Analysis of Heterogeneous Delay-Tolerant Networks with Non-Cooperative Nodes and Limited Message Lifetime

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Abstract—Delay-Tolerant Networks (DTNs) routing protocols assume nodes to be cooperative in forwarding packets from one node to other nodes. However, in real world most of the nodes because of resource and energy constrains are non-cooperative. In this paper, node cooperation is considered with probability ps and pr, respectively in sending and receiving a message. We also investigate the impact of limited message lifetime on the performance of routing schemes in heterogeneous DTN (in terms of transmission radii) with non-cooperative nodes. This node cooperation behavior is modeled by using Ordinary Differential Equations (ODEs) and the performance study of the Two-Hop Routing (2HR) and Epidemic Routing (ER) in a realistic DTN setting that comprises of nodes with different transmission radii. Our model is validated by the extensive simulations.

Keywords — performance modeling, routing, DTN, heterogeneity, Non-cooperation

I. INTRODUCTION

Most of the time Delay-Tolerant Networks (DTNs) [1], [2], [3] are the wireless mobile networks which do not have end-to-end paths between source and destination nodes. Potential DTN applications include deep-space interplanetary networks [2], Vehicular Ad hoc NETworks (VANETs) [4], underwater networks [5], and military networks [6]. The characteristics of such networks include node mobility, sparse node density, and intermittent connections.

In such applications the DTN nodes are mostly battery-operated, mobile phones, sensor nodes, war tanks, and solar energy harvesting-battery powered satellites are limited-resource hardware devices.

In order to stay long in the system the energy in these nodes has to be carefully utilized (or the nodes have to stay alive until next energy harvesting cycle as determined by their planetary motion towards the Sun’s direction in the case of energy-harvesting nodes such as satellites). The energy of a node which is directly proportional to the message forward is mainly consumed in its communication subsystem; and the routing protocol impacts these message forwards at the network level. For the routing protocols it is therefore vital to be equipped with the energy-efficient design. However, the contemporary DTN routing protocols such as Two-Hop Routing (2HR) [7] and Epidemic Routing (ER) [8] are designed in a way that a node forwards all messages in the same manner; without considering the individual message requirements (such as lifetime and delivery probability).

This conservative nature of protocols, that do not cater to the individual message demands, may lead to unwanted message forwards and hence inefficiently utilize the node’s energy.

The energy spent during a message forward is directly proportional to the communication range/radius of the node.
from the node-level perspective. Different nodes exist with different transmission radii in reality. This is due to the availability of a wide spectrum of mobile computing devices that come with different form factors, different communication radios, and power tunable radios that control the communication range. By choosing the appropriate nodes these routing protocols under heterogeneous network setting should also have to handle node-level energy consumption in an efficient way having highlighted the need for an energy efficient routing protocol at the network-level.

The contributions of this paper are as follows to this end:

- We propose an ODE model to study the performance of 2HR and ER protocols in heterogeneous DTN with non-cooperative nodes and limited message lifetime $E_l$, Validate the proposed analytical model via extensive simulation results.
- Our result shows the impact of message lifetime on the performance of 2HR and ER protocols with non-cooperative nodes.

The remainder of this paper is organized as follows: Some related work in the context of DTN routing and the analytical tools that are used to study the performance are discussed in Section II. The system model under consideration is discussed in Sections III. The analytical framework used to describe the two routing protocols is presented in Section IV, followed by providing performance indices closed-form expression in Section V. The theoretical results through extensive simulations are validated in Section VI. Finally, the paper with some future research directions is concluded in Section VII.

II. RELATED WORK

The widely used DTN routing protocols and their corresponding performance modeling tools used in the literature are discussed in this section.

