Incentive Mechanisms for User-Provided Networks

George Iosifidis[†], Lin Gao[*], Jianwei Huang[*], and Leandros Tassiulas[†]

[†]Dept. of Electrical and Computer Engineering, University of Thessaly, and CERTH, Greece
[*]Dept. of Information Engineering, The Chinese University of Hong Kong, Hong Kong

Abstract

The increasing mobile data demand and the proliferation of advanced handheld devices place the user-provided networks (UPNs) at a conspicuous position in next-generation network architectures. There has been growing consensus that UPNs can play a crucial role both in self-organizing and in operator-controlled wireless networks, as they enable the exploitation of the diverse communication needs and resources of different users. However, in UPNs both the availability and the demand for Internet access depend on mobile devices, and therefore the success of such networks relies on active user participation. In this paper, we analyze the design challenges of incentive mechanisms for encouraging user engagement in user-provided networks. Motivated by recently launched business models, we focus on mobile UPNs where the energy consumption and data usage costs are critical and have a large impact on users' decisions both for requesting and offering UPN services. We outline two novel incentive schemes that have been proposed for such UPNs, and discuss the open issues that must be further addressed.

I. Introduction

Today we are witnessing two important socio-technological advances that herald the advent of a new era in communication networks. First, the ever increasing needs of users for ubiquitous Internet connectivity has created an unprecedented volume of mobile data traffic. Second, the recent technological developments have resulted in sophisticated user-owned equipment such as Wi-Fi access points (APs) and smartphones with enhanced-capabilities. These devices not only can satisfy the communication needs of their owners, but can also be employed to provide related services to other users. In this context, each user is transformed to a *micro-operator* (a *host*) who may offer Internet access or related communication services to nearby users, giving rise to the so-called *user-provided networks* (UPN) [1].

One prominent commercial UPN example is the Wi-Fi sharing service introduced by FON (www.fon.com), where users offer Internet connectivity through their residential Wi-Fi APs to other (mobile) users, in exchange for receiving such services when they need them. This service exchange model is based on earlier peer-to-peer Wi-Fi sharing models, which proposed pricing schemes for maximizing the system's efficiency [2]. Since then, many similar models have been proposed where a user may host other users (clients) by acting as an Internet gateway, or even as a relay connecting them to users-gateways. This novel UPN communication paradigm has recently attracted the interest of academia, and it has also inspired many business models employed either by small startups or major network operators[1]. This interest is not surprising though as UPNs have substantial performance and economic benefits both for users and for network operators.

Currently, there exist several UPN models that differ on the architectures and the services they offer to the users. On the other hand, one common aspect of these models is that users must agree to serve each other. This is a central issue in UPNs, as both the demand (clients' requests) and the provision (hosts' availability) depend on users' participation. The challenge is that often the participants have conflicting interests. For example, clients would prefer to receive services at low cost, while hosts would prefer to charge high prices. Similarly, an operator's incentive of supporting UPNs would be high if he can directly gain from such services. Clearly, it is of paramount importance to design incentive mechanisms for reconciling the objectives of all the participants. Such mechanisms need to effectively tackle the following questions:

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[1]Henceforth, we will use the term *network operator* for Internet Service Providers (ISPs), Mobile Network Operators (MNOs), and Mobile Virtual Network Operators (MVNOs).

- How much a host need to be compensated through payment (directly), or through service exchange (indirectly), for offering UPN services to clients?
- Which bundles of charged prices and offered services render UPNs more attractive than conventional infrastructure-based communication services?
- If the UPN service is enabled by a network operator, how much he should charge the users-clients, and reimburse the users-hosts?

Designing the proper UPN incentive scheme is particularly challenging when the hosts are mobile, i.e., when their devices are portable (such as a smartphones), not attached to power-sources, and not having wireline Internet connections. First of all, mobile Internet access cost is highly varying and often quite expensive[2]. Moreover, mobile devices have tight energy budgets which lead to stringent energy consumption constraints for the UPNs. Therefore, hosts are reluctant to participate in such mobile UPN services unless significantly compensated. These concerns are further perplexed due to the inherent volatility of the wireless medium that often results in varying Internet access performance.

Despite these difficulties, mobile UPNs are attracting an increasing interest, and we expect to see in the near future more related studies and business cases. Two such interesting models have been proposed and implemented recently by the Open Garden (www.opengarden.com) and Karma (www.yourkarma.com) startups. The former service enables mobile users to share their Internet access. The main idea is to exploit the diversity of users' needs and resources and crowdsource Internet connectivity by building an autonomous UPN, i.e., without the intervention of the operator. On the other hand, the Karma mobile operator enables her subscribers to act as mobile Wi-Fi hotspots (MiFi) and serve nonsubscribers with proper compensations. In this case, the UPN service is controlled (or assisted) by the operator, who has to ensure the consensus of the hosts.

Open Garden and Karma constitute two forward looking examples of autonomous and network-assisted UPN services respectively, both relying on mobile hosts and clients. However, these models currently lack of proper incentive mechanisms and hence do not address the previous three questions that we raised. Our goal in this article is to analyze such incentive issues and propose potential solutions. We begin in Section II with an overview of UPNs by focusing on recently proposed models. We discuss the technical issues pertaining to resource allocation for these services, and explain the importance of incorporating incentive schemes. Section III analyzes mobile UPN models that are inspired by Open Garden and Karma. We discuss the challenges in designing incentive mechanisms for these services, and we present two appropriate solution schemes. Section IV analyzes further key challenges for incentive mechanisms for mobile UPNs. We conclude in Section V.

