The Right Content for the Right Relay in Self-Organizing Delay Tolerant Networks: A Matching Game Perspective

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Abstract—**In this paper, we deal with the store-and-forward paradigm for self-organizing Delay Tolerant Networks (DTN). To overcome the decentralized nature and the infrastructureless constraint of such a network, highly distributed design and efficient incentive mechanisms are needed in order to convince relay nodes to disseminate the content. Here, we exhibit a new way to set the store-and-forward scheme based on the emerging matching game theory. This approach serve to match between on one hand different kinds of files generated by a source node and on the second hand relay nodes that may forward these files. In order to make incentive for cooperation, the source node offers a strategic reward to relay nodes that have accepted to forward a given file. Moreover, each relay and file can be defined by a context, i.e. its characteristics. Based on that, the source would prefer maximize the overall delivery probability at the same time as the relay would try to guarantee the highest possible reward while considering its battery status. Our matching-game-based scheme promises an efficient tradeoff between the overall delivery probability and the energy consumption. For practical considerations, we propose an algorithmic solution to achieve a stable matching between the sets of source files and the set of relay stations. Extensive simulations show that our scheme outperforms the legacy two-hop routing and illustrate the impact of preferences of each set involved in the game, and how such a tool can meet a high delivery rate at a reasonable energy budget.**

Keywords Delay Tolerant Network, Matching Game, Energy efficiency, Delivery Probability, Distributed Algorithm.

I. Introduction

Over the past few years, wireless network technologies have known a rapid growth and a notable success, which can be justified by the exponential increase of the number of mobile communication equipments. However, the existing technologies have already shown their limits and have reached their maximum capacity. This overload can be especially observed during peak hours or during some special events (cultural events, sport events, etc.) where the number of connected devices in a specific geographic location increases tremendously compared to the usual. To this kind of issues, operators tend usually to deploy provisional extra infrastructure to support the legacy one and temporary expand the capacity of the network. Meanwhile, such a solution incurs additional costs and additional engineering work. Delay Tolerant Networks (DTNs) can be one of the solutions that can be adopted to relieve the pressure on the existing or future networks in such conditions.

DTNs are complex distributed communication system composed by mobile devices. These could include smartphones, laptops, tablets or other types of mobile devices. These devices are equipped by wireless communications chipsets and adequate programs that allow them to communicate with each other and exchange data directly, with no need of installed infrastructure such as base stations [1]. Thus, communications in these networks are achieved through mobile devices themselves that act as relays, transporting data from a source to a destination using the storing-carrying-forwarding paradigm. Thus, relays can receive a given file from the source node, store it and carry it until they find an opportunity to be in contact with the destination in order to finally forward it and complete the transmission. However, the storing-carrying-forwarding mechanism obliges DTNs to be tolerant to long transmission delays and intermittent connectivity. Moreover, the mobility capability of relay nodes impacts their limited energy as in [2][3] where authors employ DTN and exploit unused channels for the last hop in order to save mobile user equipments energy. Then, as the energy consumption is a central performance measure studied in DTNs literature, the work of [4] designed to ensure an efficient trade-off between the overall delivery probability and the energy consumption by using coalitional game theory can be of great importance.

In order to deploy a DTN network, make it fully operational and highly compatible with the existing or future networks, these issues must be solved. In this respect, we design a distributed matching-game-inspired store-and-forward mechanism. Our scheme is expected to enable self-organizing feature to DTN networks and promises to offer an efficient tradeoff between successful data transmission and energy consumption as well. However, the overhead cost is still to be evaluated.

