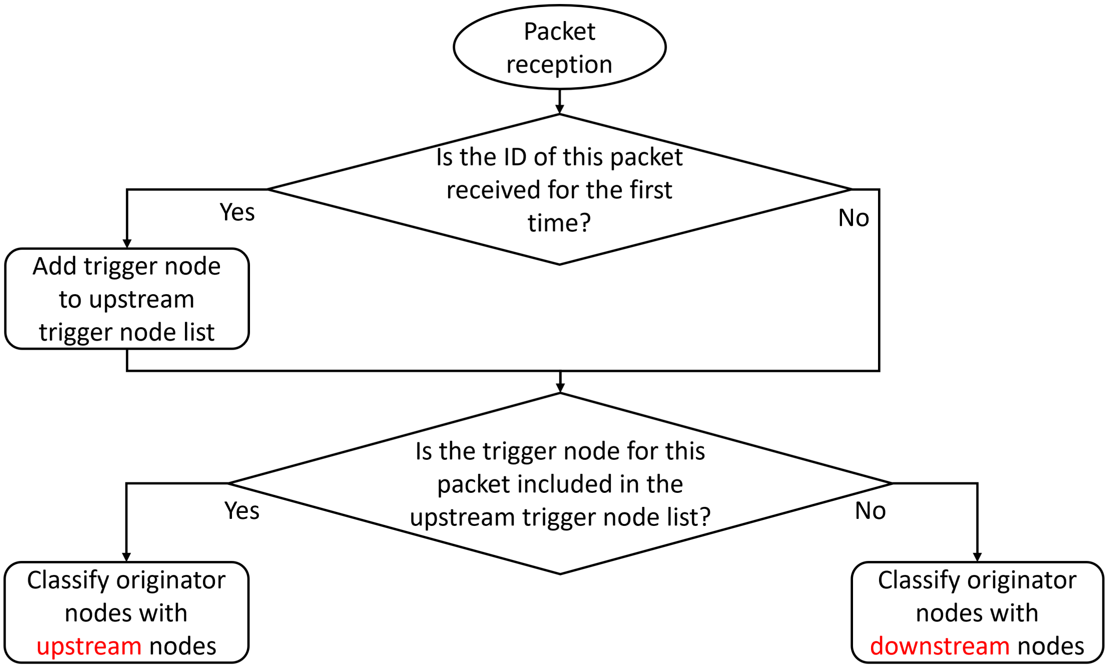


Figure 5: Flowchart of estimation of packet flow

node. Fourth, node C receives a transfer from node E, which is the second reception of the packet (ID = 1) for node C. Therefore, node C checks for the trigger node contained in the packet. In this case, because the trigger node included in the packet is node A, it exists in the upstream trigger node list of node C; thus, node C classifies node E as an upstream node. Finally, node C receives a packet (ID = 1) from node D. For node C, this is the third reception and thus checks the trigger node in the packet. The trigger node is node C and does not exist in node C's upstream trigger node list; node C classifies node D as a downstream node.

This packet flow estimation is based on a normal packet reception. Therefore, the estimation accuracy may decrease in an environment with many NC transmissions, or where a node does not receive enough normal packets. The transmission control is based on the mobility of the downstream node. The impact of misestimating an upstream node as a downstream node was relatively small. However, assume that the downstream node is misestimated to be an upstream node. In this case, the downstream node information that should be included is lost, which affects proximity estimation. In this packet flow estimation method, nodes other than the upstream nodes are classified as downstream nodes. Therefore, an upstream node may be misestimated as a downstream node; however, a downstream node cannot be misestimated as an upstream node.

