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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.