Incentive-rewarding mechanisms to stimulate participation in heterogeneous DTNs

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***Abstract*—Delay Tolerant Networks (DTNs) rely on the cooperation of nodes in a network to forward a message from its source to its destination. Most of previous studies on DTNs have focused on the design of routing schemes under the hypothesis that each relay node is willing to participate in the forwarding process. However, the delivery of a message incurs energy and memory costs. In this paper we handle the problem of how to incentivize mobile nodes to participate in relaying messages using a reward mechanism. We consider heterogeneous relay nodes where the cost for taking part in the forwarding process varies as a function of the mobility patterns of the relays. We show that under fairly weak assumptions on the mobility pattern, the expected reward the source pays remains the same irrespective of the information it conveys to the relays, provided that the type of information does not vary dynamically over time. We also characterize the effect of time to live (TTL) counters on the delivery probability and memory usage. Using simulations based on a synthetic mobility model and real mobility traces, we perform a few tests that show a good accordance among theoretical and simulation results.**

***Index Terms*—Delay tolerant networks, Reward incentive mechanism, Information setting.**

I. Introduction

Delay Tolerant Networks (DTNs), also known as Intermittently Connected Mobile Networks, are mobile wireless networks in which there is no persistent end-to-end link from a source to a destination. DTNs take advantage of mobile nodes to ensure the communication between users; the connectivity is maintained by mobile nodes which communicate when they are in range of each other. When a node receives a message and is not in range of any other node at that time, it stores the message in its buffer and forwards it to another node whenever a useful communication opportunity arises.

Various routing protocols have been proposed for DTNs, their aim being to increase the delivery probability at low costs. Some routing protocols attempt to enhance the delivery ratio by aggressively replicating the messages (e.g., flooding). Other protocols employ specially crafted metrics, which capture some sort of knowledge of the domain under consideration, to achieve this purpose (e.g., forwarding routing) [3].

Two-hop routing provides a good compromise between delay and resource consumption when compared against flooding or epidemic routing [1]. In addition, from the standpoint of feasibility and implementation, the optimal control can be implemented by the source node, with no need to install new routing control protocols on relay nodes; one can prescribe target performance metrics (e.g., delay) and then determine to which relays the source node should deliver messages to, and for how long the delivery process should last [1], [2]. Currently, there are no corresponding results for multi-hop routing protocols. Finally, it has been shown in [2] that if we have a network with a complete mixing of the trajectories of the nodes, two-hop routes are sufficient to achieve the throughput capacity region of the network. For this reason, we shall assume a two-hop routing protocol in the remainder of this paper.

A. Problem Statement

DTNs overcome the problems associated to intermittent connectivity and guarantee communication through cooperation between nodes; each node is supposed to be willing to participate in relaying messages of other nodes. However, as in any fully distributed system, nodes may misbehave; certain nodes may not be able to relay messages of other nodes in order to save resources (especially energy), which in turn degrades network performance. Hence, one of the fundamental questions in the realm of DTNs concerns incentives: *how to incentivize mobile nodes to participate in relaying messages?*

To handle this problem, in [18] a reward mechanism was proposed in order to encourage nodes to relay messages of others. Under this mechanism, the source node promises a reward to each relay who accepts relaying its message, but informs them that only the first one to deliver the message to the destination will effectively receive the reward. A relay accepts to forward the message to the destination if the proposed reward offsets its expected cost, as estimated by the relay when it meets the source. The assessment of the reward expected by the relay depends on the time at which it meets the source, and on any information given by the source to the relay that may assist the relay in the estimation of its probability of success. The model proposed in [18] assumed a homogeneous mobility for all relays: all the relays have the same statistics for the inter-contact time with the source and the destination. However, in many applications real traces reveal the existence of heterogeneity in mobile relays [17]. Indeed, in real traces [4] we observed that different types of mobile nodes have very different characteristics in terms of their communication ability and mobility patterns.

In this paper, we generalize the results of [18] to a heterogeneous mobility model in which relays can have different statistics for inter-contact times. The heterogeneity also gives rise to a richer set of structures of information sharing from which the source can choose from, and its analysis involves an

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application of results on order statistics [9]. When the source meets a relay, it has now four options of information sharing strategies, as opposed to the three discussed in [18].

1) **full information:** the source reveals to the relay the number and the age of all existing copies of the message in the network.

2) **partial information:** in this case we distinguish two options: (a) the relay will be informed about the identities of the relays that got the message before or (b) the relay will know the number of copies circulating in the network, but not the identities of nodes involved in previous contacts.

We note that in the homogeneous case (a) and (b) give the same information. In the heterogeneous case considered in this paper, in contrast, knowing the identity (and the mobility pattern) of nodes involved in previous contacts gives additional information for the computation of the success probability.

3) **no information:** the source does not reveal any information to the relay, in which case the relay only knows at what time it met the source.

B. Related studies

There is a vast literature on incentive schemes to promote cooperation in DTNs [10], [22], [6], [18], [19], [8], [14]. Shevade *et al.* [19] uses Tit-for-Tat (TFT) to design an incentive-aware routing protocol that allows selfish DTN nodes to maximize their individual utilities while conforming to TFT constraints. Mobicent [8] is a credit-based incentive system which integrates credit and cryptographic technique to address edge insertion and edge hiding attacks among nodes. PI [14] proposes the inclusion of an incentive on the bundle sent by the source to incentivize selfish nodes to cooperate in message delivery.

Game theory is one of the common tools used to study strategic behavior. Ning et al. [16] proposed a credit-based incentive scheme to promote nodal collaboration in a DTN with multiple interest types; they assume that a message may be desired by multiple destinations. The authors formulate nodal communication as a two-person cooperative game. Wei et al. [21] proposed a user-centric reputation based incentive protocol. They defined a game-theoretic framework to design costs that leads to a Perfect Bayesian Equilibrium.

Reputation mechanisms involving social networks have also been considered to cope with selfish behavior. MobiGame [21] is a user-centric and social-aware reputation based incentive scheme for DTNs. [13] proposes socially selfish routing in DTNs, where a node exploits social willingness to determine whether or not to relay packets for others. In [20], authors proposed an incentive driven dissemination scheme that encourages nodes to cooperate and chooses delivery paths that can reach as many nodes as possible with fewest transmissions.

A fundamental aspect that is usually ignored in the DTN literature concerns the challenge to transmit feedback messages. In DTNs, feedback messages may experience large delays and for this reason the exchange of rewards between relays should not require feedback to other nodes. To overcome such a challenge, the mechanism proposed in [18], and also considered in this paper, assumes that a relay receives a positive reward if and only if it is the first to deliver the message to the destination. Similar ideas have been considered in [6], where a credit-based incentive system using the theory of minority games is adopted to attain coordination in a distributed fashion. The mechanism considers costs for taking part in the forwarding process which vary with device technologies or users habits.

The mechanism investigated in this paper is a generalization of the one studied in [18] in which the relay nodes were assumed to be homogeneous with identical statistical model of mobility. Motivated by the fact that a realistic mobility is heterogeneous [4], we generalize the results in [18] to heterogenous DTN network where different pairs of nodes might meet at different rates.

C. Summary of the Contributions

Incentive mechanisms under heterogenous settings (Section III): we propose a model to enable incentives in DTNs accounting for relays that can have different inter-contact time statistics, under multiple information sharing structures. We show that the average reward paid by the source is independent of the information sharing setting and depends upon the mobility pattern only through the mean inter-contact times.

For exponentially distributed inter-contact times, we also give expressions for the reward the source must promise to a relay, as a function of the instant of time at which the encounter occurs and the information sharing structure under consideration.

TTL analysis (Section IV): we show that nodes equipped with TTL caches can efficiently tune the TTL so as to trade between the costs of actively searching for the destination and the probability to satisfy the source demands.

Trace driven validation (Section V): we validate and parameterize the proposed model using real traces collected from taxi cabs in the city of Rome [4]. One of the main observations we make from these trace-driven experiments is that our results are robust against variations in the statistical distribution of the mobility pattern. Specifically, even though the actual inter-contact distribution may not be known, one can compute the rewards assuming an exponential distribution, and this will still result in a fair outcome for the relays and for the source. By fair, we mean that neither the relay nor the source gain by making the assumption of exponential inter-contact times. This experimental evidence suggests that it is sufficient to know the mean inter-contact times for this mechanism to work.

The rest of this paper is organized as follows: in the next section we introduce the system model and our working assumptions. In Section III we present the main result - the average reward paid by the source for a message is independent of the information sharing setting and depends upon the mobility pattern only through the mean inter-contact times. In Section IV, we characterize the effect of the time to live (TTL) counter on the delivery probability and energy storage. Section V provides simulation results, performed using both synthetic as well as real traces, that validate our analytical findings. Section VI discusses the assumptions and the potential improvements to the model and Section VII concludes.

II. SYSTEM MODEL

Consider a heterogenous DTN wherein nodes are equipped with wireless interfaces allowing communication with other mobiles in their proximity. The network comprises a source node, a destination node and N mobile relays. The set of relay nodes is denoted by $\mathcal{R} = \{r_1, \ldots, r_N\}$, where r_k refers to the node with identifier k. Assume that the source and the destination are fixed and that they are not in range of each other. The source seeks help from relays to send its messages. A *contact* occurs when two nodes move within the transmission range of each other. As the density of relay nodes is assumed to be sparse, we consider contacts exclusively between relays and the source or the destination. Such routing strategy is referred to as *two-hop routing*, as messages that reach the destination traverse two-hops.

To incentivize relay transmissions, the source promises to each relay it meets a (time-varying) reward with the condition that only the first relay to deliver the message to the destination will get its reward. When a contact between a relay and the source occurs, the relay can choose to participate in delivering the message. If the relay chooses to participate, it receives the message and incurs an energy reception cost denoted by C_r. The reception cost C_r is fixed and is the same for all relays. The relay should have enough buffer space to store the message and carry it until encountering the destination. Let C_s be the energy cost per time unit for storing and carrying the message. Finally, if a relay is the first to meet the destination among all relays that have the message, it delivers the message and receives the reward promised by the source. Sending the message to the destination incurs a transmission cost denoted by C_d. Hence, the reward proposed by the source has to, at least, offset the expected cost as estimated by the relay to deliver the message to the destination.

The source can use a number of different mechanisms to implement micropayment to relays. For instance, it can issue electronic cheques encrypted with the public-key of the destination. The first relay who delivers the message sends the e-cheque to the destination who decrypts it and returns it to the relay.

A. The Role of Information

Relay nodes estimate costs and revenues associated to the delivery of messages to the destination based on the expected time to reach the destination and the probability of success (i.e. the probability to be the first one to deliver the message to the destination). The success probability, in turn, depends on 1) how many relays have already joined the transmission efforts (*counts*), 2) their *identities* and 3) the *time instants* at which they have met the source.

Aiming towards reducing its costs, the source can act strategically, and choose the amount of information to share with relays. We consider four information sharing strategies, with increasing levels of information provided by the source to the relays. The strategies are summarized in Table I, and vary according to the three factors that determine the success probability, as discussed in the previous paragraph. In our analysis we assume that the information sharing strategy is fixed and given and does not discriminate between relays or between the times at which the source meets the relays. In addition, in all cases we assume that relays know the inter-contact time distributions between each relay, the source and the destination, i.e., statistical information is common knowledge. In section V, it will be shown using simulations that knowledge of the inter-contact times is not essential. It is sufficient to know the mean inter-contact times in order to compute the rewards in a fair manner.

