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# Delay Performance of Network Coding-based Epidemic Routing

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***Abstract*—In this paper, we first challenge the accuracy of the so-called innovative assumption which is widely adopted in delay performance analysis of Network Coding-based Epidemic Routing (NCER) in Delay Tolerant Networks (DTNs). We demonstrate that this optimistic assumption severely underestimates data delivery delay, and solve this problem successfully by introducing an extra encounter factor $\delta$. Based on this, we propose a Coloring Process (CP) based analytical model to evaluate the delay performance of NCER. Numerical results show that our CP-based method outperforms traditional Ordinary Differential Equations (ODE) based methods on estimating the delay performance under different network sizes. Furthermore, in order to mitigate potential competitions among multiple data streams from different nodes, we propose a Feedback-based Recovery Protocol (FRP) that takes advantage of finite buffer space and significantly reduces the number of ineffective transmissions between nodes. As a result, FRP can achieve much better delay performance compared with existing protocols in prior work.**

***Index Terms*—Epidemic routing, delay tolerant networks, delay performance modeling, recovery protocol.**

## I. Introduction

Wireless networks without fixed infrastructures are becoming increasingly popular, where network components are organized in an Ad-hoc fashion [1–4]. In this type of networks, communication opportunities are usually intermittent due to low node density and limited communication range of mobile nodes. Applications in such networks have to tolerate some data delivery latency. Therefore, Delay Tolerant Network (DTN) is termed to describe such a network.

In DTNs, transmission opportunities arise only when two nodes encounter, i.e., two nodes move into the transmission ranges of each other. Under this setup, if a source node transmits its data to its destination node when they encounter, the data delivery will suffer a considerable delay, which may be unacceptable even for delay tolerant applications. Epidemic routing (ER) [5] has been proposed to alleviate this problem at the cost of significant communication resource occupancy. The general process of ER can be divided into two phases, namely, the propagation phase and the recovery phase. In the propagation phase, data is injected into the network from the source node and propagated to the destination node with the assistance of other nodes as relays. Once the destination has successfully received one copy of the data, the network nodes need to remove data copies from their respective buffers, and this is termed the recovery phase [6].

However, in many applications the sizes of data files are larger than the capacity that a single transmission opportunity supports due to bandwidth limitation. In such cases, the delivery delay of the original ER increases sharply, because the original data file needs to be segmented and transmitted in turn. Considering that the segmented packets may compete for transmission opportunities, the delay performance can be further deteriorated.

Recently, network coding [7–9] provides a novel way to take advantage of valuable transmission opportunities under limited bandwidth. Several schemes [10, 11] exploiting random linear network coding [8] in ER have been proposed, whose benefits for data delivery in DTNs have been demonstrated through simulations. Under Network Coding-based Epidemic Routing (NCER), first, a large data file is segmented into $K$ smaller packets. Then linear combinations (referred to hereafter as encoded packets) of these segmented packets are injected into the network together with combination/coding coefficient vectors. Intermediate nodes will forward random combinations of encoded packets they have received, till the destination receives enough *innovative* encoded packets to decode the original data. Here, innovative means the coding coefficient vector of the newly received encoded packet can increase the rank of a coding matrix which is stored in nodes for each data file and is composed of received coding coefficient vectors that have been received. Apparently, to decode $K$ segmented packets, $K$ encoded packets, of which the coding coefficient vectors are linearly independent, are needed.

To facilitate future designs of network coding-based routing protocols in DTNs, it is imperative to quantify the performance gain brought by network coding in a rigorous and analytical way. To the best of our knowledge, [12, 13] are the few efforts for analytically modeling the delay performance of NCER in DTNs with the help of Ordinary Differential Equations (ODEs). They adopt an assumption that a node carrying one or several encoded packets is able to transmit an innovative



Manuscript received December 11, 2014; revised March 17, 2015; accepted April 20, 2015.

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The material in this paper has been partially presented at the 2015 IEEE International Conference on Communications (ICC), 8-12 June, London, UK.

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encoded packet to another node as long as the number of encoded packets it carries is not enough for decoding. This assumption, referred to hereafter as the *innovative assumption*, is a corollary of the theoretical result derived in [14]. However, the network model where that result is not derived is not identical to that of the data delivery process under NCER in DTNs. In other words, its validity for NCER in DTNs is still largely unknown. Besides, as aforementioned, prior studies [12, 13] use ODEs to model the data delivery process of NCER. However, [15] which aims at modeling the delay performance of ER points out that ODE-based analytical approaches such as that proposed in [16] are asymptotic in nature. That is, ODE-based analytical approaches can be rather inaccurate [15] when applied to networks of realistic size, i.e., networks with modest number of nodes.

In lieu of those insufficiency, in this paper, we aim to propose a new analytical method targeting at calculating an accurate data delivery delay for NCER in DTNs. We first show that in fact the innovative assumption is inaccurate for NCER in DTNs, which leads to underestimation of the true data delivery delay. To elaborate, for a data file divided into $K$ smaller packets, if the innovative assumption holds, then the time elapsed between the instant at which the original data file is generated at the source and the instant at which the destination encounter $n$ nodes carrying encoded packets is equivalent to the data delivery delay by setting $n = K$. However, for small/intermediate scale DTNs, the innovative assumption does not always hold as shown later in Section III. Thus, the packet delivery delay estimated under $n = K$ is in essence smaller than the real data delivery delay. In order to compensate for such discrepancy, we propose to include an extra encounter factor $\delta$ and use the delay for receiving $n = K + \delta$ packets to approximate the real data delivery delay. The value of $\delta$ is characterized empirically.

