Adaptive Infection Recovery Schemes for Multicast Delay Tolerant Networks

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***Abstract*—Conventional Delay Tolerant Networks (DTN) use "store-carry-forward" paradigm to pass the message between the nodes that meet occasionally which results in intermittent connectivity. Once the message meets the destination, the network initiates the so called "infection recovery process" in order to remove the delivered messages from the rest of the nodes. This process starts as soon as the message reaches the first destination which, in the case of multicast sessions, may reduce the chances that the other destination nodes receive the message. In this paper, we present an analytical framework to study the performance of different infection recovery schemes for multicast DTN. New *adaptive recovery schemes* are developed where the *recovery probability* is adjusted to the multicast traffic. The performance of these new algorithms is compared to a number of unicast recovery schemes modified for multicast DTN, which also represents a contribution of this paper. Our analytical framework can be easily extended to model the recovery process for different multicast routing schemes. Numerical results show that by *adaptive immune*, *immune_TX* and *vaccine* schemes the delivery delay can be reduced up to 75% compared to the conventional schemes. By *timeout* recovery scheme, when applied to multicast session, the reduction in the delivery delay can reach up to 90% at the expense of larger recovery delay.**

I. Introduction

Delay Tolerant Networks (DTN) [1] provide communication in highly challenging scenarios where only intermittent connectivity exists, and it is difficult to maintain paths between any source and destination pair. In these scenarios, there has been a growing interest in multicast DTN protocols that enable the distribution of data to multiple receivers [2].

Multicast in DTN is a fundamentally different and hard problem compared to multicast in Ad Hoc networks due to the frequent disconnections. Consequently, there is growing interest in developing new protocols tailored for DTNs [3]-[6]. Epidemic Multicast Routing (EMR) [3] applies epidemic algorithm to the multicast communication in DTNs but exhibits poor efficiency due to the flooding incurred by the epidemic resource management. In [4] several multicast algorithms are developed with different strategies depending on the availability of knowledge about network topology and group membership. However, the use of learning processes for discovering the topology would cause increase in overhead.

A *RelayCast* scheme based on 2-hop forwarding is proposed by [5] to study the scalability property of DTN multicast routing. This scheme does not completely exploit the characteristics of opportunistic forwarding, since there is a single relay node for a given packet. An improved scheme, *RelayCast* with Multicast Receiver Relay (RelayCast-MRR) allows that each relay node can use all nodes for relaying. However, they have shown that *RelayCast*-MRR cannot improve the delay except in the broadcast case.

The multicast problem, from the social network perspective, is addressed by [6]. They formulate the relay selection as a knapsack problem and demonstrate the efficiency of the proposed schemes by simulation results. The main drawback of this scheme is the low rate of node contacts in DTN which results into high delivery delays. A form of network coding and epidemic routing for unicast in DTN was suggested by [7] to improve the node contacts rate. The efficiency of network coding in multicast DTN was also showed by [8] through simulations for Spray and Wait forwarding. In our model, we include network coding too combined with epidemic routing and extend the study to the network behavior in multicast scenario. The resulting routing protocol will be referred to as Polymorphic Epidemic Routing (PER).

There are very limited works on recovery schemes for multicast DTN. In [8] a kind of recovery schemes, denoted as purging schemes, is proposed with different options for delivery information propagation. In these schemes, the users keep a list of the destinations that have received the packets. Similar approach is also used in [9]. Our recovery schemes guarantee the delivery without requiring any knowledge of neither contact information nor packet delivery. As users in DTN may have limited memory and computational capabilities, our recovery schemes reduce the overhead just to the exchange of anti-packets.

The main focus of this paper is to analytically study the effect of different recovery schemes on the performance of multicast DTN. New adaptive recovery schemes are developed where the recovery probability is adjusted to the multicast traffic. The efficiency of our schemes is also compared to a number of unicast recovery schemes modified for multicast DTN. The performance measures considered include the delivery delay to the destinations, recovery delay from the infection process and, energy efficiency in terms of the number of packet copies made until the time of delivery and recovery.

The analytical framework proposed is based on use of Ordinary Differential Equations (ODEs) [7], [10]. Our analytical study is able to provide insights for future designs of recovery process for any routing protocol in multicast DTN. To the best of our knowledge, we are the first to study analytically the efficiency of the recovery schemes on the performance of *multicast DTN*. Numerical results show the outstanding performance of our new adaptive recovery schemes.

The rest of this paper is organized as follows. The system model and Polymorphic Epidemic Routing (PER) are described in Section II. In Section III, we present our adaptive infection recovery schemes along with the performance analysis in Section IV. Numerical results are provided in Section V. Finally, Section VI concludes the paper.