A. Routing Protocols

Direct transmission [9] routing protocols and ER [8] are the two extreme cases in terms of their performance bound. While the former performs worst-in-class delivery cost and with best-in-class delivery delay, the latter performs with the worst-in-class delivery delay and best-in-class delivery cost. In the direct delivery scheme, the source node delivers the message only on its encounter with the destination node as the name suggests. On the other hand, ER is a flooding-based protocol that replicates messages on every new contact opportunity. ER is considered to be energy inefficient owing to its large cost overhead. To this end, several variants [10], [11], [12], [13], [14] to limit the forwards have been proposed by several researchers

2HR protocol have been proposed by the authors in [7], wherein the relay nodes deliver the messages only to the corresponding destination nodes (similar to the direct transmission routing scheme) and the source nodes deliver messages to all relay nodes (an epidemic forwarding manner). A probabilistic forwarding based routing approach that opportunistically forwards to the relay nodes that have maintained good encounter statistics with the forwarding node have been proposed by the authors in [12]. The authors in [10] have used social similarity metrics among nodes to choose for their forwarding strategy in a similar probabilistic approach, and the authors have used geometric distance among nodes in the forwarding strategy in [14].

B. Analytical Performance Modeling Tools

With the help of mathematical techniques such as Markov model [7], [15], and ODE [16] model, performance of the Spray-and-wait [11] routing and routing protocols such as 2HR, ER are analyzed.

Continuous Time Markov Chain (CTMC) model have been used by the authors in [7] to study the propagation of a message from source to destination node under Random Way-Point (RWP) mobility model [17]. Using ODE model in [16] performance modeling of epidemic routing under the same mobility model has been studied. These works however are focused on the homogeneous network settings.

The authors in [15] studied the performance model of DTN routing under two different node speeds using CTMC and ODE model in a realistic heterogeneous network.

III. SYSTEM MODEL

The system model considered in this paper is presented in this section. The network consists of two different classes of nodes with different transmission radius for each class ($r_1$ and $r_2$, and $r_1 < r_2$). Each class of nodes henceforth is named as $r_1$ and $r_2$, respectively.

A. Traffic Model

We study the performance of single message propagation in the network without loss of generality. With a sufficient buffer size and communication bandwidth, the performance modeling under this setting can be applied for a low load system.
### TABLE 1 NOTATION

<table>
<thead>
<tr>
<th>Notation</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>Total number of nodes</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Fraction of $r_1$ nodes</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Fraction of $r_2$ nodes ($\beta = 1 - \alpha$)</td>
</tr>
<tr>
<td>$\lambda_{mn}$</td>
<td>IMR between $r_m$ and $r_n$ nodes</td>
</tr>
<tr>
<td>$E_t$</td>
<td>Message life time</td>
</tr>
<tr>
<td>$D_p$</td>
<td>Message delivery probability</td>
</tr>
<tr>
<td>$(c,d)$</td>
<td>State of the system with $c$ and $d$ copies of Message to $r_1$ and $r_2$ nodes, respectively.</td>
</tr>
<tr>
<td>$P_{ij}[E_t;(c,d)]$</td>
<td>Delay CDF of the system at the time $E_t$ with $(c,d)$ copies from the node combination of type $ij$. Note that for two classes of nodes, there are four different node type combinations 11, 12, 21, 22, respectively.</td>
</tr>
</tbody>
</table>

### B. Mobility Model

According to the RWP mobility model, the nodes move in a 2-D terrain. This mobility model is characterized by the Inter-Meeting Time (IMT) of the nodes. The time period from the instant two nodes move out of contact to the point of time until they meet again is defined as IMT. And, the corresponding rates are defined as Inter-Meeting Rates (IMR). Under RWP mobility the IMT of any two nodes follows exponential distribution \[18\] with parameter $\lambda$ (IMR) given as follows:

$$\lambda \approx \frac{8\omega r^2 v}{\pi L^2},$$  \hspace{1cm} (1)

Where $\omega \approx 1.3683$ is a RWP constant, $L$ is the side of a square terrain, $v$ is the constant velocity of the nodes, and $r$ is the transmission radius of the nodes.

The computation of IMR for nodes between two different classes is as follows:

$$\lambda_{12} = \lambda_{21} \approx \frac{8\omega \min(r_1, r_2)^2 v}{\pi L^2}.$$  \hspace{1cm} (2)

$\lambda_{11}$ and $\lambda_{22}$ can be computed from Eq. 1.