TABLE I
AVAILABLE INFORMATION UNDER DIFFERENT SHARING STRATEGIES

Information sharing strategy	statistics (CDFs)	previous contacts info. counts	identities	instants
Full (F)	✓	✓	✓	✓
Partial with identities $(P+)$	✓	✓	✓	
Partial without identities $(P-)$	✓	✓		
None (N)	✓			

To appreciate some of the implications of the different information settings, we compare the payments requested by the relays to the source under the different settings. Under the full information setting, if a relay knows that there are many copies of a message in circulation, it will infer that it has a higher risk of failure compared to if it were the first one to meet the source. Therefore, the larger the number of copies of a message in circulation, the higher the reward requested by the relay. Under the no information setting, in contrast, the first relay who meets the source will certainly underestimate its probability of success and ask for a higher reward compared to the setup wherein it knew it were the first to encounter the source.

A natural question which we will address in Section III refers to the optimal information sharing strategy from the perspective of a strategic source who aims towards minimizing its costs. As suggested in the paragraph above, the full information setting favors higher payments to late arrivals, whereas the no information setting favors newcomers. Interestingly, we will show that the balance between newcomers and late arrivals implies that *the expected payment incurred by the source is the same in all the considered settings.*

B. Mobility Patterns

Next, we introduce the considered mobility model. Let $\tilde{T}_s^i$ (resp. $\tilde{T}_d^i$) be a random variable characterizing the time between any two consecutive contacts between relay i and the source (resp. the destination). We assume that the inter-contact times between relays and the source (resp. the destination) are independent and non-identically distributed. In addition, we assume that the contacts between relays and the source or the destination are instantaneous, i.e., the duration of these contacts can be neglected.

The instant at which a message is generated by the source can be seen as a random point in time with respect to the contact process of a relay with the source. Hence, the random time between the instant at which the message is generated and the instant at which relay i will meet the source corresponds to the residual life of its inter-contact time, which we denote by T_s^i. Similarly, the time instant at which relay i meets the destination after contacting the source is a random point in time with respect to the contact process of this relay with the destination. Hence, the time to meet the destination is given by the residual life of the inter-contact time distribution with the destination, and is denoted by T_d^i. The complementary cumulative distribution function (CCDF) of T_s^i (resp. T_d^i) is denoted by $F_s^i(x) = \mathbb{P}(T_s^i > x)$ (resp. $F_d^i(x) = \mathbb{P}(T_d^i > x)$). The mean residual inter-contact time of relay i with the source and the destination is given by $\mathbb{E}[T_s^i] = \mathbb{E}[(\tilde{T}_s^i)^2]/(2\mathbb{E}[\tilde{T}_s^i])$ and $\mathbb{E}[T_d^i] = \mathbb{E}[(\tilde{T}_d^i)^2]/(2\mathbb{E}[\tilde{T}_d^i])$, respectively.

III. Expected Costs and Rewards

In this section, we shall first compute the probability of success as estimated by a relay that meets the source. Then, we compute the reward that this relay will ask the source, so as to assist in the transmission of the message. Finally, we shall investigate the cost incurred by the source for transmitting a message to the destination. Both these quantities will be studied in all the four information settings. All proofs are available in our technical report [?].

A. Probability of Success

Let s_i, $i = 1, .., N$, be the random time at which the source meets the i-th relay. We denote by $\boldsymbol{s}$ the vector $(s_1, .., s_N)$. In order to simply the notation, we shall write $\boldsymbol{s}_{-n}$ to denote the vector $(s_1, .., s_{n-1}, s_{n+1}, .., s_N)$ and $\boldsymbol{s}_{m:n} = (s_m, .., s_n)$.

Let L be an ordered set comprising all the possible orderings of the N nodes in the system, $|L| = N!$. The elements in L are ordered in lexicographic order. Let $\boldsymbol{\ell} \in L$ denote an ordering of the N nodes in the system, and let $\boldsymbol{\ell}_m \in L$ be the m-th ordering. Then, $\ell(i) = r_k$ if the i-th node to meet the source under ordering $\boldsymbol{\ell}$ is node r_k. Node $\ell(i)$ meets the source at time s_i. We denote by $\ell^{-1}(r_k)$ the index of relay r_k in vector ℓ, i.e., $\ell^{-1}(r_k) = i$ if $\ell(i) = r_k$ under ordering $\boldsymbol{\ell}$. To simplify notation, we shall write $\boldsymbol{\ell}_{-\mathbf{n}}$ to denote the vector $(\boldsymbol{\ell}_1, .., \boldsymbol{\ell}_{n-1}, \boldsymbol{\ell}_{n+1}, .., \boldsymbol{\ell}_N)$ and $\boldsymbol{\ell}_{\mathbf{m:n}} = (\boldsymbol{\ell}_m, .., \boldsymbol{\ell}_n)$.

Let $p_j^{(k)}(\boldsymbol{s}, \boldsymbol{\ell})$ be the success probability estimated by the j-th relay to meet the source under setting $k \in \{F, P+, P-, N\}$. Let $p_j(\boldsymbol{s}, \boldsymbol{\ell})$ be the actual success probability of relay $\ell(j)$ accounting for all contact times. The probability of success of r_k under the full information setting given $\boldsymbol{s}$ and ℓ is given by $p^{(F)}_{\ell^{-1}(r_k)}(\boldsymbol{s}, \boldsymbol{\ell})$. Recall that $p_j^{(F)}(\boldsymbol{s}, \boldsymbol{\ell})$ depends only on $\boldsymbol{s}_{1:j}$ and $\boldsymbol{\ell}_{1:j}$. Similar notation is used for the other settings. To simplify presentation, with some abuse of notation we may drop elements from $\boldsymbol{s}$ whenever they are unnecessary. The first and last nodes to meet the source satisfy the following relations,

$$p_1^{(P+)}(s_1, \boldsymbol{\ell}) = p_1^{(P-)}(s_1, \boldsymbol{\ell}) = p_1^{(F)}(s_1, \boldsymbol{\ell}), \quad (1)$$

$$p_N^{(F)}(\boldsymbol{s}, \boldsymbol{\ell}) = p_N(\boldsymbol{s}, \boldsymbol{\ell}). \quad (2)$$

The first equality in (1) follows from the fact that the first relay to meet the source obtains the same information under the partial and full information settings. Similarly, (2) follows from the fact that in the full information setting, the last relay knows the contact times of all other relays with the source.

Let $f_{r_k}(x)$ be the pdf of the meeting time between r_k and the source, and let $f_i(x, \boldsymbol{\ell})$ be the pdf of the meeting time between the i-th relay in $\boldsymbol{\ell}$ and the source. Given $\boldsymbol{\ell}$, we have $f_i(x, \boldsymbol{\ell}) = f_{r_{\ell(i)}}(x)$. Then,

$$f(\boldsymbol{s}, \boldsymbol{\ell}) = \prod_{i=1}^{N} f_i(s_i, \boldsymbol{\ell}), \quad f(\boldsymbol{s}_{j:k}, \boldsymbol{\ell}) = \prod_{i=j}^{k} f_i(s_i, \boldsymbol{\ell}) \quad (3)$$

$$f(\boldsymbol{s}_{1:N}) = \sum_{m=1}^{N!} f(\boldsymbol{s}_{1:N}, \boldsymbol{\ell}_m) \quad (4)$$

Let $f_i(\boldsymbol{s}, \boldsymbol{\ell})$ be the pdf of the meeting time between the source and the i-th relay in $\boldsymbol{\ell}$, conditioned that the first $i-1$ encounters between the source and relays have already occurred. We let

$$f_{i:j}(\boldsymbol{s}, \boldsymbol{\ell}) = \frac{\prod_{k=i}^{j} f_k(s_k, \boldsymbol{\ell})}{\int_{s_{i+1}=s_i:s_j=s_{j-1}}^{\infty} \prod_{k=i}^{j} f_k(s_k, \boldsymbol{\ell}) ds_{j:i+1}} \quad (5)$$

Then, if $j = i$ we have

$$f_i(\boldsymbol{s}, \boldsymbol{\ell}) = \frac{f_i(s_i, \boldsymbol{\ell})}{1 - F_i(s_{i-1}, \boldsymbol{\ell})} \quad (6)$$

If inter-contact times are exponentially distributed, the following proposition provides closed-form expressions for the probability of success. Let λ_i (resp., μ_i) be the inter-contact rate between relay i and the source (resp., the destination).

Proposition 1 (See the proofs in appendix A)***. Full information setting:*** *given information about previous inter-contact time instants through the first n entries of* $\boldsymbol{s}$ *and* $\boldsymbol{\ell}$*, we have*

$$p^{(F)}_{\ell(n)}(s_n) = \prod_{k=1}^{n-1} e^{-\mu_{\ell(k)}(s_n - s_k)} \sum_{i=n}^{N} \frac{\mu_{\ell(n)}}{\sum_{l=i+1}^{N} \lambda_{\ell(l)} + \sum_{l=1}^{i} \mu_{\ell(l)}} \times \prod_{k=n+1}^{i} \sum_{j=k}^{N} \frac{\lambda_{\ell(j)}}{\sum_{l=k}^{N} \lambda_{\ell(l)} + \sum_{l=1}^{k-1} \mu_{\ell(l)})}$$

Partial information setting with identity information: *given the number and the identity of relays that previously contacted the source, we have*

$$p_n^{(P^+)}(s_n) = \prod_{i=1}^{n-1} \lambda_i \psi(i, n) \times$$

$$\sum_{i=n}^{N}\prod_{k=n+1}^{i}\sum_{j=k}^{N}\frac{\lambda_j}{\sum_{l=k}^{N}\lambda_l+\sum_{l=1}^{k-1}\mu_l}\frac{\mu_n}{\sum_{l=i+1}^{N}\lambda_l+\sum_{l=1}^{i}\mu_l}$$

where

$$\psi(i,n)=\begin{cases}\frac{(e^{-\mu_i s_n}-e^{-\lambda_i s_n})}{(\lambda_i-\mu_i)(1-e^{-\lambda_i s_n})}, & \text{if } \lambda_i\neq\mu_i,\\ s_n e^{-\lambda_i s_n}/(1-e^{-\lambda_i s_n}), & \text{otherwise}\end{cases}$$

Partial information setting without identity information: *given only the number of relays that previously contacted the source, $n-1$, we have*

$$p_n^{(P^-)}(s_n)=\sum_{i=1}^{C_{N-1}^{n-1}}\prod_{j=1}^{n-1}\lambda_{\ell_i(j)}\psi(\ell_i(j),n)\prod_{k=n+1}^{N}e^{-\lambda_{\ell_i(k)}s_n}\times$$
$$\sum_{i=n}^{N}\prod_{k=n+1}^{i}\sum_{j=k}^{N}\frac{\lambda_j}{\sum_{l=k}^{N}\lambda_l+\sum_{l=1}^{k-1}\mu_l}\frac{\mu_n}{\sum_{l=i+1}^{N}\lambda_l+\sum_{l=1}^{i}\mu_l}$$

where

$$\psi(\ell_i(j),n)=\begin{cases}\frac{(e^{-\mu_{\ell_i(j)}s_n}-e^{-\lambda_{\ell_i(j)}s_n})}{(\lambda_{\ell_i(j)}-\mu_{\ell_i(j)})(1-e^{-\lambda_{\ell_i(j)}s_n})}, & \text{if } \lambda_{\ell_i(j)}\neq\mu_{\ell_i(j)},\\ s_n e^{-\lambda_{\ell_i(j)}s_n}/(1-e^{-\lambda_{\ell_i(j)}s_n}), & \text{otherwise}\end{cases}$$