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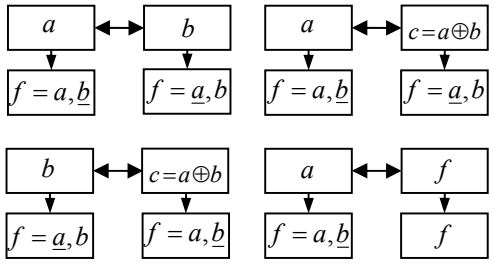

Fig.1.Polymorphic infection process

II. System Model

A. Traffic Model

We study a network consisting of $N+1$ wireless mobile nodes where there is one source and a set of relaying nodes $\mathcal{N}$ moving within a constrained area according to a random mobility model. Multicast communication is considered from the source node to a set of destinations $\mathcal{D}$. The option where the destinations can also forward the packet to each other is referred to as destination cooperative multicast (DCM). Comments on the case of destination non-cooperative multicast (DNCM) will be provided in Section III. Since the density of nodes is sparse in DTN environment, two nodes can communicate and thus forward packets only when they come within the transmission range of each other. As the node density is low, in the following we neglect the interference among nodes [10].

Without loss of generality, it is assumed that when two nodes meet, the transmission opportunity is only sufficient to completely transmit one data packet per flow. This assumption is justified by choosing the proper packet length (maximum packet length allowed by the rendezvous time) and allowing *only one packet transmission per flow per node* during the nodes' rendezvous [7]. It is straightforward to extend this to the general case where an arbitrary number of packets can be delivered when the communication opportunity arises. Also, we consider that the nodes buffer can accommodate all packets that they receive.

It is assumed that the time between two consecutive transmissions opportunities (when nodes meet) follows an exponential distribution with a rate λ. This model has been widely adopted in the recent literature, e.g., in [7], [10] which also enables the theoretical analysis by using continuous Markov model.

B. Polymorphic Epidemic Routing (PER)

In general it is known that in conventional multicast/ broadcast networks, network coding improves the performance of the network [12]. For this reason, we include in our DTN model network coding too and extend the study to the network behavior in *multicast* scenarios. In order to have a tractable model for the analysis of the infection recovery schemes, we introduce a number of improvements into the concept of epidemic routing which represents a part of the contributions of this paper.

We assume that a set of destinations $\mathcal{D}$ request a common message f from the multicast source. Let us first consider the case where the multicast source splits the message in two packets a and b (i.e., $f=a,b$). Accordingly, the source infects the network with both packets a and b, and their combination $c=a+b$ where "+" stands for the *XOR* operation on the binary data stream. By analogy between epidemic routing and disease spreading, infection with two different packets (i.e., agents) is referred to as *polymorphic infection* and the *DNA* combination of these agents, c, is referred to as the mutation. The incentive behind this approach is that now every rendezvous between the two users increases the probability that a useful transmission will take place. User c[1] will transmit a useful packet if it meets either user b (since $c+b=a$) or user a (since $c+a=b$). A user is infected with f when it has received a and b ($f=a,b$). The infection process is illustrated in details in Fig.1, where the new packet received by each node is underlined.

To model Polymorphic Epidemic Routing (PER) the following notation is used. We denote by $A(t)$, $B(t)$, $C(t)$, and $F(t)$ the number of users infected by agents a, b, $c=a+b$ and $f=a,b$ respectively in time t. We denote by $I(t) = A(t) + B(t) + C(t) + F(t)$ the overall number of infected users in the network. We model the infection rate for users a, b, c and f by using ODEs as a fluid limit of the Markovian model [10]. Hence, we have

$$X'(t) = \lambda\left[X(t) + \frac{1}{3}F(t)\right]\left[N - I(t)\right] - \lambda X(t)\left[I(t) - X(t)\right] \quad (1)$$

for $X \in \{A, B, C\}$, and

$$\begin{aligned} F'(t) = {} & \lambda A(t)\left[B(t) + C(t)\right] + \lambda B(t)\left[A(t) + C(t)\right] \\ & + \lambda C(t)\left[A(t) + B(t)\right] + \lambda F(t)\left[I(t) - F(t)\right] \end{aligned} \quad (2)$$

where λ is the meeting rate. In (1) an increment in $X(t)$, denoted as $X'(t)$ for $X \in \{A, B, C\}$, is given by the contribution of two terms. The first term represents the rate at which a node infected by packet x meets a non infected node, plus the rate that a node infected by f meets a non infected node. This will occur randomly, with probability 1/3, when f chooses one of the three infection options: packet a, b or c. It cannot infect by f since this would require transmission of two packets. The second term represents the event of losing packet x (negative increment) which happens when it becomes f after meeting a node infected by any other packet except x.

An increment in $F(t)$ in (2), denoted as $F'(t)$, is obtained if a node carrying packet a meets a node carrying packet b. Then, after they exchange the packet, two new nodes will be created carrying packet f. This occurs with a rate proportional to $A(t)B(t)+B(t)A(t)$ (first part of the first and the second term in (2)) and it will further propagate randomly one of the three options specified above. Similarly other terms in (2) can be justified. On the other hand, if f meets a, b or c only one extra f will be created, which is included in the last term of (2). This equations can be solved with initial conditions $A(0)=B(0)=C(0)=1$ and $F(0)=0$.