### C. Routing Protocols

Under consideration the two routing protocols are described as follows:

- **ER protocol** [8]: The source node replicates/infects the message to any other (uninfected) node it meets and the other nodes can also replicate the message to any other relay nodes that do not have a message. This behavior is similar to the spreading of disease in a population and hence the name.

- **2HR protocol** [7]: The relay nodes can only forward the message to the destination node whereas the source node replicates the message to other relay node it meets.

### IV. PERFORMANCE MODELING

We present the performance modeling of 2HR and ER protocols under the considered heterogeneous settings with node cooperation by using ODEs in this section.

The two types of nodes $r_1$ and $r_2$ in the network would lead to four combinations of source-destination pairs. We solve each combination with separate ODEs. The $mn$ denotes the corresponding ODEs with source node from class $rm$ and destination node from class $rn$, respectively. The performance indices are computed as follows:
\[ Delay^{(c,d)} = \sum P_{mn} \times Delay^{(c,d)}_{mn} \]  
\[ Cost^{(c,d)} = \sum P_{mn} \times Cost^{(c,d)}_{mn} \]  
\[ Deliver \ ratio^{(c,d)} = \sum P_{mn} \times Deliver \ ratio^{(c,d)}_{mn} \]

where \( Delay^{(c,d)}_{mn} \), \( Cost^{(c,d)}_{mn} \), and \( Deliver \ ratio^{(c,d)}_{mn} \) are the respective average delay (average time a message takes to reach the destination), average cost (average number of copies of a message in the system, at the time of reaching the destination) and average delivery ratio (ratio of the number of messages that reached destination and the number of messages generated in the system) for a system that contains a source node from class \( m \) and a destination node from class \( n \) and \( P_{mn} \) is the probability of choosing a source node from class \( m \) and a destination node from class \( n \). \( P_{mn} \) for all the four combinations are computed as follows:

\[ P_{11} = \frac{N\alpha}{N} \times \frac{N\alpha - I_{0}}{N - 1}, \quad P_{12} = \frac{N\alpha}{N} \times \frac{N\beta}{N - 1}, \]
\[ P_{21} = \frac{N\beta}{N} \times \frac{N\alpha}{N - 1}, \quad P_{22} = \frac{N\beta}{N} \times \frac{N\beta - 1}{N - 1}. \]

We present individual ODEs for the respective 2HR and ER protocols for each of the aforementioned four combinations.

1) **2HR Protocol:**

Type 11: In type 11, source node is r1 and destination node is also r1. Out of Na nodes of type r1, we have Na−1 nodes to potentially relay the message, since one node of type r1 is the destination node. We consider the message transmission process when the system is at time \( t \). Let \( I_{11t1} [t; (c, d)] \) and \( I_{11t2} [t; (c, d)] \) represent the number of r1, r2 (infected) nodes with the message at time \( t \), respectively. There are \( N\alpha - I_{0} \) nodes of type r1 without message and \( N\beta - I_{12t} [t; (c, d)] \) nodes of type r2 without message other than destination in the system at time \( t \) when one of these uninfected relay nodes of type r1 meets the source node of the same type r1, then there is an increase in the infected nodes of type r1. Let the rate of change of this infection of r1 nodes is denoted by \( I_{11t1} [t; (c, d)] \). Therefore,

\[ I'_{11r1} [t; (c, d)] = (N\alpha - I_{11r1} [t; (c, d)] - 1)\lambda_{11} I_{11r1} [t; (c, d)], \quad \text{for} \quad I_{11r1} [t; (c, d)] \in [1, c]; \]

Where, \( \lambda_{11} \) is the contact rate between the source and the relay node from the r1 class. In a similar way, \( I_{11t2} [t; (c, d)] \) is obtained as follows:

\[ I'_{11r2} [t; (c, d)] = (N\beta - I_{11r2} [t; (c, d)])\lambda_{12} I_{11r2} [t; (c, d)], \quad \text{for} \quad I_{11r2} [t; (c, d)] \in [0, d]; \]

