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Network-coded cooperative information recovery in cellular/802.11 mobile Networks

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ABSTRACT

By utilizing free WiFi transmissions, network coded cooperative peer-to-peer (P2P) information repair (NC-CPR) has been proposed to mitigate packet loss incurred during cellular Base Station (BS) broadcast. However, most of the work focuses on static network environment. While considering peer movement, the challenge part is the dynamically changed network topology, making it hard to control the transmission collisions to achieve good repair performance. In this paper, we propose the network coded cooperative information repair protocol with mobility concern (NC-CIRM) to recover the lost packets under the mobile scenario. Peer transmissions are scheduled with different channel access priorities based on their neighborhood information. Then, the NC-CIRM with known distribution (NC-CIRMD) protocol is presented which obtains neighborhood information based on the knowledge of node spatial distributions. Simulation results show that these two protocols achieve similar repair performance and work efficiently under both uniform and stationary node spatial distributions. Furthermore, a tunable parameter – coded packet generating rate based repair protocol (TP-RP) is proposed to further improve repair performance when the peers uniformly distribute within the system area. At the mean time, an analytical model is developed, then based on which parameter optimization is studied and theoretical results are derived. Extensive simulation results illustrate the improvement made by TP-RP protocol compared with the other two protocols and validate the accuracy of the optimal value of the tunable parameter.

1. Introduction

Multimedia Broadcast/Multicast Service (MBMS) (Technical Specification Group, 2006) in cellular networks has been emerged recently as a promising distribution model to provide rich content distribution where a batch of packets are broadcast to a large number of mobile peers. However, ensuring efficient error-free message delivery in such a scenario is a challenge, since packet loss is inevitable due to the time-varying nature of wireless transmissions, and the server is probably overwhelmed by floods of individual retransmission requests from peers which is known as the NAK implosion problem (Liu et al., 2008a). By observing the widespread availability of mobile devices equipped with both cellular and IEEE 802.11 wireless interfaces (Raza et al., 2007; Sharma et al., 2005), several distributed network coding (NC) based cooperative P2P repair (CPR) schemes (DNC-CPR) (Liu et al., 2008a, 2010b, 2008b, 2008c, 2009a) have been proposed to achieve out-of-band repair for the packets lost during cellular Base Station (BS) broadcast by allowing peers to cooperatively repair lost packets among themselves via WiFi transmissions. In the DNC-CPR problem, when nodes operate on the same frequency, one of the critical things needs to be considered is the interference from neighbors' concurrent transmissions. Thus, the essence of DNC-CPR problem is a repair scheduling problem, i.e., to determine which peer should transmit packet at what time so as to reduce the impact of transmission collisions.

In practice, mobile peers may stay at a certain location for a while, or may move with low or high speed around certain area according to different scenarios. However, the aforementioned work (Liu et al., 2008a, 2010b, 2008b, 2008c, 2009a) only focus on the static network topology when solving the repair problem. When the application scenario shifts from static to mobile environment, the following issue arises: Without the knowledge of node locations, the information of each node's interference neighbors is unknown and consequently it is hard to control the transmission collisions to achieve good repair performance. Lots of references (Bettstetter et al., 2003, 2004; Navidi and Camp, 2004; Blough et al., 2004; Bandyopadhyay et al., 2007) propose and investigate different mobility models for mobile and vehicular networks, to characterize the behavior of mobile entities. One of the most prevalent mobility models used for mobile networks

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is the random waypoint (RWP) (Bettstetter et al., 2003, 2004; Navidi and Camp, 2004) model. The RWP model is a general mobility model that each node randomly picks a location within the moving area as its next destination with or without pausing at the current location for a while and moves to the destination under certain velocity. In this paper we consider such an application scenario that several students use mobile devices such as smart phones to receive MBMS packets from cellular BS while moving randomly within the university area. Some of the packets are lost and they are recovered based on our proposed repair protocol through WiFi connections. Thus, the moving behavior in our application scenario can be characterized by the RWP model.

To the best of our knowledge, there is no work studies the DNC-CPR problem in the mobile scenario and illustrates the corresponding results. In this paper we propose the network coded cooperative information repair protocol with mobility concern (NC-CIRM) which schedules peer transmissions with different channel access priorities based on the number of interference neighbors for each peer and the benefit that a peer's transmission can bring to its receiving neighbors. The number of interference neighbors for each peer is estimated through the control packet exchange when the node movement behavior is unknown. Then the NC-CIRM protocol is evolved to NC-CIRM with known distribution (NC-CIRMD) when we know the node spatial distribution, and the number of interference neighbors for each peer is calculated based on that information. Simulation results demonstrate these two proposed protocols achieve similar repair performance and work efficiently under both uniform and stationary node spatial distributions. Later on, we propose a tunable parameter – coded packet generating rate based repair protocol (TP-RP) to minimize the repair latency by optimizing the tunable parameter when nodes uniformly distribute within system area. Furthermore, we derive an analytical model for TP-RP and obtain the optimal value of that coded packet generating rate. Extensive simulation results verify the accuracy of the theoretical analysis, and show that TP-RP can efficiently combat the interference and achieve better repair performance compared with the other two protocols. In summary, we elaborate the protocol design by devising efficient scheduling schemes, developing analytical model, and studying parameter optimization while considering the node movement.

The rest of the paper is organized as follows: Section 2 reviews related work. Section 3 describes system model and mobility model used in this paper. In Section 4, the NC-CIRM protocol and the NC-CIRMD protocol are illustrated in detail. The TP-RP protocol and the corresponding theoretical analysis are elaborated in Section 5. Performance evaluation and comparisons are shown in Section 6. Section 7 gives the conclusions and future work.

2. Related work

Network coding was first proposed in the seminal paper (Ahlswede et al., 2000) to achieve the network capacity in multicast scenario. By mixing packets at the intermediate nodes, NC can largely reduce the scheduling complexity in the CPR problem, and several recent works have attempted to apply NC in the CPR problem to further improve the repair performance. The authors in Fan et al. (2009a) propose a peer-to-peer information exchange (PIE) scheme with an efficient and light-weight peer scheduling algorithm to minimize the number of transmissions and the total repair latency, with the assumption that all peers are within the transmission range with each other. However, the PIE scheme is not scalable for large-scale networks and finding the optimal scheduling for CPR problem with minimum latency is proved to be NP-hard in Cheung et al. (2006) and Liu et al. (2008a).

