C2M: Mobile Data Offloading to Mesh Networks

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***Abstract*—As the unprecedented growth of mobile data traffic places significant strain on cellular networks, alternative plans for exploiting already existing and under-utilized wireless infrastructure, become quite attractive. In this paper, we study cellular-to-mesh (C2M) data offloading for LTE-A cellular mobile users to WiFi mesh networks, which are built and managed collaboratively by users. Such networks are developed in the context of community networks or, recently, as commercial services among residential users. Mobile network operators can lease these mesh networks to offload their traffic and reduce their servicing cost. In this context, we introduce an analytical framework that determines which mobile users should be offloaded, based on the energy cost incurred to the cellular base stations (eNB) for serving their demands. Accordingly, we design a routing policy that the mesh network can employ so as to serve the offloaded traffic with the minimum possible cost. Moreover, the reimbursement offered by the operator should be dispensed to the different mesh users, according to their contribution and added-value significance. We address this issue by employing the Shapley value profit sharing rule, which ensures the participation of the mesh nodes in this joint task. We evaluate our work by simulating the operation of the LTE-A network, and conducting testbed experimentation for the mesh network. The results reveal significant savings for eNBs power consumption and compensation profits for mesh users.**

***Keywords* – Data Offloading, Network Economics.**

I. Introduction

A. Motivation

Today we are witnessing an unprecedented growth of mobile data traffic [1] that places significant strain on cellular networks and increases the CAPital and OPerational EXpenditures (CAPEX, OPEX) of mobile network operators (MNOs). Therefore, it is not surprising that methods for offloading part of this traffic to WiFi networks are gaining increasing interest both from industry and academia [2]. At the same time, recent technological advances and standardization efforts, such as the Hotspot 2.0 protocol defined by the WiFi Alliance, and the ANDSF service of 3GPP [3], render such solutions highly attractive by encompassing simplified roaming and seamless handover techniques. In this new era, WiFi mesh networks that are built and managed collaboratively by users, can play a very important role.

Such mesh networks emerge nowadays in various different contexts. First, several community networks (CNs) have been deployed by residential users for sharing content and network resources [4]. CNs complement conventional cellular network infrastructures, mainly in areas where coverage is poor, and/or access is expensive. Therefore, they constitute an ideal solution for offloading mobile data. Similar models have been recently

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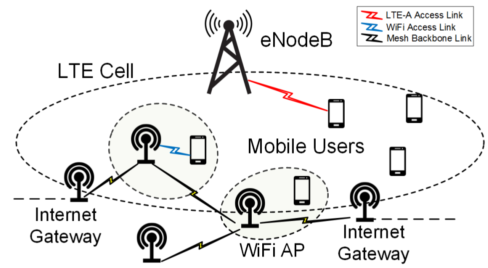

Fig. 1: An LTE-A macrocell serving mobile users that are partially covered by a mesh network.

commercially launched[1] [6], [7]. For example, the BeWifi service of Telefonica [7] enables residential users in proximity to create mesh networks and share their Internet access. The idea is to exploit the diversity, in the time domain, of users' needs and network resources, and increase the average Internet capacity per user, through resource pooling. Such mesh networks can serve as an offloading solution under a proper (monetary) compensation offered by the MNO.

This promising *cellular-to-mesh (C2M) collaborative data offloading architecture* inevitably raises three basic issues. First, the MNO should determine which mobile users (MUs) are the most intense resource-consumers and hence more preferable to be offloaded. The answer depends on the demand of each user, the quality of her cellular channel, as well as her eligibility to be offloaded based on the mesh network coverage. Second, the mesh network should devise the minimum-cost servicing policy for admitting this offloaded traffic. This policy should take into account the energy consumption of the mesh nodes, the available capacities of the point-to-point and Internet access links, and the respective Internet usage costs. Finally, the mesh nodes should agree on a rule for sharing the compensation offered by the MNO, based on their contribution and incurred servicing costs. This is necessary to ensure mesh nodes participation in this collaborative offloading service.

B. Methodology and Contributions

The proposed architecture is depicted in Fig. 1. We consider a macrocell of an LTE-A network where a base station (BS), also known as eNB, serves a set of mobile users MUs (or user equipments UEs) who also have WiFi interfaces. The macrocell partially overlaps with a WiFi mesh network that is managed by a set of residential users (other than the MUs) [7]. Hence, a subset of the MUs are in range with one or more access points (APs) of the mesh network. The users differ also on the amount of data they need to download or upload from/to the Internet, and their channel conditions with the base station.

