Enabling Wireless Cooperation in User Provided Networks

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***Abstract*—This paper investigates user provided networks. Such networks have become important research in the field of informatics engineering due to the recent popularity of smart phones. User provided networks are independent from traditional Internet service providers. Communication and information exchange between users occurs opportunistically, i.e., when the smart phones are close enough to exchange information. Most user provided networks are based on the radio standard IEEE 802.11, popularly known as '*wi-fi*'. However, some networks are based on other low range radio standards, such as Bluetooth and IEEE 802.15.4.**

User provided networks are important to the society when the traditional Internet service providers become unavailable. For example, this may occur in terrorist attacks, earthquakes, or even cyber attacks. In these emergency situations, when users have a greater interest in common, an efficient system for non-presencial information exchange is necessary. Such networks are also interesting in a social context, when users must be incentivized to share their resources (storage capacity, wireless connectivity and battery) to enable the exchange of information. This paper addresses both situations: i) networks whose users have a common interest and ii) networks whose users need to be encouraged to share resources.

Basically, the contributions of this paper can be summarized as the *Delay Tolerant Reinforcement-Based* routing solution and the *Messages on oFfer* incentive mechanism. The first is a routing solution for user provided networks when the users have a prior interest in common. The second is an incentive mechanism to encourage users to exchange information. Both solutions showed excellent results in the simulation environment.

I. Introduction

Within the past few years, the Internet has experienced a critical shift. The explosion of wireless mobile computing and the exponential growth of users in densely populated areas enables the general public to become providers of communication services. User Provided Networks (UPN) are revolutionizing wireless communications by allowing users to interact with other users outside of the typical provider infrastructure.

Wireless IEEE (Institute of Electrical and Electronics Engineers) 802.11 [1], Bluetooth [2], and IEEE 802.15.4 [3] technologies have become ubiquitous in densely populated urban areas because of the increasing number of fixed access points and the multitudes of smart phone users. This phenomenon creates a foundation for UPN. When the end-user becomes a provider and shares wireless opportunities based on some form of incentive, a potential alternative radio communication channel becomes available [4].

Incentive mechanisms are fundamental for UPN development, because they encourage user cooperation and prevent selfish behaviour. An effective incentive mechanism motivates users to share, promotes development of new applications for offloading 3G/4G networks, stimulates competition among traditional Internet Service Providers (ISP), and strengthens new UPN communities. However, these new networks depend on the user's willingness to share their wireless connectivity, storage capabilities, and energy resources. Most applications available to the end-user today still depend upon the ISP infrastructure. Incentive mechanisms are important to encourage users to cooperate for effective information sharing [5].

The rest of this first section is divided into two subsections. The next subsection introduces different types of UPN Communities. The research questions are presented in the second subsection.

A. UPN Communities: Tethering-based and New Generation

Tethering is the practice of sharing a subscribed Internet (3G/4G or cable) connection through IEEE 802.11 with a smart phone or a fixed home wireless router. Tethering-based UPN communities incentivize the users to cooperate by sharing their wireless resources as well as Internet services. Currently most UPN do not implement multi-hop routing among devices, merely forwarding data from the wireless local area network to the Internet and vice-versa, which limits the coverage of tethering-based UPN communities.

These user networks range from the basic, those with the ability to create a wireless local area network on-the-fly with a simple personal computer or smart phone, to more elaborate cases of commercial success, for example, the Spanish telecommunications company FON [6]. In order to join the FON UPN community, the user has to acquire a home wireless router. This device creates a private network used by the owner and a public network used/shared by other members of the user provided community. FON members have free Internet access in any FON access point. Figure 1 shows how FON access points became ubiquitous in downtown Lisbon, Portugal. OpenSpark [7] uses the same basic idea, where the