The studies in Liu et al. (2008b, 2008c, 2009a, 2010a) consider the distributed cooperative video stream repair strategies via NC for the energy-limited scenario in a rate-distortion manner. In Liu et al. (2009b), the authors perform joint source/channel coding of WWAN video multicast for a CPR collective using both structured network coding and WWAN FEC, while the authors in Liu et al. (2010c) propose a CPR packet loss recovery strategy for peers to cooperatively repair packets of video stream in different views in a multiview video multicast scenario. In BenSaleh and Elhakeem (2010), the authors propose an XOR based scheduling algorithm for network coding in cooperative local repair. However, Liu et al. (2010a), Liu et al. (2010c) and BenSaleh and Elhakeem (2010) do not describe how to deal with the transmission interference, and Liu et al. (2008b), Liu et al. (2008c), Liu et al. (2009a), Liu et al. (2009b) claim that the interference problem can be solved by the scheduling algorithm in Liu et al. (2008a).

In Liu et al. (2008a), the authors take the transmission interference into account and propose the DNC-CPR algorithm to minimize the network repair latency. The basic idea of the DNC-CPR algorithm is that each peer waits for a Transmit Wait Interval (TWI) before sending out the coded packet, in order to reduce the impact of transmission collisions. Their DNC-CPR algorithm is demonstrated to be effective only when the four undetermined parameters of TWI are chosen appropriately. However, many factors will affect the choice of the parameters, e.g., network topology, packets distribution among the peers, etc. Thus, it is hard to find the suitable parameters for different cases. The authors in Xie et al. (2007) propose two popularity aware scheduling schemes for network coding based content distribution in ad hoc networks. These two schemes adjust the contention window (CW) at the MAC layer according to the usefulness that the broadcast coded packets bring to the neighbors and the total number of packets received. However, the usefulness check requires each node to buffer and update all the neighbors' information and run gaussian elimination (GE), which largely increases extra overhead and computational complexity. Our previous work (Liu et al., 2010b) propose a PPIR protocol to minimize the total repair latency under the static network environment, which is more efficient compared with the DNC-CPR algorithm. The PPIR protocol divides the network into clusters based on the constructed CDS (Wan et al., 2002). Our PPIR protocol reduces the transmission collisions by dividing network into clusters and only CHs being allowed to send the coded packets during the second phase.

However, none of the aforementioned work considers nodes movement when design algorithms and protocols for the DNC-CPR problem.

3. Preliminaries

3.1. System model

In this paper, we consider a wireless P2P network consisting of several mobile nodes which are also called peers. These peers are equipped with two wireless interfaces, one for cellular communications and the other for IEEE 802.11 communications. Our system model is shown in Fig. 1. Cellular BS broadcasts packets to all the peers batch by batch, providing MBMS service. The data packets are assumed to have the same packet size. For packets with different sizes, we can pad zeros at the end of small-sized packets making them have the same size. Each peer receives some of these packets during BS broadcast depending on channel condition between the peer and BS. Then peers trigger the repair protocol and recover the lost packets using their IEEE 802.11 interfaces within each repair epoch. The repair epoch is defined as the time interval from t_i to t_{i+1}, where t_i is the time instant that BS starts to broadcast packet for batch $i+1$ and t_{i+1} is the time instant that BS starts to broadcast packet for batch $i+2$, as shown in Fig. 2.

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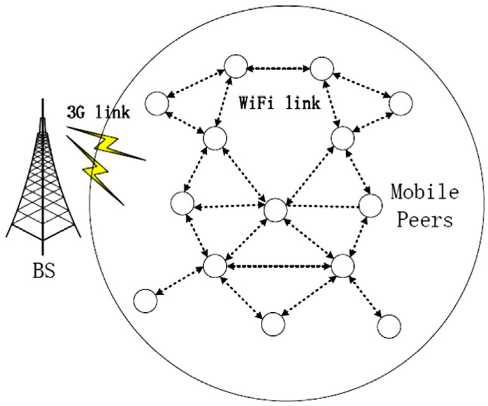

Fig. 1. System model.

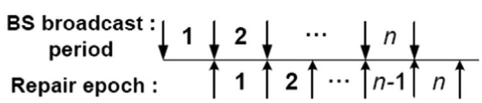

Fig. 2. Repair epoch illustration.

All the nodes operate in broadcast mode when using the IEEE 802.11 interface during the repairing process, and each node's transmission is overheard by all of its one-hop neighboring nodes who are within its transmission range. We assume all the nodes have the same transmission range and they operate on the same frequency during the repair process. A node can successfully receive a packet if and only if one of its neighboring nodes transmits the packet, and it is not within the interference range of any other concurrent transmitting nodes. The medium access control (MAC) layer (Zhai et al., 2005, 2004) of each peer adopts carrier sense multiple access with collision avoidance (CSMA/CA) mechanism (Cheng et al., 2009; Chen et al., 2007a) and works on distributed coordination function (DCF) mode (Bianchi, 2000).

During the repair process, all the transmitted data packets are coded packets. Whenever a peer wants to transmit a data packet, it always generates a coded packet based on the random linear network coding (RLNC) (Chu and Jiang, 2010), that it encodes all the packets it possessed using linear combination with coding coefficients which are carried in the packet header. The coding coefficients are randomly generated from a finite field GF (256) with the property that the generated coded packets are linearly independent with each other with high probability as long as the finite field is large enough (Fan et al., 2009b). When a node has received enough linear independent coded packets, it can decode them and obtain the original data packets by solving the system equations via GE.