Where, \( \lambda_{12} \) is the contact rate between the source node from r1 and the relay node from r2. The probability of reaching the destination node (\( P' [t; (c, d)] \)) is given by

\[ P'_{11} [t; (c, d)] = (I_{11r1} [t; (c, d)]\lambda_{11} + I_{11r2} [t; (c, d)]\lambda_{12})I_{11r1} [t; (c, d)]P_{11} [t; (c, d)](1 - P_{11} [t; (c, d)]), \]

\[ \text{for} \quad I_{11r1} [t; (c, d)] \in [1, c], \quad I_{11r2} [t; (c, d)] \in [0, d]; \]

Where \( P_{11} [t; (c, d)] \) is the CDF of delivery delay.

At initial time \( t = 0 \), one of the r1 node (source node) has a message, r2 nodes do not have the message and the probability of message reaching the destination node is zero. Hence, \( I_{11r1} [0; (c, d)] = 1, \quad I_{11r2} [0; (c, d)] = 0, \) and \( P_{11} [0; (c, d)] \neq 0 \).
Type 12: In type 12, source node is $r_1$ and destination node is $r_2$. Out of $N\beta$ nodes of type $r_2$ we have only $N\beta - 1$ nodes, since one node of type $r_2$ is the destination node. At initial time $t = 0$, one of the $r_1$ nodes have a message and the probability of message reaching the destination node is zero. So, $I_{12r_1}[0; (c, d)] = 1$, $I_{12r_2}[0; (c, d)] = 0$, and $P_{12}[0; (c, d)] = 0$. The system rates (obtained in similar lines, as described in previous section) are summarized as follow:

\[
\begin{align*}
I'_{12r_1}[t; (c, d)] &= (N\alpha - I_{12r_1}[t; (c, d)])\lambda_{11}p_s p_r, \\
& \text{for } I_{12r_1}[t; (c, d)] \in [1, c]; \\
I'_{12r_2}[t; (c, d)] &= (N\beta - I_{12r_2}[t; (c, d)] - 1)\lambda_{12}p_s p_r, \\
& \text{for } I_{12r_2}[t; (c, d)] \in [0, d]; \\
P'_{12}[t; (c, d)] &= (I_{12r_1}[t; (c, d)])\lambda_{11} \\
& +I_{12r_2}[t; (c, d)]\lambda_{22} p_s p_r (1 - P_{12}[t; (c, d)]), \\
& \text{for } I_{12r_1}[t; (c, d)] \in [1, c], I_{12r_2}[t; (c, d)] \in [0, d].
\end{align*}
\]

Type 21: In type 21, source node is $r_2$ and destination node is $r_1$. Out of $N\alpha$ nodes of type $r_1$ we have only $N\alpha - 1$ nodes, since one node of type $r_1$ is the destination node. At initial time $t = 0$, $r_1$ nodes do not have a message, one of the $r_2$ nodes (source node) has the message and the probability of message reaching the destination is zero. So, $I_{21r_1}[0; (c, d)] = 0$, $I_{21r_2}[0; (c, d)] = 1$, and $P_{21}[0; (c, d)] = 0$. The system rates are summarized as follow:

\[
\begin{align*}
I'_{21r_1}[t; (c, d)] &= (N\alpha - I_{21r_1}[t; (c, d)] - 1)\lambda_{12}p_s p_r, \\
& \text{for } I_{21r_1}[t; (c, d)] \in [0, c]; \\
I'_{21r_2}[t; (c, d)] &= (N\beta - I_{21r_2}[t; (c, d)])\lambda_{22} p_s p_r, \\
& \text{for } I_{21r_2}[t; (c, d)] \in [1, d]; \\
P'_{21}[t; (c, d)] &= (I_{21r_1}[t; (c, d)])\lambda_{11} \\
& +I_{21r_2}[t; (c, d)]\lambda_{12} p_s p_r (1 - P_{21}[t; (c, d)]), \\
& \text{for } I_{21r_1}[t; (c, d)] \in [0, c], I_{21r_2}[t; (c, d)] \in [1, d].
\end{align*}
\]