A. Related Work

Recently, many researchers have proposed different solutions to handle the fundamental challenge of routing in wireless networks. Among these solutions, one of the newly used techniques is matching game theory. Indeed, matching games can be very practical to overcome many problems in emerging wireless network applications, Such as cognitive radio, device to device communication,... That is the case of [5], where the authors examine the problem of allocating resources in a heterogeneous network using matching theoretic tools through different wireless applications. Also, we can find in the literature many works that apply matching game theory in order to optimize the performances of Cognitive radio network. In instance, authors in [6] associate secondary users (SU) to licensed frequency bands of primary users (PU) using matching theory. Also, authors in [7] propose a concept of stable matching as a solution to optimize both the SUs and PUs performance through coordinated and cooperative distributed channel assignment for communication in a cognitive radio network. Another example that proves the solid contribution that can bring matching game to wireless network is the work in [8]. In this article, authors apply the matching game between small base stations (SBS) and service providers servers in order to reduce the backhaul load and the experienced delay. Within the same aspect of small cells network [9], authors discuss two parts: Firstly applying matching theory to assign resource blocks to multiple operators (OPs), and secondly in order to maximize the expected rate of OPs, they associate each SBS with an OPs via a distributive power allocation way. Also there are several recent studies applying matching theory in user-provider networks (UPN). In instance, [10] proposes a distributed algorithm that combines notions from matching theory and market equilibrium. This develops an analytical market model for buyer-seller data trading association as a matching game between buyers and sellers, where each player rank the opposition side according to its preferences.

As it can be observed after quoting these works, matching game theory has been applied in many wireless applications, but not in DTN. However, we think that such a concept can bring so much improvement to this kind of networks. That is why, taking into account the limited storage and battery constraints of DTNs, the tow-hop routing in those networks is formulated as a matching game between the set of relay stations and the set of content files.

In this work, and taken into account that the DTN suffers from limited storage and battery constraints, we have designed a framework based on matching game theory to control the trade-off between the number of successfully delivered packets and energy consumption in DTN.

B. Our contribution

Our objective in this work is to study one of the solutions that can be used in the next generations of mobile communication networks or in the actual ones, in order to support the installed infrastructure. Thus we believe that the use of DTNs can provide a lot to the future fifth Generation of mobile communication systems, in condition that some drawbacks of these networks are solved. In this respect, we formulate the files forwarding problem in DTNs as a one-to-one matching game between files generated by the source and the relays in charge of the transmission. This matching will insure that the files generated are transmitted by the adequate relay that can guarantee a reasonable delay, while managing the energy consumption of the relays. Therefore, the main contribution of this paper lies in solving this matching game, by proposing a novel distributed algorithm that is capable of leading our system to a stable matching between generated files and relays in charge of their transmission.

C. Paper organization

The rest of this paper is organized as follows: In Section II, we describe the system model and exhibit the mechanisms followed by source and relay nodes. In Section III, we briefly review the matching game approach, also the preferences of both source files and relay stations are provided in this section. Next, we describe the proposed algorithm of stable one-to-one matching in Sections VI. Illustrative examples and simulations are provided in Section V. Finally, we draw some concluding remarks in Section VI

II. System Model

In this part, we consider a DTN network that contains a single source, a single destination and a set of relay stations $R = \{R_1, R_2, ..., R_m\}$. The source station has several type of files, represented by the set $C = \{C_1, C_2, ..., C_n\}$, that have to be sent to the destination through the relays. To avoid overloading the network with copies of the files, the transmission should be done only in two hops, i.e. once a relay has received a copy of the file from the source, it should transmit it only and directly to the destination. To do that, the relays must have a storage unit in order to store copies of files until being in contact with the destination. However, the storage capacity of these units is limited $Q = \{q_1, q_2, ..., q_m\}$ which restricts the number and size of files that can be saved. Speaking of size, the files can belong to different categories (e.g. videos, text, audio, etc.), so can be of different sizes $S = \{S_1, S_2, ..., S_n\}$.

In the current work, and seen that the DTN suffers from limited storage and battery constraints, relays must control the trade-off between the numbers of files delivered to destination and the energy consumption.

A. Energy Consumption

As the relay stations are mobile, the energy consumption is highly important and must be taken into account in the study of DTN networks. Thus, the relays have a limited energy and must choose intelligently the files to transmit in order to not waste it. Therefore, the energy consumed during storing a file is directly linked to its size and the expected time until the next contact with the destination. As a result, the energy consumed by a relay R_i carrying a file C_j is as follow:

$$\sigma_{ij} = \left(2\sigma_d + \sigma_m \frac{1}{\lambda_i}\right) S_j \tag{1}$$

Thus for any node, the time expected to be spent before the next contact with the destination, is the average arrival rate of contacts λ_i. And σ_d is the energy consumed by a relay forwarding a file of one unity of size, and σ_m the energy consumed in a unity of time, by a relay carrying out a file of one unity of size.