3.2. Mobility model

Our application scenario can be considered as several students move randomly within the university area and receive MBMS packets from cellular BS. The lost packets are recovered based on our proposed repair protocol. Thus, the movement can be characterized by the RWP mobility model. Under RWP model, each node is assigned an initial location (x_0, y_0). This initial point is chosen independently and uniformly on which region the nodes move. Then each node randomly chooses a destination from the uniform distribution independently. The speed for each node is chosen uniformly on an interval $[V_{\min}, V_{\max}]$, independently of both initial location and destination. $V_{\min}$ and $V_{\max}$ are the allowed minimum node velocity and maximum node velocity, respectively. After reaching the destination, a new destination and a new speed are chosen in the same manner. Upon reaching each destination, nodes may pause for a while at that destination or may move directly to the next destination without pausing, according to the pause probability P_{pause}. If they pause, the pausing times are chosen from the pausing interval $[T_{pause}^{\min}, T_{pause}^{\max}]$, independent of the nodes location and speed. If we define $E(T_{pause})$ as the expected time period of a node pause, and define $E(T_{move})$ as the expected time period of a node traveling between two pauses, the long-run proportion of time (pause probability) a node spent paused is

$$P_{pause} = \frac{E(T_{pause})}{E(T_{pause}) + E(T_{move})}. \quad (1)$$

With the uniform distribution on the interval $[T_{pause}^{\min}, T_{pause}^{\max}]$, $E(T_{pause})$ can be expressed as

$$E(T_{pause}) = \frac{T_{pause}^{\max} + T_{pause}^{\min}}{2}. \quad (2)$$

To compute $E(T_{move})$, we define random variable L as the trajectory length between two consecutive destinations and define random variable V as the node velocity on the moving length L, then $E(T_{move})$ can be expressed as

$$E(T_{move}) = E\left(\frac{L}{V}\right) = E(L)E\left(\frac{1}{V}\right) = \frac{E(L)\ln(V_{\max}/V_{\min})}{V_{\max} - V_{\min}} \quad (3)$$

since L and V are independent. According to Random Distances (1951), $E(L)$ can be expressed as

$$E(L) = 0.521405 \cdot l_{area} \quad (4)$$

where 0.521405 is the expected distance between two points on the unit square chosen independently and uniformly, and l_{area} is the considered square side length during the repair process. Thus, P_{pause} can be rewritten as

$$P_{pause} = \frac{T_{pause}^{\max} + T_{pause}^{\min}}{T_{pause}^{\max} + T_{pause}^{\min} + \dfrac{1.04281 \cdot l_{area} \cdot \ln(V_{\max}/V_{\min})}{V_{\max} - V_{\min}}}. \quad (5)$$

The peer moving region is a square area with side length l_{area}, and we consider that peers move at slow speed from 2 m/s to 5 m/s based on the RWP model.

4. NC-CIRM and NC-CIRMD illustration

4.1. NC-CIRM

The idea of NC-CIRM is that each time a node receives a coded packet, it waits for a period of time T_w. Then it generates a new coded packet by encoding all the packets it possessed currently, and broadcasts this coded packet. The value of T_w is determined by two factors – the number of interference neighbors of that node and the benefit brought from that node transmission. The less the number of interference neighbors a node has and the more the benefit brought from a node transmission, the smaller the waiting time T_w should be. The number of interference neighbors for each node is estimated based on the control packets exchange among peers during the repair process. When a node broadcasts a coded packet, its 1-hop neighbors may receive this packet. If this packet is innovative to the receiving node's existing buffered packets, it brings 1 credit. Thus, the benefit brought from a node transmission is the sum of all the credits from its receiving neighbors. However, this calculation requires the transmitting node to buffer all the neighbors' existing packets and presents the same problem as Xie et al. (2007) described in section 2. Thus, we use the available packets information to reflect the benefit brought from a node transmission. For example, suppose node i originally has packets 1, 2, and 4, and node j has packets 2, 5, and 6, then we say that node i has 3 available packet information and node j has 3 available packet information. Then node j encodes the 3 packets it possessed and broadcasts this coded packet. When node i receives this coded packet, it has 5 available packets information. This is because even though node i cannot decode the received coded packet based on its current available information, when it generates and broadcasts a new coded packet with its original packets and the received coded packet, this new generated coded packet may still bring benefit to its neighbors. For example, another node k originally has packets 1, 2, 4, and 5. When it receives the new coded packet from node i, this new packet is innovative to it. Therefore, the larger the available packets information a node has, the larger the benefit might be brought by that node transmission. The details of NC-CIRM protocol are shown in Algorithm 1.

Algorithm 1. Repair protocol.

1 Each node calculates n_w at the beginning of each repair epoch, and sends a coded packet at time $T_w = n_w \cdot t_{unit}$.
2 Every time a node receives a coded packets, it updates its local variable *label* and n_w. Then it sends a new one at time $T_w = n_w \cdot t_{unit}$.
3 At the half time of each repair epoch, each node stops sending coded packets and starts to transmit control packets which contain the number of its 1-hop neighbors, at a very low frequency, e.g., one control packets every 10 ms.
4 Each node updates the number of its 2-hop neighbors once receives a control packet, and updates the number of its interference neighbors, used for next repair epoch.

Algorithm 2. n_w calculation.

1 $I = 2 \cdot N_{2-hop}$
2 **if** *There is no packets information of its neighbors* **then**
3 | **if** $N_r > B \cdot (1-P_L)$ **then**
4 | | $cw = ceil(\frac{I}{2})$
5 | **else**
6 | | $cw = I$
7 | **end**
8 | $n_w = random(0, cw)$
9 **end**
10 **if** Received n neighbors' packet information **then**
11 | $cw = \min\left\{ ceil\left(\frac{I}{n+1}\right) \cdot label, I \right\}$
12 | $n_w = random(0, cw)$
13 **end**

Algorithm 3. *Label* update.

1 Node has received coded packets from n different 1-hop neighbors
2 $label = n+1$
3 $j = 1$
4 **while** $j \le n$ **do**
5 | **if** *Number of non−zero coding coefficients in the most recent received*
6 | *coded packet of the node in position j is smaller than the one in itself*
7 | **then**
| | $label = label - 1$
8 | **else if** *Number of non−zero coding coefficients in the received coded*
9 | *packets is the same as the one in itself* **then**
10 | | **if** *the node ID of the received coded packet is larger than itself* **then**
11 | | | $label = label - 1$
12 | | **end**
| **end**
| $j = j+1$
13 **end**