Type 22: In type 22, source node is $r_2$ and destination node is also $r_2$. Out of $N\beta$ nodes of type $r_2$ we have only $N\beta - 1$ nodes, since one node of type $r_2$ is the destination node. At initial time $t = 0$, $r_1$ nodes do not have the message, one of the $r_2$ nodes (source node) has the message and the probability of message reaching the destination is zero. So, $I_{22r_1}(0) = 0$, $I_{22r_2}[0; (c, d)] = 1$, and $P_{22}[0; (c, d)] = 0$. The system rates are summarized as follow:

\[
\begin{align*}
I'_{22r_1}[t; (c, d)] &= (N\alpha - I_{22r_1}[t; (c, d)])\lambda_{12}p_s p_r, \\
& \text{for } I_{22r_1}[t; (c, d)] \in [0, c]; \\
I'_{22r_2}[t; (c, d)] &= (N\beta - I_{22r_2}[t; (c, d)] - 1)\lambda_{22} p_s p_r, \\
& \text{for } I_{22r_2}[t; (c, d)] \in [1, d]; \\
P'_{22}[t; (c, d)] &= (I_{22r_1}[t; (c, d)])\lambda_{11} \\
& +I_{22r_2}[t; (c, d)]\lambda_{12} p_s p_r (1 - P_{22}[t; (c, d)]), \\
& \text{for } I_{22r_1}[t; (c, d)] \in [0, c], I_{22r_2}[t; (c, d)] \in [1, d].
\end{align*}
\]
2) **ER Protocol:**

The probability of reaching the destination node $P_{11}[t; (c, d)]$ is same as Eq. 8.

Type 12: In type 12, source node is $r_1$ and destination node is $r_2$. Out of $N\beta$ nodes of type $r_2$ we have $N\beta - 1$ relay nodes, since one node of type $r_2$ is the destination node. The system rates are summarized as follow:

$$
I_{12_{r_1}}[t; (c, d)] = (N\alpha - I_{12_{r_1}}[t; (c, d)]) \\
(I_{12_{r_1}}[t; (c, d)]\lambda_{11} + I_{12_{r_2}}[t; (c, d)]\lambda_{22})p_{s}p_{r},
$$

for $I_{11_{r_1}}[t; (c, d)] \in [1, c]$, $I_{11_{r_2}}[t; (c, d)] \in [0, d]$.

$$
I_{12_{r_2}}[t; (c, d)] = (N\beta - I_{12_{r_2}}[t; (c, d)] - 1) \\
(I_{12_{r_1}}[t; (c, d)]\lambda_{12} + I_{12_{r_2}}[t; (c, d)]\lambda_{22})p_{s}p_{r},
$$

for $I_{12_{r_1}}[t; (c, d)] \in [1, c]$, $I_{12_{r_2}}[t; (c, d)] \in [0, d]$.

$$
P'_{12}[t; (c, d)] = (I_{12_{r_1}}[t; (c, d)]\lambda_{12} + I_{12_{r_2}}[t; (c, d)]\lambda_{22})p_{s}p_{r}(1 - P_{11}[t; (c, d)]),
$$

for $I_{12_{r_1}}[t; (c, d)] \in [1, c]$, $I_{12_{r_2}}[t; (c, d)] \in [0, d]$.