Subsequently, we propose a new method for analyzing the exact distribution of the packet delivery delay. That is, we deduce the exact expression of the Cumulative Density Function (CDF) of the time for the destination node to encounter any $n$ nodes carrying encoded packets. Compared to the ODE-based method which is asymptotic in nature, our proposed method, calculating the exact expression directly, achieves better accuracy. In combination of an exact calculation of packet delivery delay, as a function of $n$, and an appropriate extra encounter factor $\delta$, we can calculate the data delivery delay with considerable accuracy, and these constitute the complete analytical framework. Numerical simulations are conducted to verify the correctness of our analytical framework.

In addition to analyzing the propagation phase of NCER, we also address its recovery phase since it also impacts the delay performance of NCER. In general, to save buffer space for other data files, packets of an already decoded data file should be deleted from network nodes under a recovery protocol in the recovery phase. Moreover, we point out that those obsolete packets not only occupy the buffer but also compete for transmission opportunities with data files from different source nodes. That is, obsolete packets may lead to ineffective transmissions which waste valuable transmission opportunities and deteriorate the average data delivery delay. Hence, a quick deleting of obsolete packets is worth studying.

Works in [11, 13] adopt a recovery protocol which is similar to the VACCINE [6] recovery protocol for ER in the recovery phase of NCER. This protocol initiate the recovery process (to delete obsolete packets from network nodes) after successful decoding of a data file. In this paper, we further propose a new recovery protocol called Feedback-based Recovery Protocol (FRP) to accelerate the recovery process, which not only makes use of the finite buffer space more efficiently but also facilitates the delay performance of NCER when multiple data files exist. Simulation results show that FRP, which reduces the buffer occupancy and the number of ineffective transmissions during data delivery, can achieve better delay performance compared with the widely adopted recovery protocol in prior work.

The main contributions in this work are summarized as follows.

- We first identify the inaccuracy of the innovative assumption for DTNs, which will drastically impact the validity of analytical results adopting it and leads to underestimation of the true delay. To address this issue, we propose an empirical method to compensate such discrepancy.
- A new analytical method is proposed to characterize the exact distribution of the packet delivery delay for NCER in DTNs. This method, which is not ODE-based, achieves higher accuracy compared with the ODE-based approach.
- FRP is proposed to accelerate the recovery process, which not only efficiently uses finite buffer space but also significantly improve the efficiency of transmissions, thus facilitating the delay performance of NCER.

The remainder of this paper is organized as follows. In section II, system model is described together with a brief introduction to NCER. In section III, the inaccuracy of the innovative assumption is demonstrated and a compensation approach is introduced and studied. Then, in section IV, a new analytical method is developed and validated in section IV. Furthermore, FRP is proposed and evaluated in section V. Finally, Section VI concludes the paper.

## II. System Model

In this section, we present in detail the system models adopted in this paper, and give a short introduction to the typical NCER scheme.

### A. System Model

We consider a network running unicast data delivery applications as shown in Fig. 1. The network consists of $M$ mobile nodes moving independently in a closed area. A data file is generated at a source node and delivered to a destination node. All nodes can exchange data packets through a shared wireless channel when they encounter, i.e., two nodes move into the radio radius $R$ of each other. Due to bandwidth limitation, a data file is segmented into $K$ packets of $S$ bits, so that one packet can be delivered during each transmission opportunity. Assume that nodes reserve enough buffer space for accommodating up to $K$ data packets for each data file.

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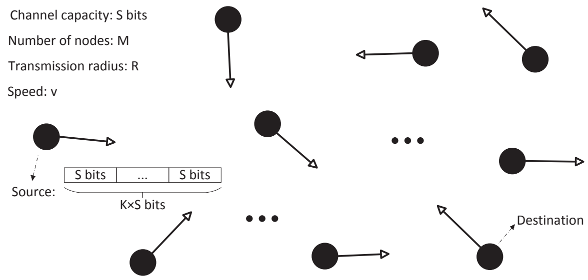


Fig. 1: A sketch of DTN running unicast data delivery applications.

The *inter contact time* of a node mobility model is defined as the random time elapsed between encounters of two same nodes. Many popular random mobility models, such as random waypoint [17] and random walk [3], are supposed to have the property that their inter contact times are exponentially distributed. Trace-based experimental results [18] confirm that the inter contact time of realistic vehicle traffic is exponentially distributed. In this paper, we assume that nodes move with a constant velocity $v$ under the random waypoint mobility model,[1] and the inter contact time is exponentially distributed with a rate of $\lambda$. Above assumptions are also adopt in much prior work [11, 13, 15, 16].