II. UPNs: Technology and Economic Issues

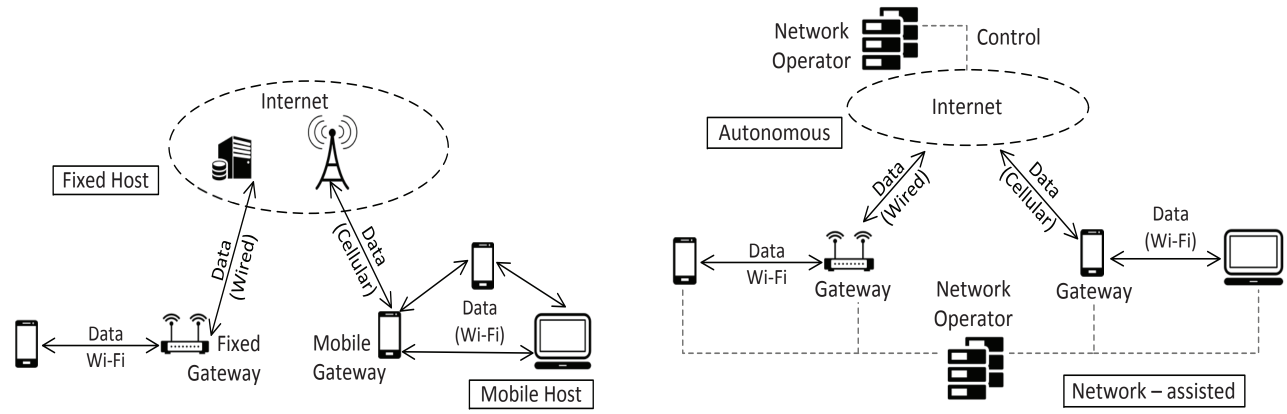
A. Overview of UPN models

The most prevalent example of UPN is the Wi-Fi sharing model of FON, which was followed by other companies such as OpenSpark (https://open.sparknet.fi/). In some cases users need to purchase new equipment, e.g., customized Wi-Fi routers as in the case of FON, or install proprietary software, e.g., as the cases with Whisher (http://www.whisher.com/), and KeyWiFi (http://www.keywifi.com/). The cooperation of users in these services is based on reciprocation (FON), or in simple pricing rules where clients pay to gain instant Internet access (KeyWifi). A slightly different proposal came recently by Telefonica (http://www.bewifi.es), where users in proximity create Wi-Fi mesh networks so as to increase the average available bandwidth per user through resource pooling.

While these previous models involve mainly fixed hosts, the proliferation of mobile devices and the growth of mobile data have inspired the development of UPN models that are only based on mobile hosts. For example, the mobile operator Karma equips each of her subscribers with a portable device (USB router), which operates as a MiFi hotspot and offers Internet access to other nonsubscribers (clients). Each subscriber pays a constant price per MByte of data she consumes, and earns a free quota of 100MBytes for every client she serves, at the expense of additional energy consumption and Internet access sharing (which reduces her Internet access speed). This network-assisted mobile Internet sharing model, with the hybrid pricing-reimbursement scheme, enables the operator to increase the population of clients, and the subscribers to augment their data plans with free quotas.

A different model is employed by Open Garden, which allows mobile users to create a mesh network and share their Internet connections. In this service, each user may act as a *client* node (consuming data), a *relay* node

[2]See ITU Report "Measuring the Information Society (MIS)", 2013: http://www.itu.int/.



(a) Fixed host and Mobile host Architectures

(b) Autonomous and Network-assisted Architectures

Fig. 1. The architecture and operation of a UPN depend on whether the host is fixed or mobile, and on the intervention of the network operator in the sharing and pricing rules.

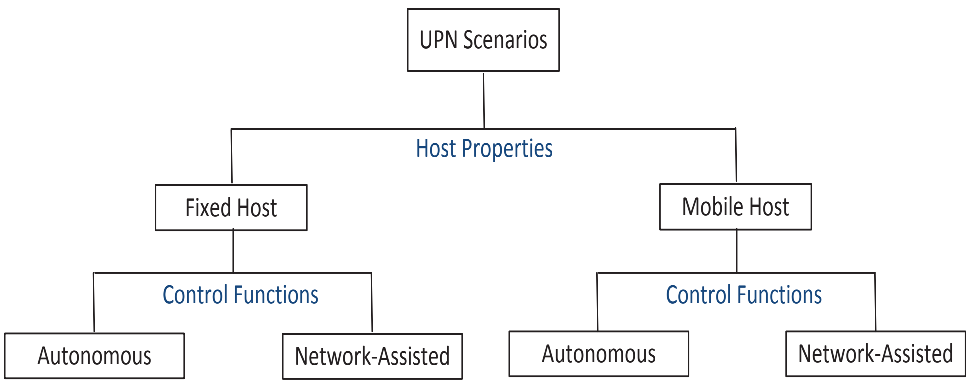


Fig. 2. Taxonomy of UPN models according to two criteria: (i) fixed or mobile host, (ii) autonomous or network-assisted servicing.

(relaying data to other nodes), or a *gateway* node connecting the mesh overlay to the Internet through a Wi-Fi or a cellular connection. Each user may play multiple roles either simultaneously or sequentially during different time slots. Every user who cooperates and offers her services to others, incurs an additional energy cost when acting as relay, and an additionally monetary cost when acting as gateway. In this autonomous UPN, the operators do not have any control over the traffic exchanged among the users and transferred across heterogeneous networks in an ad hoc fashion.