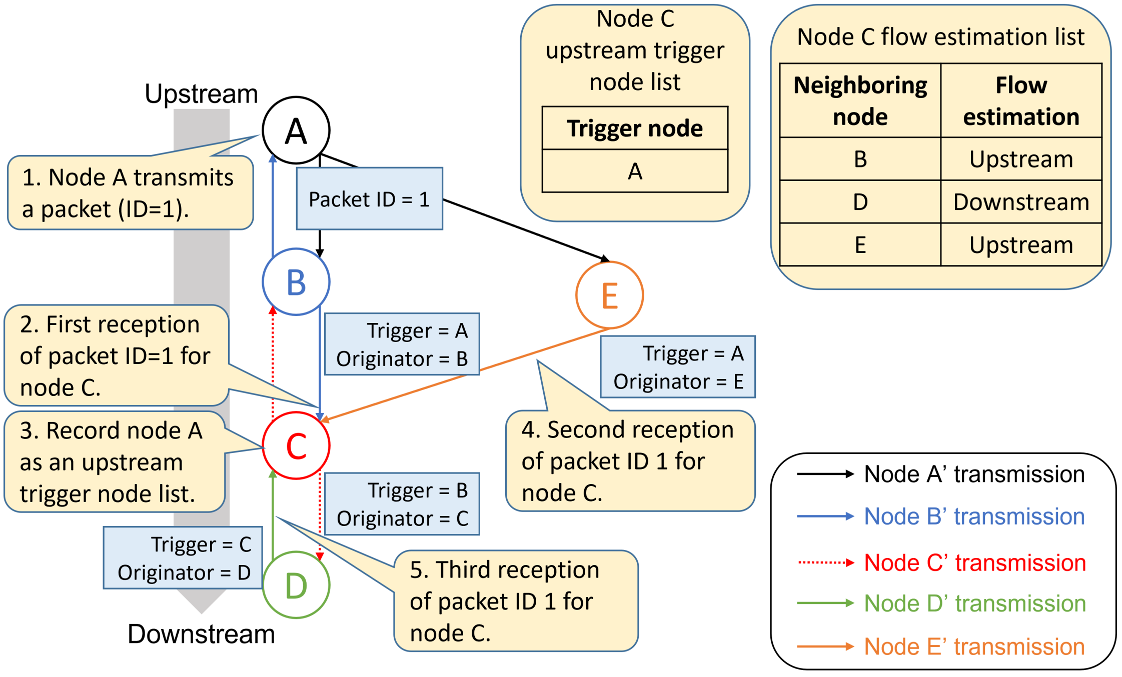


Figure 6: An example of packet flow estimation

3.2 Proximity Estimation

We estimated the proximity to neighboring downstream nodes based on the received signal strength indicator (RSSI) information, which was obtained from the transceiver link layer (layer 2). First, when a node receives a packet, its proximity to the originator node of this packet is estimated using its RSSI. This RSSI information will be preserved for future studies. When a node receives a packet from the same node consecutively, it compares its previously recorded RSSI with that of the new arrival (Figure 7). If the difference between these two values is negative, the proximity between the originator and current node is considered to decrease. Conversely, an increased proximity is estimated if the difference is numerically positive. After this calculation, the node discards the previously received RSSI and replaces it with the newly received packet. This process was repeated for each received packet. Each node recorded the estimation results for each neighboring node.

Figure 7 shows the proximity estimation for a downstream node that approaches the node.

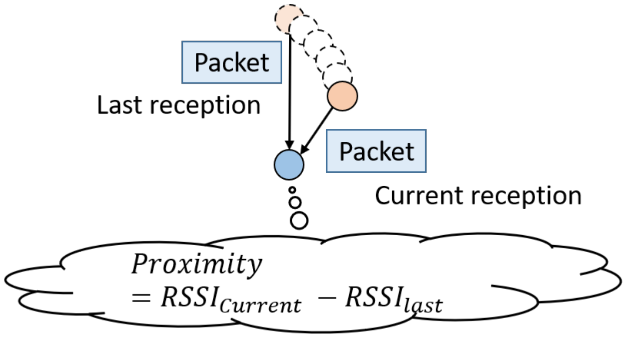


Figure 7: Estimating neighboring node proximity

3.3 Packet Transmission Type Selection

Before deciding on the transmission type (coded or uncoded), the nodes divide their neighboring nodes into two groups according to their communication transmission range. Nodes located within distance r from the current node or those beyond distance r, but classified as increasing proximity nodes, are considered group A. Nodes beyond distance r with decreasing proximity are considered group B. If the number of nodes in group A is smaller than that in group B, uncoded packet transmission is used. Conversely, coded transmission is used if group A nodes are larger than or equal to group B nodes. For example, in Figure 8, the nodes in groups A and B are eight and four, respectively; therefore, a coded transmission method is used. Figure 9 shows the proposed algorithm, which summarizes the adaptive forwarding control method. Each node counts the number of nodes in each area. Based on the proximity estimation, the nodes in the edge area are further divided into two categories, depending on whether they are approaching or leaving. NC is used for transmission if the sum of the number of neighboring downstream nodes in the inside area and that of approaching nodes in the edge area is larger. If the number of leaving nodes in the edge area is larger, uncoded transmission is selected. Figure 9 shows the flow from packet reception to the determination of transmission type.