First, we investigate the cost savings of the operator when

[1]Besides, today there exist many WiFi communities, such as FON [5], where users can coordinate and provide similar offloading services.

offloading user requests. We assume that the main cost component of the cellular network for this setting is the energy consumption of the base station [8], [9]. The MNO determines the spectrum and the transmission power that needs to allocate to each MU so as to satisfy her requests, while minimizing the aggregated energy consumption cost of the base station [10], [11]. Accordingly, the eNB decides to offload the user(s) that consume the most energy. This decision is constrained by the availability of the mesh network, as the offloaded users should be in range with an AP having adequate capacity.

Once the MNO has decided the traffic that should be offloaded, the mesh network determines how this data will be further routed to/from the Internet gateways. These decisions are based on the network available resources, i.e., the point-to-point and Internet access capacities of the nodes, and also take into consideration the respective energy consumption and Internet usage costs. We cast this as a multi-commodity minimum-cost flow optimization problem, where each commodity corresponds to the data of each offloaded MU. Nowadays, such policies can be imposed in a very small time scale [12].

Accordingly, we design a mechanism for dispensing the net benefit of the mesh network, i.e., the received compensation minus the servicing cost, among the mesh nodes. This rule is based on the notion of the Shapley value [13] which ensures that the cooperating mesh nodes will agree to jointly provide the offloading service. In particular, we define a respective cooperative game [14] and prove that, based on this sharing rule, all the mesh nodes will have positive net benefits, and hence an incentive for willingness to participate.

The proposed offloading architecture takes into consideration the particular characteristics of such systems. For example, user association (and hence the offloading decisions) cannot be derived in a very small time scale as base station re-selection requires several seconds [15], [10]. On the other hand, the eNB's resource allocation decisions can be made in *ms* (every transmission time interval, TTI), but channel quality feedback information (CQI) from the MUs to the eNB, which are used for estimating the channel gains, are available every tens of ms (with a minimum of 8ms). We explicitly model these limitations. Moreover, for investigating the offloading potential of the mesh network, we executed experiments in the NITOS wireless testbed [16], using a setup that resembles a mesh network among residential users, e.g., such as in BeWifi [7].

To this end, the contributions of this work can be summarized as follows:

- *C2M Architecture*. We propose a new architecture for offloading data to collaborative mesh networks. The proliferation of community mesh networks [4], and similar commercial mesh networking platforms [7], [6], render such solutions promising for alleviating cellular network congestion.
- *Optimization Framework*. We introduce an optimization framework that can be used for calculating the cellular energy cost benefits, for each user, and the respective energy and Internet usage costs for the mesh network that admits the offloaded traffic. Our analysis can be used for different mesh network architectures [7], [4]. Moreover, we provide a cost-sharing rule, based on the Shapley value, and prove that it ensures the participation of all the mesh nodes.
- *Performance Evaluation*. We evaluate the above decision framework, using a detailed simulation analysis. Moreover, we conducted extensive experiments in an actual mesh network deployed in the NITOS testbed [16], and we measured the energy consumption costs and the perceived user performance in terms of experienced delay.

The rest of this paper is organized as follows: In Section II we discuss related works. Section III introduces the system model for the cellular and the WiFi mesh network. We formulate the respective optimization decision frameworks in Section IV. In Section V we present the numerical results, the experimental setup and the experiments' outcomes. Finally, we conclude in Section VI.

II. Related Work

Several recent studies have quantified the benefits of cellular data offloading to WiFi networks [17], [18]. These benefits can be further enlarged when the user needs are delay tolerant [19]. Clearly, the offloading performance depends on the APs' availability. Apart from operator deployed APs, another recently proposed solution for addressing the availability issue, is the leasing of third-party WiFi APs [20], [21]. This method enables the dynamic expansion of network offloading capacity, without any significant CAPEX/OPEX costs.

We extend this architecture by proposing data offloading to third-party mesh networks deployed and managed by users [4], [6], [7]. The offloading capacity of these networks is significantly larger from single APs as, not only they aggregate more network resources (e.g., in terms of Internet capacity), but also increase their availability through resource pooling, exploiting the diversity of the nodes' needs and resources. An AP missing currently Internet access (e.g., because it has exceeded its monthly quota), can admit/relay the mobile data traffic to another mesh node with adequate Internet capacity.

To quantify the benefits of this architecture, the operator needs to determine the resource allocation policy, in terms of resource blocks assignment and power transmission. This is particularly challenging for LTE-A networks since it requires the solution of a multi-variable optimization problem [10], [22]. Among the different possible policies, such as proportional allocation, the total power transmission minimization policy [10], [11], is of paramount importance for cost savings [8]. However, this is a well known NP-hard problem that can be either solved using exhaustive search methods for small instances (e.g., branch-and-bound), or various approximation techniques [23]. Here, we do not delve into the details of such an analysis. Besides, in order to reduce the complexity of the proposed mechanism, we decide which traffic will be offloaded based on the resource allocation policy of the eNB scheduler, which has to be devised for serving the users.