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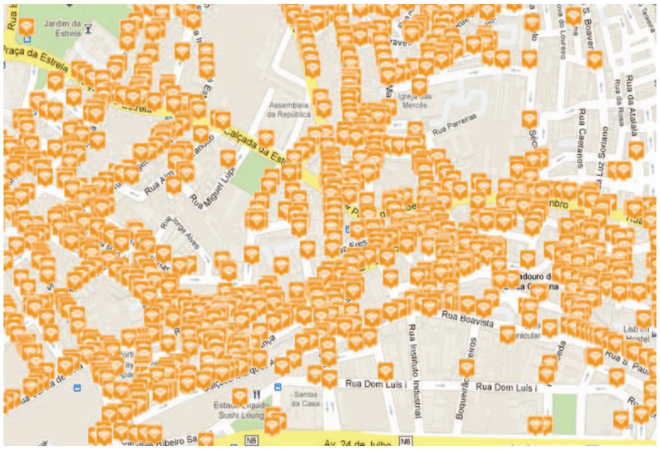

Fig. 1. FON access points in downtown Lisbon, Portugal [6].

community members agree to share cooperatively their extra broadband connection capacity to the Internet, in exchange for receiving free access to other community members access points when in roaming. The Android [8] and iOS (iPhone Operating System) [9] have inbuilt software that enables the owner to provide his smart phone as a IEEE 802.11 hotspot to share his 3G/4G subscribed Internet connection.

The new generation of UPN implements multi-hop routing among wireless links. To join the Freifunk UPN community [10], one has to set up a home wireless router device with OpenWrt [11] using the ad hoc wireless local area network mode, and run the Freifunk routing daemon to implement the OLSR protocol [12]. The OpenWrt is a Linux distribution for embedded devices that frees the end-user from the application selection and configuration provided by the vendor, allowing him to customize the device. The Athens Wireless Metropolitan Network (AWMN) UPN community [13] is also based on OpenWrt, and uses the Border Gate Protocol (BGP) [14] to forward messages. The Lancaster University in United Kingdom operates a new generation UPN [15]. The University supplies the nearby village of Wray with Internet access running Ad hoc On-demand Distance Vector (AODV) protocol [16].

Bytewalla [17] is a new generation UPN community that implements the idea that people travelling from villages to cities and vice-versa shall carry data on their smart phones. In the village a user downloads data from a IEEE 802.11 access point (without Internet connectivity). Then, he carries the data to the city, where he can connect to another IEEE 802.11 access point to upload the data to the Internet. Emails downloaded at the village will finally be delivered in the city. This data-mule operation is transparent to the user, who is able to use his mobile phone as usual. Bytewalla uses the Probabilistic Routing Protocol using History of Encounters and Transitivity (PRoPHET) [18] on Android smart phones.

At first, the tethering-based UPN emerged with the aim of providing Internet access to roaming users by sharing subscribed Internet connections using home wireless routers with members of the same UPN community. Because of smart phones popularization a new generation of UPN communication that could be ISP independent arises. Here are some examples of applications based on delay tolerant routing solutions that can be executed in UPN: urban transport system control [19], 3G/4G offloading [20], driver to driver content sharing [21], epidemic text message exchange [22], rural villages content delivery [17], conference systems [23], advertising [24], and dissemination of weather and tourist information.

Two key aspects for the development and wide adoption of the UPN paradigm are: i) delay tolerant routing solutions and ii) incentive mechanisms. These two aspects are the main objects of this research.

1) Since UPN do not have predefined infrastructure (like traditional ISP), and wireless IEEE 802.11, Bluetooth, and IEEE 802.15.4 technologies have limited transmission ranges, delay tolerant routing solutions play an important role to provide end-to-end data delivery in UPN. Delay tolerant routing solutions can deal with the lack of instantaneous end-to-end paths and ISP infrastructure. These routing solutions use a store-carry-forward approach to adeptly deliver the message to the destination. Examples of distinguished delay tolerant routing solutions are: PRoPHET [18], Delay Tolerant Reinforcement-Based (DTRB) [25], and Spray and Wait (SnW) [26].
2) Users may have conflicting interests in UPN, especially when limited resources are crucial, for instance battery and storage capacity. Thus, the development of incentive mechanisms, which promote sharing and are compatible with delay tolerant routing solutions is necessary. Examples of distinguished incentive mechanisms for UPN are: Messages on oFfer (MooF) [27], SMART [28], and the Practical incentive (Pi) [29].