Given this, the impact that can have the energy consumption on the choice of a relay to carry a certain file can be given by:

$$I_{energy}(i,j) = 1 - \frac{\sigma_{ij}}{\sum_{k=1}^{n} \sigma_{ik}} \tag{2}$$

B. Files value

When generating a file, the source station affects to it a certain value that represents its importance and its urgency. To encourage relays to transmit the file, the source proposes a reward, corresponding to the file value, to relays succeeding to forwarding it. Let consider h_j the time to live (TTL) of a given file C_j, i.e. the time within the file must be delivered to the destination. This means that after this time h_j, the destination will be no more interested in the file. Thus, the file value can be expressed as follow:

$$\alpha_j = \frac{\alpha_0}{h_j} \tag{3}$$

Given this definition, the impact of the reward proposed by source in order to motivate relay stations to accept forwarding the file can be given by:

$$I_{reward}(i,j) = \frac{\alpha_{ij}}{\sum_{k=1}^{n} \alpha_{ik}} \tag{4}$$

Taking in account these parameters, the purpose of this work is to find an acceptable trade-off between the energy consumptions of relay nodes and the number of files delivered to destination. Therefore, we formulate first this problem as a one-to-one matching game, where the source node aim to send their files through the relays that reduce the transmission time to destination, while relays prefer to carry files that have higher values and that lead to lower energy consumption. Then we will concentrate on the case on a one-to-one matching, in order to propose a adequate algorithm aiming to find a stable matching.

III. Matching Game and Protocol Design

A. Matching Concept

The routing problem in DTN can be formulated as a matching between files of the source station and relay stations. The outcome of our model is a one-to-one matching game that is defined as an assignment of files in C to relay stations in R.

Definition 1: As shown in Fig.1, a one-to-one matching μ is a mapping from the set $C \cup R$ into the set of all subsets of $C \cup R$

Lets take two sets, set R of N relays and set C of N files. For each $r \in R$, we can state a function $f_r(c) : R \to [N]$ that ranks the preferences of r among C. And for each c in C, we state in the same manner a function $g_c(r) : C \to [N]$ that ranks the preferences of c among R. Thus $\mu(c)$ being the set of relay files' partners under the matching μ.

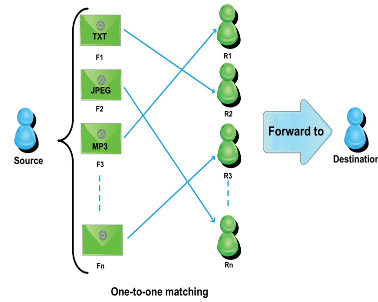

Fig. 1. One-to-One matching game

In order to perform the matching between files of different categories and relay stations, both source and relay stations need to identify their preferences for their own partners in the matching. We use $>_c$ ($>_r$) to define the ordering of the relationship of file c generated by the source station (relay station r respectively). For example, $r >_c r'$ means that the source prefers to store the file c in relay r over r'.

Our aim is to achieve a stable solution to this matching game, where all users prefer to be partners and there is no one who prefers to play otherwise.

Definition 2: A one-to-one matching μ is stable if it is not blocked by any pair of file generated and relay station. Otherwise, the matching μ is blocked by the pair (c,r) if $\mu(c) \neq r$ and if $c >_r \mu(r)$ and $r >_c \mu(c)$.

B. Preference of the Source Station

To achieve our goal of ensuring a successful transmission in the network, the source station prefers to send the file to adequate relay, in other words to the relay with high contact probability with the destination station.