Type 21: In type 21, source node is $r_2$ and destination node is $r_1$. Out of $N\alpha$ nodes of type $r_1$ we have $N\alpha - 1$ relay nodes, since one node of type $r_1$ is the destination node. The system rates are summarized as follows:

$$
I'_{21_{r_1}}[t; (c, d)] = (N\alpha - I_{21_{r_1}}[t; (c, d)] - 1) \\
(I_{21_{r_1}}[t; (c, d)]\lambda_{11} + I_{21_{r_2}}[t; (c, d)]\lambda_{12})p_{s}p_{r},
$$

for $I_{21_{r_1}}[t; (c, d)] \in [0, c]$, $I_{21_{r_2}}[t; (c, d)] \in [1, d]$.

$$
I'_{21_{r_2}}[t; (c, d)] = (N\beta - I_{21_{r_2}}[t; (c, d)] - 1) \\
(I_{21_{r_1}}[t; (c, d)]\lambda_{12} + I_{21_{r_2}}[t; (c, d)]\lambda_{22})p_{s}p_{r},
$$

for $I_{21_{r_1}}[t; (c, d)] \in [0, c]$, $I_{21_{r_2}}[t; (c, d)] \in [1, d]$.

$$
P'_{21}[t; (c, d)] = (I_{21_{r_1}}[t; (c, d)]\lambda_{11} + I_{21_{r_2}}[t; (c, d)]\lambda_{12})p_{s}p_{r}(1 - P_{21}[t; (c, d)]),
$$

for $I_{21_{r_1}}[t; (c, d)] \in [0, c]$, $I_{21_{r_2}}[t; (c, d)] \in [1, d]$.

Type 22: In type 22, source node is $r_2$ and destination node is also $r_2$. Out of $N\beta$ nodes of type $r_2$ we have $N\beta - 1$ relay nodes, since one node of type $r_2$ is the destination node. The system rates are summarized as follows:

$$
I''_{22_{r_1}}[t; (c, d)] = (N\alpha - I_{22_{r_1}}[t; (c, d)]) \\
(I_{22_{r_1}}[t; (c, d)]\lambda_{11} + I_{22_{r_2}}[t; (c, d)]\lambda_{12})p_{s}p_{r},
$$

for $I_{22_{r_1}}[t; (c, d)] \in [0, c]$, $I_{22_{r_2}}[t; (c, d)] \in [1, d]$.

$$
I''_{22_{r_2}}[t; (c, d)] = (N\beta - I_{22_{r_2}}[t; (c, d)] - 1) \\
(I_{22_{r_1}}[t; (c, d)]\lambda_{12} + I_{22_{r_2}}[t; (c, d)]\lambda_{22})p_{s}p_{r},
$$

for $I_{22_{r_1}}[t; (c, d)] \in [0, c]$, $I_{22_{r_2}}[t; (c, d)] \in [1, d]$.

$$
P''_{22}[t; (c, d)] = (I_{22_{r_1}}[t; (c, d)]\lambda_{12} + I_{22_{r_2}}[t; (c, d)]\lambda_{22})p_{s}p_{r}(1 - P_{22}[t; (c, d)]),
$$

for $I_{22_{r_1}}[t; (c, d)] \in [0, c]$, $I_{22_{r_2}}[t; (c, d)] \in [1, d]$. 

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V. PERFORMANCE INDICES COMPUTATION

**A. Delivery Ratio** \( Delivery Ratio^{(c,d)}_{11} \) Computation

For ODE of type 11, \( P_{11}[t; (c, d)] \) is CDF of the message delivery. Hence the delivery ratio for the system with \( c \) copies of message to \( r_1 \) nodes and \( d \) copies of message to \( r_2 \) nodes is given by,

\[
Delivery Ratio^{(c,d)}_{11} = P_{11}[E_t; (c, d)]
\]

Where \( E_t \) is the message expiry time. In a similar way, \( Delivery Ratio^{(c,d)}_{12} \), \( Delivery Ratio^{(c,d)}_{21} \), and \( Delivery Ratio^{(c,d)}_{22} \) can be computed.

**B. Delay** \( Delay^{(c,d)} \) Computation

The ODE for average delivery delay of type 11 (\( Delay^{(c,d)}_{11} \)), for a message with expiry time \( E_t \) is given by [19],

\[
Delay^{(c,d)}_{11} = \frac{1}{P_{11}[E_t; (c, d)]} \int_0^{E_t} t P_{11}^{t'}[t; (c, d)] dt
\]

\[
= E_t - \frac{1}{P_{11}[E_t; (c, d)]} \int_0^{E_t} P_{11}[t; (c, d)] dt.
\]

In a similar way, \( Delay^{(c,d)}_{12} \), \( Delay^{(c,d)}_{21} \) and \( Delay^{(c,d)}_{22} \) can be computed.