### B. Network coding-based epidemic routing

Under NCER, a set of random linear combinations of packets are injected into the network together with coding coefficient vectors instead of original segmented packets. An encoded packet $x$ can be written as

$$x = \sum_{i=1}^{K} \alpha_i e_i, \tag{1}$$

where $\alpha_i$s are randomly generated coding coefficients and $e_i$s denote the original segmented packets. It is important to note that the aforementioned addition and multiplication operations are over a finite Galois Field $\mathbb{F}_q$ of size $q = 2^8$. Obviously, for successful decoding, the source should infuse at least $K$ encoded packets to the network. When a node receives an innovative packet, it stores the packet in its buffer. For intermediate node $u$ holding $m$ encoded packets in its buffer, where $1 \leq m \leq K$, node $u$ will transmit a random linear combination of all of its encoded packets to new nodes that it encounters. It is not difficult to reach that this newly generated linear combination is also a linear combination of the original segmented packets. If two encountered nodes both hold several encoded packets, only the innovative packets will be delivered, i.e., nodes accept packets that can increase the rank of its coding matrix (consist of coding coefficients). At last, if the destination receives $K$ encoded packets that are independent from each other, i.e., the rank of the coding matrix equals to $K$, the original segmented packets can be recovered.

[1] In all simulations of this work, the nodes velocity $v$ is set to $6m/s$, and the radio radius $R$ is fixed at 100 meters.

## III. Accuracy Study of Innovative Assumption

In prior work [11–13], the inaccuracy of innovative assumption is considered negligible, which is however not true for NCER in realistic DTNs with small/intermediate sizes.

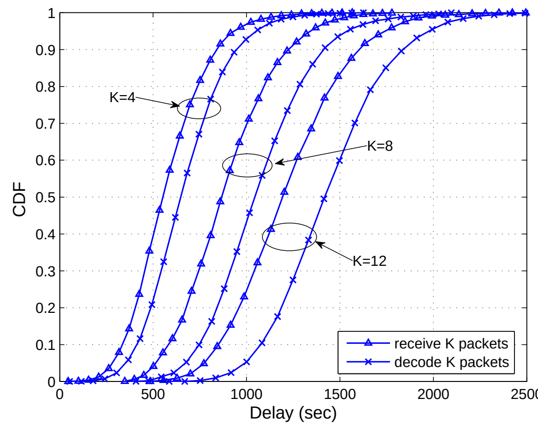


Fig. 2: The inaccuracy of innovative assumption.

In Fig. 2, for a DTN with 20 nodes, a considerable gap is observed between the delay curves of encountering $K$ nodes with encoded packets against successful decoding $K$ packets. This figure demonstrates that encountering $K$ nodes with encoded packets are far from receiving $K$ innovative packets.

To close this gap and enable accurate analysis of delay performance, let us assume the destination needs to encounter an extra $\delta$ nodes with encoded packets to receive $K$ innovative packets for a successful decoding process. Intuitively, this extra encounter factor $\delta$ is likely to be affected by parameters such as the number of segmented packets $K$, network size (number of nodes) $M$ and network coverage area $A$.[2] However, extensive numerical studies (Figs. $3-5$) show that $\delta$ is mainly determined by parameter $K$, or more precisely, an empirical equation has been derived as $\delta \approx \lceil K/4 \rceil$.

Figs. $3-5$ show the extra encounter factor $\delta$ can effectively close the delay performance gaps in Fig. 2, for different packet segmentations, network sizes and coverage areas. More interestingly, from these figures, we can easily identify the dominating impact of parameter $K$ on $\delta$. Compared with $K$, the impacts of parameters $M$ and $A$ on $\delta$ are insignificant, as illustrated in Fig. 4 and Fig. 5, respectively. Based on these new findings, the encounter factor $\delta \approx \lceil K/4 \rceil$ is adopted in next Section to develop a new accurate analytical approach for delay performance evaluation of NCER in DTNs.

## IV. Delay Performance Analysis

Referring to Fig. 1, let random variable $T_r$ be the time elapsed between the instant at which the original data file is generated at the source, and the instant at which $K$ independent encoded packets are received at the destination. Let random variable $T_{D,n}$ be the time elapsed between the

[2] The velocity of nodes will not impact $\delta$. That is because it does not change the mobility trace of nodes but only influences the speed of data delivery process. In all the simulations we assume that nodes moves with a velocity of 4m/s.

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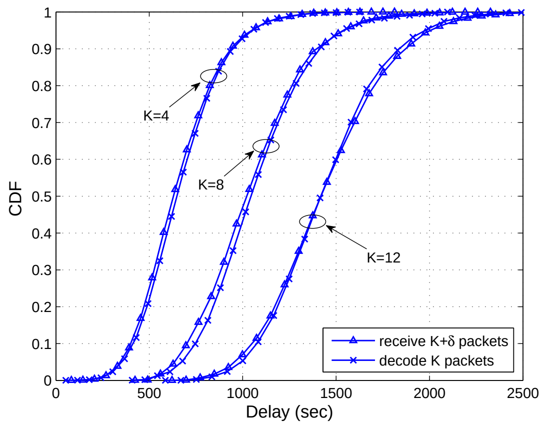


Fig. 3: Delay performance under different packet segmentations. $M = 20$, $A = 1km^2$ and $\delta = \lceil K/4 \rceil$.