From the above examples, it is clear that the diverse UPN models can be broadly classified as follows:

- *Fixed Host or Mobile Host*. One criterion for differentiating UPN services is whether they are offered by fixed hosts (e.g., FON) or mobile hosts (e.g., Karma), as it is shown in Fig. 1(a).
- *Autonomous or Network-assisted*. Autonomous UPNs are transparent to the operators who do not intervene (e.g., Open Garden). On the other hand, in network-assisted UPNs the operators may determine the pricing rules (as Karma does) and/or the Internet bandwidth sharing policy, Fig. 1(b).

Based on these criteria, each UPN model can be classified in one of the four categories as shown in Fig. 2. One can identify more categories, based for example on whether the sharing is realized over special equipment (e.g., FON) or software (e.g., Open Garden). Moreover, UPNs may be managed independently, by each pair of host and client [3], or can be bound to rules predetermined by users' communities [4].

B. Technical Challenges of Resource Allocation

UPNs introduce challenging technical issues, since the users undertake many of the tasks and services traditionally executed by network operators. For example, one main concern of hosts is security. Fortunately, recent standards such as the Hotspot 2.0, address many of these problems. Another problem for mobile UPNs is the device discovery which consumes energy and network resources. Here, the intervention of the operator can benefit the users. Clearly though, the largest challenge in UPNs is the efficient allocation of the network and energy resources.

A first question that one may ask about UPN services is how much users can benefit from them. This has been studied in the context of data offloading where mobile users, instead of connecting to cellular networks, access the Internet through the residential Wi-Fi APs of other users[3] [5]. Namely, a related study showed that Wi-Fi offloads 65% of the total mobile data traffic, and saves 55% of battery energy [6]. Moreover, UPNs must also consider the allocation of Internet access bandwidth so as to increase the performance of the clients while ensuring a certain quality of service guarantees for the hosts [3].

This sharing problem is more challenging for mobile UPNs due to the stringent energy constraints of the mobile devices. [7] proposes an energy-prudent architecture that aggregates the cellular bandwidth of multiple hosts to build a MiFi hotspot, and schedules the clients' transmissions so as to reduce the total energy consumption. Another salient feature of mobile UPNs is that the network load and availability are very dynamic, as both clients and mobile hosts are nomadic. [8] presents a scheduling scheme that allows mobile hosts to dynamically admit client requests so as to maximize their revenue and ensure system stability. On the other hand, when each user can serve both as a client and as a gateway, a decision framework should assign these roles to users, considering their residual energy [9].

C. Incentive Issues

In all UPN models described above, the hosts need proper incentives so as to agree to share their network resources. This is very important, as network sharing may often induce a performance degradation for the hosts. For example, when a host shares her Wi-Fi AP, the additional traffic of the clients reduces the available bandwidth for the communication needs of the host. Moreover, even if the host does not have needs, hosting induces costs in terms of data usage and energy consumption.

Similar incentive issues exist for peer-to-peer and ad hoc networks. However, the solutions proposed in those contexts do not directly apply for UPNs, since they do not account for users' different types of resources, nor for their data usage costs. Also, in UPNs users can often access the Internet even without relying on other users' services, while typically this is not the case for other autonomous networks. This standalone (independent) operation should serve as a benchmark for the UPN, when computing the performance improvement to the UPN participants.

In the sequel we discuss the incentive mechanisms for UPNs, with emphasis on models with mobile hosts and clients. We consider two different classes of UPNs, namely autonomous and network-assisted. For the former class, the participation incentives are offered on the basis of a fair and efficient resource contribution and allocation of the service capacity. For the network-assisted UPNs, the incentive mechanism is designed and implemented by the operator, based on her objective to maximize her revenue and the amount of served data.

III. Incentive Mechanisms for Mobile UPNs

The incentive mechanisms for enabling cooperation among different users in autonomous networks can be classified as either reputation-based (or, reciprocation-based) or credit-based. The former class allows only for bilateral service exchange, while the latter is more flexible and enables multi-lateral exchanges [4]. It is possible to combine both approaches in UPNs with a careful design [10]. On the other hand, when the incentives are provided by the network operator, she can explicitly reward the cooperating users. For example, authors of [11] proposed a resource allocation scheme for cellular networks that rewards cooperating users by allocating to them optimal spectrum chunks. Any incentive scheme for UPNs should take into consideration that these services exhibit at the same time positive network effects and negative congestion effects [12]. That is, as more users join the service, both the number of hosts and clients increases, and the balance of demand and service provision depends on the resources and needs of the newcomers. In the sequel, we introduce two general models for mobile UPN services and present two respective incentive schemes.

[3]For example, services such as FON perform mobile data offloading as, in most cases, they offer an alternative Internet access path to roaming users who would otherwise connect through a cellular network.

A. Incentives for Autonomous Mobile UPNs

The autonomous mobile UPN service we consider here generalizes the Open Garden model by incorporating an incentive mechanism. This mechanism determines how much resources each user needs to contribute, in terms of energy and Internet bandwidth, in order to maximize the service capacity, i.e., the aggregate amount of data delivered to users. Accordingly, it dictates how this capacity will be shared by the different clients, as each one of them should receive service in accordance to her contributions. More specifically, such an incentive scheme needs to address the following issues:

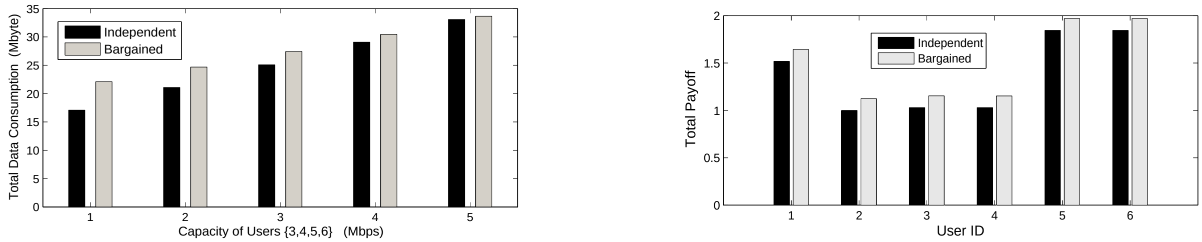
1) *Efficiency*. The mechanism should ensure the efficient allocation of the resources, i.e., maximize the user-perceived service performance by taking into account the Internet access offered to each user, as well as the energy and monetary cost the user incurs. In this context, the satisfaction and costs of users can be modeled through properly selected utility and cost functions, respectively.
2) *Fairness*. The scheme should satisfy a proper fairness rule that accounts for the different resources (energy and bandwidth) that each user contributes and consumes (due to her multiple roles). Moreover, the rule should take into consideration the standalone (independent) performance of each user, i.e., the utility she has if not participating in the UPN, and ensure that the service will improve upon it.
3) *Decentralized Implementation*. The mechanism should be amenable to distributed execution for networks with a large number of nodes. Users have information only about their own needs and resource availability, and they should be able to decide independently their routing and Internet access strategies, based only on local information and minimum signaling from their one-hop neighbors.
4) *Indirect Reciprocation*. A user being served by another user may not be able to return the favor immediately by offering similar services. Hence, a resourceful user may be reluctant to help other less resourceful users. The incentive mechanism needs to induce cooperation among users even for these cases.
5) *Future Provision*. Some users may not have communication needs in a certain time period, and therefore may not be willing to participate. This may deteriorate the overall service performance. The mechanism should manage to encourage users to participate even if they currently have no communication needs.

In our recent work [13], we proposed a mechanism that tackles the above challenges. Namely, the last two issues can be addressed by a virtual currency system. This way, users can pay and receive services even if they cannot reciprocate, while others with no communication needs, are motivated to participate in the service so as to increase their currency budget. In this context, the payoff of each user is the performance from the service plus the value of the virtual currency that she collects by serving others.

We use the Nash bargaining solution (NBS) to encourage users' efficient and fair contribution of resources and determine the corresponding service capacity allocation to each user [13]. The NBS is an axiomatic game theoretic concept suggesting how a group of players should share the surplus of their joint effort, in order to ensure that every participant will agree to cooperate. In particular, the NBS is derived by the solution of a convex optimization problem, where the objective function is based on the payoff functions of the players, by taking into consideration their standalone performance. The latter, which is known as the *disagreement point*, significantly affects how much each cooperating player hopes to receive through the cooperation [14]. For UPNs, NBS is attractive as it is Pareto optimal, i.e., no user can improve its payoff without decreasing another user's payoff. Moreover, it ensures that all users receive at least the payoffs they had if not participating in the UPN.

Finally, the NBS can be calculated in a distributed fashion by the users, thus enabling the decentralized implementation of the incentive mechanism [13]. Although this latter property improves the scalability of the mechanism, it is clear that such an incentive scheme induces additional overhead that may affect the system's performance. In particular, as it is explained in detail in [13], this NBS-based distributed incentive scheme has a message exchange overhead of $O(N^3)$, where N is the number of cooperating users. Moreover, the mechanism needs to recalculate the servicing policy each time a user joins or leaves the system, or when users' demands and/or their resources' availability change significantly.

The performance of this crowd-sourced UPN service increases with the diversity of the resources and needs of the participating users. This is depicted in Fig. 3(a), where we plot the data consumption and payoff functions for a group of 6 users, who are randomly located in a small area and are cooperating under the proposed incentive mechanism. The energy consumptions and data costs are taken into account when deciding who will act as Internet gateway and who will relay data to the clients. Fig. 3(b) shows that this scheme ensures that users perceive higher



(a) Impact of Capacity Diversity on Performance

(b) Comparison of Independent and Bargained Solution

Fig. 3. (a): Impact of capacity diversity on the service performance: $C_1 = C_2 = 12.7$ Mbps, and capacities $C_3 = C_4 = C_5 = C_6$ are equal and change from 1 to 5 Mbps (x-axis). Internet access prices and energy consumptions (per MByte) are identical for all users. (b): Comparison of independent and bargained solution. For each user, the bargained solution ensures a higher performance than the independent (standalone) operation. Moreover, the aggregate total payoff improvement of the bargained solution (compared to the independent solution) is approximately 10%. More details can be found in [13].

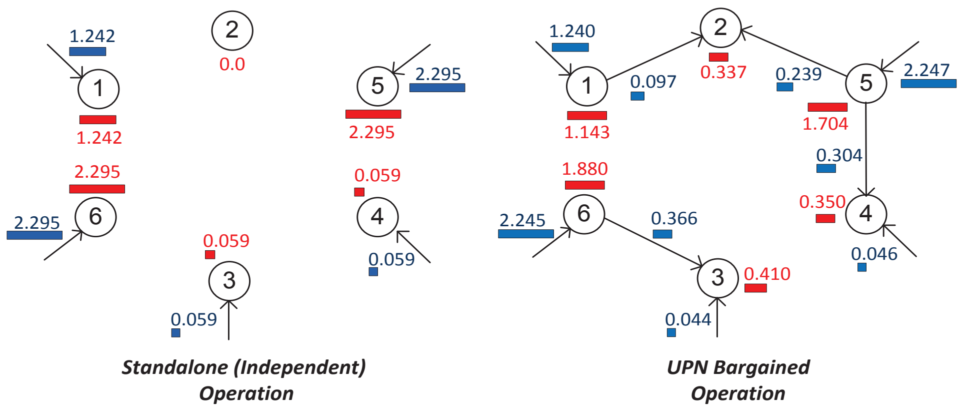


Fig. 4. Left figure: Independent-Standalone user performance (downloading scenario). Each user consumes (values shown next to nodes) only as much data as her Internet access capacity allows to download (values shown next to links). Right figure: UPN performance based on NBS. Each user downloads and relays or receives data to/from others, as it is shown by the arrows.