In Algorithm 1, n_w is the number of time units that a node should wait before the transmission. Different nodes may have different n_w's and the derivation of n_w for each node is shown in Algorithm 2. t_{unit} is the smallest time granularity that a node should wait before its transmission, and we set $t_{unit} = M/R_d$ which is the transmission time of a coded packet. M is the packet size, R_d is the transmission rate among peers. Lines 1 and 2 in Algorithm 1 illustrate how the repair process works. In line 3, the effectiveness of control packet transmissions starts at the half time of each repair epoch should satisfy two conditions: (1) lost packets for each batch should be repaired within the half time of the repair epoch such that the coded packets transmission will not affect the control packets transmission and (2) peers should not move too fast so that the network topology is almost unchanged for each repair epoch. The simulation results show that condition (1) can always be maintained, and under our RWP low velocity model condition (2) is also valid. Note that although the network topology is almost unchanged during each repair epoch, the long-run network topology still varies with time, e.g., the network topology in epoch 35 may be quite different from the one in epoch 1. Lines 3 and 4 in Algorithm 1 describe how the nodes obtain their neighborhood information. Initially, each node has no knowledge about its neighborhood. Once a node receives a control packet from its 1-hop neighbor, it updates its 1-hop neighbor list and 2-hop neighbor list. When this node transmits a control packet, it inserts its 1-hop neighbor list information into the control packet. Thus, at the end of each repair epoch, each node can have a rough estimate of which nodes are its 1-hop neighbors and which nodes are its 2-hop neighbors.

In Algorithm 2, lines 1–9 illustrate how to set cw if no coded packets have been received. The $ceil(\cdot)$ function is to find the smallest integer value that is no less than the value inside the parentheses. N_{2-hop} is the number of 2-hop neighbors and I is the estimated number of interference neighbors. The intuition behind these lines is that since the average packet loss rate during the last BS broadcast is P_L, if a node has received more data packets than the average received data packets ($B \cdot (1-P_L)$), this node should have a higher probability to access the channel and we set cw to the half of I. Otherwise, we set cw equal to I. Then we set the number of waiting time units n_w, to be a random number uniformly selected from 0 to cw. Lines 10–13 illustrate that if a node has already received coded packets from n different 1-hop neighbors, it partitions the length I into $n+1$ sections.

label is a variable which reflects the benefit that a node transmission brings. Its value is the node position in the set which contains node IDs in a descending order with respect to the number of available packet information. The *label* update algorithm is shown in Algorithm 3. According to the current value of *label*, the node chooses the upper limit of the corresponding section as cw and then generates n_w. For example, if $I=6$, $n=2$, $label=2$, then I will be equally partitioned into 3 sections and cw is set to 4, and n_w is randomly chosen from 0 to 4.

4.2. NC-CIRMD

If the node spatial distribution is known, we can omit the control packet exchange part and NC-CIRM can be simplified by estimating the number of interference neighbors for a node based on the node spatial distribution.

4.2.1. Uniform distribution

Under the RWP mobility model, initially nodes are uniformly distributed within a small time period since the initial location and next destination are independently and uniformly chosen from the system area for each node. Thus, we can consider that the network topology remains unchanged for the first few repair epochs.

Under the uniform distribution, the pdf of each node spatial distribution can be expressed as

$$f(x,y)=\frac{1}{l_{area}^2} \quad 0\le x\le l_{area},\ 0\le y\le l_{area} \tag{6}$$

where (x,y) are the node's coordinates in two-dimensional system area. Then, we can estimate the number of interference neighbors for a node as

$$I=N_{node}\cdot\iint_{(x,y)\in A_I}\frac{1}{l_{area}^2}\,dx\,dy \tag{7}$$

where N_{node} is the number of nodes considered during the repair process, A_I is the circular region with radius r_I and centered at the current node location. r_I is the interference range for a node. Thus, based on Eq. (7), the number of interference neighbors can be precalculated before the repair process and the rest of the repair procedures are the same as NC-CIRM without control packet exchange.

4.2.2. Stationary distribution

Under the RWP mobility model, when the peers' moving time is long enough, their spatial distributions become stationary. In this case, according to Bettstetter et al. (2004) the pdf of the node spatial distribution can be expressed as

$$f(x,y)=P_{pause}f_p(x,y)+(1-P_{pause})f_m(x,y) \tag{8}$$

P_{pause} can be calculated based on Eq. (5). $f_p(x,y)$ represents the spatial distribution of a node that is currently pausing at a destination point and can be calculated based on Eq. (6). $f_m(x,y)$ represents the moving node distribution without pausing and can be expressed as

$$f_m(x,y)\approx\frac{36}{l_{area}^6}\left(\left(x-\frac{l_{area}}{2}\right)^2-\frac{l_{area}^2}{4}\right)\left(\left(y-\frac{l_{area}}{2}\right)^2-\frac{l_{area}^2}{4}\right) \tag{9}$$

Based on $f(x,y)$, we can estimate the number of interference neighbors for a node as

$$I=N_{node}\cdot\iint_{(x,y)\in A_I}f(x,y)\,dx\,dy \tag{10}$$

Similar to the uniform distribution, the number of interference neighbors can be precalculated based on Eq. (10) before the repair process and the rest of the repair procedures are the same as NC-CIRM without control packet exchange.

5. TP-RP under uniform distribution

In this section, we propose the TP-RP protocol which can further improve the repair latency when nodes are uniformly distributed. At the beginning of each repair epoch, peers start to repair the packets lost from the last BS broadcast period by generating coded packets at a fixed rate λ. If λ is set too large, the network will become more congested, resulting in large repair latency. On the other hand, if λ is set too small, the repair process may not fully utilize the network bandwidth which results in unnecessary delay. Therefore, the value of λ should be carefully selected. In this section, we theoretically analyze the repair process based on TP-RP and derive the expression of the coded packet generating rate λ which is optimized to reduce the total repair latency.

Since peers broadcast coded packets at a constant rate λ, each of them can be modeled as a $G/G/1$ queuing system which can be characterized by the arrival process and the service time distribution. The arrival process is characterized by the coded packet generating rate λ. The service time T_s is defined as the time interval between the time instance a packet enters the service (becoming the head of the output queue and can start to contend for transmission) and the time instance this packet is broadcast out. The collision probability is the same as the probability that at least one of this peer's interference neighbors is transmitting a packet at the current time slot, and this probability can be expressed as

$$p_c=1-\left(1-\frac{\lambda}{\mu}\tau\right)^n \tag{11}$$

where n is the peer's number of interference neighbors, τ is the probability that a peer transmits a packet at the current time slot, μ is the average packet service rate so that $1/\mu=E[T_s]$, and λ/μ represents the probability that a peer has an non-empty queue. τ is given from Chen et al. (2007b):

$$\tau=\frac{2}{W+1} \tag{12}$$

where W is the initial minimum backoff window size used in DCF.