**C. Cost** \( Cost^{(c,d)} \) Computation

In delivering a message from source node to the destination node, forwards can be made by any of the relay nodes of either types \( r_1 \) and \( r_2 \). The overall cost is the sum of the number of forwards made by nodes of different combinations from type \( r_1 \) and \( r_2 \).

**Type 11:** Let \( U^{r_1} \) and \( U^{r_2} \) represent the number of (uninfected) nodes of the respective \( r_1 \) and \( r_2 \) nodes that do not have a message at time \( t \). Hence,

\[
U^{r_1} = (N \alpha - I_{11r_1}[t; (c, d)] - 1),
\]

\[
U^{r_2} = (N \beta - I_{11r_2}[t; (c, d)]),
\]

for \( I_{11r_1} \) and \( I_{11r_2} \) in \([1, c])\) and \([0, d])\), respectively.

Let \( F^{r_1} \) and \( F^{r_2} \) represent the rate of forwards made by \( r_1 \) and \( r_2 \) nodes, respectively. At time \( t = 0 \), there will not be any forwards of message in the network.

Hence, \( F^{r_1} = 0 \) and \( F^{r_2} = 0 \).

2HR Protocol: In 2HR protocol only source node spreads the message to all the relay nodes in the network. And relay nodes can spread the message only to the destination node. Hence,
ER Protocol: In ER protocol source node spreads the message to all the nodes in the network. Relay nodes also spread the message to all the nodes they meet. Hence,

\[
\begin{align*}
F'_{11_{r1}} [t; (c, d)] &= I_{11_{r1}} [t; (c, d)](\lambda_{11} U_{11}^{p1} + \lambda_{12} U_{11}^{p2}) p_{s} p_{r}; \\
F'_{11_{r2}} [t; (c, d)] &= 0.
\end{align*}
\]

The expected number of forwards made by r1 nodes at the time of reaching the destination node is given by,

\[
\text{Cost}_{11_{r1}}^{(c,d)} = \frac{1}{P_{11}[E_{l}; (c, d)]} \int_{0}^{E_{l}} R_{11_{r1}} [t; (c, d)] P'_{11} [t; (c, d)] dt.
\]

where

\[
R_{11_{r1}} [t; (c, d)] = F_{11_{r1}} [t; (c, d)] + \frac{I_{11_{r1}} [t; (c, d)] \lambda_{11}}{I_{11_{r1}} [t; (c, d)] \lambda_{11} + I_{11_{r2}} [t; (c, d)] \lambda_{12}}.
\]

In a similar way,

\[
\text{Cost}_{11_{r2}}^{(c,d)} = \frac{1}{P_{11}[E_{l}; (c, d)]} \int_{0}^{E_{l}} R_{11_{r2}} [t; (c, d)] P'_{11} [t; (c, d)] dt.
\]

where

\[
R_{11_{r2}} [t; (c, d)] = F_{11_{r2}} [t; (c, d)] + \frac{I_{11_{r2}} [t; (c, d)] \lambda_{12}}{I_{11_{r1}} [t; (c, d)] \lambda_{11} + I_{11_{r2}} [t; (c, d)] \lambda_{12}}.
\]

The message delivery cost for the ODE of type 11 is given by,

\[
\text{Cost}_{11}^{(c,d)} = \text{Cost}_{11_{r1}}^{(c,d)} + \text{Cost}_{11_{r2}}^{(c,d)}.
\]