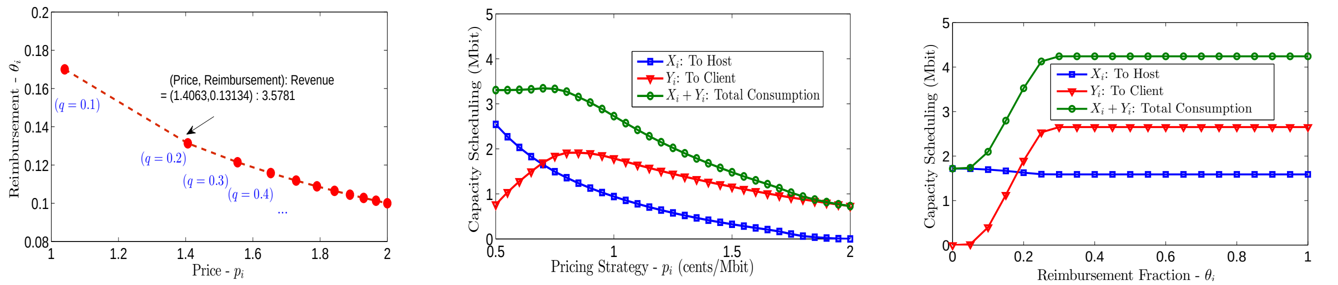
performance comparing with the standalone (independent) operation.

Finally, Fig. 4 presents an example of the independent operation and the bargained UPN operation for a downloading scenario. Namely, we consider a group of 6 mobile users in proximity, which have different Internet access capacities. When the users act in a standalone fashion, each user's data rate is limited by her Internet access capacity. In this case, some users may not be capable of accessing the Internet (e.g., user 2). On the other hand, in the UPN bargained operation, the actual amount of data that each user will download and relay for others depends on their Internet access capacities, demands, and data usage costs. Through cooperation, a user who does not have direct Internet access may be able to receive data with the help of other users. For simplicity, we have assumed that users have identical utility functions and data plans, and that each user can only serve her one-hop neighbors (in the circle).

B. Incentives for Network-assisted Mobile UPNs

The network-assisted mobile UPN service that we considered is based on the Karma model. However, the latter has certain limitations. First, each host is reimbursed with the free data quota, independently of the actual amount of data that she routes for the clients. Moreover, the reimbursement is identical for all hosts while they may have different bandwidth and energy constraints. Here, we consider a generalized network-assisted mobile UPN service which allows for data price and quota reimbursement differentiation across users. This hybrid pricing scheme can be leveraged to increase the revenue of the operator and the amount of data served by the hosts, by addressing the following issues:

1) *Quota-Price Balance*. This scheme should select a proper combination of charged data prices and free quotas. Changing the price or the quota size has different impacts on the hosts' decisions to serve the clients, and



(A) Trajectory of optimal pricing-reimbursing policy.

(B) Host's servicing strategy for different MVNO's data usage prices and $\theta_i = 0.2$.

(C) Host's servicing strategy for different MVNO's quota values and $p = 0.7$.

Fig. 5. Operators' optimal pricing-reimbursing strategy, and (average) host's servicing decisions for different data prices (fixed reimbursement), and different reimbursement quotas (fixed charged prices). Network parameters: 400 clients uniformly assigned to 50 hosts, user elastic demand with respect to data prices, price variation from 0.5 to 2 (while $\theta_i = 0.2$), and free quota fraction from 0 to 1 (for $p_i = 0.7$). Further details can be found in [15].

on the operator's revenue.

2) *Effort-based Reimbursement*. The free quota reimbursement should be effort-based, i.e., to depend on the amount of data each host serves. This will motivate the hosts to increase the service they offer to the clients.
3) *Users' demand-awareness*. The scheme should consider whether the communication needs of the users are inelastic or elastic. Clearly, users with elastic needs are less willing to pay high prices for Internet access. On the other hand, hosts with elastic needs are more willing to share their Internet access, even under small compensations.
4) *Price Discrimination*. Finally, different hosts have different needs, energy limitations, and available cellular bandwidths (e.g., due to different locations and channel conditions). Hence, the incentives for routing traffic of the clients should be host-dependent.

A proper incentive scheme for this class of network-assisted mobile UPNs has been proposed in [15]. Unlike the incentive scheme for the autonomous UPN service, in this case, the mechanism is designed and applied by the operator. The latter determines the free quota reimbursement and the data price that is charged to each user (host or client), in order to achieve her goal. That is, to increase the amount of served data and maximize her revenue. Based on the operator's decisions, each host determines accodingly how much traffic to admit and serve for other clients, and how much to consume for herself. If the charged prices are high and the reimbursements are low, it is possible that a host will not utilize all her available bandwidth. The operator anticipates the hosts' strategies and optimizes her decisions accordingly. This type of interaction can be modelled as a non-cooperative Stackelberg two-stage game [15].