Given that the relay nodes are mobile; their contact probability with the destination must be estimated. In that order and to simplify the analysis, we assume nodes move according to the random waypoint mobility model. For any node, the average arrival rate of contacts is λ_i. That is to say, each node i will meet with another node every $\frac{1}{\lambda_i}$ seconds on average. The random waypoint mobility model implies that the arrival of contacts follows a Poisson random process, i.e. the number of times a relay meets destination within t seconds is a random variable $X(t)$ and the distribution of (t) is written as follow:

$$P(X(t) = x) = \frac{(\lambda_i t)^x}{x!} e^{(-\lambda_i t)} \tag{5}$$

As the inter-contact between a pair of nodes follows an exponential distribution with rate λ_i, the probability that a single relay succeed to deliver the file within time h_j is:

$$P_{suc}(i,j) = 1 - Q_h(i,j) \tag{6}$$

Where

$$Q_h(i,j) = (1 + \lambda_i h_j) e^{-\lambda_i h_j}$$

C. Preference of Relay Stations

In fact, a relay station is more interested in transporting files of high values affected by the source station. In the same time, a relay will care about its energy consumption and will prefer files that do not need much energy to be transported. Then we define the preference of relays as follows:

$$P_r = \gamma I_{energy}(i,j) + (1-\gamma) I_{reward}(i,j) \qquad (7)$$

Where $\gamma \in [0,1]$ is a weight that balances the impact of both energy consumption by relay and the reward affected by source.

D. Protocol Design and Implementation Considerations

Now, we describe some implementation considerations of our routing scheme. We recall that our scheme is a variant of the well-known two hope routing algorithm developed for DTN networks. IoT, smart-city context...

For lack of simplicity, we assume that all relay nodes are initially within the source transmission range. The matching-game inspired routing protocol is described as follows:

1) The source node advertises her content/file list and their respective sizes/rewards;
2) Each relay node announces its current energy level and its preference list as well;
3) The source node announces the content/file preference list;
4) Repeat last two steps till each single content/file is allocated to a relay nodes;
5) Whenever a relay forwards successfully the content/file to the destination, this latter give a reward (virtual coins, bonus, some reputation metric, etc.);

IV. Algorithm analysis of stable matching

Our purpose is to build a framework based on many-to-many stable matching between the sets mentioned above. However, we have chosen in this paper to start with designing a one-to-one algorithm, before generalizing in future works. Therefore, we suppose from there that a file can be carried only by one relay, and a relay can only transmit one file at once.

In this order, we will refer to the Gale-Shapley algorithm, one of the most used algorithms in order to solve stable marriage problems. So in this section, we will adapt this algorithm to our case of DTN, in order to result in a stable one-to-one matching between n relay stations and n files.

Before the first iteration of the algorithm, all relay stations and files are not matched. Each of them must have already determined the list of their preferences among the opposite set. More precisely, both relay stations and files must have established the list of their preferences based on the equations (6) and (7) respectively.

During each iteration, the files are either free or carried by a relay. In a similar manner, the relays are either free or carrying a file. Once a relay is carrying a file, it can never be free again, on the contrary of files. In each iteration, the source propose each file F to the most preferred relay R in its preference list, that has not already rejected F. If R is already carrying another file F', it reject the less preferred one of F and F', and carry the other. The rejected file becomes free, and must wait until the next iteration to be proposed to the next relay in its preference list. Finally, when all relays and files are matched, then the algorithm returns the stable matching.

Algorithm 1 Stable Matching for DTN

Input: The preferences of each set of relays R and files F
Output: The stable one-to-one matching between n relay stations and n files
while some file F is free **do**
  R:= First relay on F's list to which F has not been yet proposed
  if R is free **then**
    assign F and R to each other
  else if R prefers F to the carried file F' **then**
    assign R and F to each other and $F'$to be free
  else
    R rejects F, then F remains free
End.
Result: Stable matching of n pairs of {Relay,file}

For the example, consider the stable matching instance of size 4 specified by the following preference lists:

$$\begin{array}{ll} R_1 : F_1F_4F_2F_3 & F_1 : R_2R_1R_4R_3 \\ R_2 : F_3F_4F_1F_2 & F_2 : R_2R_4R_1R_3 \\ R_3 : F_4F_2F_3F_1 & F_3 : R_2R_1R_3R_4 \\ R_4 : F_1F_3F_4F_2 & F_4 : R_4R_1R_2R_3 \end{array}$$

Then for iteration i=1:

$$\begin{array}{l} F_1 \rightarrow \not{R_2} \\ F_2 \rightarrow \not{R_2} \\ F_3 \rightarrow R_2 \\ F_4 \rightarrow R_4 \end{array}$$