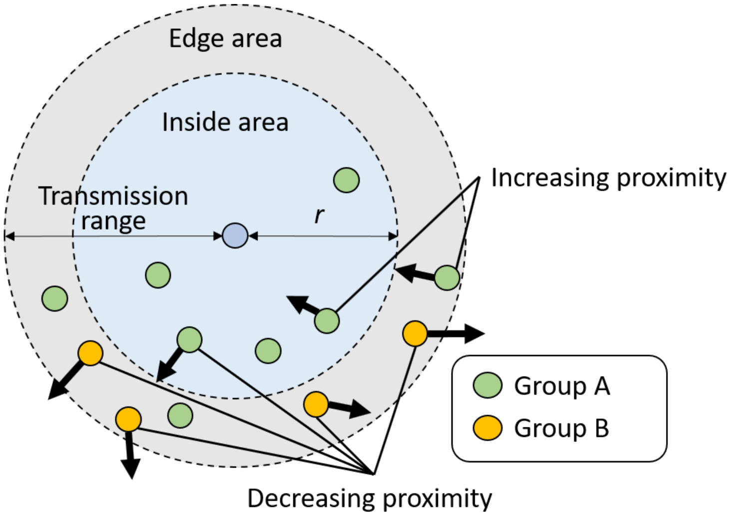


Figure 8: Neighboring node area division

3.4 Packet Transmission Procedure

In our proposed method, packets can be transmitted using either uncoded or coded transmission. An uncoded transmission entails rebroadcasting the newly received packet only once, implying that previously broadcasted packets are not rebroadcasted. In this study, we used an NC method known as *random NC*. In this type of NC, each node determines the coding vector according to a single common coding number (N) shared by the entire network. That is, N packets are collected according to the coding number value, transformed into a coded packet, and then broadcasted. When the nodes receive N coded packets, they attempt to decode them. If the decoding is successful, the process is repeated. The node estimates the neighboring node proximity, decides between uncoded or coded transmissions, and proceeds according to the broadcasting rules of these transmissions.

In the case of coded transmission and a minimum $N/2$ packets among the decoded packets that have already been broadcasted, the re-encoding of packets is canceled, and the packets are not rebroadcasted. However, in the case of uncoded transmission, if a few of the decoded packets have already been broadcasted, the node ignores the previously transmitted packets and broadcasts only