III. Recovery Schemes for Multicast DTN

In this section, we first illustrate the most common recovery schemes [11] applied so far to unicast scenarios and extend them to the multicast case as well as to the Polymorphic Epidemic Routing (PER). Later on, we present the new adaptive recovery schemes.

[1] In the following, for worth of brevity, we identify the user with the agent it is infected by.

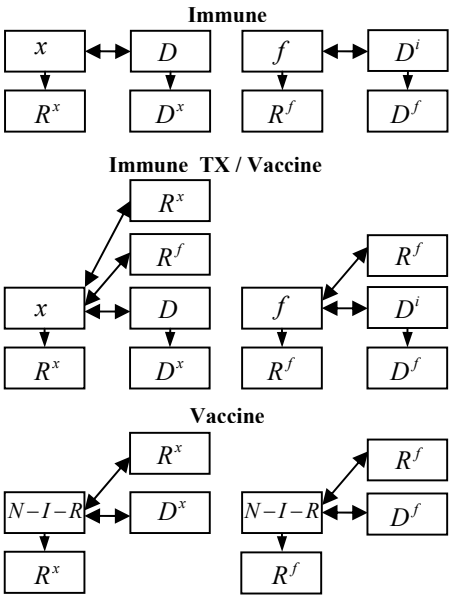

Fig.2.Recovery schemes

A. Overview of Recovery Schemes

Once a node delivers a packet to the destination, it should delete the copy from its buffer both to save storage space, and to prevent the node from infecting other nodes. This process is called "infection recovery process". The packet is deleted for efficient buffer and bandwidth utilization. On the other hand, a node retains "packet delivered" information in the form of an *anti-packet* that prevents it from accepting another copy of the same packet. Reference [11] refers to this scheme as *immune* scheme. With *immune* scheme, a node stores a packet copy in the buffer until it meets the destination, often long after the first copy of the packet is delivered. A more aggressive approach to delete obsolete copies is to propagate the anti-packets among the nodes. The anti-packet can be propagated (transmitted) only to those infected nodes (*immune*_TX scheme), or also to susceptible nodes (*vaccine* scheme).

The conventional infection recovery process starts as soon as the packet reaches the first destination which in the case of multicast session may reduce the chances that the rest of the destination nodes receive the message. So, in multicast applications there is the need to delay the initialization of this recovery process in order to allow more efficient delivery of the information to all intended destinations.

B. Conventional recovery schemes applied to multicast DTN

Similar to our earlier analysis presented in Section II, we can derive ODEs to model the infection and recovery process as the limit of Markov models [10].

In general, by modifying (1) and (2) to include the recovery process, the infection rate for user *x*, $x \in \{a,b,c\}$ and f are

$$X'(t) = \lambda\left[X(t) + \frac{1}{3}F(t)\right]\left[N - I(t) - R(t)\right] - \lambda X(t)\left[I(t) - X(t)\right] - R^x{}'(t), \qquad X \in \{A,B,C\} \quad (3)$$

$$F'(t) = \lambda A(t)\left[B(t) + C(t)\right] + \lambda B(t)\left[A(t) + C(t)\right] + \lambda C(t)\left[A(t) + B(t)\right] + \lambda F(t)\left[I(t) - F(t)\right] - R^f{}'(t) \quad (4)$$

The difference between (1)-(2) and the previous equations is in the last term $R^x{}'(t)$ and $R^f{}'(t)$ which represents the recovery rate for users x, $x \in \{a,b,c\}$ and *f*, respectively.

In the following, we derive the expressions for the number of recovered nodes for all three schemes (immune, immune_TX and vaccine) extended to our multicast system and PER. These expressions are obtained for two scenarios:

- Destination Cooperative Multicast (DCM): the destinations can exchange the messages among themselves too.
- Destination Non-Cooperative Multicast (DNCM): the destinations do not exchange the messages between themselves.

In line with the assumptions made in Section II, it is assumed that the node can deliver only one packet when it reaches the destination: the destination should be already infected by *a* or *b* or *c* in order to become *f*.