For iteration i=2:

$$\begin{array}{l} F_1 \rightarrow R_1 \\ F_2 \rightarrow \not{R_4} \\ F_3 \rightarrow R_2 \\ F_4 \rightarrow R_4 \end{array}$$

For iteration i=3:

$$\begin{array}{l} F_1 \rightarrow R_1 \\ F_2 \rightarrow \not{R_1} \\ F_3 \rightarrow R_2 \\ F_4 \rightarrow R_4 \end{array}$$

For iteration i=4:

$$\begin{array}{l} F_1 \rightarrow R_1 \\ F_2 \rightarrow R_3 \\ F_3 \rightarrow R_2 \\ F_4 \rightarrow R_4 \end{array}$$

Hence a matching $\{(F_1,R_1),(F_2,R_3),(F_3,R_2),(F_4,R_4)\}$ is stable

V. Simulation Analysis

We are interested in this section in deriving the utility function of relays, in function of the interaction details and the reward described above. Studying this utility function can help us to understand the contribution that could bring matching games theory to DTNs. Moreover, this utility is defined as the difference between the reward that can be won and the energy consumed during transmission.

As we already mentioned before, each relay will win a reward depending on the file that is matched with. This means each relay can bring a specific utility depending on the file that is carrying. Then, the average utility that can be obtained by the relays is defined as following:

$$U(i,j) = \frac{1}{n}\sum_{j=1}^{n}\sum_{i=1}^{n}\alpha(j)P_{suc}(i,j) - \sigma(i,j) \qquad (8)$$

Delivery probability: This performance metric is the probability that a relay i ($i = 0, 1, \cdots, n$) succeeds to deliver a given file to its destination. Let us denote $\Psi(i,j)$ the probability that relay node i accept to cache content file j. Thus, The average delivery probability can be formulated as following:

$$P_{delivery} = \sum_{i=1}^{n} P_{suc}\left(i, \mu(i)\right) \cdot \Psi\left(i, \mu(i)\right), \qquad (9)$$

where $\mu(i)$ is a file matched with the relay i. In the rest of this paper, we consider the following three probability distributions

$$\Psi(i,j) = \begin{cases} \frac{\alpha_j}{\sum_{k=1}^{n}\alpha_k} & \text{Ascending distribution} \\ \frac{1}{n} & \text{Uniform distribution} \\ \frac{\alpha_{max}-\alpha_j}{\sum_{k=1}^{n}(\alpha_{max}-\alpha_k)} & \text{Descending distribution} \end{cases} \qquad (10)$$

For our simulation, we used the following setting: $\alpha_0 = 5$ is the initial positive reward, while the positive regret that is incurred by the relay depending of initial values of both the energy consumed due to the relay mobility $\sigma_m = 2.10^{(-6)}$ and the energy consumed in result to downloading the file from the source, and uploading it to the destination $\sigma_d = 2.10^{(-4)}$. We must note also that $\gamma \in [0, 1]$, and the arrival rate of relays is a variable value that belongs to the interval $\lambda \in [0.1, 0.6]$.

In this section, we evaluate the performances of our model. Namely: The delivery probability and the energy consumption for different size of network, and different values of the main parameters.

From the simulation results in Fig.2, in which we plot the delivery probability $P_{delivery}$ as function of different sizes of network, for several cases of the probability that a relay accept a source file. On one hand, we took the case where matching game is implemented and presume that this probability is equally distributed among matched content files, i.e. equals to $1/m_i$ (m_i is the number of matched content to relay i). In the other hand, in the case where matching is not applied, we studied three different forms of this probability: an ascending order and a descending order probability that both depends on the file value, and finally an equally distributed probability (equals to $1/n$). So it can be seen that for all values of stations number and for different values of file lifetime, the delivery probability is practically greater when matching approach is integrated compared to the reverses case. And for all four, the figure shows that the more the network is dense the higher is the delivery probability. Also, we can note that the delivery probability tends to 0.9 as long as the network become more dense, for the case of matching. However, for the other case when matching game is not integrated, the delivery probability does not reach values as high as in the first case, and that for all three forms of the adopted accepting probability, it tends to 0.8 in the best case of equally distributed probability. Similarly, we plot the delivery probability in terms of the size of network, but we fix the values of file lifetime to $[5, 12, 40]$ as can be noticed on Fig.3. We can observe that for both cases already quoted (With matching theory and without it), the more the file lifetime increases, the greater the successful transmission probability is.