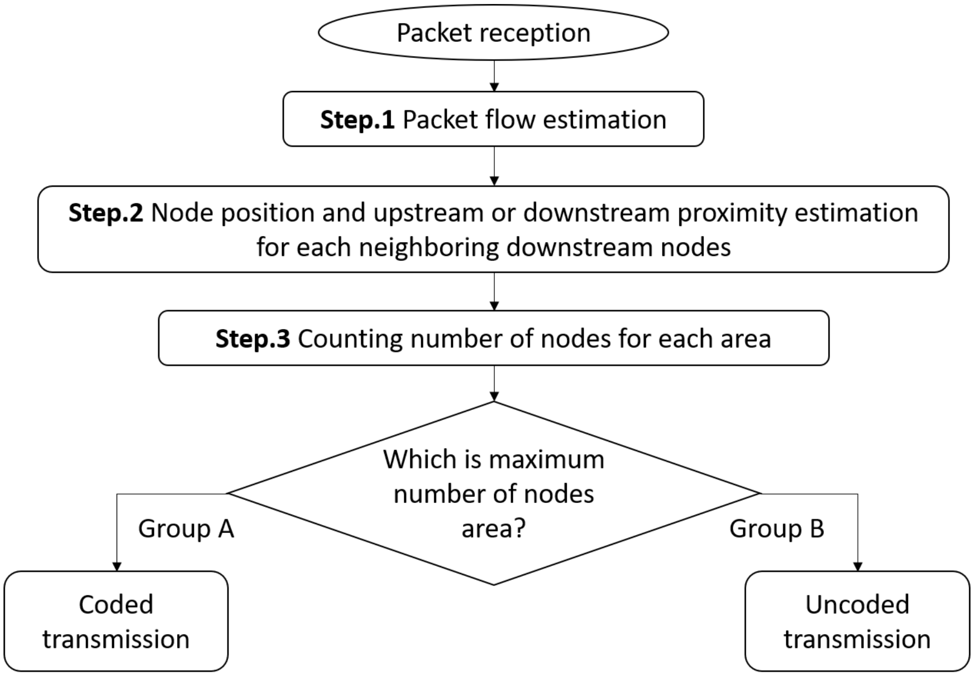


Figure 9: Flowchart of determination of packet transmission method

the packets not broadcasted earlier. Figure 10 illustrates the process. Moreover, if the number of neighboring downstream nodes is less than the coding number N, the coded transmission is canceled and uncoded transmission is selected. Uncoded transmission prevents decoding failure in downstream nodes owing to a lack of sufficient neighboring nodes. If decoding fails, the coded packet is stored in the decoding waiting queue. Each time a new packet is received, the packets in the decoding wait queue attempt to be decoded.

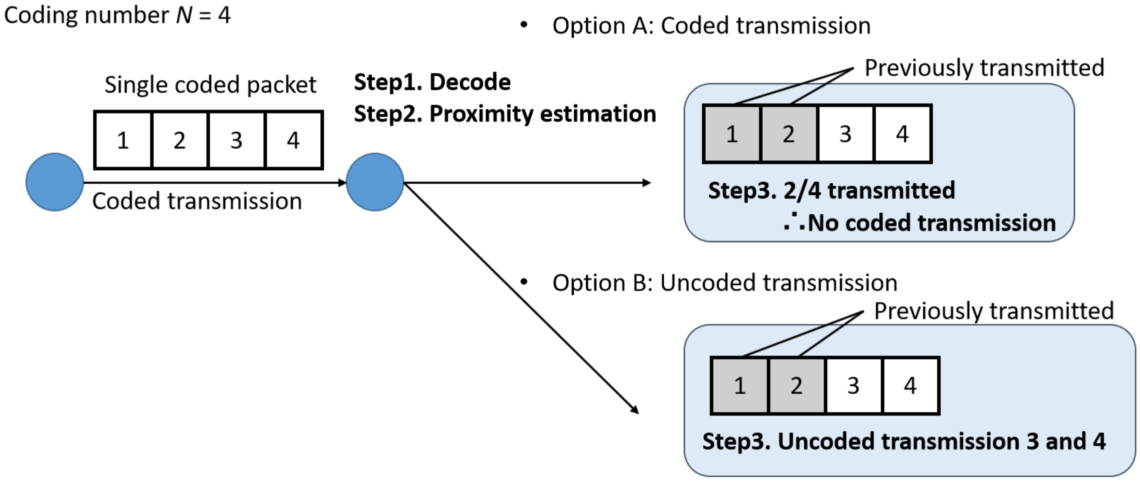


Figure 10: Rebroadcasting of successfully decoded packet

In this section, we explain our proposed ANCF method, which can switch between coded and uncoded transmissions based on the proximity of neighboring nodes and their relative position estimation, among other factors. Naturally, we can also switch between coded and uncoded packets arbitrarily. For example, in our evaluations, we included tests with a random selection of coded and uncoded transmissions. We refer to this transmission method as random network coding forwarding (RNCF). The following section describes our comparative evaluation of ANCF, RNCF, NC, and uncoded transmissions.

4 Performance Evaluation

Evaluations were performed using ns2 network simulations [2]. The evaluation compared the performance of four transmission methods: ANCF, RNCF, linear NC, and uncoded transmission (pure flooding). In our evaluation, we calculated the network load by counting the number of packets transmitted by all nodes in the network. Furthermore, we measured PDR to evaluate the reliability of the proposed method. PDR was calculated using Equation 4: In this evaluation, the coding numbers (N) were set as two, 4, six, eight, and ten.