B.1) Immune

In immune scheme, as illustrated in Fig. 2, the infected node is recovered when it meets the destination. So, the recovery rates $R^x{}'(t)$ and $R^f{}'(t)$ are obtained as follows

$$R^x{}'(t) = \lambda X(t) D; \quad R^f{}'(t) = \lambda F(t)(D^i(t)) \qquad R(t) = R^a(t) + R^b(t) + R^c(t) + R^f(t) \quad (5)$$

With this scheme, the infection rate *X*(t) in (3) decreases when a packet $x \in \{a,b,c\}$ meets the destinations *D*. In (4), as the users can transmit just one packet, users infected by *f* are recovered when they deliver the packet to the destination, in the case that the destination was already infected by other packet *a*, *b*, *c* or *f*. This is denoted as $D^i(t)$ where

$$D^i(t) = D^a(t) + D^b(t) + D^c(t) + D^f(t) \quad (6)$$

In the case of Destination Cooperative Multicast (DCM), the destinations cooperate and forward the packet to other destinations. Consequently, the infection rate of the destinations infected by $x \in \{a,b,c\}$ is modeled as:

$$D^x{}'(t) = \lambda\left[X(t) + \frac{1}{3}F(t) + D^x(t) + \frac{1}{3}D^f(t)\right]\left[D - D^i(t)\right] - \lambda D^x(t)\left[I(t) - X(t) + D^i(t) - D^x(t)\right] \quad (7)$$

where D^x and $D^f(t)$ are the number of destinations infected by packet *x* and *f*, respectively and $D^i(t)$ is given by (6). The infection rate $D^x{}'(t)$ in time *t* is increased when packet *x* or a destination infected by *x* meets a destination that has not been infected $(D - D^i(t))$. $D^x{}'(t)$ can be increased also if a packet *f* or a destination infected by *f* meets, with probability 1/3, an uninfected destination. On the other hand, $D^x{}'(t)$ decreases when a destination infected just by *x* meets other user or destination infected by other type of packet (last term in (7)). The same reasoning applies for the infection rate $D^f{}'(t)$ which can be written in compact form as

$$D^f{}'(t) = \lambda\left[F(t) + D^f(t)\right]\sum_{x\in\{a,b,c\}} D^x(t) + \sum_{x\in\{a,b,c\}} \lambda\left[X(t) + D^x(t)\right]\sum_{y\in\bar{x}} D^y(t) \quad (8)$$

where $y \in \bar{x}$ denotes other type of packet different than x.

The logic behind $D^f{}'(t)$ can be easily deduced from the previous explanations. The modification of (7) and (8) for the Destination Non-Cooperative Multicast (DNCM) scenario is straightforward by assuming that the destination nodes will not participate in the infection.

B.2) Immune_TX

In this scheme, the anti-packet can be transmitted to those infected nodes. So, a new recovered node is obtained when an infected node meets a node that has been recovered or the destination. This is illustrated in Fig. 2.

The infection rates for user $x \in \{a,b,c\}$ and *f* are defined as (3) and (4) and the recovery rates are obtained as

$$\begin{aligned} R^x{}'(t) &= \lambda X(t)\left[D + R^x(t) + R^f(t)\right] \\ R^f{}'(t) &= \lambda F(t)\left[D^i(t) + R^f(t)\right] \\ R(t) &= R^a(t) + R^b(t) + R^c(t) + R^f(t) \end{aligned} \tag{9}$$

By immune_TX a node that has been recovered from *f* can recover a node infected by $x \in \{a,b,c\}$. This is justified by the fact that if packet *f* has been received, there is no need to transmit more packets *a*, *b* or *c*.

B.3) Vaccine

In this scheme, in addition to the previous schemes, we also vaccinate the uninfected users that are susceptible of receiving the packet. We recover (vaccinate) the users that have neither been infected nor recovered $(N - I(t) - R(t))$ when they meet a recovered node or a destination that has been infected by that packet. The behavior of this scheme is shown in Fig. 2.

The infection rates for users *a*, *b*, *c* and *f* are defined as in (3) and (4). But the recovery rates are now obtained as

$$\begin{aligned} R^x{}'(t) &= \lambda X(t)\left[D + R^x(t) + R^f(t)\right] \\ &\quad + \lambda\left[N - I(t) - R(t)\right]\left[D^x(t) + R^x(t)\right] \\ R^f{}'(t) &= \lambda F(t)\left[D^i(t) + R^f(t)\right] \\ &\quad + \lambda\left[N - I(t) - R(t)\right]\left[D^f(t) + R^f(t)\right] \end{aligned} \tag{10}$$

where the last term in (10) indicates the fact that the recovery rates $R^x{}'(t)$ and $R^f{}'(t)$ are increased if a uninfected node $\left[N - I(t) - R(t)\right]$ meets the destination infected by *x* and *f*, or a recovered node from *x* and *f*, respectively.

C. Adaptive Recovery Schemes

The previous recovery schemes start deleting the packets when the first destination is reached. This slows down the infection process in multicast DTN as the packets are recovered before all destinations have received them. In this section, we present different options for improvement of the recovery schemes depending on the level of signaling available in the network.

We denote by $p_r(t)$ the recovery probability at time *t*. When a node meets a destination, the destination will send the anti-packet to the node with probability $p_r(t)$. In the existing recovery schemes, $p_r(t) = p_r = 1$. The aim of the adaptive recovery schemes is to modify $p_r(t)$ based on the number of destinations *D*, so that the recovery is performed in such a way that the packets are removed slower while the infection process is still being performed or, the recovery is delayed until all (most) destinations have received the packets. In general for a multicast application with more destinations the initialization of the recovery process will be postponed longer. In this way, the recovery probability is adjusted to the multicast traffic.