B. Research Questions

This work investigates the use of delay tolerant routing solutions in UPN based on IEEE wireless technologies. First, it is considered that nodes (users) are willing to cooperate. This is true when the nodes have a common interest, for example during natural disasters or virtual terrorism. Citizens, teams of firefighters and doctors need to act in an environment without communication infrastructure. UPN are important during emergency situations due to the possible absence of ISP infrastructure. An important question that arises when the nodes have a common interest is:

1 - Is it possible to have a high delivery rate of text messages with a tolerable delay in IEEE 802.11 (or IEEE 802.15.4) user provided networks?

Typically nodes do not belong to the same domain, which may lead to conflicting interests among users, especially when they have limited resources, such as battery and storage capacity. Taking into account the possibility of user cooperation and the level of user selfishness in a UPN, the following question arises:

2 - Is there an incentive mechanism to encourage users to cooperate, given the amount of smart phones in urban centers today and their limited resources?

The answers to the research questions here presented are given in the conclusion of this paper. The rest of the document is organized as follows. Section II introduces the related work on delay tolerant routing solutions and incentive mechanisms. Section III presents the Delay Tolerant Reinforcement-Based (DTRB), a delay tolerant routing solution for UPN. Section IV introduces the Messages on oFfer (MooF), a credit-based incentive mechanism for UPN. Section V concludes the paper, and discusses future research.

II. Related Work

This section is divided in two parts: related work on delay tolerant routing solutions and related work on incentive mechanisms for UPN.

A. Delay Tolerant Routing Solutions

Lack of instantaneous end-to-end paths occurs in UPN. Routing solutions for these types of networks must use a store-carry-forward approach to opportunistically deliver the message to the destination. Currently, single-copy and multi-copy delay tolerant routing solutions are known. The multi-copy class allows multiple copies of the same message in the network, while the single-copy class does not allow message replication. Multi-copy delay tolerant routing solutions, for instance PRoPHET [18] and Spray and Wait [26], receive more attention from the research community because of their high delivery rates and low end-to-end delays. These routing solutions are known to suffer from waste of network resources. Applications based on single-copy routing solutions [30] have limitations, such as long delays and low delivery rates. Delay tolerant routing solutions are important when the nodes have a common interest, for example during natural disasters (e.g. earthquake). Consequently, emergency teams (doctors) need to act and communicate in an environment without communication infrastructure [31].

The PRoPHET [18] is a multi-copy delay tolerant routing solution that relies on the calculation of delivery predictability to forward messages to the reliable node. Probability is used to decide if one node is reliable to forward a message to. A node that is often encountered has a higher delivery predictability than the others. If two nodes do not encounter each other during an interval, they are less likely to exchange messages, thus the delivery predictability values must be reduced. PRoPHET utilizes a rather simple forwarding strategy: when two nodes meet, a data message is replicated to the other node, only if the delivery predictability of the destination of the message is higher at the encountered node.

SnW [26] is a multi-copy delay tolerant routing solution that attempts to limit the number of possible replicas of a given message. The protocol restricts the number of message copies, improving network resource efficiency. A number L represents the upperbound maximum number of message copies in the network. The source of a new message *spray* (delivers) L copies to distinct delay tolerant nodes. When a node receives one of the L copies, the *wait* phase begins, and continues until the destination is encountered. There are different routing decisions in the Spray and Wait family protocol. One of them consists in the source node transmitting a single-copy of the message to the first L distinct nodes it encounters after the message is created. In another one, called Binary Spray and Wait (BSW), the source node transfers half of its copies to nodes it encounters. Then, each of these nodes transfers half of the total number of copies they have to future nodes they meet.