For the simulation scenario, we created a random scenario and a highway scenario. We tested the four methods using ten random node distributions in a random scenario. In the random scenario, the node placement and movement speed were set randomly using the random waypoint model. The node speed was randomly set between 4 km/h and 60 km/h. When the node arrived at the set waypoint, it posed for 5 s. This is a harsh environment for estimating node mobility. A highway exists between the two random scenario areas in the highway scenario. The two random scenario areas used in the highway scenario were also generated using a random waypoint model. The node speed was randomly set between 1.1 km/h and 30 km/h to simulate pedestrians and bicycles. When the node arrived at the set waypoint, it posed for 5 s. No nodes crossed the highway. The highway has two lanes on each side, with a total of four lanes. Highway nodes move at 100km/h while maintaining a distance of 100 m between nodes. Figure 11 shows an example of a highway scenario.

$$\begin{matrix} packet \\ delivery\,rate \end{matrix} = \frac{the\,number\,of\,received\,packets}{\substack{the\,number\,of\,packets \\ sent\,by\,a\,source\,node}}. \tag{4}$$

Table 1: Simulation parameter values

Parameters	Values
Source node	1
Field size	$1000 * 1000\,m^2$
Simulation time	30 s
Source node send rate	2 $packets/s$
Packet size	1000 $byte$
Galois field size (m)	8
Area division (r)	70 m
NC probability in RNCF	50 %
Transmission range	100 m

Figures 12 and 13 show the network load and PDR, respectively, in a 200-node scenario. As shown in Figures 12 (d) and 13 (d), for uncoded transmissions, the network achieves the maximum PDR performance, albeit with a high network load cost (a high number of redundant packets). However, for linear NC, although the network load was the lowest, the PDR was also the lowest (Figures 12 (c) and 13 (c)). The results of the linear NC figures show that both the network load and PDR decrease with increasing coding number (N). This is particularly noticeable for $N \geq 4$, where the decrease is significant. This decrease was caused by the inability of multiple nodes to decode the coded packets because they did not receive the required number of packets. In RNCF, the decrease in network load and PDR was proportional to the increase in coding number (Figures 12 (b) and 13 (b)). For $N = 2$, the network load in ANCF decreased by 20% compared to that

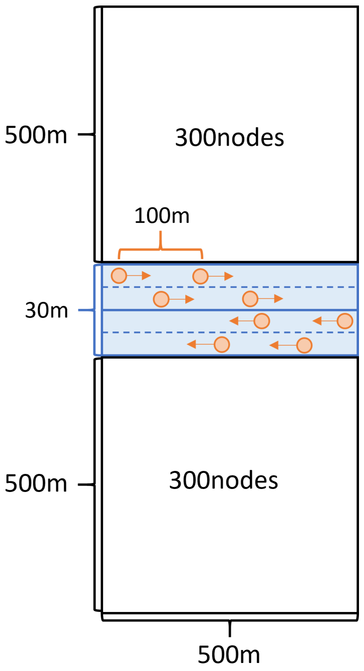


Figure 11: An example of highway scenario

in uncoded transmission, whereas PDR decreased slightly by 3%. This is because, in ANCF, the packet transmission type switches according to the proximity to neighboring nodes. However, the network load and PDR of RNCF were lower than ANCF. This is because NC is performed randomly in RNCF, and packet delivery is interrupted owing to decoding failures. In ANCF, the network load increases when $N = 4$ or more, but PDR maintains the same level as uncoded transmission. The number of neighboring nodes is insufficient to collect the necessary number of coded packets to decode encoded packets when $N = 4$ or more. However, in the case of ANCF, NC is judged unsuitable for adaptive control, and uncoded transmission is frequently used, as shown in Figure 12 (a).

As shown in Figures 14 and 15, we tested the same transmission methods by increasing the number of nodes to 300. The overall tendencies of uncoded transmission, linear NC, and RNCF were the same for the 200 nodes. However, as the number of neighboring nodes increases, the effectiveness of NC increases, even with a high coding number. ANCF can detect that the number of neighboring nodes has increased, and using packet flow direction estimation, it actively applies NC even with a coded number of $N = 4$. Therefore, the network load decreases. When $N = 6$ or more, the network load of ANCF started to increase. This is because it detects that the number of neighboring nodes is not satisfied and NC is not performed.