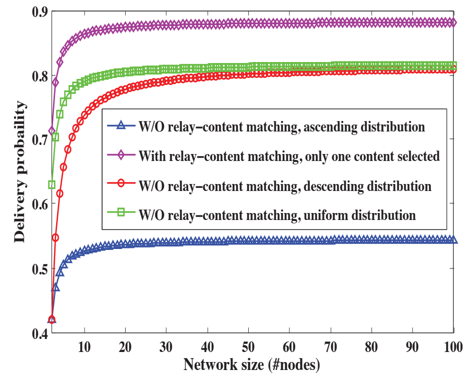

Fig. 2. The delivery probability for different size of network. Where file lifetime $h \in [5, 50]$

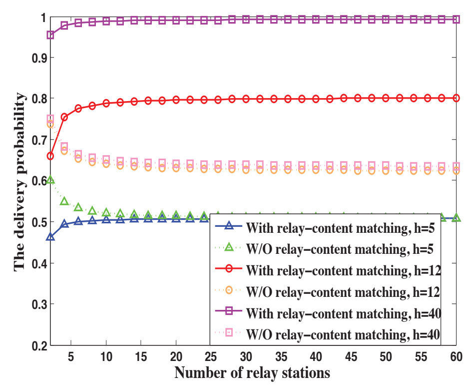

Fig. 3. The delivery probability for different lifetime of file. Where file lifetime $h \in [5, 12, 40]$

This improvement is normal, because where the lifetime of a given file are great enough, it has a more chances to be transmitted successfully within this lifetime. However, Fig.3 shows that the approach of matching reports an improvement of delivery probability for a higher values of lifetime h.

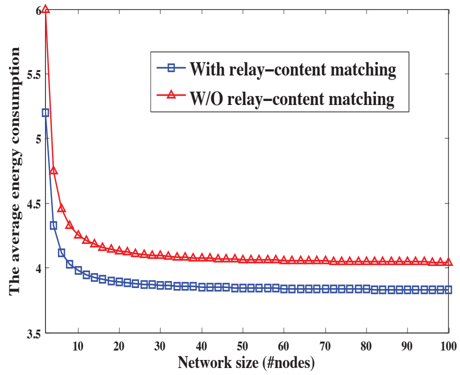

Fig. 4. The energy consumption for different size of network. Where file lifetime $h \in [5, 50]$

However, for lower values of h, the delivery probability seems to be the same for both cases. So we can deduce that matching approach can be more beneficial for DTNs for non urgent data (non-real-time data).

Also we notice that Fig.4 shows that the energy consumption decreases as the number of relay stations raises. Still, when comparing the two cases; basic model of DTN and when matching game theory is implemented, Fig.4 indicates that the energy is more preserved with matching approach. This is due to the fact that the relays try to satisfy their preferences when choosing the file to be carried, including the energy consumption.

VI. Conclusion

Achieving high energy efficient routing while guaranteeing a satisfactory delivery rate is one of the most crucial issue in delay tolerant networks. In this paper, we exhibit a new store-and-forward scheme inspired from the emerging matching game theory.

Yet, we develop a comprehensive analytical model allowing to sustain cooperation among relay nodes, and to define an efficient tradeoff between the overall delivery probability and the mean energy consumption. Next, we propose an iterative learning algorithm to discover the stable one-to-one matching for relay-content in the network. As a benchmark, we consider the case where each relay nodes may store and forward any of the available content files according to some probability distribution instead of performing a stable matching. Performances of all schemes are measured through the overall delivery probability and the energy consumption. We notice that the matching-inspired routing scheme outperforms other schemes while varying the message/file lifetime, the network size and the energy consumption.

As a future work, we are developing the general case of many-to-many matching game where each relay may store more than a single file, and a given file can be forwarded by multiple relay nodes. This allows capturing more realistically the network behaviour and providing some interesting feature of the store-and-forward structure. Preliminary results show that a threshold-like strategy may exist in terms of the number of files to be forwarded by a relay node.

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