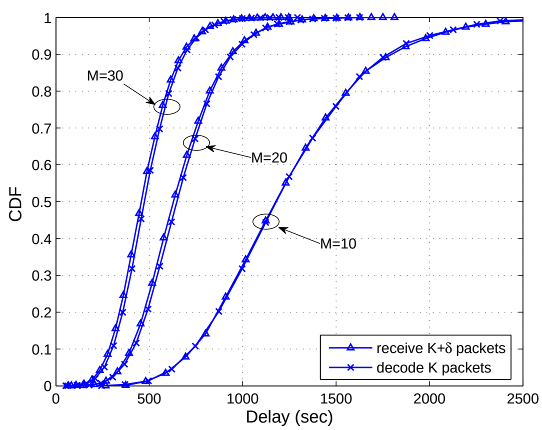


Fig. 4: Delay performance under different network sizes. $K = 4$, $A = 1km^2$ and $\delta = \lceil K/4 \rceil$.

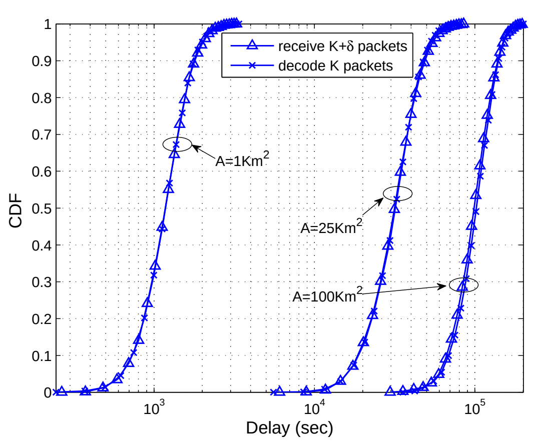


Fig. 5: Delay performance under different network coverage areas. $K = 4$, $M = 10$ and $\delta = \lceil K/4 \rceil$.

instant at which the original data file is generated at the source, and the instant at which the destination encounter $n$ nodes with encoded packets. Since $T_r$ can be approximated by $T_{D,n}$ $(n \geq K)$.[3] In this section, we present a new analytical framework for characterizing the data delivery delay performance of NCER by calculating $P(T_{D,n} < t)$, i.e., the exact CDF of $T_{D,n}$.

### A. Coloring Process Approach

Data delivery under NCER can be modeled as a coloring process [15]: nodes are subdivided into two states, uncolored and colored, according to whether there are any encoded packets in their buffers; a node turns from uncolored to colored state if it encounters a colored node, and this process is termed as a coloring event.

We begin with the case of ER without network coding. Let $E_i$ be the event that a coloring event occurs at the state that there are $i-1$ colored nodes in the network. Let $C_i$ be the state that the destination has been colored $i$ times. Let random variable $T_i$ be the time that $i$ coloring events take. For this case, the packet delivery process terminates when the destination is colored the first time. When the destination is colored, there may be $i$ $(i = 1, 2, ..., M-1)$ colored nodes in the network. Hence, the probability of interest $P(T_r < t)$ can be expressed as follows,

$$P(T_r < t) = \sum_{i=1}^{M-1} P(T_r < t \,|E_i, C_1) P\left(E_i, C_1\right). \tag{2}$$

Since the destination is identical to other nodes, it is not difficult to reach that $P\left(E_i, C_1\right) = 1/(M-1)$. Define the interval of two sequential coloring processes as $\tau_k = T_k - T_{k-1}$ for $1 < k < M$. Then $P(T_r < t \,|E_i, C_1)$ can be expressed as

$$\begin{aligned} P(T_r < t \,|E_i, C_1) &= P(T_i < t) \\ &= P\left(\sum_{j=1}^{i} \tau_j < t\right). \end{aligned} \tag{3}$$

Clearly, the distribution of random variable $\tau_j$ depends on the features of the mobility pattern, i.e., the characteristics of the inter contact time. As generally assumed, the inter contact time between two nodes is exponentially distributed with rate $\lambda$. For $\tau_1$, there are only one colored node and $M-1$ uncolored nodes. Hence, $\tau_1$ is an exponentially distributed random variable with rate $(M-1)\lambda$. Likewise, $\tau_k$ is an exponentially distributed random variable with rate $k(M-k)\lambda$, where $k$ and $M-k$ denote the number of colored and uncolored nodes respectively. Now, the problem is translated into computing the distribution of the sum of a set of exponentially distributed random variables which can be calculated conveniently according to the formula in [19].

Different from conventional ER, the destination needs to receive $K$ innovative/independent packets for successfully decoding under NCER paradigm. As aforementioned, we now

[3] If the innovative assumption holds, $T_r$ is equivalent to $T_{D,K}$. However, as shown in Section III, for successfully decoding $K$ independent encoded packets, the destination needs to receive an extra number of encoded packets, i.e., $n > K$.

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use $P(T_{D,n} < t)$ ($n = K + \delta$ in this case according to the result of Section III) to approximate $P(T_r < t)$.