For this purpose, we introduce a time dependent probability of packet recovery

$$p_{r_e}(t) = 1 - e^{-\left(\frac{\lambda N}{D}\right)t} \tag{11}$$

where the decay parameter is proportional to the meeting rate λ and *N*, and inversely proportional to the number of destinations D. This approach requires low level of signaling as all parameters λ, *N* and *D* are known in the network.

As an alternative, we also propose to delay the recovery for certain time T_D^f which is estimated as the time needed to deliver the packets to all *D* destinations (delivery delay). This scheme will be referred to as *adaptive global timeout scheme* as T_D^f depends on the number of destinations *D*. The calculus for estimating T_D^f will be elaborated in next section. In this case, we assume that certain level of signaling is available in the network (i.e., provided by a cellular network) so when the last destination receives the packet *f* can signal the source and then, the recovery process will start with probability

$$p_{r_T}(t) = \begin{cases} 1, & t \geq T_D^f \\ 0, & t < T_D^f \end{cases} \tag{12}$$

Equations presented in Section III.B should be modified by replacing the meeting rate λ by $\lambda \to \lambda(t) \to \lambda p_r(t)$ to model adaptive *immune*, *immune_TX* and *vaccine* schemes.

D. Timeout recovery scheme

This scheme was first introduced in [11] and referred to as *just-TTL* recovery scheme. In this section, we extend it to PER for multicast in DTN. The scheme behaves as follows: when a node receives a packet, it initializes a timer with duration drawn from an exponential distribution with rate μ. When the time expires, the packet will be removed from the buffer and the node stores an anti-packet to avoid future infections by the same packet. The node is recovered from the infection *x* after the timer associated to it expires. So, there is no need for explicit transmission of anti-packets. The infection rates for users *a*, *b*, *c* and *f* are defined as in (3) and (4), where the number of packets recovered is obtained as

$$\begin{aligned} &R^x{}'(t) = \mu(X(t) - 1); \quad R^f{}'(t) = \mu(F(t) - 1) \\ &R(t) = R^a(t) + R^b(t) + R^c(t) + R^f(t) \end{aligned} \tag{13}$$

IV. Performance Analysis

The recovery schemes are evaluated in terms of the message delivery delay, energy consumption, time efficiency of the recovery scheme and number of packets transmitted in the network. These performance metrics are obtained from the previous analysis of ODEs.

A. Delivery Delay

We define the packet delivery delay T_D^f as the time from the moment when packets *a*, *b* and *c* are generated at the source to the time when *f=a,b* is received by all destinations *D*. Its Cumulative Distribution Function (CDF) is denoted as $P_D^f(t) = Prob(T_D^f < t)$.

We start by considering the delay when there is one destination ξ (unicast case), and later on we extend it to multicast. Let us denote by $P_N(t)$ the CDF of T_ξ. Then, we can derive the following expression

$$P_N(t+dt) - P_N(t) = Prob\{t \le T_\xi < t+dt\}$$
$$= Prob\{\text{destination receives the packet } f \text{ in } [t,t+dt] \mid T_\xi > t\}$$
$$= Prob\{\text{destination receives the packet } f \text{ in } [t,t+dt]\}(1-P_N(t))$$
$$= E\{Prob\{\text{destination receives the packet } f \text{ in } [t,t+dt] \mid F(t)\}\}$$
$$\approx E\{\lambda D^f(t)dt\}(1-P_N(t)) = \lambda E\left\{D^f(t)\right\}(1-P_N(t))dt$$

where $D^f(t)$ is given by (8) for DCM. In DNCM, the same reasoning applies and $D^f(t)$ will be obtained as explained in the previous section. Hence the following equation holds for $P_N(t)$:

$$\frac{dP_N}{dt} = \lambda E\left\{D^f(t)\right\}(1-P_N(t)) \tag{14}$$

As *N* increases, $P_N(t)$ converges to the solution of the following equation:

$$P^f{}'(t) = \lambda D^f(t)(1-P^f(t)) \tag{15}$$

where $P_\xi^f(t) = P^f(t)$ is the cumulative probability of the time needed for the packets *f=a,b* to reach the destination $\xi \in D$. Solving (8) and (15), gives *P*(*t*) with initial condition *P*(0)=0.

From $P_\xi^f(t)$, the average delivery delay can be explicitly found in closed form as:

$$E[T_\xi^f] = \int_0^\infty (1-P_\xi^f(t))dt \tag{16}$$

In the multicast case, with the set of destination nodes $\mathcal{D}$ of size $D = |\mathcal{D}|$, eq. (15) for each destination node ξ gives $P_\xi^f(t)$. The multicast delay is defined as the time needed for all destinations to receive *f=a,b*. Formally, it can be defined as $T_D^f = \max_\xi T_\xi^f$.