No information setting: *given solely statistical information about inter-contact times, we have*

$$p_n^{(N)}(s)=\sum_{m=1}^{N}\sum_{i=1}^{C_{N-1}^{m-1}}\prod_{j=1}^{m-1}(1-e^{-\lambda_{\ell_i(j)}})\prod_{k=m+1}^{N}e^{-\lambda_{\ell_i(k)}}p_m^{(P)}(s)$$

B. Expected Cost for a Relay

Next, our goal is to compute the expected cost estimated by a relay to transmit a packet. Let $V_i^{(k)}(\boldsymbol{s},\boldsymbol{\ell})$ be the net expected cost incurred to transmit a packet to the destination, as estimated by the i-th node in $\boldsymbol{\ell}$ under setting k. Let $R_i^{(k)}(\boldsymbol{s},\boldsymbol{\ell})$ be the expected reward offered by the source to the i-th node in $\boldsymbol{\ell}$ to transmit a packet to the destination under setting k, $k\in\{F,P+,P-,N\}$. Recall that the reward is granted only to successful nodes. Then,

$$V_i^{(k)}(\boldsymbol{s},\boldsymbol{\ell})=c_r+c_s\mathbb{E}(T_d^{\ell(i)})+(c_d-R_i^{(k)}(\boldsymbol{s},\boldsymbol{\ell}))p_i^{(k)}(\boldsymbol{s},\boldsymbol{\ell}) \quad (7)$$

The first term in the net expected cost (7) is the reception cost, which is always incurred. The second term represents the expected in transit (storage) cost. It is directly proportional to the mean of the residual inter-contact time between relay $\ell(i)$ and the destination. The last term is the cost of transmitting the message to the destination which in turn confers a reward to the relay. This term enters into play only if relay $\ell(i)$ is the first one to reach the destination, which explains the factor $p_i^{(k)}(\boldsymbol{s},\boldsymbol{\ell})$.

C. Expected Reward Paid by the Source

Relay r_k will accept to forward a message to the destination if the reward promised by the source offsets it expected cost, that is, if $R_i^{(k)}(\boldsymbol{s},\boldsymbol{\ell})$ is such that $\mathbb{E}(V_i^{(k)}(\boldsymbol{s},\boldsymbol{\ell}))\leq 0$. Thus the minimum reward that the source has to promise relay $r_k=\boldsymbol{\ell}^{(-1)}(i)$ is

$$R_i^{(k)}(\boldsymbol{s},\boldsymbol{\ell}) = c_d+\mathcal{C}_{\ell(i)}/p_i^{(k)}(\boldsymbol{s},\boldsymbol{\ell}) \quad (8)$$

where $\mathcal{C}_{\ell(i)}=c_r+c_sE(T_d^{\ell(i)})$. Thus we have

$$R^{(k)}(\boldsymbol{s},\boldsymbol{\ell})=c_d+\sum_{i=1}^{N}\mathcal{C}_{\ell(i)}p_i(\boldsymbol{s},\boldsymbol{\ell})/p_i^{(k)}(\boldsymbol{s},\boldsymbol{\ell}). \quad (9)$$

Note that the reward requested by relay r_k depends on the information given by the source only through the estimated probability of success $p_j^{(k)}(\boldsymbol{s},\boldsymbol{\ell})$.

Now we turn our attention to the expected reward paid by the source when the expectation is taken over all possible meeting times. This quantity can be thought of as the long-run average reward per message the source will have to pay if it sends a large number of messages (and assuming that message generation occurs at a much slower time scale than that of the contact process).

Lemma 1 (See the proofs in appendix B)**.** *The expected reward paid by the source under setting (k) is given by*

$$R^{(k)}=$$
$$c_d+\sum_{\boldsymbol{\ell}_m\in L}\sum_{i=1}^{N}\mathcal{C}_{\boldsymbol{\ell}_m(i)}\int_{s_1=0:s_i=s_{i-1}}^{\infty}\frac{f(\boldsymbol{s}_{1:i},\boldsymbol{\ell}_m)}{p_i^{(k)}(\boldsymbol{s},\boldsymbol{\ell}_m)}\varphi_i(\boldsymbol{s},\boldsymbol{\ell}_m)ds_{i:1} \quad (10)$$

where

$$\varphi_i(\boldsymbol{s},\boldsymbol{\ell}_m)=\int_{s_{i+1}=s_i:s_N=s_{N-1}}^{\infty}p_i(\boldsymbol{s},\boldsymbol{\ell}_m)f(\boldsymbol{s}_{i+1:N},\boldsymbol{\ell}_m)ds_{N:i+1} \quad (11)$$

From the probability of success estimated by the relays in the four settings, we can prove that the expected reward paid by the source for delivering its message is the same in all four settings, as stated in Theorem 2.

Theorem 2 (See the proofs in appendix C)**.** *The expected reward to be paid by the source under setting $k\in\{F,P^+,P^-,N\}$ is*

$$R^{(k)}=c_d+\sum_{i=1}^{N}\mathcal{C}_{r_i} \quad (12)$$

Theorem 2 shows that the excepted reward paid by the source remains the same irrespective of the information it conveys. As mentioned in Section II-A, this is due to the balance of the flow between late arrivals and newcomers: the former are favored by the sharing of information, whereas the later benefit from information concealing.

IV. The Effect of Time To Live (TTL)

Next, we consider the scenario wherein relays stop trying to forward a packet after a prescribed period of time. To this aim, we associate to each node and to each packet a time to live (TTL) counter. After this time is elapsed, the message will be dropped. The counter associated to node i ticks at rate μ_i'. We further assume that the time between ticks is exponentially distributed. By the time the timer at node i ticks, its packet is dropped and the node enters into sleep mode.

In what follow, we study the impact of the TTL counter accounting for the tradeoff between energy gains and the probability that the destination does not receive the packet of interest. We address the following question: *what is the impact of the TTL on the delivery probability and on the energy spent by relays in order to transmit the message?*

We consider a single source-destination pair, and assume exponentially distributed inter-contact times. Future work consists of extending the analysis to relays equipped with TTL caches that transmit multiple packets between different source-destination pairs.

Recall that μ_i is the rate at which relay i meets the destination. Let $\mu_i' = \mu_i \epsilon$, with $0 < \epsilon < 1$. Let W_i be the time it takes for relay i to either meet the destination or drop a packet when its TTL expires, whatever occurs first. Then, W_i is an exponentially distributed random variable, with rate $\mu_i(1+\epsilon)$. Let D be the probability that the destination does not get the packet of interest, assuming that the source sets incentives so that all relays opt to assist in the transmission,

$$D = \prod_{i=1}^{N} \frac{\epsilon \mu_i}{\epsilon \mu_i + \mu_i} = \left(\frac{\epsilon}{\epsilon + 1} \right)^N \qquad (13)$$

Then, $\epsilon = D^{1/N}/(1 - D^{1/N})$.

Let ρ_i be the mean reduction in the length of time during which relay i tries to transmit a packet, due to the TTL counter,

$$\rho_i = E[T_d^i] - E[\tilde{T}_d^i] = \frac{1}{\mu_i} - \frac{1}{\mu_i(1+\epsilon)} = \frac{\epsilon}{1+\epsilon} E[T_d^i] \qquad (14)$$

where T_d^i and $\tilde{T}_d^i$ are the times invested in transmitting a packet before and after equipping node i with TTL counters, respectively. Let G be the relative gain of a relay node i in terms of the expected in transit (storage) cost due to the introduction of the TTL counter. Thus

$$G = \frac{c_s E[T_d^i] - c_s E[\tilde{T}_d^i]}{c_s E[T_d^i]} = \frac{\epsilon}{1+\epsilon} \qquad (15)$$

Note that neither D nor G depend on the rates at which relays meet the destination. We write $D(N, G)$ as a function of N and G, $D(N, G) = G^N, 0 \leq G < 1$. Therefore, a linear increase in G yields a sub-linear increase in $D(N, G)$.

V. Simulation Results

To validate our theoretical results, we run simulations using two types of mobility traces: (i) synthetic traces generated using the ONE (Opportunistic Network Environment) simulator [12] and (ii) real traces collected from taxi cabs in the city of Rome [4]. Our goals are to (a) parameterize the inter-contact times using real data and validate our analytical model, (b) assess the average reward set by the source under a realistic setting and (c) estimate the instantaneous rewards received by relays over time.

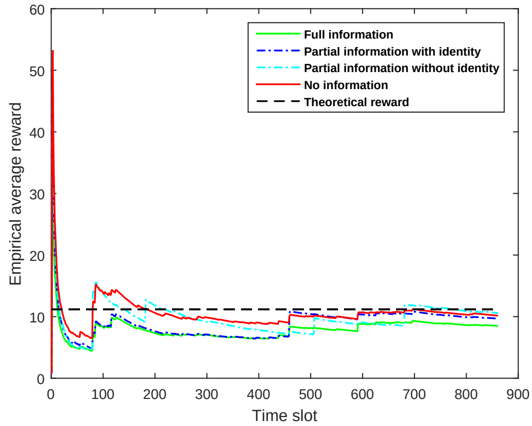

Fig. 1. Empirical average reward under the four information settings vs the theoretical reward With $N = 10$, $C_d = 0.4$, $C_r = 0.04$, $C_s = 0.01$

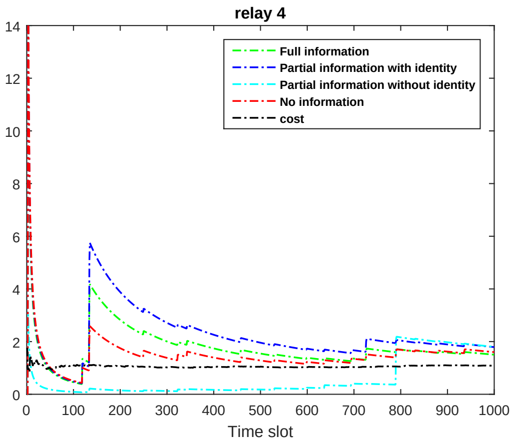

Fig. 2. Empirical average reward and the energy cost of a relay under the four information settings for $N = 10$

The key metrics that we extract from our traces are the inter-contact time distributions between relays and the source, and between relays and the destination. In our simulations, when the source meets a relay it uses the inter-contact time distribution between relays and the destination to compute the success probability as estimated by the relay. This probability of success is then used to obtain the reward that the source promises to the relay. In addition, from the traces we determine which relay gets the reward from the destination, for each message generated by the source. Finally, we make use of the mean inter-contact time between relays and the destination to compute the desired metrics of interest, using the theoretical results presented in Section III, and contrast them against our simulation results.