As shown in Figures 16 and 17, we tested the same transmission methods by increasing the number of nodes to 400. The overall tendencies of uncoded transmission, NC, and RNCF were the same for the 300 nodes. Although the number of nodes increased, the PDR did not reach 90%, even when $N = 2$ with a linear NC. In RNCF, the network load decreased for all coding numbers, so did the PDR. ANCF decreased the network load by 20% compared with the uncoded transmission when $N = 2$, whereas the PDR decreased by less than 1%.

Figures 18 and 19 show the network load and PDR, respectively, in a highway scenario. Linear NC effectively reduced the number of packets; however, when $N = 6$ or more, the PDR decreased significantly. When $N = 2$, linear NC had a higher advantage than ANCF. However, ANCF reduced the network load while maintaining a PDR of 95 % or more for all coding numbers. RNCF also achieved a PDR of 90 % or more for all coding numbers, but the network load was high and the

PDR was low compared with ANCF.

Figure 20 shows a visualization of the packet delivery flow to confirm the effects of high-moving nodes running on the highway. The yellow arrow indicates uncoded packet transmission and the blue arrow indicates coded packet transmission. In the case of uncoded transmissions, there are only yellow arrows. In the case of NC, decoding fails at the node that receives the coded packet and packet delivery is interrupted. In the case of RNCF, the transmission type is randomly selected based on the probability; thus, the yellow and blue arrows are mixed throughout the network. In the case of ANCF, the packet flow is estimated, and the transmission type is selected according to the mobility of the downstream nodes. Therefore, uncoded transmission is selected when passing through the highway, and the arrow is yellow. These results demonstrated that ANCF can adaptively select the transmission type.

(a) ANCF (b) RNCF

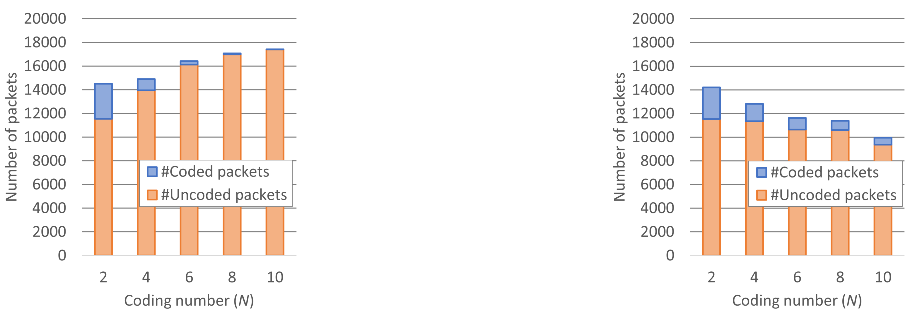
(c) Linear NC (d) Uncoded

Figure 12: Network load (200 nodes)

(a) ANCF (b) RNCF

(c) Linear NC (d) Uncoded

Figure 13: PDR (200 nodes)



(a) ANCF (b) RNCF

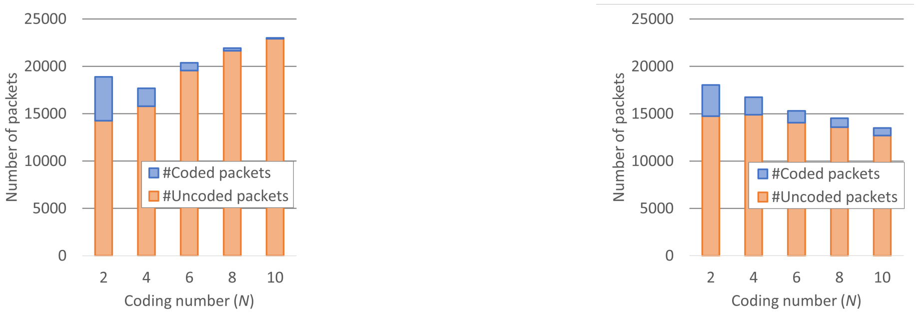
(c) Linear NC (d) Uncoded

Figure 14: Network load (300 nodes)