The CDF of the time needed for the double packet *f* to reach all destinations can be expressed as

$$P_D^f(t) = \left(P_\xi^f(t)\right)^D \tag{17}$$

Finally, the average delay for multicast

$$E[T_D^f] = \int_0^\infty \left(1-P_D^f(t)\right)dt \tag{18}$$

Another metric that quantifies how efficient the recovery schemes are is the *average lifetime*. We define the average *lifetime* L^f of a packet *f* as the time from when packet *a*, *b* and *c* are generated at the source node to the time when all copies of the packets are removed (*i.e*, there are no more infected nodes by packets *a*, *b*, *c* and *f* in the network). So, the lifetime of packet *f* is calculated as

$$L^f = \arg\min_{t>0} t, \text{ subject to } \Delta R_t = 0 \tag{19}$$

where $\Delta R_t = R_t - R_{t-\Delta t}$ is the difference of the recovery rate for *a*, *b*, *c* and *f* between two consecutive time instants and is obtained for *immune*, *immune_TX* and *vaccine* by solving (5), (9) and (10), respectively.

The ratio $\varepsilon_t = E[T_D^f]/L^f$ will be referred to as *system time efficiency*. We also define the recovery delay as $E[T_R^f] = L^f - E[T_D^f]$.

B. Energy Consumption

Two metrics related to the energy consumption are considered: the number of times a packet is copied in its entire lifetime G_{L^f} and, the number of times a packet is copied at the time of delivery $G_{T_D^f}$. These are random variables taking value in the interval $[0,\infty]$. The energy consumption grows linearly with the number of transmissions. The energy efficiency of the system will be defined as $\varepsilon_e = G_{T_D^f}/G_{L^f}$, where G_{L^f} is obtained as

$$G_{L^f} = \sum_{t=0}^{L^f} \Delta I_t + \Delta R_t$$
$$\Delta I_t = I_t - I_{t-1}; \quad \Delta R_t = R_t - R_{t-1} \tag{20}$$

where ΔI_t, and ΔR_t are calculated for *immune*, *immune* _TX and *vaccine* by solving (5), (9) and (10), respectively. Equation (20) counts in each time slot all transmissions. Part of these transmissions is visible as an increase in the number of infected packets but part of these infections is erased by recovery process so, both terms should be included in (20).

Similarly, the number of times that a packet is copied in the network until the time that the packet is received by all destinations *D* is

$$G_{T_D^f} = \sum_{t=0}^{E[T_D^f]} \Delta I_t + \Delta R_t \tag{21}$$

where $E[T_D^f]$ is the delivery delay given by (18).

V. Numerical Results

In this section, we compare the performance of our proposed adaptive recovery schemes to the conventional recovery schemes modified for multicast DTNs. We set the meeting rate λ=0.004, *N*=100 and the number of destinations from *D*=1…*N*, unless otherwise indicated. The system of nonlinear ODEs is solved by Matlab.

The efficiency of *immune*, *immune_TX* and *vaccine* schemes is shown in Fig. 4 in terms of average delivery delay $E[T_D^f]$ and lifetime L^f with respect to the number of destinations *D*. We assume that the recovery probability is fixed to $p_r(t)$=1 and destination cooperative multicast (DCM) is considered as discussed in Section III.B. We can observe a number of interesting phenomena.

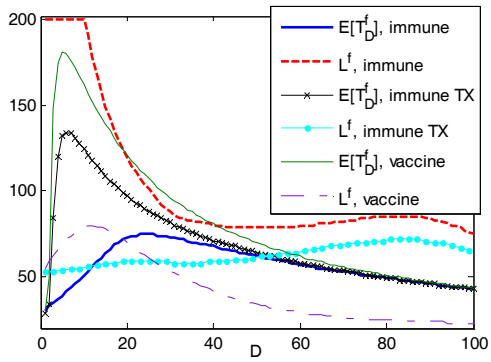

Fig. 4. Average delivery delay and lifetime versus *D*.

By immune scheme, $E[T_D^f] < L^f$ for any number of destinations *D*. This is because in immune scheme the recovery from infection is very slow and all destinations receive the packet before all packets are recovered. By immune_TX, $E[T_D^f] > L^f$ is obtained for D>50. The recovery now works faster than in immune scheme and the packets are recovered before the infection of set $\mathcal{D}$ is completed. Finally, *vaccine* is the fastest recovery scheme and $E[T_D^f] > L^f$ for any *D*. The average delay $E[T_D^f]$ for vaccine is the largest one as the number of infected packets is significantly reduced during the infection process.