A. Rewards and Costs under Synthetic Traces

In our initial set of simulation results, we consider mobility traces generated using the Random Way Point mobility model (RWP). In this setting, our simulations were conducted using the ONE simulator [12]. Under the RWP model, each node moves independently to a randomly chosen destination with a randomly selected velocity. Upon reaching the destination, the node waits for a period of time (known as pause time) before choosing another destination and velocity. We consider

$N = 10$ relays placed randomly in an area of 2500×2500 m^2. The transmission range of each relay is 10 m. To take into account the heterogeneity, we have considered two classes of relays: the first class contains 10 relays who choose their velocities and pause times uniformly at random in the ranges $[1, 13.9]$ m/s and $[0, 14400]$ s, respectively. The second class contains 6 relays that choose their velocities and pause times uniformly at random in the ranges $[0.5, 1.5]$ m/s and $[0, 3600]$ s, respectively. We collect inter-contact times for a simulation time of over 1 year. Once the inter-contact time distribution is generated, we use it to compute the reward promised to each relay at each contact (refer to our technical report [?] for further details on the inter-contact times and additional statistics obtained via simulations).

To compute the probability of success and the reward requested by a relay to deliver a message we use the results presented in Proposition 1 making the assumption that the inter-contact times between relays, the source and the destination are exponentially distributed. Each message is generated by the source every 10 hours. This period of 10 hours will be called a time-slot. In Figure 1 we plot the analytical and the empirical average reward paid by the source as a function of time (measured in time-slots) under the three information settings. The empirical average reward at time-slot t is given by $\frac{1}{t}\sum_{n=1}^{t} R(n)$, where $R(i)$ is the reward paid by the source for the message generated at time-slot n. We observe that the empirical reward under the three information settings converges to the theoretical reward given by Theorem 2. In addition, the convergence time of the full and partial information settings is faster when contrasted against the no information case.

Next, we consider the rewards and costs (of energy and storage) associated to the relays. For this purpose, we tag a relay chosen arbitrarily among the 10 relays, and plot the empirical average reward received by that relay from the source as well as the associated average cost, as a function of the time-slot (see Figure 2). We observe that the reward paid by the source in the four settings offsets the expected cost of that relay as predicted by the analytical model.

B. Sensitivity Analysis and Robustness

Next, we further investigate the sensitivity of our results with respect to the assumption that inter-contact times are exponentially distributed. To this aim, we consider a source and relays that assess rewards using the exponential assumption even when the inter-contact times between relays and the source or destination follow other distributions. As in the previous section, we consider $N = 10$ relays, each of which associated to a different inter-contact time distribution (see Table II). Figure 3 shows that the empirical reward under the four information settings converges to the theoretical reward given by Theorem 2. Similarly, in Figures 4 and 5 we consider hyper exponential and Weibull inter-contact distributions, respectively. We note that the proposed reward mechanism remains robust against changes in the mobility patterns. In particular, the observations made about Figure 3 also hold for Figures 4 and 5: the empirical rewards converge to the theoretical values given by Theorem 2.

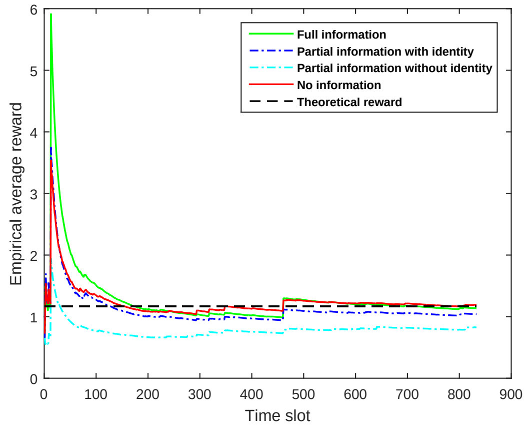

Fig. 3. Empirical average reward under the four information setting vs the theoretical reward With $N = 10$, $C_d = 0.4$, $C_r = 0.04$, $C_s = 0.01$

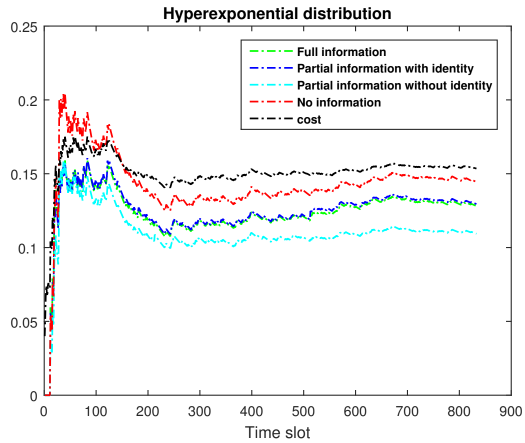

Fig. 4. Empirical average of the reward and the energy cost for a relay with hyper exponential distribution of the inter-contact time under four information settings for $N = 10$, $C_d = 0.4$, $C_r = 0.04$, $C_s = 0.01$

TABLE II
CONTACT RATES OF RELAYS WITH SOURCE AND DESTINATION

Relay	Distribution	λ	μ
r_1	Exponential	0.6530	0.7945
r_2	Exponential	0.5296	0.2824
r_3	Hyperexponential	0.6714	0.6704
r_4	Hyperexponential	0.6685	0.6670
r_5	Weibull	0.2483	0.2492
r_6	Weibull	0.1647	0.1996
r_7	Weibull	0.2500	0.2000
r_8	Folded normal	0.1999	0.1991
r_9	Folded normal	0.2002	0.2015
r_{10}	Folded normal	0.1991	0.2005

C. Real-World Traces

Next, we consider a dataset comprising traces of taxis moving in the city of Rome. Each taxi is equipped with an Android tablet device running an application that updates the current position of the taxi every 7 seconds. This dataset contains GPS coordinates of approximately 320 taxis collected over 30 days. The traces were compiled in February 2014 [4].

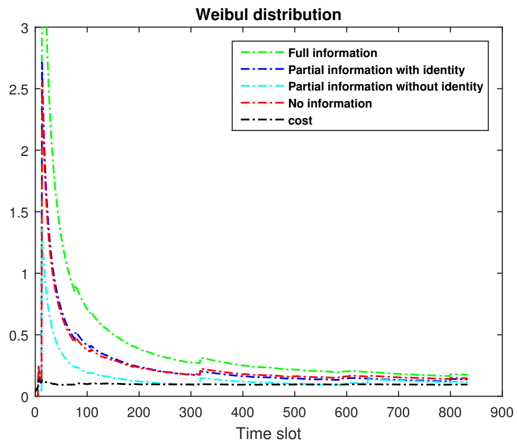

Fig. 5. Empirical average reward and energy cost for a relay with the weit distribution inter-contact time under four information settings for $N = 1$ $C_d = 0.4$, $C_r = 0.04$, $C_s = 0.01$

Fig. 6. Position of the source and the destination in the city of Rome

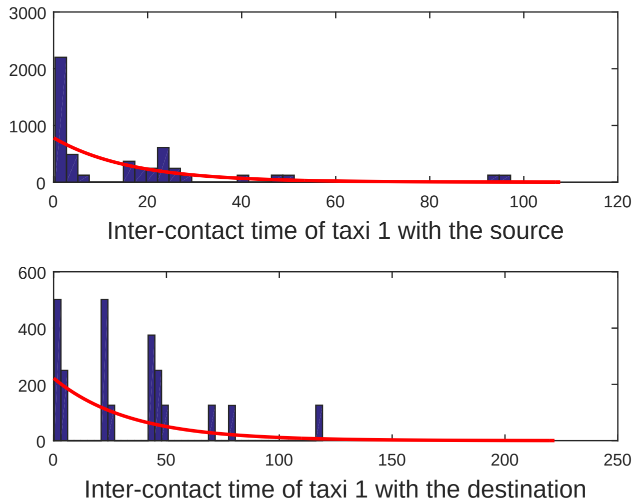

Fig. 7. Inter-contact time frequencies between a taxi, the source (top) and the destination (bottom).

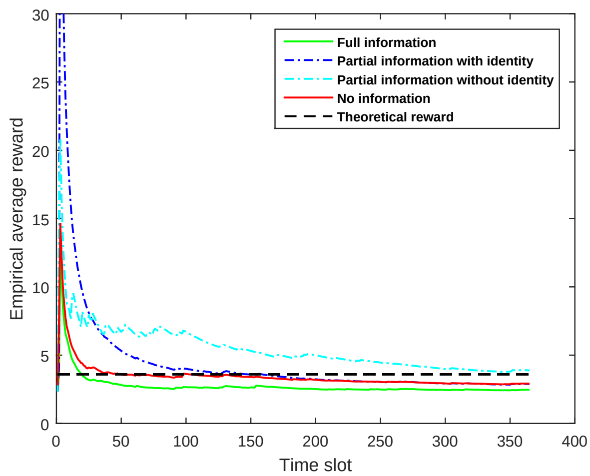

Fig. 8. Empirical average reward under four information settings vs the theoretical reward With $N = 10$

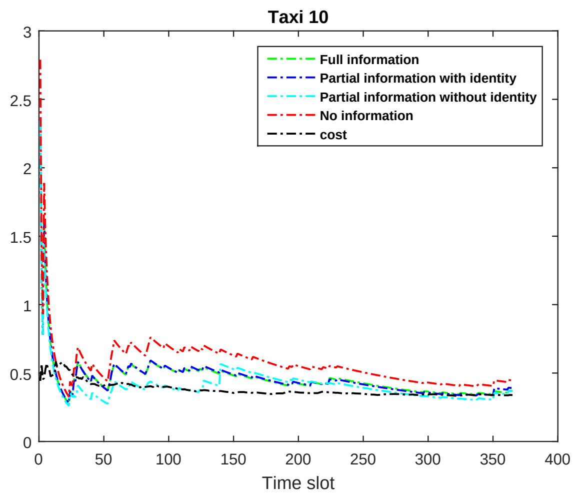

Fig. 9. Empirical average reward and energy cost for a relay under four settings, under static strategies for $N = 10$

In this simulation scenario, we consider a source-destination pair in the centre of Rome. The distance between the source and the destination is roughly 2.8 Km. Using Google Maps, Figure 6 shows the positions of the source and the destination. The transmission range of each taxi is 50 m.

We collect inter-contact times of 16 taxis with the source and the destination. In Fig. 7, we illustrate the density function of the contact time for a taxi with the source and the destination, which can be seen to be non-exponential. Table III shows the contact rates between each taxi and the source (resp. the destination), denoted by λ_i (resp. μ_i).

During the simulations, the source generates a message every 24 hours. As in Section V-B, the source computes the reward to be promised to relays assuming an exponentially distributed inter-contact time distribution.

Figure 8 shows the empirical average reward paid by the source as a function time for 10 taxis and for the four information settings. The curves clearly shows the close agreement between the analytical and simulation results. Recall that the expected reward proposed by the source to a relay was computed analytically under the exponential approximation

TABLE III

CONTACT RATES OF THE TAXIS WITH THE SOURCE AND DESTINATION.

Relay	λ	μ	Relay	λ	μ
t_1	0.0613	0.0298	t_6	0.0731	0.0445
t_2	0.0423	0.0345	t_7	0.0452	0.0322
t_3	0.0616	0.0382	t_8	0.0691	0.0513
t_4	0.0340	0.0370	t_9	0.0596	0.0309
t_5	0.0842	0.0510	t_{10}	0.1095	0.0252

for inter-contact times, whereas the simulation results were obtained using the empirical inter-contact time distribution. Figure 9 shows the empirical average reward as well the expected cost as a function of the time slot. It is interesting to note that the empirical average reward earned by the taxis, in the four information setting, converges to the theoretical reward calculated using the proposed analytical model.