(a) ANCF (b) RNCF

(c) Linear NC (d) Uncoded

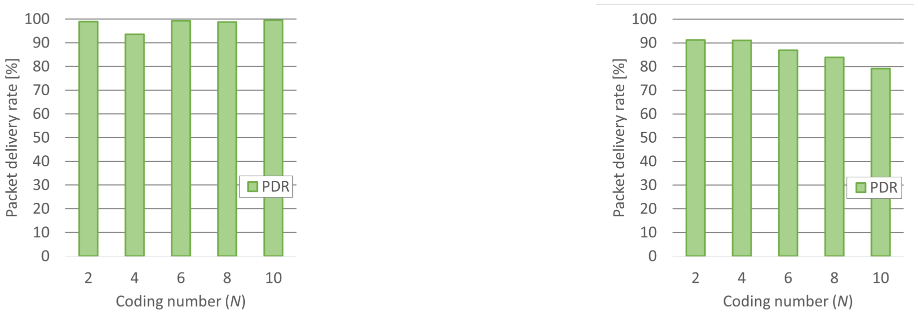
Figure 15: PDR (300 nodes)



(a) ANCF (b) RNCF

(c) Linear NC (d) Uncoded

Figure 16: Network load (400 nodes)

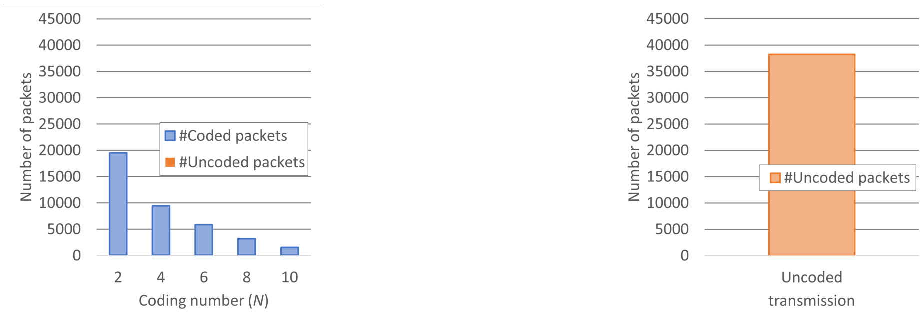


(a) ANCF (b) RNCF

(c) Linear NC (d) Uncoded

Figure 17: PDR (400 nodes)