For the same scenario, the average number of times that a packet is copied in its entire lifetime, G_L, and at the time of delivery, $G_{T_D^f}$, are shown in Fig.5. For small number of destinations *D* and immune scheme, $G_L > G_{T_D^f}$. As mentioned before, the recovery with immune is very slow and many transmissions are made after the packets are delivered to the destinations ($t > T_D^f$). The values obtained for G_L and $G_{T_D^f}$ for immune_TX are practically the same. For vaccine, the recovery process finishes before the delivery to all destinations is completed (this is more evident for larger *D*). As DCM is considered, the destinations continue infecting each other until all destinations have received the packet even when the rest of the users are recovered from the infection. For this reason, we can see that $G_L < G_{T_D^f}$ for large *D*.

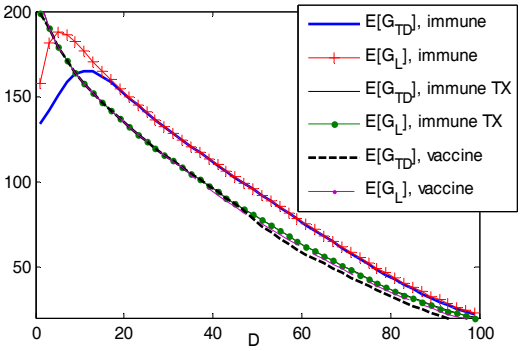

Fig. 5. Average number of copies versus *D*.

In Fig. 6, the effects of destination non-cooperative multicast (DNCM) are shown in the destination infection rate $D^f(t)$ for immune_TX scheme. Similar effects were noticed with immune and vaccine, but due to space constraints these figures are not presented. We assume *D*=30, and we can see that when $p_r(t)$=1, $D^f(t) = 18$ for $t \to \infty$. As the packets are recovered while the infection to the destinations is still taking place, in average just 18 destinations out of 30 are infected by packet *f*. When adaptive immune_TX is used with $p_r(t) = p_{r_e}(t)$ or $p_r(t) = p_{r_T}(t)$ we can see that the performance is significantly improved and all destinations receive *f*.

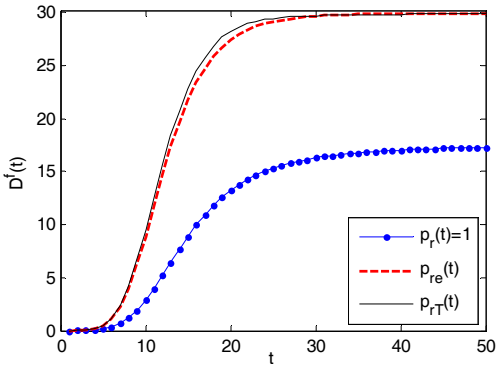

Fig. 6. $D^f(t)$ versus *t* for immune_TX scheme and DNCM.

In Figs. 7 to 9, the behavior of immune, immune_TX, vaccine and timeout recovery scheme is shown for different recovery probabilities $p_r(t)$. We assume that *D*=30 and destination cooperative multicast (DCM) is performed.

In Fig. 7, the recovery from infection for packet *a* is presented versus the time t. We can see that for *immune*, *immune_TX* and *vaccine*, $R^a(t)$ decreases for $p_r(t) = p_{r_e}(t)$ and $p_r(t) = p_{r_T}(t)$ compared to the case with fixed $p_r(t)$=1. This is because with these adaptive recovery schemes, the recovery is slower while the infection of the destination users is still taking place, so the number of users infected by *a*, *b*, or *c* decreases with *t* while a number of new packets *f* are created.

We can also see this effect in Fig.8 where $R^f(t)$ is shown for the same schemes. The highest number of recovered packets is obtained by vaccine scheme. It also worth noticing that by $p_r(t) = p_{r_T}(t)$, the recovery is delayed and starts in $t > T_D^f$. For timeout recovery scheme, the number of packets recovered depends on the timeout factor μ, and the recovery is much slower than with any other scheme.

In Fig. 9, the average delivery delay $E[T_D^f]$ is shown for the previous schemes. The highest $E[T_D^f]$ is obtained for vaccine and immune_TX scheme with fixed $p_r(t)$, while the lowest delay is obtained by timeout recovery with $\mu = \lambda$ and with adaptive *immune* schemes, at the expense of larger recovery delays. We can see that the improvement obtained by using adaptive schemes compared to those with fixed $p_r(t)$ can reach up to 50% for immune scheme, 30% for immune_TX and 75% for vaccine scheme, when *D*<30. For higher *D*, $E[T_D^f]$ decreases in the same proportion for all schemes as there are more destinations to propagate the infection within themselves. We can also see that the choice of parameter μ results in different values of $E[T_D^f]$.