VI. Discussion of Assumptions and Limitations

In this section we discuss the main assumptions that were adopted to yield a tractable model.

a) Information setting: We assume that mobile relays know the inter-contact time distribution between every node and the source as well as the destination. This assumption may be restrictive in some settings. Nonetheless, with growing mobile access to the Internet and cloud-based services, we envision a shared knowledge base maintained by the nodes. Such knowledge base makes our incentive reward mechanism realistic in practical settings such as those related to smart cities. The analysis of real-world traces indicates that our results are robust against the distribution of inter-contact times. Thus, making use of the exponential assumption for inter-contact times, knowledge of contact rates suffices to obtain a good assessment of costs and rewards.

b) Mobility patterns: A key challenge in developing our results has been to make general assumptions about the mobility of DTN nodes. In particular, the properties derived from the proposed model hold under any set of time-invariant heterogeneous mobility patterns. It is well known that human mobility patterns change during a day. Future work consists in accounting for time-variant mobility processes, and extending our results to consider time-of-the-day effects.

c) Buffer management: In this paper we presented preliminary results on the impact of time to live (TTL) counters on the delivery probability and relay memory usage, accounting for a single message to be transmitted from a source to its destination. Buffer management using TTL caches allows us to trade between delivery probability, memory footprint and congestion in the network. A detailed analysis of the impacts of the TTL parameters on system performance, as well as the study of the interplay between the delivery of multiple contents, are left as subject for future work.

VII. Conclusion

In this work, we investigated incentive mechanisms for heterogeneous mobile networks. We considered a source node working under one of four information sharing structures and showed that the expected reward to be paid by the source to relays remains the same irrespectively of the information it conveys. Finally, sensitivity analysis performed using extensive simulations indicated that the average reward paid by the source under different information sharing assumptions, in realistic settings, closely matches the expected reward estimated by our model.

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APPENDIX

A. Proof of proposition 1

Assume that the inter-contact times between a relay $i = 1, .., N$ and the source (resp. the destination) fallow an exponential distribution with rate λ_i (resp. μ_i).

*1) **Full information setting** :* The source gives information about when (the instant time) and who (identity) is encountered before. Thus, we know the vector of the contact times $\mathbf{s} = (s_1, .., s_n)$ and $\overrightarrow{\ell}$ where $\ell(i)$ denotes the relay who encounter the source at $s_i, i = 1, .., n$.

The probability that none of the relays who got the message before time s_n have not yet deliver it to the destination is

$$\prod_{k=1}^{n-1} e^{-\mu_{\ell(k)}(s_n - s_k)}$$

.

Next, we calculate the probability of a relay to be the first to encounter the destination. For example, Let $X_1, .., X_n$ be an exponential random variables with respective parameters $\lambda_1, .., \lambda_n$, the probability that the minimum is X_i is $\lambda_i / \sum_{j=1}^n \lambda_j$. Thus, the probability that the relay $\ell(n)$ is the first to meet the destination among the relays $1, .., n-1$ and before that the other relays, i.e. relays that are not yet meet the source, get the message from the source is,

$$\frac{\mu_{\ell(n)}}{\sum_{l=n+1}^{N} \lambda_{\ell(l)} + \sum_{l=1}^{n} \mu_{\ell(l)}}$$

For each time interval $(s_i, s_{i+1}], i > n$ the probability that a relay i, who have not yet the message, get the message from the source before that the others who have the message deliver it to the destination is:

$$\prod_{k=n+1}^{i} \sum_{j=k}^{N} \frac{\lambda_{\ell(j)}}{\sum_{l=k}^{N} \lambda_{\ell(l)} + \sum_{l=1}^{k-1} \mu_{\ell(l)}}$$

.

Hence, the probability that the relay $\ell(n)$ is the first to deliver the message to the destination in time interval $(s_i, s_{i+1}], n \le i < N$ is,

$$\frac{\mu_{\ell(n)}}{\sum_{l=i+1}^{N} \lambda_{\ell(l)} + \sum_{l=1}^{i} \mu_{\ell(l)}} \times \prod_{k=n+1}^{i} \sum_{j=k}^{N} \frac{\lambda_{\ell(j)}}{\sum_{l=k}^{N} \lambda_{\ell(l)} + \sum_{l=1}^{k-1} \mu_{\ell(l)}}$$

Thus, the probability of the relay $\ell(n)$ to be the first to meet the destination after the instant meeting time s_n is,

$$\sum_{i=n}^{N} \frac{\mu_{\ell(n)}}{\sum_{l=i+1}^{N} \lambda_{\ell(l)} + \sum_{l=1}^{i} \mu_{\ell(l)}} \times \prod_{k=n+1}^{i} \sum_{j=k}^{N} \frac{\lambda_{\ell(j)}}{\sum_{l=k}^{N} \lambda_{\ell(l)} + \sum_{l=1}^{k-1} \mu_{\ell(l)}} \quad (16)$$

*2) **Partial information setting with identity information**:* The source informs the relay about who got the message before but not about the instant time when they had the message. We assume that the source informs the relay about the identity of the encountered relays. Next we are going to calculate, $p_n^{(P^+)}(s_n)$, the probability of success as estimated by the relay n who met the source at s_n.

Proof. $p_n^{(P^+)}(s_n)$ is (1) the probability that none of the relays, who had the message before, have not yet met the destination and (2) the probability that the relay n is the first to meet the destination among all relays who have the message.

(1) The probability that a relay $i = 1, .., n-1$ who have the message before s_n does not yet meet the destination can be expressed as,

$$\int_0^{s_n} \frac{\lambda_i e^{-\lambda_i s} e^{-\mu_i(s_n - s)}}{1 - e^{-\lambda_i s_n}} = \begin{cases} \frac{\lambda_i}{\lambda_i - \mu_i} \frac{e^{-\mu_i s_n} - e^{-\lambda_i s_n}}{1 - e^{-\lambda_i s_n}}, & \text{if } \lambda_i \neq \mu_i, \\ \lambda_i s_n \frac{e^{-\lambda_i s_n}}{1 - e^{-\lambda_i s_n}}, & \text{otherwise} \end{cases}$$

Thus, the probability that none of the relays $1, .., n-1$ that received the message before s_n did not deliver it to the destination is,

$$\begin{cases} \prod_{i=1}^{n-1} \frac{\lambda_i (e^{-\mu_i s_n} - e^{-\lambda_i s_n})}{(\lambda_i - \mu_i)(1 - e^{-\lambda_i s_n})}, & \text{if } \lambda_i \neq \mu_i, \\ \prod_{i=1}^{n-1} \lambda_i s_n \frac{e^{-\lambda_i s_n}}{1 - e^{-\lambda_i s_n}}, & \text{otherwise} \end{cases} \quad (17)$$

(2) The probability that the relay n is the first to deliver the message to the destination is calculated as in full information setting, equation (16).

Hence,

$$p_n^{(P^+)}(s_n) = \prod_{i=1}^{n-1} \lambda_i \psi(i, n) \times \sum_{i=n}^{N} \prod_{k=n+1}^{i} \sum_{j=k}^{N} \frac{\lambda_j}{\sum_{l=k}^{N} \lambda_l + \sum_{l=1}^{k-1} \mu_l} \frac{\mu_n}{\sum_{l=i+1}^{N} \lambda_l + \sum_{l=1}^{i} \mu_l}$$

where

$$\psi(i, n) = \begin{cases} \frac{(e^{-\mu_i s_n} - e^{-\lambda_i s_n})}{(\lambda_i - \mu_i)(1 - e^{-\lambda_i s_n})}, & \text{if } \lambda_i \neq \mu_i, \\ \frac{s_n e^{-\lambda_i s_n}}{1 - e^{-\lambda_i s_n}}, & \text{otherwise} \end{cases}$$

□

*3) **Partial information setting without identity information**:* The source informs the encountered relay only about the number of relays that have the message. The relay is informed only about how many relays got the message before. We are going to calculate the probability of success as estimated by a relay n which met the source at the instant time s_n.

Proof. The probability that the relay n is the first to deliver the message to the destination is: (1) the probability that the relay who got the message before have not yet delivered it to the destination and (2) the probability to be the first to meet the destination among all relays who have the message.

(1) As the relay does not know the identity of relays who got the message before, thus the probability that the message has not reached the destination is: the sum of all possible ordering of $n-1$ element from $N-1$ that the $n-1$ relays met the source and they have not delivered the message to the destination yet times the probability that the other relays (i.e., $(N-1)-(n-1)$) have not met the source. this probability is calculated as follows

$$\sum_{i=1}^{C_{N-1}^{n-1}} \prod_{j=1}^{n-1} \lambda_{\ell_i(j)} \psi(\ell_i(j), n) \prod_{k=n+1}^{N} e^{-\lambda_{\ell_i(k)} s_n} \tag{18}$$

(2) The probability that the relay n is the first to deliver the message to the destination is calculated as in full information setting, equation (16).

Hence, the probability that the relay n is the first one who delivers the message to the destination knowing that $n-1$ they have already the message is:

$$p_n^{(P^-)}(s_n) = \sum_{i=1}^{C_{N-1}^{n-1}} \prod_{j=1}^{n-1} \lambda_{\ell_i(j)} \psi(\ell_i(j), n) \prod_{k=n+1}^{N} e^{-\lambda_{\ell_i(k)} s_n} \times \sum_{i=n}^{N} \prod_{k=n+1}^{i} \sum_{j=k}^{N} \frac{\lambda_j}{\sum_{l=k}^{N} \lambda_l + \sum_{l=1}^{k-1} \mu_l} \frac{\mu_n}{\sum_{l=i+1}^{N} \lambda_l + \sum_{l=1}^{i} \mu_l}$$

where

$$\psi(\ell_i(j), n) = \begin{cases} \frac{(e^{-\mu_{\ell_i(j)} s_n} - e^{-\lambda_{\ell_i(j)} s_n})}{(\lambda_{\ell_i(j)} - \mu_{\ell_i(j)})(1 - e^{-\lambda_{\ell_i(j)} s_n})}, \text{if } \lambda_{\ell_i(j)} \neq \mu_{\ell_i(j)}, \\ s_n e^{-\lambda_{\ell_i(j)} s_n} / (1 - e^{-\lambda_{\ell_i(j)} s_n}), \quad \text{otherwise} \end{cases}$$

□

*4) **No information setting**:* The source does not give any information to the relay. The relay only knows the instant meeting time s with the source.