Finally, offloading can be seen as a type of vertical handover. Such mechanisms have been studied for integrating 3G and operator-managed WLANs. The handover policies vary from simple signal strength-based rules, to sophisticated schemes that consider the network load and the QoS requirements [24], [25]. The proposed offloading architecture here however, differs in that the WiFi resources are not controlled by the MNO. Moreover, such offloading schemes are typically used for best-effort services and hence there are no QoS concerns. Therefore, the main decision criterion is the cost reduction of the MNO, while ensuring the delivery of the requested data.

III. Background and Model

LTE-A Network. We consider the downlink operation[2] of one macrocellular base station for a time period of T subframes, possibly expanding over multiple frames. There exists a set $\mathcal{N}$ of N users within the cell. Every user $n \in \mathcal{N}$ needs to download an amount of $D_n \geq 0$ bytes during this period. Some mobile users may be in range with one or more access points (APs), while some others may not be covered by any AP. The base station has a set $\mathcal{M}$ of M available resource blocks (RB) that can be allocated to users in each subframe $t = 1, 2, \ldots, T$. The value of M depends on the available spectrum. Hence, there are in total $M \cdot T$ RBs. The system is considered quasi-static, i.e., users do not join or leave the cell during the current time period, and the channels do not change significantly (flat fading). Note that, even if channels change rapidly, the eNB will not be aware of this fact, as users transmit their CQI parameters only once during this time period.

In the beginning of the period, the eNB devises the resource block assignment and power allocation policy for serving his users. Let $x_{nm}(t) \in \{0,1\}$ denote whether RB $m \in \mathcal{M}$ is allocated to user $n \in \mathcal{N}$ during subframe t. Let $P_{nm}(t)$ denote the respective transmission power. For each RB the base station can determine a different transmission power. However, the total power consumption should not exceed a maximum level of aggregated transmission power $P_{\max}$ Watt. Assuming orthogonal allocation of RBs [15], and ignoring inter-cell interference, i.e., we assume proper eICIC techniques are applied, the instant rate (in bps) for each user n is:

$$r_n(t) = \sum_{m=1}^{M} x_{nm}(t) W_b \log\left(1 + \frac{h_{nm} x_{nm}(t) P_{nm}(t)}{\sigma^2}\right), \quad (1)$$

where W_b is the symbol rate per RB[3], and h_{nm} the channel gain of user n in RB m during the current time period. These parameters are estimated through the CQI feedback that is provided by the users, once every period T.[4] Hence, the scheduling policy of the base station consists of: (*i*) the RB assignment vector $\boldsymbol{x} = (x_{nm}(t) : n \in \mathcal{N}, m \in \mathcal{M}, t = 1, \ldots, T)$, and (*ii*) the power allocation vector $\boldsymbol{P} = (P_{nm}(t) \geq 0 : n \in \mathcal{N}, m \in \mathcal{M}, t = 1, \ldots, T)$. Notice that this policy is derived by the eNB so as to serve the current user requests. At the same time, based on this policy, the operator determines which users will consume the most power and hence are more costly and should be offloaded.

Mesh Network. The mesh network is described by a directed graph $G = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V}$ is the set of the $V = |\mathcal{V}|$ APs, and $\mathcal{E}$ the set of the available links. Each node v comprises a wireless mesh router for the backbone links, and possibly a WiFi AP for serving local traffic (hereafter called *local AP*). Moreover, some of the nodes may have Internet connections. The channel fading gains, and the network configuration are considered constant during the time period of interest[5].

In particular, every mesh point-to-point link $(v, u) \in \mathcal{E}$ has an average available capacity of $C_{vu} \geq 0$ bps. Moreover, each node $v \in \mathcal{V}$ serving as an AP has an available capacity of $C_{v0} \geq 0$ bps for serving local traffic, and an Internet access capacity of $C_{vg} \geq 0$ bps. Notice that these are the available ("*idle*") capacities, i.e., those that the mesh network has decided to assign to this offloading mechanism. Therefore, they may vary across different APs and backbone links.

The policy of the mesh network comprises the data routing decisions for serving the set $\mathcal{N}_o \subseteq \mathcal{N}$ of the users that are offloaded by the cellular network. Let $f_{vu}^{(n)} \geq 0$ denote the average flow (bps) of data transfer over link (v, u) for the offloaded user $n \in \mathcal{N}_o$ (commodity n). Also, $f_{v0}^{(n)} \geq 0$ denotes the WiFi flow of node v for serving locally offloaded traffic, and $f_{vg}^{(n)} \geq 0$ the Internet average rate of flow from node v. The mesh network policy denoted $\boldsymbol{f} = (f_{vu}^{(n)}, f_{v0}^{(n)}, f_{vg}^{(n)} : (v, u) \in \mathcal{E}, n \in \mathcal{N}_o)$, is constrained by the respective link capacities.