Similar to the decomposition process used in (2), the probability of interest $P(T_{D,n} < t)$ can be computed as follows,

$$P(T_{D,n} < t) = \sum_{i=1}^{M-1} P(T_{D,n} < t\,|E_i, C_n) P(E_i, C_n). \quad (4)$$

For brevity, denote $P(T_{D,n} < t\,|E_i, C_n)$ as $P(T_{D,n,i} < t)$, the above can be reorganized as

$$P(T_{D,n} < t) = \sum_{i=1}^{M-1} P(T_{D,n,i} < t) P(E_i, C_n). \quad (5)$$

The problem is transformed into two sub-problems, i.e., computing $P(T_{D,n,i} < t)$ and $P(E_i, C_n)$ respectively. We can calculate them individually.

Derive $P(T_{D,n,i} < t)$ first. It can also be decomposed as

$$P(T_{D,n,i} < t) = \sum_{j=1}^{i} P(T_{D,n,i} < t\,|E_j, C_{n-1}) P(E_j, C_{n-1}), \quad (6)$$

where $P(E_j, C_{n-1})$ introduces the state of last coloring event into (6) as assumed conditions.

$P(T_{D,n,i} < t\,|E_j, C_{n-1})$ can be further decomposed,

$$\begin{aligned} P(T_{D,n,i} < t\,|E_j, C_{n-1}) &= P\left(T_{D,n-1,j} + \sum_{k=j}^{i} \tau_k < t\right) \\ &= \int_0^t P\left(T_{D,n-1,j} + \sum_{k=j}^{i} \tau_k < t \,\middle|\, \sum_{k=j}^{i} \tau_k = x\right) f_{\sum_{k=j}^{i} \tau_k}(x)\, dx \\ &= \int_0^t P(T_{D,n-1,j} < t - x) f_{\sum_{k=j}^{i} \tau_k}(x)\, dx, \end{aligned} \quad (7)$$

where $f_{\sum_{k=j}^{i} \tau_k}(x)$ is the Probability Distribution Function (PDF) of $\sum_{k=j}^{i} \tau_k$, and can be calculated conveniently.

This problem is now turned to compute $P(T_{D,n-1,j} < t)$. If we decompose $P(T_{D,n-1,j} < t)$ recursively as (6) and (7), the problem will be transformed into calculating $P(T_{D,1,i} < t)$. In fact, $P(T_{D,1,i} < t)$ for $i = 1, 2, \ldots, M-1$ is equivalent to $P(T_r < t\,|E_i, C_1)$ in (3). Hence, the derivation of $P(T_{D,n,i} < t)$ is completed.

Next comes the calculation of $P(E_i, C_n)$. Note that $P(E_i, C_1) = 1/(M-1)$, it is not difficult to reach that $P(E_1, C_2) = P(E_1, C_1)/(M-1)$, since $(E_1, C_1)$ is the prerequisite of $(E_1, C_n)$. By this analogy, we have $P(E_1, C_n) = 1/(M-1)^n$. For $P(E_i, C_n)$ $(i, n \neq 1)$, a recursive calculation method is presented as follows,

$$P(E_i, C_n) = P(E_{i-1}, C_n) + P(E_i, C_{n-1})/(M-i), \quad (8)$$

where $P(E_i, C_{n-1})/(M-i)$ denotes the probability that the destination is colored in the next successive time after $(E_i, C_{n-1})$.

Hence in summary, $P(E_i, C_n)$ can be computed as follows,

$$P(E_i, C_n) = \begin{cases} \frac{1}{M-1} & n = 1 \\ \frac{1}{(M-1)^n} & i = 1 \\ P(E_{i-1}, C_n) + \frac{P(E_i, C_{n-1})}{M-i} & else \end{cases} \quad (9)$$

To conclude, in this section we use $P(T_{D,n} < t)$ to approximate the probability of interest. Computing $P(T_{D,n} < t)$ is an iterative process. First, $P(T_{D,n} < t)$ is decomposed into two parts as (5), i.e., $P(T_{D,n,i} < t)$ and $P(E_i, C_n)$. $P(E_i, C_n)$ can be computed based on (9), and $P(T_{D,n,i} < t)$ can be further decomposed as (6) and (7). Since $f_{\sum_{k=j}^{i} \tau_k}$ can be easily computed, the problem is translated to computing $P(T_{D,n-1,j} < t)$. The above process repeats $n-1$ times, and by then the only problem is to compute $P(T_{D,1,i} < t)$ for $i = 1, 2, \ldots, M-1$, which is solved in (3). The validity of the analytical method will be verified in the next section.

### B. Numerical Results

In this section, in order to demonstrate the validity of our proposed analytical method (referred to as CP approach in the figures), our analytical results are compared with the real delay performance (simulated results). Besides, the ODE-based analytical results [13] are also presented as a comparison.

As shown in Fig. 6, combination with the empirical expression of $\delta = \lceil K/4 \rceil$, our proposed analytical results match the simulation results much better than the ODE-based analytical results under different $K$. For instance, in Fig. 6(a) it can be seen that when the CDF equals $90\%$ under $K = 4$, our analytical delay result is close to the simulated delay result with an error of $2\%$ while the result obtained by ODE-based approach underestimates the delay performance by $28\%$. And in Fig. 6(b) the exact PDF curves of different delay results clearly show that ODE-based approach will underestimate the delay performance of data delivery delay while the CP-based approach achieves a good approximation. Similar conclusion can also be derived from Fig. 7 which are conducted under a larger network size. Above results validate the correctness and accuracy of our analytical method, and also reconfirm that the validation of the ODE-based analytical model degrades when applied to networks of realistic size and node density.