The particularly challenging aspect here is that the pricing and reimbursement decisions are intertwined and have different impacts on the hosts' data consumption and servicing policy. To illustrate this, we considered a scenario where 400 clients are uniformly assigned to 50 hosts. The demand of the clients and the hosts is elastic. Fig. 5(a) depicts the operator's optimal pricing-reimbursement strategy when the average user demand varies from q = 0 to q = 1 Mbit (per time period). Namely, each point represents the pair of charged price and free quota, which ensures the highest operator revenue for a given value of average user demand q. Observe that when data demand increases, the operator increases the charged prices and reduces the free quotas.

In Fig. 5(b) we plot the total amount of data that a host i consumes on average, as a function of the charged data price. Moreover, we show how this data is allocated for the needs of the host and her clients. As it is anticipated, the aggregate consumed data $X_i + Y_i$ (Mbit) decreases with the price, since the demand of the users is considered elastic. What is interesting is that as the price increases, the host is motivated to allocate a larger portion of her servicing capacity to her clients (Y_i) and less for her own needs (X_i). This is because the reimbursement becomes relatively more beneficial for the hosts. However, for higher charged prices the total transmitted data decreases, and for even higher prices the host only downloads or uploads data to serve the needs of her clients. Finally, Fig. 5(c) depicts the hosts' optimal downloading (uploading) and servicing policy as the operators reimbursement policy changes. The latter is described by the parameter $\theta_i \in [0, 1]$ that determines the fraction of the data served by a host i, that is returned as a reimbursement to her. For example, if $\theta_i = 0.5$, for every 1 Mbit host i serves, she receives 0.5 Mbits of free data. We see that as the reimbursement increases, the amount of served data Y_i increases as well.

It is clear that the implementation of this hybrid pricing policy, which incentivizes the participation of the hosts, requires a monitoring and charging system so as to reward the hosts according to the traffic they serve. Such a system however, can be easily implemented as part of the accounting system that an operator already has. Finally, the design of this mechanism requires the collection and analysis of usage statistics so as to assess the average user demand and the elasticity of this demand. This will further introduce additional signaling overhead.

IV. Key Challenges in Mobile UPN Incentive Mechanisms

Despite the recent efforts from industry and academia, there are still many open issues pertaining to incentive mechanisms for mobile UPNs that must be carefully addressed.

A. Autonomous Mobile UPNs

1) Consensus of the Network Operator: A particularly important aspect of the autonomous UPN services is that they bridge heterogeneous networks in an uncontrolled fashion. In other words, users participating in such services may transfer data from cellular to Wi-Fi networks (offloading), or from Wi-Fi to cellular networks (onloading). Furthermore, this is accomplished in an ad hoc basis, i.e., without the approval of the network operators. Clearly, this could lead to an additional servicing cost and even to significant congestion for some networks. Therefore, it is not surprising that operators have expressed their concerns regarding the adoption of these services[4].

An important next step in designing incentive mechanisms for autonomous UPNs is to reconcile the conflicting objectives of operators and users. This will result in hybrid schemes where the mobile UPNs are not fully controlled by the operator nor are completely autonomous. To this end, a possible solution could be to design cost sharing policies that balance the benefits of the users (for participating in such UPNs) and the cost of the operators (for admitting traffic from nonsubscribers).

2) Dynamic Setting: In these autonomous UPNs, user interactions are often spontaneous and short term. Therefore, the question that arises is how users can cooperate (reciprocate) in such a dynamic environment. Similar problems that appeared in peer-to-peer and ad hoc networks were addressed by reputation schemes, where the contribution of each user is quantified though accumulative metrics. However, in mobile UPNs, simple scalar metrics cannot characterize the multi-resource consumption that each user incurs in order to serve others, nor her communication needs.

A possible solution for this problem could be the adoption of a virtual currency system, as we described in the previous section. Nevertheless, in such a dynamic environment users are not able to predict the efficacy of this currency, since it is not guaranteed that, in the near future, they will find gateways or relays to serve them, even if they can pay for these services. Therefore, it is required to carefully tune the currency system's parameters (e.g., how much a relay service costs), based on extensive numerical simulations and field experiments.

B. Network-assisted Mobile UPNs

1) Modeling the Clients: Our analysis so far did not focus on the clients of UPN services. In a competitive environment with more than one hosting options (or, even different types of UPN services), the clients will be able to select the most beneficial solution. To understand this strategic decision, it is first important to model the specific needs of the clients. For example, some users may have needs for delay-sensitive video streaming services, while others may prefer low-cost low bandwidth basic access to the Internet.

The different user needs can be described, for example, with properly selected utility functions [3]. Moreover, it is important to understand how the decisions of clients affect the servicing cost of hosts and in turn the expenditures of the operators. The coupling of these three decision planes renders the design of any resource allocation mechanism particularly challenging, as it requires the coordination of many different entities.

[4]For example, regarding the concerns raised by AT&T for Open Garden, please see: http://en.wikipedia.org/wiki/Open_Garden.

2) Incomplete Market Information: Many times, the interaction of the operators, hosts, and clients will be realized without complete network information to any of the parties involved. For example, the operator will not be aware of the actual communication needs of the hosts, which are essential to derive the proper charge and reimbursement rules. Similarly, a host may not know which client is willing to pay the highest price. For these cases, it is necessary to leverage market mechanisms, such as auctions, in order to elicit this hidden information.

Ideally, one would like to design a network-assisted UPN market where hosts and clients will reach agreements dynamically, based on their time-varying needs and the network congestion level. However, this mobile data market has hierarchical structure, with the hosts acting as intermediaries, that renders the design of such mechanisms very challenging. For example, auctions, which constitute the prominent market clearing mechanism under incomplete information, are only designed for two classes of market entities (sellers and buyers). This calls for new auction-based mechanisms tailored to this hierarchical setting.