B. Incentive Mechanisms for UPN

Incentive mechanisms for UPN are a novel theme among wireless research circles because they potentially solve the problem of selfish behaviour among nodes. Incentive mechanisms encourage the end-user to share his opportunistic connectivity, storage capabilities and energy resources. Wireless cooperation is a trend topic in the computer networks field [32]. Currently, credit- and reputation-based incentive mechanisms are known. Credit-based mechanisms use the notion of virtual currency to guide the data exchange in UPN. Cooperation rewards virtual payment whenever the node acts as a forwarder, and such monetary value (credit) can later be used to encourage others to cooperate with them. Reputation-based mechanisms evaluate the cooperation levels of nodes and provide better services to nodes with a higher reputation. Selfish behaviour is not condoned resulting in partial or total network disconnection. This second subsection presents existing research on incentive mechanisms for UPN.

The SMART [28] credit-based incentive mechanism assumes the existence of an off-line central trusted authority for virtual banking. An example of virtual banking is given in Section IV. The intermediate nodes involved in successful message delivery receive a dividend of the total credit provided by the source node. The payment, the remuneration conditions, the class of service and the reward policies are information attached to a new message. Based on such information, the intermediate nodes agree (or not) to provide forwarding service under the predefined class of service. If the provided forwarding service satisfies the remuneration conditions defined in the reward policy, each forwarding node along one or multiple paths shall share the credit, when in contact with the virtual bank.

The Pi [29] incentive mechanism combines reputation-based and credit-based incentive schemes. The intermediate nodes can get credit from the source node, only if the message arrives at the destination. In the case of message forwarding failure, the intermediate nodes get good reputation scores from the off-line central trusted authority. The credit-based part follows the same idea of SMART. The reputation-based part rewards the effort of a node that participates in the forwarding process, even if the node was not able to deliver the message.

III. Delay Tolerant Reinforcement-Based (DTRB)

Delay Tolerant Reinforcement-Based [25] is a delay tolerant routing solution for IEEE 802.11 wireless networks which enables device to device data exchange without the support of any pre-existing network infrastructure. The solution utilizes Multi-Agent Reinforcement Learning (MARL) techniques to learn about routes in the network and forward/replicate the messages that produce the best reward. The rewarding process is executed by a learning algorithm based on the distances between the nodes, which are calculated as a function of time from the last meetings. The simulation results show that DTRB can deliver more messages than a traditional delay tolerant routing solution does in densely populated areas, with similar end-to-end delay and lower network overhead.

MARL systems are dedicated to the development of autonomous agents which can solve distributed problems or control complex systems. Multi-agent systems have engineering applications in a variety of domains, such as: robotic teams [33], intelligent transportation systems [34], games [35], collaborative decision support systems [36], and resource and network management [37]. The methodology is based on a set of algorithms and protocols that enable the design of agents which learn the solutions to non-linear stochastic tasks about which the agent has limited prior knowledge.MARL is the next generation of Reinforcement Learning (RL). RL algorithms have reliable convergence when solving the single-agent task, but are ineffective in a multi-agent system. Several new challenges exist in MARL, mostly because of the $non\text{-}stationary$ (because of simultaneous multi-agent learning the best policy is continually changing [38]) behavior that invalidates the convergence properties of single-agent algorithms, such as multi-agent unexpected communication delays. Convergence to an optimal equilibrium or a stationary global state is improbable because the objective function is constantly shifting and consequently continuous simulation is essential while evaluating and implementing MARL algorithms. Please, refer to reference [25] for a detailed DTRB explanation.

A. Evaluation

DTRB was compared to PRoPHET, because it is well-known by the research community and can achieve fair delivery rates in heterogeneous network scenarios. PRoPHET reference implementation is maintained by the Internet Research Task Force. While PRoPHET utilizes a rather simple replication/forwarding strategy: when two nodes meet, a data message is replicated to the encountered node, only if the delivery predictability of the destination of the message is higher at the encountered node, DTRB evaluates the distance as a function of time between two nodes to decide whether a message replication is necessary. Consequently, DTRB only replicates a data message to an encountered node, if the encountered node is “closer” to the destination of the message. This idea justifies the lower network overhead reported by DTRB, because it does not replicate data messages unnecessarily.