## V. FEEDBACK-BASED RECOVERY PROTOCOL

In this section, aiming at the data delivery delay reduction of NCER we introduce FRP to accelerate the deleting of obsolete packets in the network nodes.

### A. Feedback-based Recovery Protocol

VACCINE [6] is proposed to tackle the resource occupancy issue in the recovery phase of ER, in which an ACK signal is propagated into the network to delete obsolete copies of packet after successful delivery. Similar recovery protocols [11, 13] are proposed for NCER schemes. Under those protocols, the destination propagates an ACK into the network to delete all the encoded packets of an already decoded data file after

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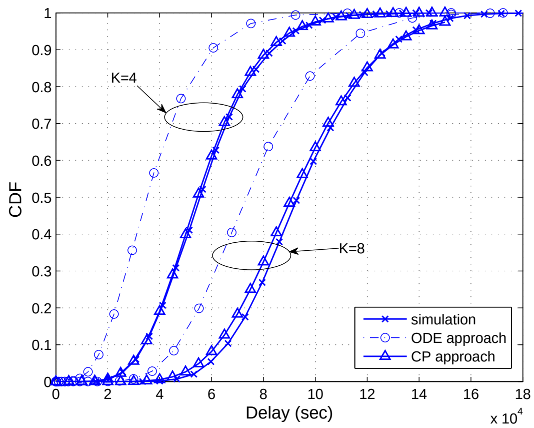
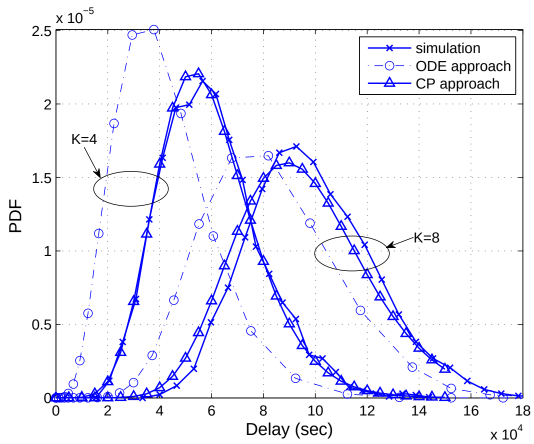
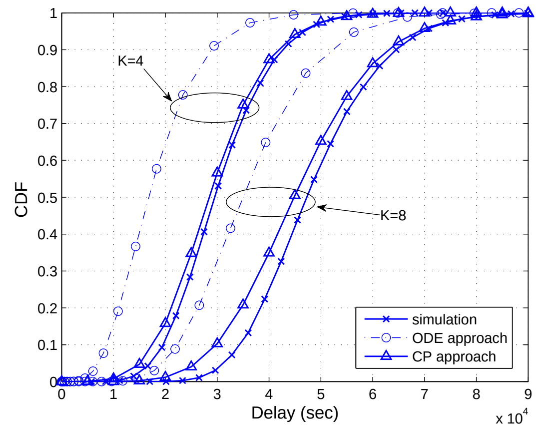



(a) CDF

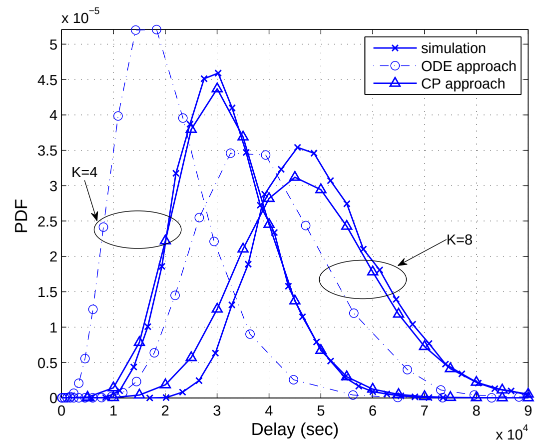



(b) PDF

Fig. 6: Delay performance under ODE and CP approaches. $M = 10$ and $A = 100km^2$.




(a) CDF




(b) PDF

Fig. 7: Delay performance under ODE and CP approaches. $M = 20$ and $A = 100km^2$.

successful decoding. Due to the great comparability, we also refer those protocols to as VACCINE in this paper.

In this paper, we point out that recovery protocols also impact the delay performance of NCER. That is because obsolete packets may lead to ineffective transmissions and lower the transmission efficiency. When multiple data files exist in the network, those obsolete packets compete for transmissions with other packets, which drastically deteriorate the average delay performance of NCER. Hence, we propose FRP to accelerate the deleting process, which facilitates the reductions of nodes buffer occupancy and average delay performance of NCER.

The key idea of FRP is initiating the packets deleting process once the first encoded packet is received at the destination. Before introducing FRP, we first define a new term: *feedback matrix*. Feedback matrix is in essence the coding matrix that the destination transmitted to the intermediate nodes. Obviously, it indicates the state of the decoding process, and is constantly changing.