V. Conclusions

UPN services are expected to play a crucial role in the future [1], both for autonomous self-organizing communication structures and for network-controlled decentralized communication services. Designing proper incentive schemes for these models is a particularly challenging problem, as requires us to bridge the interests of the clients, the hosts, and the network operators. In this paper, we considered both the technical and the economic issues that arise in this context. Motivated by recently launched business models, we presented two novel mobile UPN models. For each one of them, we analyzed the salient features that a suitable incentive mechanism should have, and outlined a potential solution. Finally, we discussed the remaining open challenges in this area along with possible solutions.

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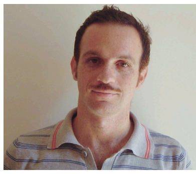
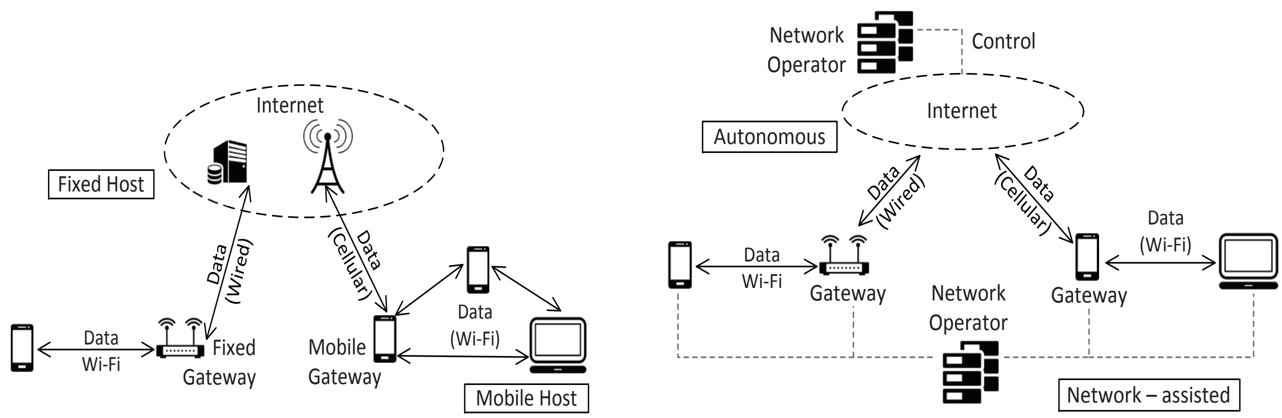


George Iosifidis obtained the Diploma in Electronics and Telecommunications Engineering from the Greek Air Force Academy, in 2000, and the M.S. and Ph.D. degrees in Electrical Engineering from the University of Thessaly, Greece, in 2007 and 2012, respectively. Currently he is a Post-doc Researcher at the University of Thessaly and CERTH, Greece. His research interests lie in the broad area of network optimization and network economics.

Lin Gao is a Postdoctoral Researcher in the Department of Information Engineering at the Chinese University of Hong Kong. He received the M.S. and Ph.D. degrees in Electronic Engineering from Shanghai Jiao Tong University in 2006 and 2010, respectively. His research interests lie in the field of wireless communications and networking with emphasis on the economic incentives in various communication and network scenarios, including cooperative communications, dynamic spectrum access, cognitive radio networks, cellular-WiFi internetworks, and user-provided networks.

Jianwei Huang (S'01-M'06-SM'11) is an Associate Professor in the Department of Information Engineering at the Chinese University of Hong Kong. He is the recipient of 7 Best Paper Awards in leading international journal and conferences, including the 2011 IEEE Marconi Prize Paper Award in Wireless Communications, and he is the co-author of three recent monographs in wireless network optimization. He is the Editor of IEEE JSAC-Cognitive Radio Series and IEEE Transactions on Wireless Communications, and Chair of IEEE Communications Society Multimedia Communications Technical Committee.

Leandros Tassiulas (S'89-M'91-SM'06-F'07) obtained the Diploma in Electrical Engineering from the Aristotelian University of Thessaloniki, Greece in 1987, and the M.S. and Ph.D. degrees in Electrical Engineering from University of Maryland in 1989 and 1991, respectively. He is Professor in the Dept. of ECE, University of Thessaly, since 2002. Dr. Tassiulas received an NSF Research Initiation Award in 1992, an NSF CAREER Award in 1995, an Office of Naval Research Award in 1997, and a Bodosaki Foundation award in 1999. He also received the INFOCOM 2007 achievement award.



(a) Fixed host and Mobile host Architectures

(b) Autonomous and Network-assisted Architectures

Fig. 6. The architecture and operation of a UPN depend on whether the host is fixed or mobile, and on the intervention of the network operator in the sharing and pricing rules.