We adopt the method used in Chen et al. (2007b) to obtain $E[T_s]$ and μ,

$$\frac{1}{\mu}=E[T_s]=\frac{L_{hdr}+L_{pkt}}{R}+\frac{(W-1)\sigma}{2}+\frac{(W-1)T}{2}p_c \tag{13}$$

and

$$T=\frac{L_{hdr}+L_{pkt}}{R}+T_{DIFS}+\delta \tag{14}$$

where T is the packet transmission time. L_{hdr} is the size of packet header including the physical layer header plus MAC layer header, and L_{pkt} is the size of packet payload. R is the system transmission rate, σ is the smallest time unit of the backoff timer. T_{DIFS} is the time period for a DCF inter-frame space and δ is the propagation delay.

Based on our TP-RP protocol, we can easily find that to minimize the total repair latency T_{repair}, we can minimize $f(\lambda)$ where

$$\begin{aligned}f(\lambda)&=\frac{1}{1-p_c}\times\frac{1}{\lambda}+\frac{\lambda E[T_s^2]}{2(1-\frac{\lambda}{\mu})}+\frac{1}{\mu}\\&=\frac{1}{\left(1-\frac{\lambda}{\mu}\tau\right)^n}\times\frac{1}{\lambda}+\frac{\lambda E[T_s^2]}{2\left(1-\frac{\lambda}{\mu}\right)}+\frac{1}{\mu}\end{aligned} \tag{15}$$

$E[T_s^2]$ can be obtained as

$$E[T_s^2]=var[T_s]+(E[T_s])^2=P''_{T_s}(1)+P'_{T_s}(1) \tag{16}$$

where $var[T_s]=P''_{T_s}(1)+P'_{T_s}(1)-(P'_{T_s}(1))^2$ is obtained based on the PGF of T_s Chen et al. (2007b). If we let $\alpha=\lambda/\mu$ where $0<\alpha<1$ to make the queue stable, and based on results from Eqs. (13) and (16), Eq. (15) can be rewritten as

$$\begin{aligned}g(\alpha)=&\frac{\alpha\{a+c+(b+d)[1-(1-\alpha\tau)^n]+e[1-(1-\alpha\tau)^n]^2\}}{2(1-\alpha)\{a+b[1-(1-\alpha\tau)^n]\}}\\&+\{a+b[1-(1-\alpha\tau)^n]\}\end{aligned} \tag{17}$$

where

$$a=\frac{L_{hdr}+L_{pkt}}{R}+\frac{(W-1)\sigma}{2} \tag{18}$$

$$b=\frac{(W-1)T}{2} \tag{19}$$

$$\begin{aligned}c=&\frac{L_{hdr}+L_{pkt}}{R}\left(\frac{L_{hdr}+L_{pkt}}{R}-1\right)+\frac{L_{hdr}+L_{pkt}}{R}(W-1)\sigma\\&+\frac{1}{3}\sigma^2(W-1)(W-2)+\frac{1}{2}\sigma(\sigma-1)(W-1)\end{aligned} \tag{20}$$

$$d = \frac{L_{hdr}+L_{pkt}}{R}(W-1)T + \frac{2}{3}\sigma T(W-1)(W-2) + \frac{1}{2}T(T+2\sigma-1)(W-1) \tag{21}$$

$$e = \frac{1}{3}T^2(W-1)(W-2) \tag{22}$$

The optimal value of α which minimizes $g(\alpha)$ can be derived through numerical method. Based on the optimal value of α, μ can be obtained using Eq. (13), and consequently the optimal coded packet generating rate λ can be obtained.

6. Performance evaluation and comparison

In this section, we evaluate the performance of our proposed protocols, NC-CIRM, NC-CIRMD, and TP-RP in terms of total repair latency. We also demonstrate how coded packet generating rate λ affects the repair performance under TP-RP. All the results presented here are averaged over 50 s run in NS-2. The parameters used in the simulations are summarized in Table 1.

Table 1
Parameters used in simulation.

Transmission range t_r	110 m	Simulation time	50 s
Interference range t_I	242 m	N_{node}	100
Peer transmission rate R_d	36 Mbps	L_{hdr}	464 *bit*
BS transmission rate R_b	384 Kbps	l_{area}	1000 m
Initial backoff window size W	31	V_{min}	2 m/s
Unit time slot σ	20 μs	V_{max}	5 m/s
DCF inter-frame space T_{DIFS}	50 μs	T_{pause}^{min}	1 ms
Propagation delay δ	0.4 μs	T_{pause}^{max}	5 ms

6.1. NC-CIRM and NC-CIRMD under stationary distribution

In this subsection, we demonstrate the performance of NC-CIRM and NC-CIRMD in terms of total repair latency over different network settings when the mobile peers' spatial distribution is stationary. The repair epoch T_{re} is an important baseline to measure the efficiency of the proposed protocols, and it is expressed as $T_{re} = (B \times M \times 8)/R_b \times 1000$ ms.

Figure 3 (a), (b), and (c) illustrates that NC-CIRM achieves similar performance as NC-CIRMD under the stationary distribution case. Furthermore, Fig. 3(a) shows that the repair latencies for both protocols increase as the loss rate increases under the same batch size and packet size, since more packets were lost during the last BS broadcast period and need more time to repair them. In this figure we can see that even at loss rate being 0.6, the repair latencies are only 90.9 ms and 90.1 ms for NC-CIRMD and NC-CIRM, respectively, which are below 22 percent of the repair epoch 417 ms. Figure 3(b) shows similar results that the repair latencies for both protocols increase as the batch increases and the repair latencies are below 12 percent of the corresponding repair epoch. Figure 3(c) shows similar results and the repair latencies are below 13 percent of the corresponding repair epoch. Thus, both NC-CIRM and NC-CIRMD work efficiently under the stationary distribution case and NC-CIRM works well when we do not have the knowledge of node spatial distribution.