The evaluation was made using the Omnet++ network simulator version 4.1 with the INETMANET framework [39]. DTRB and PRoPHET were implemented as network layer modules on the INETMANET. The goal of the simulation is to verify if the routing solutions can achieve a reasonable level of delivery rate with a tolerable delay and less overhead on the network. Two different mobility models were utilized: the traditional random waypoint model (RWP) and the UDEL model [40]. The last one is a suite of tools for simulating urban networks that includes a simulator of realistic urban mobility. The mobility simulator is able to simulate daily life pedestrian dynamics (e.g. arrival times at work, lunch time, breaks) and vehicle traffic dynamics (e.g. traffic lights). The TwoRayGround [41] propagation simulates the physical layer. The IEEE 802.11 transmission range is $250m$. All nodes have synchronized clocks [42]. Please, refer to reference [25] for simulation parameter details.

B. Remarkable Results

Figure 2 shows the delivery rate for different transmission ranges (network densities). As expected, in sparse networks with a transmission range of less than 150m, DTRB delivers fewer messages than PRoPHET. Sparse networks lead to longer distances and less knowledge of the network neighbours for DTRB, consequently less rewards are offered in the network. With increasing density, DTRB achieves on average higher delivery rates than PRoPHET.

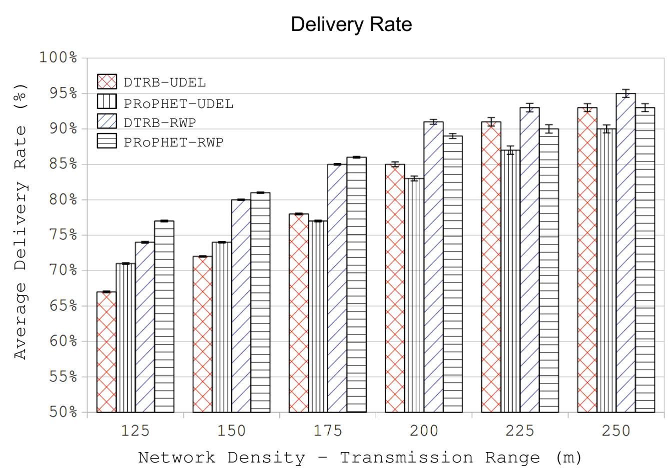

Fig. 2. Delivery rate with different network densities.

In delay tolerant systems, the overhead can be measured by the amount of unnecessarily replicated messages, as depicted in Figure 3. Unwanted messages were messages that arrived late to the destination plus the messages that were too old to be stored by a custodian node during a contact, due to flooding. Using Multi-Agent Reinforcement Learning, DTRB is able to overload 33% less than PRoPHET in both scenarios yielding more available bandwidth in the network. PRoPHET’s faster end-to-end delay is derived from its higher network overhead, i.e., its higher data messages replications. DTRB routing

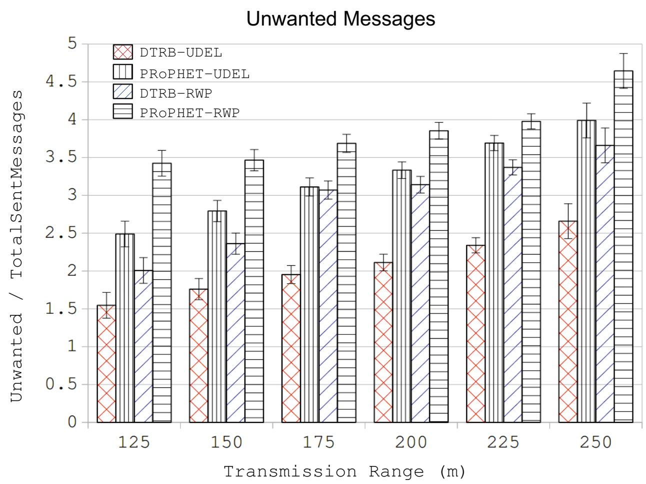

Fig. 3. Unnecessary replicated messages with different network densities.

achieves better delivery rates than PRoPHET, with a tolerable average end-to-end delay, which demonstrates the potential of reinforcement learning techniques to solve network routing problems.