We now introduce FRP in three different situations that nodes encounter. To note that the original data delivery process under NCER is omitted in the following description for brevity. In the first situation, two nodes encounter and one of them is the destination of the data file to be transmitted (denote the destination as node $i$ and the other as node $j$). Node $i$ will transmit its coding matrix to node $j$. Then node $j$ will check whether its carried encoded packets can increase the rank of this matrix. If they can not, node $j$ will delete all the encoded packets in its buffer. At last, node $j$ will store this matrix in its buffer as a feedback matrix and forward it to other intermediate nodes. In the second situation, two nodes encounter and only one of them carries a feedback matrix (denote the node with a feedback matrix as node $i$ and the other as node $j$). Node $i$ will transmit its carried feedback matrix to node $j$. Then node $j$ will perform similar operations as in the first situation. In the third situation, two nodes encounter and both of them carry feedback matrices. Two nodes exchange their carried matrices, and only keep the matrix with a bigger rank. Then the node, which updates its carried feedback matrix, will perform similar operations as in the first situation.

The detailed process of FRP is described with a pseudo-code as shown in Algorithm 1.

Compared with VACCINE, FRP include transmissions of feedback matrices, which leads to extra overheads. As afore-

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**Algorithm 1** Feedback-based Recovery Protocol

**Definition:** Encoded packets sets of data file $\mathbf{B}$ on node $i$ and $j$, $\mathbf{B}_i$ and $\mathbf{B}_j$; Feedback matrices corresponding to $\mathbf{B}$ on node $i$ and $j$, $F_i$ and $F_j$ ($\emptyset$ indicates that there is no feedback matrix on that node); Rank of matrix, $r(\cdot)$; Random linear combinations of $\mathbf{B}_i$ and $\mathbf{B}_j$, $\mathbf{b}_i$ and $\mathbf{b}_j$; Global coding coefficient vectors corresponding to $\mathbf{b}_i$ and $\mathbf{b}_j$, $\mathbf{v}_i$ and $\mathbf{v}_j$.

node $i$ and $j$ encounter;<br>
**if** node $i$ is the destination of $\mathbf{B}$, (take $i$ for example) **then**<br>
  $F_j \leftarrow F_i$;<br>
  generate $\mathbf{b}_j$ and $\mathbf{v}_j$;<br>
  **if** $r([F_j; \mathbf{v}_j]) = r(F_j)$, **then**<br>
    $\mathbf{B}_j \leftarrow \emptyset$;<br>
  **else**<br>
    transmit $\mathbf{b}_j$ and $\mathbf{v}_j$ to node $i$;<br>
    update $F_i$ and $F_j$ with $\mathbf{v}_j$;<br>
    generate $\mathbf{b}_{j,new}$ and $\mathbf{v}_{j,new}$;<br>
    **if** $r([F_j; \mathbf{v}_{j,new}]) = r(F_j)$, **then**<br>
      $\mathbf{B}_j \leftarrow \emptyset$;<br>
    **end if**<br>
  **end if**<br>
**else**<br>
  **if** $F_i \neq \emptyset$ (take $i$ for example) and $F_j = \emptyset$, **then**<br>
    $F_j \leftarrow F_i$;<br>
    generate $\mathbf{b}_j$ and $\mathbf{v}_j$;<br>
    **if** $r([F_j; \mathbf{v}_j]) = r(F_j)$, **then**<br>
      $\mathbf{B}_j \leftarrow \emptyset$;<br>
    **end if**<br>
    data delivery;<br>
  **else**<br>
    **if** $F_i \neq \emptyset$ and $F_j \neq \emptyset$, **then**<br>
      **if** $r(F_i) > r(F_j)$, (take $i$ for example) **then**<br>
        $F_j \leftarrow F_i$;<br>
        generate $\mathbf{b}_j$ and $\mathbf{v}_j$;<br>
        **if** $r([F_j; \mathbf{v}_j]) = r(F_j)$, **then**<br>
          $\mathbf{B}_j \leftarrow \emptyset$;<br>
        **end if**<br>
      **end if**<br>
      data delivery;<br>
    **end if**<br>
  **end if**<br>
**end if**

mentioned, all the addition and multiplication operations are over a finite Galois Field $\mathbb{F}_q$ of size $q = 2^8$. Therefore, packets of $S$ bits can be viewed as a vector of $d = \lceil S/log\,(q) \rceil$ symbols from finite field $\mathbb{F}_q$. Together with the encoded packet, two types of additional information, i.e., encoding vector and feedback matrix should also be transferred, occupying $K$ and $KB_f$ symbols respectively, where $B_f \in \{0, 2, \ldots, K\}$ is the rank of the feedback matrix. Hence, the ratio of the extra overheads and the payload is $(1 + B_f)K/\lceil S/log_2\,(q) \rceil \approx (1 + B_f)Klog_2\,(q)/S$. Generally, in a practical application, $K \ll S$, i.e., the number of bits is much larger than the number of packets, therefore we hold that this extra overhead would not drastically impact the performance of the entire system.

## B. Performance Evaluation

In this section, we conduct numerical analysis on the performance of FRP.