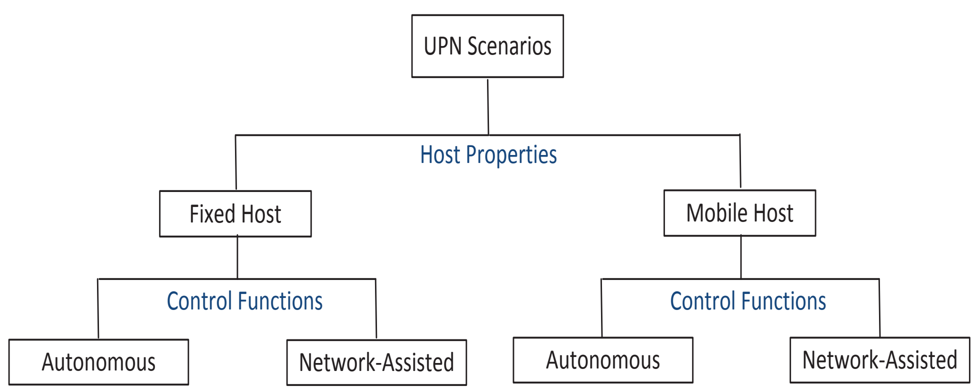
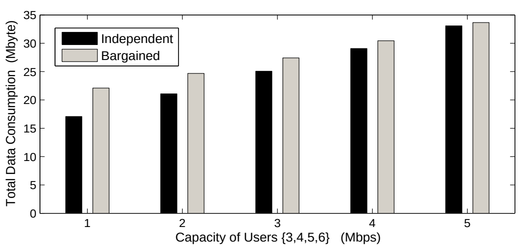
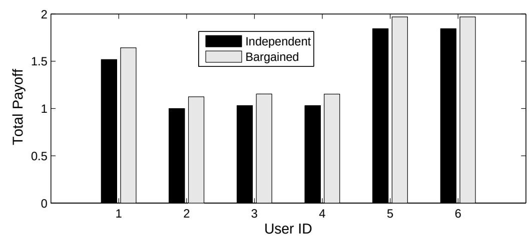


Fig. 7. Taxonomy of UPN models according to two criteria: (i) fixed or mobile host, (ii) autonomous or network-assisted servicing.



(a) Impact of Capacity Diversity on Performance



(b) Comparison of Independent and Bargained Solution

Fig. 8. (a): Impact of capacity diversity on the service performance: $C_1 = C_2 = 12.7$ Mbps, and capacities $C_3 = C_4 = C_5 = C_6$ are equal and change from 1 to 5 Mbps (x-axis). Internet access prices and energy consumptions (per MByte) are identical for all users. (b): Comparison of independent and bargained solution. For each user, the bargained solution ensures a higher performance than the independent (standalone) operation. Moreover, the aggregate total payoff improvement of the bargained solution (compared to the independent solution) is approximately 10%. More details can be found in [13].

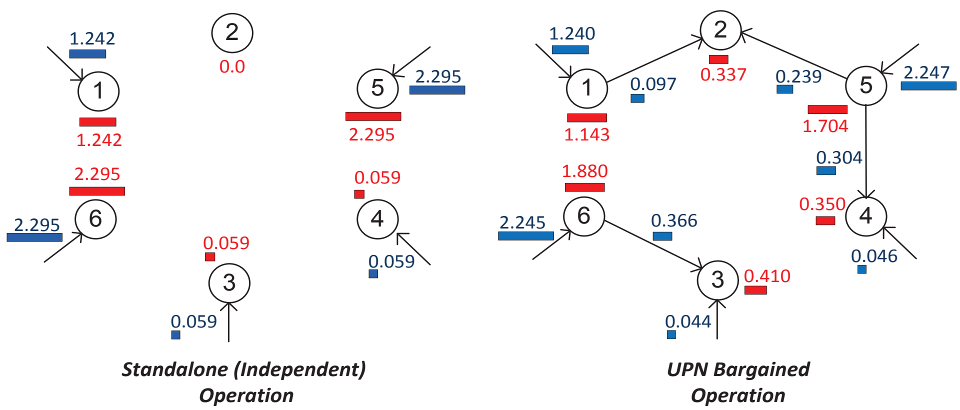
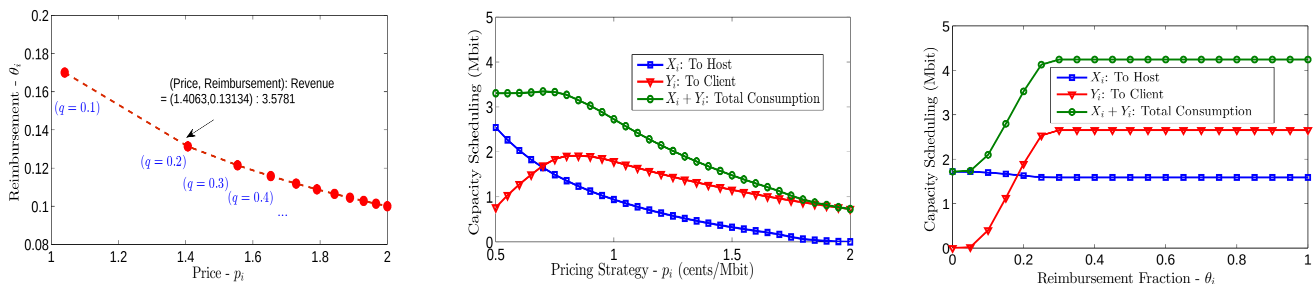


Fig. 9. Left figure: Independent-Standalone user performance (downloading scenario). Each user consumes (values shown next to nodes) only as much data as her Internet access capacity allows to download (values shown next to links). Right figure: UPN performance based on NBS. Each user downloads and relays or receives data to/from others, as it is shown by the arrows.



(A) Trajectory of optimal pricing-reimbursing policy.

(B) Host's servicing strategy for different MVNO's data usage prices and $\theta_i = 0.2$.

(C) Host's servicing strategy for different MVNO's quota values and $p = 0.7$.

Fig. 10. Operators' optimal pricing-reimbursing strategy, and (average) host's servicing decisions for different data prices (fixed reimbursement), and different reimbursement quotas (fixed charged prices). Network parameters: 400 clients uniformly assigned to 50 hosts, user elastic demand with respect to data prices, price variation from 0.5 to 2 (while $\theta_i = 0.2$), and free quota fraction from 0 to 1 (for $p_i = 0.7$). Further details can be found in [15].