In a similar way, \( \text{Cost}_{12}^{(c,d)} \), \( \text{Cost}_{21}^{(c,d)} \), and \( \text{Cost}_{22}^{(c,d)} \) can be computed for the respective type 12, type 21, and type 22 combinations.
The message delivery costs for $r_1$ and $r_2$ nodes are given by,

$$C_{cost}^{(c,d)}_{r_1} = P_{11}C_{cost}^{(c,d)}_{11_{r_1}} + P_{12}C_{cost}^{(c,d)}_{12_{r_1}} + P_{21}C_{cost}^{(c,d)}_{21_{r_1}} + P_{22}C_{cost}^{(c,d)}_{22_{r_1}}, \quad (13)$$

$$C_{cost}^{(c,d)}_{r_2} = P_{11}C_{cost}^{(c,d)}_{11_{r_2}} + P_{12}C_{cost}^{(c,d)}_{12_{r_2}} + P_{21}C_{cost}^{(c,d)}_{21_{r_2}} + P_{22}C_{cost}^{(c,d)}_{22_{r_2}}, \quad (14)$$

D. Energy($c,d$) Computation

The communication energy for the message transmission and reception is considered as the main energy consumers in the system [20] in our model. From the source to the destination node the total energy consumed for delivering a message can be expressed as follows [21] [22]:

$$Energy^{(c,d)} = C_{cost}^{(c,d)}_{r_1} \left( \frac{M(P_{recv} + \eta P_1^\gamma)}{R} \right)$$

$$+ C_{cost}^{(c,d)}_{r_2} \left( \frac{M(P_{recv} + \eta P_2^\gamma)}{R} \right). \quad (15)$$

where $M$ is the message size,
$R$ is the data rate,
$P_{recv}$ is the power consumption in radio receive mode (with $P_{recv} = 1.275W$),
$\eta$ is a proportionality constant describing overhead per bit (with $\eta = 0.05$), and
$\gamma$ is the path loss exponent (with $\gamma = 2.23$).

Note that the values of $P_{recv}$, $\eta$, $\gamma$ values are taken from [21].

VI. MODEL VALIDATION

We study the accuracy of our analytical model via extensive simulations using ns-2 simulator in this section. We have used Mathematica for the analytical results. Table II shows the simulation parameters. By varying the total number of nodes in the system as 20 and 40 the results are plotted. We have considered a network in which the copies ($c,d$) are chosen to be 50% from each of the node types. All results are plotted with 95% confidence.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrain size ($L^2$)</td>
<td>4000×4000m²</td>
</tr>
<tr>
<td>Velocity of nodes (v)</td>
<td>5m/s</td>
</tr>
<tr>
<td>Buffer size</td>
<td>$\infty$</td>
</tr>
<tr>
<td>MAC protocol</td>
<td>IEEE 802.11</td>
</tr>
<tr>
<td>Transmission range $r_1$, $r_2$</td>
<td>50m, 100m</td>
</tr>
<tr>
<td>Percentage of $r_1$, $r_2$ nodes</td>
<td>50, 50</td>
</tr>
<tr>
<td>Message size ($M$)</td>
<td>10KB</td>
</tr>
<tr>
<td>Data rate ($R$)</td>
<td>11Mbps</td>
</tr>
</tbody>
</table>

From Fig. 1 and Fig. 3, it is clear that the delivery delay and delivery ratio via simulation is in-line with the analytical results. With an increase in message life time, the delivery delay and delivery ratio increase, this is due to the fact that more messages are contributing to the delivery delay for being successfully delivered. The nodes where sending and receiving probabilities are equal will have less delivery delay compared with the nodes with unequal sending and receiving probabilities.
From Fig. 2 and Fig. 4, with the increase of transmission radii, delivery delay decreases as the number of hops needed to reach the destination decreases with the increase of transmission radii and the delivery ratio increases as the probability of reaching the destination node with the higher transmission radii increases.

As seen in Fig. 5, Fig. 6 the energy which is the function of number of forwards also increases with an increase in message lifetime.
VII. CONCLUSION AND FUTURE WORK

In this paper, we modeled and studied the impact of message lifetime on the performance of 2HR and ER protocols for heterogeneous DTNs with node non-cooperation. Our extensive simulation results validated the accuracy of the proposed framework. The results showed that for lower message life-time, delivery delay is same irrespective of node cooperation.

REFERENCES