6.2. NC-CIRM and NC-CIRMD under uniform distribution

In this subsection, we demonstrate the performance of NC-CIRM and NC-CIRMD in terms of total repair latency over different network settings when the mobile peers' spatial distribution is uniform. Figure 4 shows similar results as Fig. 3 that NC-CIRM achieves similar repair performance as NC-CIRMD under the

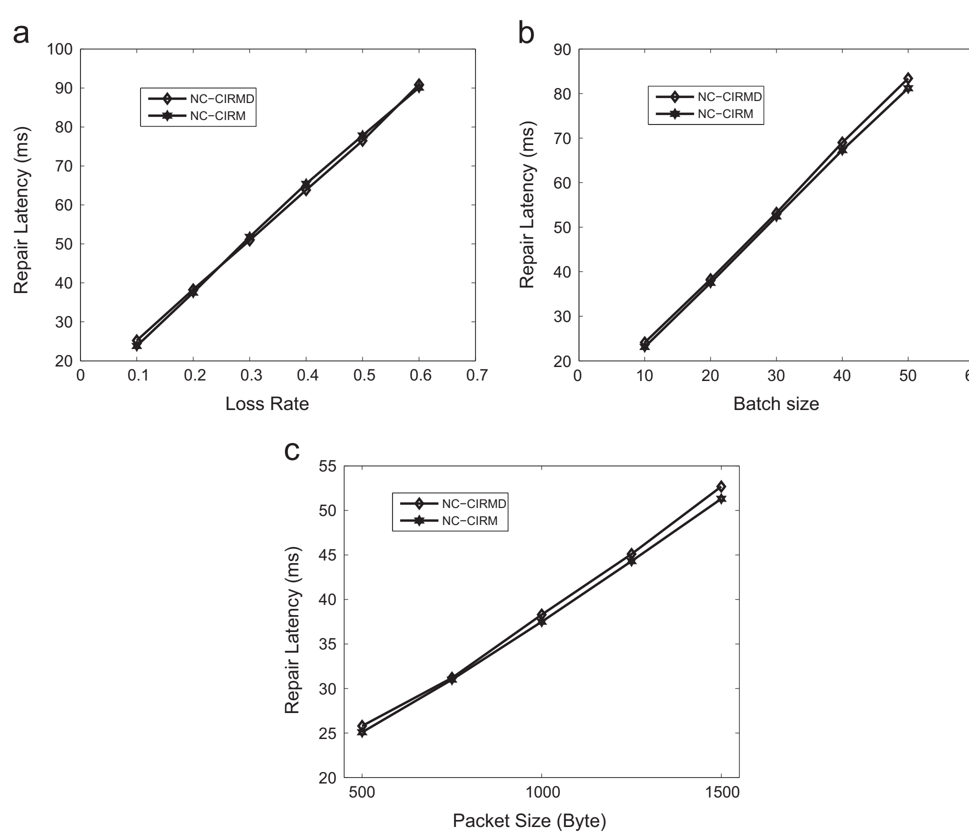

Fig. 3. Repair performance of NC-CIRM and NC-CIRMD under stationary distribution case. (a) 100 nodes, 20 batch size and 1000 packet size, with different loss rate, (b) 100 nodes, 1000 packet size and 0.2 packet loss rate, with different batch size. and (c) 100 nodes, 0.2 packet loss rate and 20 batch size, with different packet size.

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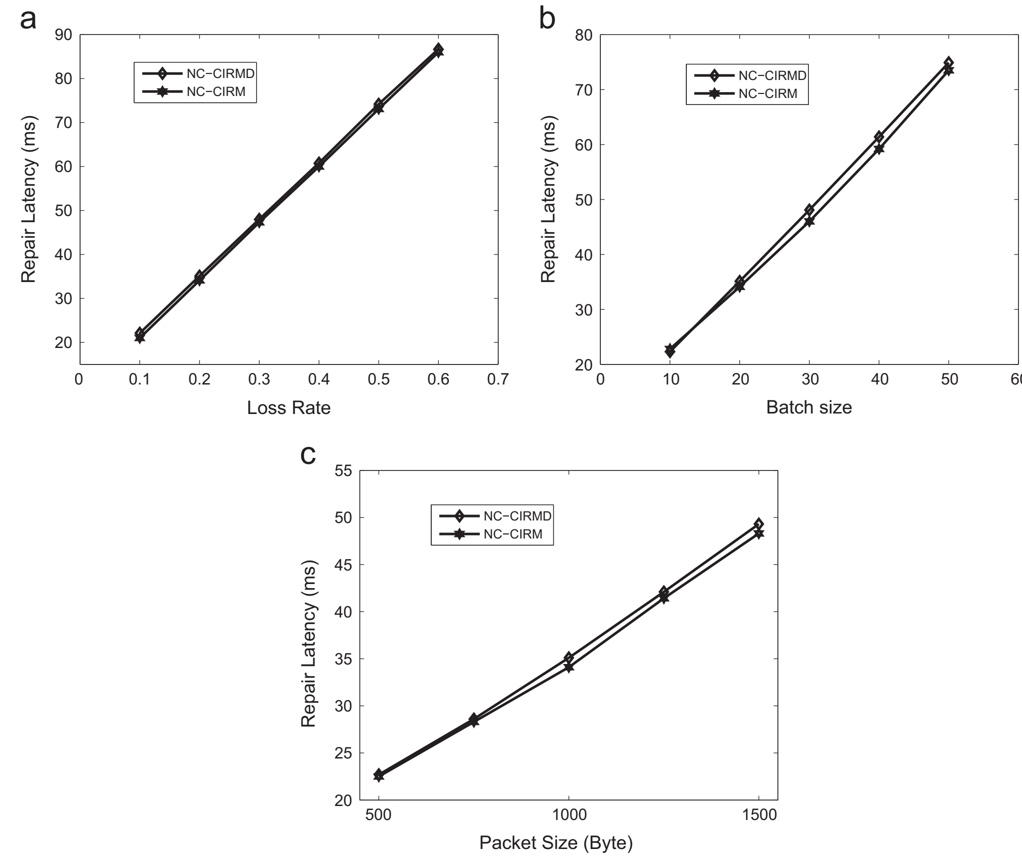

Fig. 4. Repair performance of NC-CIRM and NC-CIRMD under uniform distribution case. (a) 100 nodes, 20 batch size and 1000 packet size, with different loss rate, (b) 100 nodes, 1000 packet size and 0.2 packet loss rate, with different batch size and (c) 100 nodes, 0.2 packet loss rate and 20 batch size, with different packet size.