IV. Messages on oFfer (MooF)

This section presents a credit-based incentive mechanism for UPN which enables device to device data exchange without the support of traditional ISP. Incentive mechanisms increase the likelihood of a user to share his resources (opportunistic connectivity, storage capabilities, and energy resources) to help another user [43]. The solution uses a utility function that represents the monetary value of a given data message during its journey in the network, and a buffer management optimization algorithm to prevent selfish behaviour among nodes. Virtual banking relies on an off-line central trusted authority. Simulations with the IEEE 802.15.4 standard show the proposed incentive mechanism preventing selfish behaviour and guaranteeing extra credits to the end-user. Please, refer to reference [27] for a detailed MooF explanation.

The delay tolerant routing solution utilized in this section is BSW [26]. BSW is part of the SnW family. The protocol restricts the number of message copies in the UPN, improving network resource efficiency. Each message created in the system has a maximum replication number c attached to it. The number c represents the upper bound number of replicas of the same message in the network. Any node with $c > 1$ message copies, forwards $c/2$ and keeps $c/2$ copies when in contact with another node without a copy ($spray$ phase). When a node has only one copy of the message, it switches to direct transmission, i.e., the node will store the message with hope to meet its destination ($wait$ phase).

A. Virtual Banking

Whenever a source node creates a message, it reserves the monetary value for future payment to the virtual bank the next time it comes in contact with the central authority. For security reasons, a tamper proof hardware device to avoid fraudulent activity stores this reserved monetary value. The source node also attaches a number c of message copies to each forwarded copy so the intermediate nodes can calculate the monetary value of each message. When an intermediate node delivers a message to a destination, it receives an acknowledgement (ACK) as a delivery certificate. The next time the intermediate node is in contact with the central authority it receives the monetary value credit when presenting the ACK.

B. Evaluation

The Omnet++ network simulator version 4.1 with the INETMANET framework [39] were used in conjunction with the IEEE 802.15.4 [3] standard link layer in ad hoc mode. The IEEE 802.15.4 standard is a low-cost, low-rate, ubiquitous communication designed for wireless personal area networks and pocket switched networks. The application layer on mobile devices generates data messages to random destinations, with an interval departure time of 30 to 180 seconds uniformly distributed.

The Nakagami-m [41] propagation simulates the physical layer. The IEEE 802.15.4 transmission range is $75m$. All nodes have synchronized clocks [42]. The data collection is over 40 simulation runs for each scenario. The simulation scenarios have different selfishness rates: less selfish nodes (scenario-1 = 25%), half-split nodes (scenario-2 = 50%) and, more selfish nodes (scenario-3 = 75%) on the UPN. Consequently, 120 simulation runs were executed with the UDEL mobility model [40], and 120 simulation runs were executed with the REAL mobility traces [44]. Please, refer to reference [27] for simulation parameter details.

Simulation results evaluate MooF and two other traditional and widely used buffer management schemes: DropTail [45] and DropOldest [46]. When using DropTail a node only requests data message replications when the buffer is not full. If the buffer gets full, the node will have to deliver a data message before it requests new data replications. When using DropOldest, a node discards the oldest message in the buffer and keeps requesting data message replications.

C. Remarkable Results

The total data message delivery average for the UDEL setup was 85%, considering all 120 simulation runs. The total data message delivery average considering independent scenarios was: 87% in scenario-1, 85% in scenario-2, and 83% in scenario-3. The total data message delivery average for the REAL setup was 76%, considering all 120 simulation runs. The total data message delivery average considering independent scenarios was: 77% in scenario-1, 76% in scenario-2, and 75% in scenario-3. The system delivered more messages when the selfishness rate was lower. The 9% total difference between UDEL and REAL is due to the number of nodes and the playground size utilized within each mobility setup, as UDEL (100 nodes) is denser than REAL (32 nodes).