(a) ANCF (b) RNCF



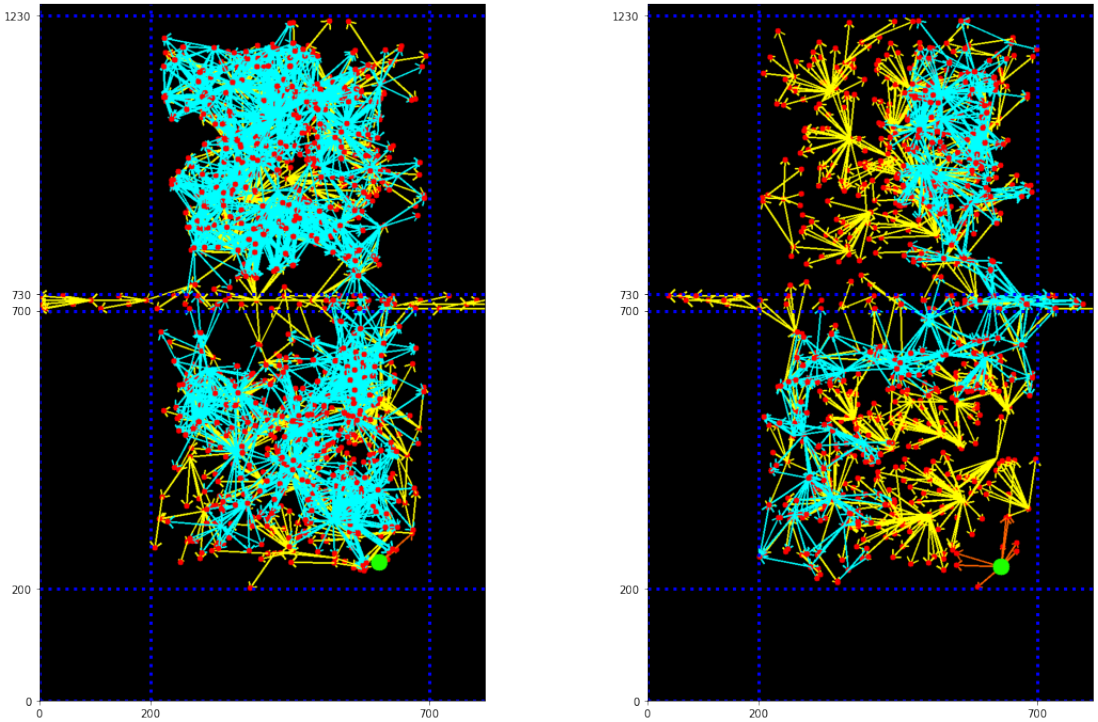
(c) Linear NC (d) Uncoded

Figure 18: Network load (Highway)

(a) ANCF (b) RNCF

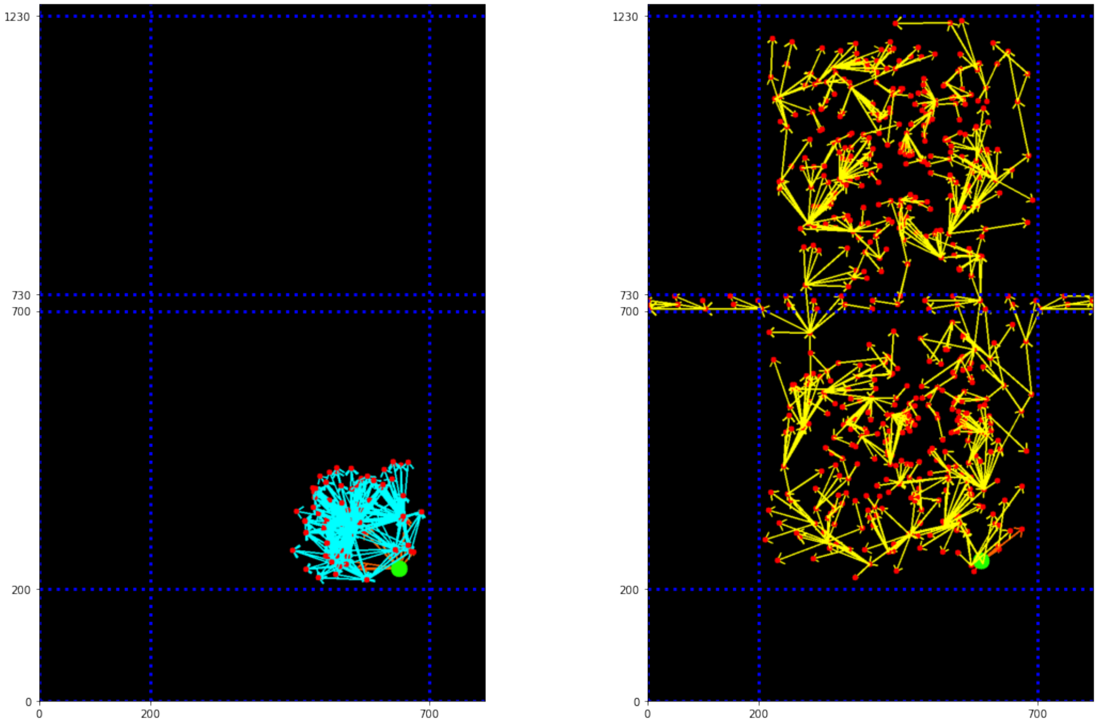
(c) Linear NC (d) Uncoded

Figure 19: PDR (Highway)



(a) ANCF

(b) RNCF



(c) Linear NC

(d) Uncoded

Figure 20: A packet flow visualization of highway scenario ($N = 10$)

5 Conclusion

In this study, we propose an adaptive forwarding control that uses both un-encoded and NC transmissions to achieve efficient broadcast communication. This method aims to decrease the total number of packets transmitted over the network, while maintaining a reasonably good PDR. To achieve this, ANCF switches between uncoded and NC transmissions based on the estimated proximity of neighboring nodes. ANCF network load gains are particularly noticeable in topologies in which at least a few relay node positions change frequently. Our evaluations showed that ANCF's performance depends on the values of the parameters (for example, the coding number).

In the future, we intend to conduct experiments using more realistic road scenarios. We also intend to develop a parameter-setting method that is tailored to the network conditions and topology.

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