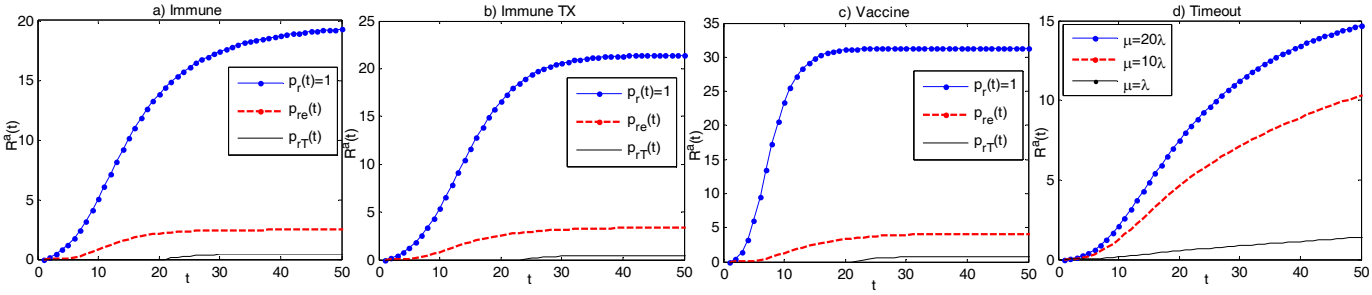

Fig. 7. $R^a(t)$ versus t for a) *immune,* b) *immune TX,* c) *vaccine* for different values of $p_r(t)$ and, d) *timeout recovery* scheme.

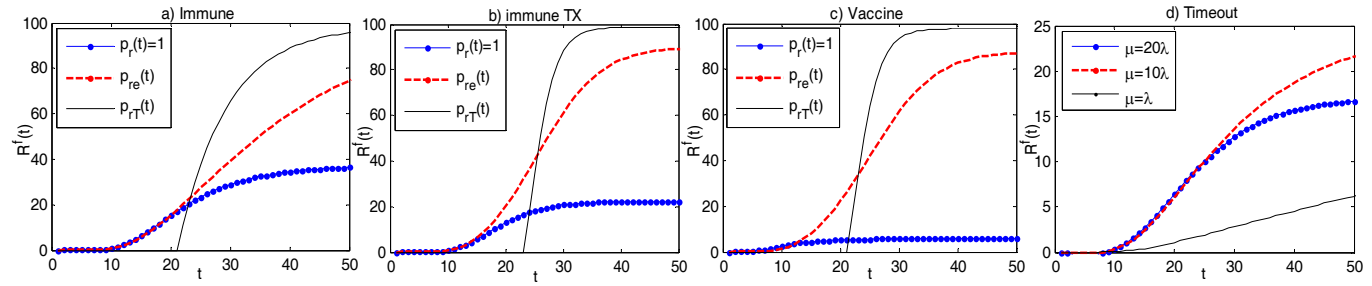

Fig. 8. $R^f(t)$ versus t for a) *immune,* b) *immune TX,* c) *vaccine* for different values of $p_r(t)$ and, d) *timeout recovery* scheme.

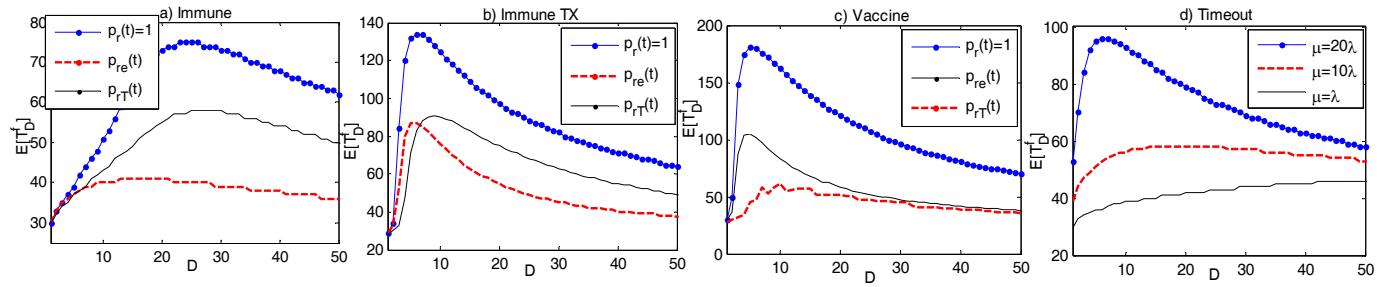

Fig. 9. $E\left[T_D^f\right]$ versus t for a) *immune,* b) *immune TX,* c) *vaccine* for different values of $p_r(t)$ and, d) *timeout recovery* scheme.

VI. Conclusion

In this paper, we have presented an analytical framework to study the performance of different infection recovery schemes for multicast DTN. New *adaptive recovery schemes* are developed where the recovery probability is adjusted to the multicast traffic. The performance of these new schemes is compared to a number of unicast recovery schemes modified for multicast DTN. The network model considered enables us to discuss the above schemes in combination with some additional advanced techniques that have been recently considered in this field like network coding. The analytical framework presented can be extended to model the recovery process for different multicast routing schemes. Numerical results have shown the outstanding performance of our new adaptive recovery schemes.

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