Proof. Given s the instant meeting time of a relay n, $1 \leq n \leq N$ with the source and note by λ_i (resp. μ_i) the meeting rate of a relay $i, i \leq N$ with the source (resp. the destination). The probability that $m-1$ relays from $N-1$ have already met the source before time s is

$$C_{N-1}^{m-1} \prod_{j=1}^{m-1} (1 - e^{-\lambda_{\ell_i(j)}}) \prod_{k=m+1}^{N} e^{-\lambda_{\ell_i(k)}}$$

The probability of success of the relay i if he knows how many nodes have already the message is $p_i^{(P^+)}(s)$. Hence, the probability of success of a relay n, $1 \leq n \leq N$ if it does not have any information is:

$$p_n^{(N)}(s) = \sum_{m=1}^{N} \sum_{i=1}^{C_{N-1}^{m-1}} \prod_{j=1}^{m-1} (1 - e^{-\lambda_{\ell_i(j)}}) \prod_{k=m+1}^{N} e^{-\lambda_{\ell_i(k)}} p_m^{(P^+)}(s)$$

□

B. Proof of lemma 1

Proof. The expected reward paid by the source under setting (k) is

$$\begin{aligned} R^{(k)} &= c_d + \int_{s_1=0:s_N=s_{N-1}}^{\infty} \sum_{\boldsymbol{\ell}_m \in L} R^{(k)}(\boldsymbol{s}, \boldsymbol{\ell}_m) f(\boldsymbol{s}, \boldsymbol{\ell}_m) ds_N \ldots ds_1 \\ &= c_d + \int_{s_1=0:s_N=s_{N-1}}^{\infty} \sum_{\boldsymbol{\ell}_m \in L} \sum_{i=1}^{N} \mathcal{C}_{\boldsymbol{\ell}_m(i)} \frac{p_i(\boldsymbol{s}, \boldsymbol{\ell}_m)}{p_i^{(k)}(\boldsymbol{s}, \boldsymbol{\ell}_m)} f(\boldsymbol{s}, \boldsymbol{\ell}_m) ds_{N:1} \\ &= c_d + \sum_{\boldsymbol{\ell}_m \in L} \sum_{i=1}^{N} \mathcal{C}_{\boldsymbol{\ell}_m(i)} \int_{s_1=0:s_N=s_{N-1}}^{\infty} \frac{p_i(\boldsymbol{s}, \boldsymbol{\ell}_m)}{p_i^{(k)}(\boldsymbol{s}, \boldsymbol{\ell}_m)} f(\boldsymbol{s}, \boldsymbol{\ell}_m) ds_{N:1} \end{aligned} \tag{19}$$

if we set

$$\varphi_i(\boldsymbol{s}, \boldsymbol{\ell}_m) = \int_{s_{i+1}=s_i:s_N=s_{N-1}}^{\infty} p_i(\boldsymbol{s}, \boldsymbol{\ell}_m) f(\boldsymbol{s}_{i+1:N}, \boldsymbol{\ell}_m) ds_{N:i+1} \tag{20}$$

we get the expression of Lemma 1:

$$R^{(k)} = c_d + \sum_{\boldsymbol{\ell}_m \in L} \sum_{i=1}^{N} \mathcal{C}_{\boldsymbol{\ell}_m(i)} \int_{s_1=0:s_i=s_{i-1}}^{\infty} \frac{f(\boldsymbol{s}_{1:i}, \boldsymbol{\ell}_m)}{p_i^{(k)}(\boldsymbol{s}, \boldsymbol{\ell}_m)} \varphi_i(\boldsymbol{s}, \boldsymbol{\ell}_m) ds_{i:1} \tag{21}$$

□

C. Proof of Theorem 2

Proof. We calculate the expected reward to be paid by the source in all information settings.

1) Full Information Setting: We relate $p_j^{(F)}(\boldsymbol{s}, \boldsymbol{\ell})$, The probability of success for the the j-th relay to meet the source under the full information setting, to $p_j(\boldsymbol{s}, \boldsymbol{\ell})$ by removing the dependency of $p_j(\boldsymbol{s}, \boldsymbol{\ell})$ on $s_{j+1}, s_{j+2}, \ldots, s_N$. We get

$$\begin{aligned} &p_j^{(F)}(\boldsymbol{s}, \boldsymbol{\ell}) \\ &= \sum_{\substack{\boldsymbol{\ell}_m \in L \\ \boldsymbol{\ell}_m(1:j) = \boldsymbol{\ell}(1:j)}} \int_{s_{j+1}=s_j:s_N=s_{N-1}}^{\infty} p_j(\boldsymbol{s}, \boldsymbol{\ell}_m) f_{j+1:N}(\boldsymbol{s}, \boldsymbol{\ell}_m) ds_{N:j+1} \\ &= \frac{\sum_{\substack{\boldsymbol{\ell}_m \in L \\ \boldsymbol{\ell}_m(1:j) = \boldsymbol{\ell}(1:j)}} \int_{s_j:s_{N-1}}^{\infty} p_j(\boldsymbol{s}, \boldsymbol{\ell}_m) \prod_{i=j+1}^{N} f_i(s_i, \boldsymbol{\ell}_m) ds_{N:j+1}}{\sum_{\substack{\boldsymbol{\ell}_m \in L \\ \boldsymbol{\ell}_m(1:j) = \boldsymbol{\ell}(1:j)}} \int_{s_j:s_{N-1}}^{\infty} \prod_{i=j+1}^{N} f_i(s_i, \boldsymbol{\ell}_m) ds_{N:j+1}} \end{aligned} \tag{22}$$

Let define $g_i(s_i, \boldsymbol{\ell}_m)$ as follows

$$g_i(s_i, \boldsymbol{\ell}) = \sum_{\substack{\boldsymbol{\ell}_m \in L \\ \boldsymbol{\ell}_m(1:j) = \boldsymbol{\ell}(1:j)}} \int_{s_{i+1}=s_i:s_N=s_{N-1}}^{\infty} \prod_{j=i+1}^{N} f_j(s_j, \boldsymbol{\ell}_m) ds_{N:i+1}$$

Thus

$$p_i^{(F)}(\boldsymbol{s}, \boldsymbol{\ell}) = \frac{\sum_{\substack{\boldsymbol{\ell}_m \in L \\ \boldsymbol{\ell}_m(1:j) = \boldsymbol{\ell}(1:j)}} \varphi_i(\boldsymbol{s}, \boldsymbol{\ell})}{g_i(s_i, \boldsymbol{\ell})} \tag{23}$$

Now we are going to calculate the average reward paid by the source taking into consideration all the possible scenarios for sending a message using the full information setting. From Lemma 1 we have:

$$\begin{aligned}
&R^{(F)} - c_d \\
&=\sum_{m=1}^{N!}\sum_{i=1}^{N}\mathcal{C}_{\boldsymbol{\ell}_m(i)}\int_{s_1=0:s_i=s_{i-1}}^{\infty} f(\boldsymbol{s}_{1:i},\boldsymbol{\ell}_m)g_i(s_i,\boldsymbol{\ell}_m)\frac{\varphi_i(\boldsymbol{s},\boldsymbol{\ell})}{\sum\varphi_i(\boldsymbol{s},\boldsymbol{\ell})}ds_{i:1} \\
&=\sum_{i=1}^{N}\mathcal{C}_{r_i}\Psi_i(\boldsymbol{s}) \qquad (24)
\end{aligned}$$

where $\Psi_i(\boldsymbol{s}) =$

$$\sum_{j=1}^{N}\sum_{\substack{\boldsymbol{\ell}_m\in L:\\ \boldsymbol{\ell}_m(j)=r_i}}\int_{s_1=0:s_j=s_{j-1}}^{\infty} f(\boldsymbol{s}_{1:j},\boldsymbol{\ell}_m)g_j(s_j,\boldsymbol{\ell}_m)\frac{\varphi_j(\boldsymbol{s},\boldsymbol{\ell})}{\sum\varphi_j(\boldsymbol{s},\boldsymbol{\ell})}ds_{j:1} \qquad (25)$$

Next, we are going to show that $\Psi_i(\boldsymbol{s}) = 1$.

$$\begin{aligned}
\Psi_i(\boldsymbol{s},\boldsymbol{\ell}) &= \sum_{j=1}^{N}\sum_{\substack{\boldsymbol{\ell}_m(1:j)\in L_j:\\ \boldsymbol{\ell}_m(j)=r_i}}\sum_{\substack{\tilde{\boldsymbol{\ell}}_m\in L:\\ \tilde{\boldsymbol{\ell}}_m(1:j)=\boldsymbol{\ell}_m(1:j)}} \\
&\quad \int_{s_1=0:s_j=s_{j-1}}^{\infty} f(\boldsymbol{s}_{1:j})g_j(s_j,\boldsymbol{\ell}_m)\frac{\varphi_j(\boldsymbol{s},\boldsymbol{\ell}_m)}{\sum\varphi_j(\boldsymbol{s},\boldsymbol{\ell})}ds_{j:1} \\
&= \sum_{j=1}^{N}\sum_{\substack{\forall\boldsymbol{\ell}_m(1:j):\\ \boldsymbol{\ell}_m(j)=r_i}}\int_{s_1=0:s_j=s_{j-1}}^{\infty} f(\boldsymbol{s}_{1:j},\boldsymbol{\ell}_m)g_j(s_j,\boldsymbol{\ell}_m)ds_{j:1} \\
&= \sum_{j=1}^{N}\sum_{\substack{\forall\boldsymbol{\ell}_m(1:j):\\ \boldsymbol{\ell}_m(j)=r_i}}\int_{s_1=0:s_j=s_{j-1}}^{\infty} f(\boldsymbol{s}_{1:j},\boldsymbol{\ell}_m)g_j(s_j,\boldsymbol{\ell}_m)ds_{j:1} \\
&= \sum_{m=1}^{N!}\sum_{j=1}^{N}1_{\boldsymbol{\ell}_j(m)=r_i}\int_{s_1=0:s_N=s_{N-1}}^{\infty} f(\boldsymbol{s}_{1:N},\boldsymbol{\ell}_m)ds_{N:1} \\
&= \sum_{m=1}^{N!}\int_{s_1=0:s_N=s_{N-1}}^{\infty} f(\boldsymbol{s}_{1:N},\boldsymbol{\ell}_m)ds_{N:1} \\
&= 1
\end{aligned}$$

Hence, the expected reward to be paid by the source under the full information setting is:

$$R^{(F)} = c_d + \sum_{i=1}^{N}\mathcal{C}_{r_i} \qquad (26)$$

2) Partial Information setting: In the partial information setting the source informs the relay about the set of encountered relays (i.e. the relays who had already the message), but it does not divulge the relays infection time. We distinguish two cases: The source can either 1) divulge the number and the identity of relays who met the source before, let denote this case by P^+. Or 2) divulge just the number of relays who met the source i.e. the relay will not know the identity of relays, let denote this case by P^-. Next we will calculate the expected reward to be paid by the source in the two cases of the partial information setting.