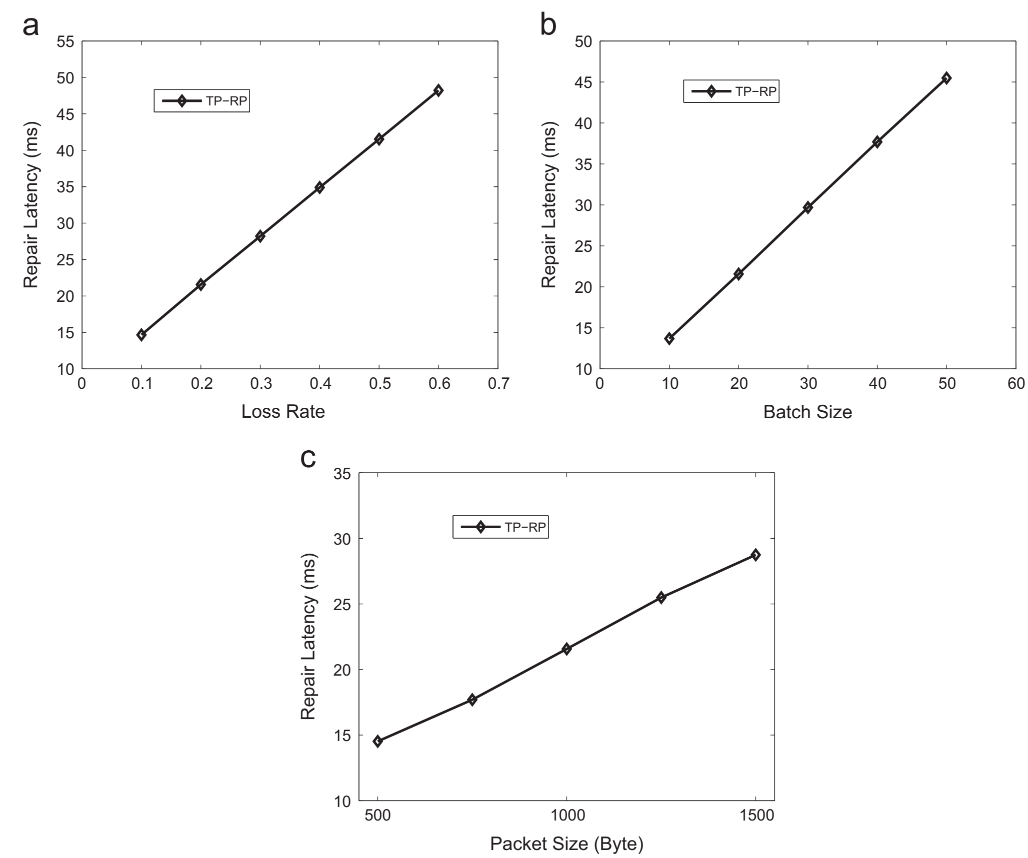

Fig. 5. Repair performance of TP-RP under different network settings. (a) 100 nodes, 20 batch size and 1000 packet size, with different loss rate, (b) 100 nodes, 1000 packet size and 0.2 packet loss rate, with different batch size and (c) 100 nodes, 0.2 packet loss rate and 20 batch size, with different packet size.

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uniform distribution case. When loss rate is 0.6, the repair latencies are only 86.7 ms and 86 ms for NC-CIRMD and NC-CIRM, respectively, which are below 21 percent of the repair epoch 417 ms. For different batch size and packet size, the repair latencies are below 11 percent of the corresponding repair epoch. Thus, both protocols work efficiently under the uniform distribution case and NC-CIRM works well when we do not have the knowledge of the node spatial distribution.

From Figs. 3 and 4 we can conclude that: (1) Both NC-CIRM and NC-CIRMD achieve a little bit better repair performance under the uniform distribution case compared with the stationary distribution case, (2) the repair latency under NC-CIRM is far less than 50 percent even when the loss rate is 0.6, which validates that the lost packets can be repaired before the starting time of the control packet exchange during each repair epoch in NC-CIRM and (3) these two protocols work efficiently under both uniform and stationary node spatial distributions.

6.3. TP-RP under uniform distribution

In this subsection, we demonstrate the simulation results under TP-RP in terms of total repair latency over different network settings when the mobile peers' spatial distribution is uniform. Figure 5(a) shows that the repair latency increases as the loss rate increases with the optimal λ being 146. When the loss rate is 0.6, the repair latency is only 48.21 ms which is below 12 percent of the repair epoch 417 ms. Figure 5(b) shows similar results and the repair latency is around 5 percent of the corresponding repair epoch. Figure 5(c) shows the repair latencies with different packet size M. From Eq. (17) we know that different packet size results in different optimal value of λ. Table 2 lists the optimal value of α, μ, and λ according to different M. With the optimal value of λ, the repair latency shown in Fig. 5(c) increases as the packet size increases and it is around 5 percent of the corresponding repair epoch. Furthermore, Figs. 4 and 5 show that under the uniform distribution case the TP-RP protocol achieves better repair performance compared with NC-CIRM and NC-CIRMD, thanks to the optimized tunable parameter λ which is used to reduce the total repair latency.

Table 2
α, $1/\mu$ and $1/\lambda$ based on different M.

Basic settings	α	$\frac{1}{\mu}$ (ms)	$\frac{1}{\lambda}$ (ms)
$P_L=0.2$, $B=20$, $M=500$	0.245	1.09	4.44
$P_L=0.2$, $B=20$, $M=700$	0.235	1.27	5.42
$P_L=0.2$, $B=20$, $M=900$	0.235	1.48	6.30
$P_L=0.2$, $B=20$, $M=1100$	0.22	1.63	7.39
$P_L=0.2$, $B=20$, $M=1300$	0.215	1.80	8.37
$P_L=0.2$, $B=20$, $M=1500$	0.21	1.97	9.37

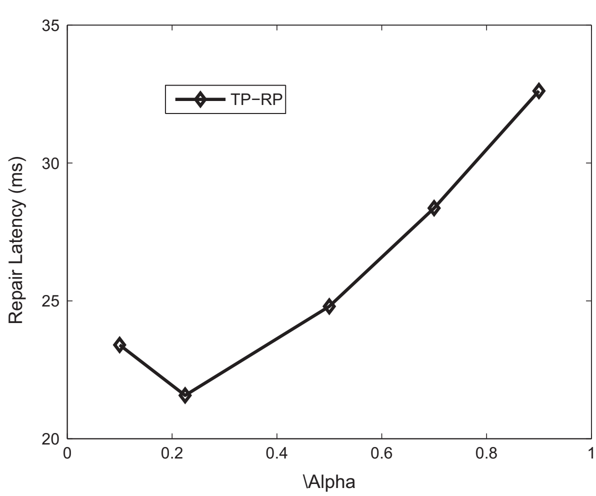

Fig. 6. TP-RP repair latency under different α with 100 nodes, 0.2 packet loss rate, 20 batch size and 1000 packet size.