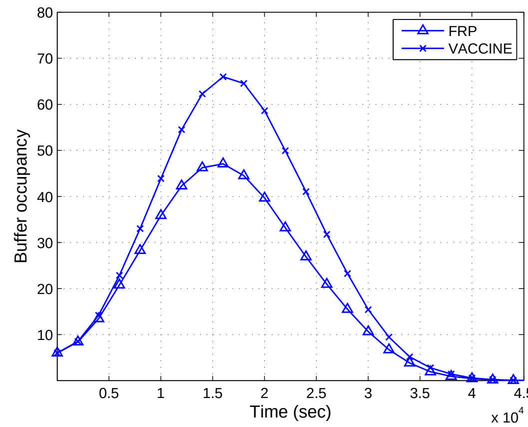


Fig. 8: Buffer occupancy for each data file.

Fig.8 shows the buffer occupancy under original recovery protocol [11, 13] (referred to as VACCINE in the figures) and FRP. It is shown that for successfully delivering a single data file, the total buffer occupancy in the network is significantly reduced under our proposed protocol. That is because the obsolete packets are deleted more rapidly, and have less opportunities to be delivered among nodes.

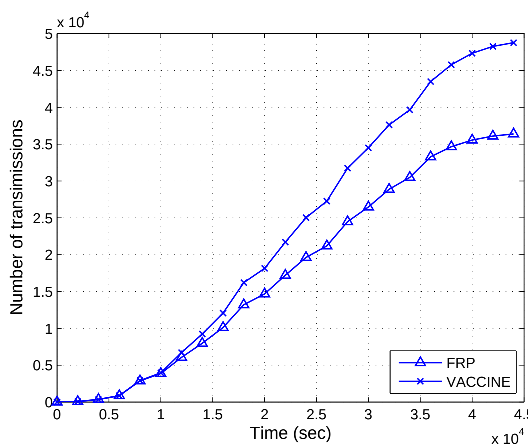


Fig. 9: The variation of the total number of transmissions.

Fig.9 shows the variation of the total number of transmissions during propagations of a group of data files under different protocols. It can be seen that the number of transmissions grows slower under FRP. That is because FRP can reduce the number of ineffective transmissions.

At last, we conduct simulations to investigate how recovery protocols impact the data delay performance when multiple data files exists. In Fig. 10, it is shown that NCER scheme with FRP can achieve better delay performance. When data files is generated at random time intervals with a mean of 500 seconds, our protocol achieves 26% delay performance

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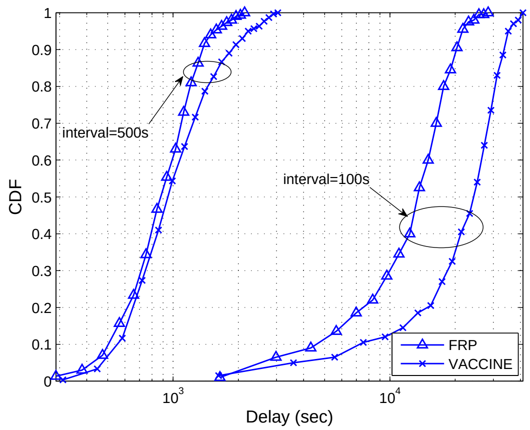


Fig. 10: Delay performance under NCER schemes with different recovery protocols when multiple data files exists. In simulations, data files are generated with different time intervals.

improvement at the CDF of $90\%$ compared to the scheme with VACCINE. When data packets are generated faster, i.e., data files is generated at random time intervals with a mean of 100 seconds, FRP performs even better. We doubt that the proposed protocol plays a better role in a more intense competition case. This result validates the benefits of our proposed protocol.

## VI. Conclusion

In this paper, we have first demonstrated the innovative assumption severely underestimates the data delivery delay of NCER in DTNs. This problem has been successfully solved by introducing an extra encounter factor $\delta$, which is mainly determined by the number of segmented packets, rather than network size or coverage area. Based on this new finding, we have proposed a CP-based analytical method to estimate the delay performance of NCER in DTNs. Numerical results show, compared with the ODE-based method, CP-based method can achieve better accuracy on characterizes the exact distribution of the delay performance of NCER. Furthermore, we have proposed FRP to mitigate potential competitions between multiple data streams from different nodes. FRP takes advantage of finite buffer space and significantly reduces the number of ineffective transmissions between nodes. More importantly, it achieves much better delay performance compared with the original VACCINE protocol.

In this paper, the value of $\delta$ have been characterized empirically. We will investigate a feasible way to derive the exact knowledge about $\delta$ theoretically in our future work.

## Acknowledgment

Yang's research is partially supported by the National Natural Science Foundation of China (NSFC) under grants 61231009 and 61461136003, and the National Science and Technology Major Project under grant 2014ZX03005001. Yao and Zhang's research is partially supported by the Science and Technology Commission of Shanghai Municipality (STCSM) under grant 13XD1403400. Ge's research is partially supported by the NSFC under grant 61210002, and the EU FP7-PEOPLE-IRSES under grants 318992 (WiNDOW) and 610524 (CROWN). Mao's research is partially supported by the Australian Research Council (ARC) under grants DP110100538 and DP120102030, and the NSFC under grant 61428102.

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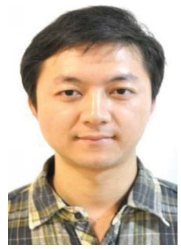

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