Partial Information with identity of relays for previous contacts: From Lemma 1, we have:

$$\begin{aligned}
&R^{(P^+)} - c_d = \\
&\sum_{m=1}^{N!}\sum_{i=1}^{N}\mathcal{C}_{\boldsymbol{\ell}_m(i)}\int_{s_1=0:s_i=s_{i-1}}^{\infty}\frac{f(\boldsymbol{s}_{1:i},\boldsymbol{\ell}_m)}{p_i^{(P^+)}(\boldsymbol{s},\boldsymbol{\ell}_m)}\varphi_i(\boldsymbol{s},\boldsymbol{\ell}_m)ds_{i:1}
\end{aligned} \qquad (27)$$

Note that $p_i^{(P^+)}$ depends on $\boldsymbol{s}$ only through s_i. Therefore, we replace the order of the integrals in the expression above, and write

$$R^{(P^+)} = c_d + \sum_{m=1}^{N!}\sum_{i=1}^{N}\mathcal{C}_{\boldsymbol{\ell}_m(i)}\int_{s_i=0}^{\infty}\frac{f(\boldsymbol{s}_i,\boldsymbol{\ell}_m)}{p_i^{(P^+)}(\boldsymbol{s},\boldsymbol{\ell}_m)}\Phi_i(\boldsymbol{s},\boldsymbol{\ell}_m)ds_i \qquad (28)$$

where

$$\begin{aligned}
&\Phi_i(\boldsymbol{s},\boldsymbol{\ell}) \\
&= \int_{s_1=0:s_{i-1}=s_{i-2}}^{s_i:s_i}\int_{s_{i+1}=s_i:s_N=s_{N-1}}^{\infty} p_i(\boldsymbol{s},\boldsymbol{\ell})\prod_{\substack{j=1\\ j\neq i}}^{N} f_j(s_j,\boldsymbol{\ell})ds_{-i} \\
&= \int_{s_{i-1}=0:s_1=0}^{s_i:s_2}\int_{s_{i+1}=s_i:s_N=s_{N-1}}^{\infty} p_i(\boldsymbol{s},\boldsymbol{\ell})\prod_{\substack{j=1\\ j\neq i}}^{N} f_j(s_j,\boldsymbol{\ell})ds_{-i} \\
&= \int_{s_{i-1}=0:s_1=0}^{s_i:s_2} f(\boldsymbol{s}_{1:i-1},\boldsymbol{\ell})\varphi_i(\boldsymbol{s},\boldsymbol{\ell})ds_{1:i-1} \\
&= \overline{g}_i(s_i,\boldsymbol{\ell})\int_{s_{i-1}=0:s_1=0}^{s_i:s_2}\hat{p}_i^{(F)}(\boldsymbol{s},\boldsymbol{\ell})\prod_{j=1}^{i-1} f_j(s_j,\boldsymbol{\ell})ds_{1:i-1}
\end{aligned} \qquad (29)$$

Next, we derive a simple expression for $p_i^{(P^+)}(\boldsymbol{s},\boldsymbol{\ell})$ as a function of $p_i^{(F)}(\boldsymbol{s},\boldsymbol{\ell})$,

$$\begin{aligned}
&p_i^{(P^+)}(\boldsymbol{s},\boldsymbol{\ell}) \\
&= \int_{s_1=0:s_{i-1}=s_{i-2}}^{s_i:s_i} p_i^{(F)}(\boldsymbol{s},\boldsymbol{\ell})f_{1:i-1}(\boldsymbol{s},\boldsymbol{\ell})ds_{i-1:1} \\
&= \frac{\int_{s_1=0:s_{i-1}=s_{i-2}}^{s_i:s_i} p_i^{(F)}(\boldsymbol{s},\boldsymbol{\ell})\prod_{j=1}^{i-1} f_j(s_j,\boldsymbol{\ell})ds_{i-1:1}}{\int_{s_1=0:s_{i-1}=s_{i-2}}^{s_i:s_i}\prod_{j=1}^{i-1} f_j(s_j,\boldsymbol{\ell})ds_{i-1:1}} \\
&= \frac{\int_{s_{i-1}=0:s_1=0}^{s_i:s_2} p_i^{(F)}(\boldsymbol{s},\boldsymbol{\ell})\prod_{j=1}^{i-1} f_j(s_j,\boldsymbol{\ell})ds_{1:i-1}}{\int_{s_{i-1}=0:s_1=0}^{s_i:s_2}\prod_{j=1}^{i-1} f_j(s_j,\boldsymbol{\ell})ds_{1:i-1}}
\end{aligned} \qquad (30)$$

We have $p_i^{(P^+)}(\boldsymbol{s},\boldsymbol{\ell})$ depends on $\boldsymbol{\ell}$. This is because we are assuming that the i-th node in $\boldsymbol{\ell}$ knows the identities of the previous $i-1$ nodes encountered by the source. Therefore, $p_i^{(P^+)}(\boldsymbol{s},\boldsymbol{\ell})$ depends on $\boldsymbol{\ell}$ through its first i entries.

Let

$$h_i(s_i,\boldsymbol{\ell}_m) = \int_{s_{i-1}=0:s_1=0}^{s_i:s_2}\prod_{j=1}^{i-1} f_j(s_j,\boldsymbol{\ell}_m)ds_{1:i-1} \qquad (31)$$

Note that whereas the function h integrates over encounters that occurred previous to s_i (backward), the function g integrates over future encounters (forward). Then, $p_i^{(P^+)}(\boldsymbol{s},\boldsymbol{\ell})$ can be written as a function of g and h as follows,

$$p_i^{(P^+)}(\boldsymbol{s},\boldsymbol{\ell}) = \frac{1}{\overline{g}_i(s_i,\boldsymbol{\ell})h_i(s_i,\boldsymbol{\ell})} \sum_{\substack{\forall \boldsymbol{\ell}_m: \\ \boldsymbol{\ell}_m(1:i)=\boldsymbol{\ell}(1:i)}} \Phi_i(\boldsymbol{s},\boldsymbol{\ell}_m) \quad (32)$$

Note that (32) is analogous to (23). Replacing (32) into (28) we get,

$$\begin{aligned}
&R^{(P^+)} - c_d \\
&= \sum_{m=1}^{N!}\sum_{i=1}^{N} \mathcal{C}_{\boldsymbol{\ell}_m(i)} \int_{s_i=0}^{\infty} \frac{f(\boldsymbol{s}_i,\boldsymbol{\ell}_m)}{p_i^{(P^+)}(\boldsymbol{s},\boldsymbol{\ell}_m)} \Phi_i(\boldsymbol{s},\boldsymbol{\ell}_m) ds_i \\
&= \sum_{i=1}^{N} \mathcal{C}_{r_i} \sum_{j=1}^{N} \sum_{\substack{m=1 \\ \boldsymbol{\ell}_m(j)=r_i}}^{N!} \int_{s_j=0}^{\infty} \frac{f(\boldsymbol{s}_j,\boldsymbol{\ell}_m)}{p_j^{(P^+)}(\boldsymbol{s},\boldsymbol{\ell}_m)} \Phi_j(\boldsymbol{s},\boldsymbol{\ell}_m) ds_j \\
&= \sum_{i=1}^{N} \mathcal{C}_{r_i} \Xi_i(\boldsymbol{s},\boldsymbol{\ell}) \qquad (33)
\end{aligned}$$

where

$$\Xi_i(\boldsymbol{s},\boldsymbol{\ell}) = \sum_{j=1}^{N} \sum_{\substack{m=1 \\ \boldsymbol{\ell}_m(j)=r_i}}^{N!} \int_{s_j=0}^{\infty} \frac{f(\boldsymbol{s}_j,\boldsymbol{\ell}_m)}{p_j^{(P^+)}(\boldsymbol{s},\boldsymbol{\ell}_m)} \Phi_j(\boldsymbol{s},\boldsymbol{\ell}_m) ds_j \quad (34)$$

Next, we are going to show that $\Xi_i(\boldsymbol{s},\boldsymbol{\ell}) = 1$.

$$\begin{aligned}
&\Xi_i(\boldsymbol{s},\boldsymbol{\ell}) \\
&= \sum_{j=1}^{N} \sum_{\substack{m=1 \\ \boldsymbol{\ell}_m(j)=r_i}}^{N!} \int_{s_j=0}^{\infty} \frac{f(\boldsymbol{s}_j,\boldsymbol{\ell}_m)}{p_j^{(P_+)}(\boldsymbol{s},\boldsymbol{\ell}_m)} \Phi_j(\boldsymbol{s},\boldsymbol{\ell}_m) ds_j \\
&= \sum_{j=1}^{N} \sum_{\substack{\forall \boldsymbol{\ell}_m(1:j): \\ \boldsymbol{\ell}_m(j)=r_i}} \sum_{\substack{\forall \tilde{\boldsymbol{\ell}}_m: \\ \tilde{\boldsymbol{\ell}}_m(1:j)=\boldsymbol{\ell}_m(1:j)}} \int_{s_j=0}^{\infty} \frac{f(\boldsymbol{s}_j,\boldsymbol{\ell}_m)}{p_j^{(P_+)}(\boldsymbol{s},\boldsymbol{\ell}_m)} \Phi_j(\boldsymbol{s},\tilde{\boldsymbol{\ell}}_m) ds_j \\
&= \sum_{j=1}^{N} \sum_{\substack{\forall \boldsymbol{\ell}_m(1:j): \\ \boldsymbol{\ell}_m(j)=r_i}} \int_{s_j=0}^{\infty} \frac{f(\boldsymbol{s}_j,\boldsymbol{\ell}_m)\overline{g}_j(s_j,\boldsymbol{\ell}_m)h_j(s_j,\boldsymbol{\ell}_m)}{\sum_{\substack{\forall \tilde{\boldsymbol{\ell}}_m: \\ \tilde{\boldsymbol{\ell}}_m(1:j)=\boldsymbol{\ell}_m(1:j)}} \Phi_i(\boldsymbol{s},\tilde{\boldsymbol{\ell}}_m)} \\
&\qquad \times \sum_{\substack{\forall \tilde{\boldsymbol{\ell}}_m: \\ \tilde{\boldsymbol{\ell}}_m(1:j)=\boldsymbol{\ell}_m(1:j)}} \Phi_j(\boldsymbol{s},\tilde{\boldsymbol{\ell}}_m) ds_j \\
&= \sum_{j=1}^{N} \sum_{\substack{\forall \boldsymbol{\ell}_m: \\ \boldsymbol{\ell}_m(j)=r_i}} \int_{s_j=0}^{\infty} f(\boldsymbol{s}_j,\boldsymbol{\ell}_m) g_i(s_i,\boldsymbol{\ell}_m) h_i(s_i,\boldsymbol{\ell}_m) ds_j \\
&= 1 \qquad (35)
\end{aligned}$$

Hence, the expected reward paid by the source under the partial information setting with identity information about previous contacts is :

$$R^{(P^+)} = c_d + \sum_{i=1}^{N} \mathcal{C}_{r_i} \quad (36)$$

Partial Information Without Identity Information About Previous Contacts: Now consider the partial information setup wherein relays are not informed about the identities of relays that have already encountered the source in the previous contacts. As the arguments are very similar to the ones presented in the previous setup, we focus only on the key steps.

First, we derive $p_i^{(P^+)}(\boldsymbol{s},\boldsymbol{\ell})$, which is a function of i, s_i and $\boldsymbol{\ell}(i)$.

$$\begin{aligned}
&p_i^{(P^+)}(\boldsymbol{s},\boldsymbol{\ell}) \\
&= \frac{\sum_{\substack{\forall \boldsymbol{\ell}_m: \\ \boldsymbol{\ell}_m(i)=\boldsymbol{\ell}(i)}} \int_{0:s_{i-1}}^{s_i:s_i} \int_{s_i:s_{N-1}}^{\infty} p_i(\boldsymbol{s},\boldsymbol{\ell}_m) \prod_{\substack{j=1 \\ j\neq i}}^{N} f_j(s_j,\boldsymbol{\ell}_m) ds_{-i}}{\sum_{\substack{\forall \boldsymbol{\ell}_m: \\ \boldsymbol{\ell}_m(i)=\boldsymbol{\ell}(i)}} \int_{s_1=0:s_{i-1}=s_{i-2}}^{s_i:s_i} \int_{s_i:s_{N-1}}^{\infty} \prod_{\substack{j=1 \\ j\neq i}}^{N} f_j(s_j,\boldsymbol{\ell}_m) ds_{-i}} \\
&= \frac{1}{\overline{h}_i(s_i,\boldsymbol{\ell}_m)} \sum_{\substack{\forall \boldsymbol{\ell}_m: \\ \boldsymbol{\ell}_m(i)=\boldsymbol{\ell}(i)}} \Phi_i(\boldsymbol{s},\boldsymbol{\ell}_m) \qquad (37)
\end{aligned}$$

where

$$\begin{aligned}
\overline{h}_i(s_i,\boldsymbol{\ell}) &= \sum_{\substack{\forall \boldsymbol{\ell}_m: \\ \boldsymbol{\ell}_m(i)=\boldsymbol{\ell}(i)}} \int_{0:s_{i-2}}^{s_i:s_i} \int_{s_i:s_{N-1}}^{\infty} \prod_{\substack{j=1 \\ j\neq i}}^{N} f_j(s_j,\boldsymbol{\ell}_m) ds_{-i} \\
&= \sum_{\substack{\forall \boldsymbol{\ell}_m(1:i): \\ \boldsymbol{\ell}_m(i)=\boldsymbol{\ell}(i)}} \int_{0:0}^{s_i:s_2} \prod_{j=1}^{i-1} f_j(s_j,\boldsymbol{\ell}_m) g_i(s_i,\boldsymbol{\ell}_m) ds_{1:i-1} \qquad (38)
\end{aligned}$$

Note that (37) is analogous to (32). Considering now the partial information setup without information about previous contacts.