6.4. Coded packet generating rate λ

In this subsection, we investigate how α or the coded packet generating rate λ affects the repair latency under TP-RP protocol. We evaluate the repair performance based on different value of α under two different network settings and the corresponding results are shown in Figs. 6 and 7, respectively. Both figures show similar results with the same optimal value of α being 0.225, μ being 649, and λ being 146. From these two figures we can see that when α or λ goes to zero, the coded packet generating time is large, resulting in large delay; when λ is large, peers generate coded packets more frequently that inserts high traffic volume into the network, resulting in high transmission collisions and large repair latency. Thus, λ is indeed a critical parameter which should be carefully selected to reduce the repair latency. The results from these two figures show that the system performance under the TP-RP protocol achieves the best with the optimal value

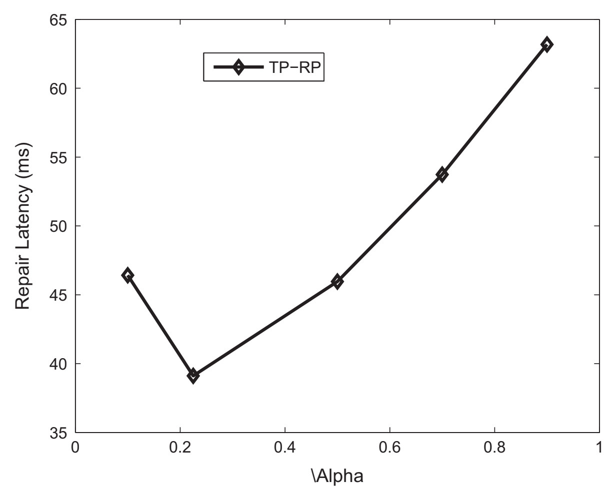

Fig. 7. TP-RP repair latency under different α with 100 nodes, 0.3 packet loss rate, 30 batch size and 1000 packet size.

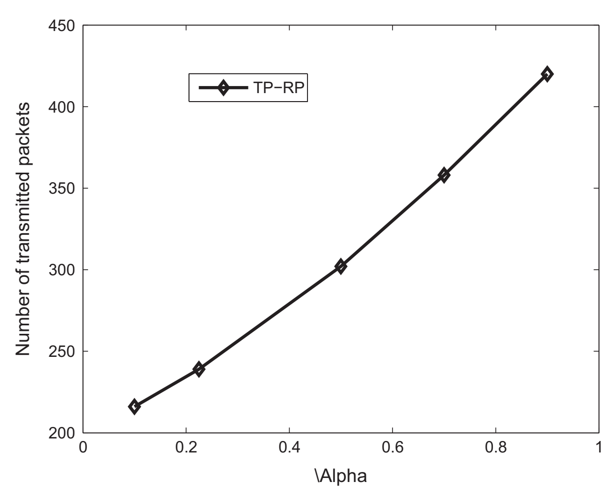

Fig. 8. Total number of generated coded packets based on TP-RP protocol under different α with 100 nodes, 0.2 packet loss rate, 20 batch size and 1000 packet size.

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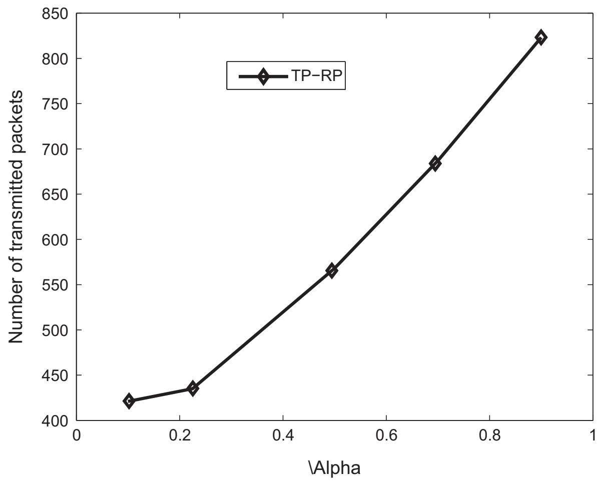

Fig. 9. Total number of generated coded packets based on TP-RP protocol under different α with 100 nodes, 0.3 packet loss rate, 30 batch size and 1000 packet size.

of α, which validates our analysis on α, or the coded packet generating rate, λ.

Figs. 8 and 9 illustrate the total number of transmitted coded packets with different α based on the two network settings mentioned above. These two figures show that as α increases the number of transmitted packets increases faster than the linear increase, since the coded packet generating rate λ increases and more packets are transmitted within the network. Combining Figs. 6, 7 and 8, 9 we can see that there is a tradeoff between the repair latency and the total number of transmitted coded packets. The number of transmitted packets reflects the power consumption for the mobile device that is another issue needed to be concerned when design protocols in mobile network. The power consumption is out of the scope of this paper, we will investigate this issue in our future work.

7. Conclusion

In this paper, we study the DNC-CPR problem in cellular/802.11 hybrid networks while considering node movement. The NC-CIRM protocol is proposed to effectively repair lost packets under the RWP mobility model. Then we propose the NC-CIRMD protocol which is a simplified version of NC-CIRM when the node spatial distribution is known. Moreover, the TP-RP protocol is proposed to further improve the repair latency under the uniform distribution case. An analytical model is developed and the theoretical result of corresponding coded packet generating rate is derived which is optimized to reduce the repair latency. Extensive simulation results illustrate the efficiency of the three proposed protocols, validate the accuracy of the optimal point of the tunable parameter λ, and provide useful guidelines for protocol design in related application scenarios.

For future work, we will analyze power consumptions for mobile devices, formulate multi-objective optimizations with repair latency and power control, as well as studying DNC-CPR problem under high mobility scenario.

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