Fig. 4. Delivery rates - Unselfish vs. Selfish data messages.

Figure 4 presents selfish and unselfish data message delivery rates for the three buffer management solutions: MooF, DropTail and DropOldest. In all three scenarios, it is clear that MooF is the only solution preventing selfish behaviour. MooF is able to overcome the selfish epidemy, when the system becomes flooded by selfish data messages (scenario-3), and delivers more unselfish data messages. DropTail and DropOldest do not differentiate between unselfish and selfish data messages. Nevertheless, in general, DropOldest is more in favour of selfish data messages than DropTail.

V. Conclusions

In the new generation of UPN, the nodes will be able to route data without the support of the ISP. The power of information exchange combined with a proper incentive mechanism will stimulate the development of new applications which will facilitate user cooperation. These new applications introduce a different user behaviour, where he/she acts independently from the ISP, and can choose to exchange data peer-to-peer before using their contracted services.

The foundation for user provided networks already exists in densely populated urban areas throughout the world. The proliferation of the IEEE 802.11, Bluetooth, and IEEE 802.15.4, combined with the increased storage capacity available for the end-user, enables widespread ISP independent user communication communities.

Incentivized user cooperation plans could result in lower Internet costs for UPN community members. It is a well-known fact that most 3G /4G networks become congested, and thus incentive mechanisms for 3G/4G offloading is an option to improve user satisfaction in 3G/4G networks.

A. Research Answers

In order to answer the research questions raised in the Introduction, an in-depth analysis of the state of the art and the results was conducted. This analysis revealed that DTRB improved the state-of-the art when the users of a UPN have a common interest, i.e., without the use of an incentive mechanism. Therefore, one can say that DTRB is a solution to the first research question raised in this paper because of the performance results presented. Typically users do not belong to the same domain, which may lead to conflicting interests among users of a UPN, especially when they have limited resources, such as battery and storage capacity. Consequently, an incentive mechanism is essential when the users of a UPN must be incentivized to share their resources to enable the exchange of information. Taking into account the possibility of user cooperation and the solid results observed, one can say that MooF is a solution to the second question raised in this paper.

B. Future Works

Future tasks for further development of the DTRB routing solution involve simulation in larger environment, the implementation of an IEEE 802.11 battery module to simulate the consumed energy in the network layer. An incentive mechanism compatible with DTRB is another research path. Future research for further development of the MooF incentive mechanism include simulation in a larger environment, and an increase in the transmission range.

C. Final Conclusion

The technology in today's smart phones can enable widespread communication without depending upon traditional ISP. The independent network concept depends upon user cooperation and UPN. These new computer networks will have a different architecture, where the nodes accumulate the roles of router, server and client. New communication opportunities will co-exist and even compete against the traditional ISP formats, and in turn will reward those whom agree to share their individual resources.

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List of Published Papers

- Vitor Rolla, Marilia Curado: Enabling wireless cooperation in delay tolerant networks, Information Sciences, Volume 290, Pages 120-133, January 2015. Impact Factor: 3.893.
- Vitor Rolla, Marilia Curado: A reinforcement learning-based routing for delay tolerant networks, Engineering Applications of Artificial Intelligence, Volume 26, Issue 10, Pages 2243-2250, November 2013. Impact Factor: 1.962.
- Vitor Rolla, Marilia Curado: A Simple Survey of Incentive Mechanisms for User-Provided Networks, Wireless Personal Communications, Paper accepted for publication. Impact Factor: 0.979.
- Vitor Rolla, Marilia Curado: Time message system for delay tolerant networks, 2nd Baltic Congress on Future Internet Communications, Vilnius, Lithuania, April 25-27, 2012.
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