Replacing (37) into (28),

$$\begin{aligned}
&R^{(P^-)} - c_d \\
&= \sum_{m=1}^{N!}\sum_{i=1}^{N} \mathcal{C}_{\boldsymbol{\ell}_m(i)} \int_{s_i=0}^{\infty} \frac{f(\boldsymbol{s}_i,\boldsymbol{\ell}_m)}{\overline{p}_i^{(P^-)}(\boldsymbol{s},\boldsymbol{\ell}_m)} \Phi_i(\boldsymbol{s},\boldsymbol{\ell}_m) ds_i \\
&= \sum_{i=1}^{N} \mathcal{C}_{r_i} \sum_{j=1}^{N} \sum_{\substack{m=1 \\ \boldsymbol{\ell}_m(j)=r_i}}^{N!} \int_{s_j=0}^{\infty} \frac{f(\boldsymbol{s}_j,\boldsymbol{\ell}_m)}{\overline{p}_j^{(P^-)}(\boldsymbol{s},\boldsymbol{\ell}_m)} \Phi_j(\boldsymbol{s},\boldsymbol{\ell}_m) ds_j \\
&= \sum_{i=1}^{N} \mathcal{C}_{r_i} \overline{\Xi}_i(\boldsymbol{s},\boldsymbol{\ell}) \qquad (39)
\end{aligned}$$

where

$$\overline{\Xi}_i(\boldsymbol{s},\boldsymbol{\ell}) = \sum_{j=1}^{N} \sum_{\substack{m=1 \\ \boldsymbol{\ell}_m(j)=r_i}}^{N!} \int_{s_j=0}^{\infty} \frac{f(\boldsymbol{s}_j,\boldsymbol{\ell}_m)}{\overline{p}_j^{(P^-)}(\boldsymbol{s},\boldsymbol{\ell}_m)} \Phi_j(\boldsymbol{s},\boldsymbol{\ell}_m) ds_j \quad (40)$$

Next, we are going to show that $\overline{\Xi}_i(\boldsymbol{s},\boldsymbol{\ell}) = 1$.

$$\begin{aligned}
&\overline{\Xi}_i(\boldsymbol{s},\boldsymbol{\ell}) \\
&= \sum_{j=1}^{N} \sum_{\substack{m=1 \\ \boldsymbol{\ell}_m(j)=r_i}}^{N!} \int_{s_j=0}^{\infty} \frac{f(\boldsymbol{s}_j,\boldsymbol{\ell}_m)}{\overline{p}_j^{(P^-)}(\boldsymbol{s},\boldsymbol{\ell}_m)} \Phi_j(\boldsymbol{s},\boldsymbol{\ell}_m) ds_j
\end{aligned}$$

$$
\begin{aligned}
&= \sum_{j=1}^{N} \int_{s_j=0}^{\infty} \frac{f_{r_i}(s_j)}{\overline{p}_j^{(P-)}(s_j, r_i)} \sum_{\substack{m=1 \\ \boldsymbol{\ell}_m(j)=r_i}}^{N!} \Phi_j(\boldsymbol{s}, \boldsymbol{\ell}_m) ds_j \\
&= \sum_{j=1}^{N} \int_{s_j=0}^{\infty} \frac{f_{r_i}(s_j)\overline{h}_j(s_j, \boldsymbol{\ell})}{\sum_{\substack{m=1 \\ \boldsymbol{\ell}_m(j)=r_i}}^{N!} \Phi_j(\boldsymbol{s}, \boldsymbol{\ell}_m)} \sum_{\substack{m=1 \\ \boldsymbol{\ell}_m(j)=r_i}}^{N!} \Phi_j(\boldsymbol{s}, \boldsymbol{\ell}_m) ds_j \\
&= \sum_{j=1}^{N} \int_{s_j=0}^{\infty} f_{r_i}(s_j)\overline{h}_j(s_j, \boldsymbol{\ell}) ds_j \\
&= \sum_{m=1}^{N!} g(\boldsymbol{\ell}_m) \\
&= 1
\end{aligned}
$$

3) No information: The source doesn't give any information about the previous contacts to the encountered relay. Recall that $p_{r_i}^{(N)}(s)$ is the probability of the relay r_i to be the first to meet the destination, given that it encountered the source at time s, as estimated by such node.

We start by deriving an expression for $p_{r_i}^{(N)}(s)$ as a function of $\Phi_i(\boldsymbol{s}, \boldsymbol{\ell})$; the probability that the i-th node, to meet the source under ordering $\boldsymbol{\ell}$, is the first to meet the destination, as estimated by such node which is given by (29). As $\Phi_i(\boldsymbol{s}, \boldsymbol{\ell})$ depends on $\boldsymbol{s}$ only through s_i, we denote it by $\Phi_i(s, \boldsymbol{\ell})$. Then,

$$
p_{r_i}^{(N)}(s) = \sum_{m=1}^{N!} \Phi_{\boldsymbol{\ell}_m^{-1}(r_i)}(s, \boldsymbol{\ell}_m) \tag{41}
$$

Alternatively, $p_{r_i}^{(N)}(s)$ is given as follows,

$$
p_{r_i}^{(N)}(s) = \sum_{n=1}^{N} \sum_{\forall \boldsymbol{\ell}_m : \boldsymbol{\ell}_m(n)=r_i} \Phi_n(s, \boldsymbol{\ell}_m) \tag{42}
$$

To see the equivalence between (41) and (42), we note that it follows from (42) that

$$
\begin{aligned}
p_{r_i}^{(N)}(s) &= \sum_{\forall \boldsymbol{\ell}_m} \sum_{n=1}^{N} 1_{\boldsymbol{\ell}_m(n)=r_i} \Phi_n(s, \boldsymbol{\ell}_m) \\
&= \sum_{m=1}^{N!} \sum_{n=1}^{N} 1_{\boldsymbol{\ell}_m(n)=r_i} \Phi_n(s, \boldsymbol{\ell}_m) \\
&= \sum_{m=1}^{N!} \Phi_{\boldsymbol{\ell}_m^{-1}(r_i)}(s, \boldsymbol{\ell}_m)
\end{aligned} \tag{43}
$$

where 1_c denotes an indicator function, equal to 1 if condition c holds and 0 otherwise.

From (10) we have that

$$
\begin{aligned}
&R^{(N)} - c_d \\
&= \sum_{m=1}^{N!} \sum_{i=1}^{N} \mathcal{C}_{\boldsymbol{\ell}_m(i)} \int_{s_1=0:s_N=s_{N-1}}^{\infty} \frac{f(\boldsymbol{s}, \boldsymbol{\ell}_m) p_i(\boldsymbol{s}, \boldsymbol{\ell}_m)}{p_{\boldsymbol{\ell}_m(i)}^{(N)}(\boldsymbol{s}, \boldsymbol{\ell}_m)} ds_{N:1} \\
&= \sum_{i=1}^{N} \mathcal{C}_{r_i} \sum_{m=1}^{N!} \int_{s_1=0:s_N=s_{N-1}}^{\infty} \frac{f(\boldsymbol{s}, \boldsymbol{\ell}_m) p_{\boldsymbol{\ell}_m^{-1}(r_i)}(\boldsymbol{s}, \boldsymbol{\ell}_m)}{p_{r_i}^{(N)}(s_j)} ds_{N:1} \\
&= \sum_{i=1}^{N} \mathcal{C}_{r_i} \sum_{j=1}^{N} \sum_{\substack{\forall \boldsymbol{\ell}_m: \\ \boldsymbol{\ell}_m(j)=r_i}} \int_{0:s_{N-1}}^{\infty} \frac{f(\boldsymbol{s}, \boldsymbol{\ell}_m) p_j(\boldsymbol{s}, \boldsymbol{\ell}_m)}{p_{r_i}^{(N)}(s_j)} ds_{N:1} \\
&= \sum_{i=1}^{N} \mathcal{C}_{r_i} \Gamma(i)
\end{aligned} \tag{44}
$$

where

$$
\Gamma(i) = \sum_{j=1}^{N} \sum_{\substack{\forall \boldsymbol{\ell}_m: \\ \boldsymbol{\ell}_m(j)=r_i}} \int_{s_1=0:s_N=s_{N-1}}^{\infty} \frac{f(\boldsymbol{s}, \boldsymbol{\ell}_m) p_j(\boldsymbol{s}, \boldsymbol{\ell}_m)}{p_{r_i}^{(N)}(s_j)} ds_{N:1} \tag{45}
$$

Next, we are going to show that $\Gamma(i) = 1$.

$$
\begin{aligned}
\Gamma(i) &= \sum_{\forall \boldsymbol{\ell}_m} \sum_{j=1}^{N} 1_{\boldsymbol{\ell}_m(j)=r_i} \int_{0:s_{N-1}}^{\infty} \frac{f(\boldsymbol{s}, \boldsymbol{\ell}_m) p_j(\boldsymbol{s}, \boldsymbol{\ell}_m)}{p_{r_i}^{(N)}(s_j)} ds_{N:1} \\
&= \sum_{\forall \boldsymbol{\ell}_m} \sum_{j=1}^{N} 1_{\boldsymbol{\ell}_m(j)=r_i} \int_{s_j=0}^{\infty} \frac{f_{r_i}(s_j)}{p_{r_i}^{(N)}(s_j)} \Phi_j(\boldsymbol{s}, \boldsymbol{\ell}_m) ds_j \\
&= \int_{s=0}^{\infty} \frac{f_{r_i}(s)}{p_{r_i}^{(N)}(s)} \sum_{\forall \boldsymbol{\ell}_m} \sum_{j=1}^{N} 1_{\boldsymbol{\ell}_m(j)=r_i} \Phi_j(\boldsymbol{s}, \boldsymbol{\ell}_m) ds \\
&= \int_{s=0}^{\infty} f_{r_i}(s) ds \\
&= 1
\end{aligned} \tag{46}
$$

Therefore, (44) together with (46) imply that

$$
R^{(N)} = c_d + \sum_{i=1}^{N} \mathcal{C}_{r_i} \tag{47}
$$

□