Additionally, each node $v \in \mathcal{V}$ is half-duplex constrained and cannot simultaneously send and receive flows with maximum rate to all her neighbors. Moreover, each node performance is limited by the concurrent transmissions occurring in her vicinity by her neighbors. Then, according to the interference protocol model [26], in order to be feasible, the policy should satisfy the following constraints [27] for each link $(u, v) \in \mathcal{E}$:

$$\sum_{n \in \mathcal{N}_o} \left(\sum_{i \in In(u)} \frac{f_{iu}^{(n)}}{C_{iu}} + \sum_{i \in Out(u)} \frac{f_{ui}^{(n)}}{C_{ui}} + \sum_{i \in In(v)} \frac{f_{iv}^{(n)}}{C_{iv}} + \sum_{i \in Out(v)} \frac{f_{vi}^{(n)}}{C_{vi}} \right) \leq 1, \quad (2)$$

where with $Out(u)$ we define the set of nodes for which the node u has an outgoing flow, and with $In(u)$ the incoming set respectively. We need to clarify here that we do not consider the possibility of different channel assignment that would allow parallel transmissions over the point-to-point links. Nevertheless, such an approach can be easily incorporated in our model, e.g., see [27]. We assume the local transmissions and the Internet access is realized over different channels and hence do not interfere with the mesh backbone links.

The mesh network policy should take into consideration the energy consumption of the mesh nodes. We denote with $e_{uv}^{\mathsf{TX}} \geq 0$ and $e_{uv}^{\mathsf{RX}} \geq 0$ (Joules/bit) the transmission and reception energy consumption for each link $(u, v) \in \mathcal{V}$, respectively. Also, $e_{v0}^{\mathsf{TX}} \geq 0$ and $e_{v0}^{\mathsf{RX}} \geq 0$ are the respective parameters for transmitting local traffic, which is expected to be lower than the point-to-point links. We do not consider the energy consumption for the Internet connections as these are considered wireline links. Finally, we denote with $p_v \geq 0$ the price node v pays per bit she downloads from the Internet. Notice that some users may have flat pricing scheme while others may have usage-based plans. In both cases, this price reflects the Internet access cost during the period of interest and without loss of generality it is assumed to be constant.

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[2] The analysis for uploading is similar, although one should take into account the possible differences that may arise in the physical layer and the respective radio resource management (RRM) techniques. We leave this as a future work.

[3] In a 3GPP LTE-A system, OFDM symbols are grouped into RBs. An RB has a total bandwidth of $180KHz$, in the frequency domain consisting of 12 subcarriers with spacing of $15KHz$. In the time domain, in one RB slot there are 7 symbols that last for $0.5ms$. Each symbol can carry from 2 up to 6 bits based on the modulation, QPSK, 16QAM, or 64QAM.

[4] It is possible to have more frequent feedback transmission. However, this increases the complexity and induces communication overhead in the uplink. Typical intervals are 8ms.

[5] Tasks such as channel reallocation and AP deployment that may change the properties of the mesh network, involve many different entities (nodes of the network). Thus, it is not reasonable to assume that reconfiguration is accomplished very often.

IV. OFFLOADING DECISION FRAMEWORK

LTE-A Offloading Policy. In order to understand what is the servicing cost for each user n, we first need to analyze how the operator devises his resource allocation policy for serving the MUs (or UEs). In this context, the problem of the operator is to minimize the aggregate transmission power for the base station, while ensuring the data delivery constraints for the users that it serves. This can be written as follows:

$$\min_{\boldsymbol{P},\boldsymbol{x}} \sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{t=1}^{T} x_{nm}(t)P_{nm}(t) \tag{3}$$

s.t.

$$\sum_{t=1}^{T} r_n(t)T_0 \geq D_n,\ \forall\, n \in \mathcal{N}, \tag{4}$$

$$\sum_{m=1}^{M}\sum_{n=1}^{N} P_{nm}(t) \leq P_{max},\ \forall\, t, \tag{5}$$

$$x_{nm}(t) \in \{0,1\},\ P_{nm}(t) \geq 0\ \forall\, n,\, m,\, t, \tag{6}$$

where $T_0 = 1ms$ is the duration of the subframe, and $r_n(t)$ is given by (1). We assume that this problem has a feasible solution [11] denoted $(\boldsymbol{x}^*, \boldsymbol{P}^*)$, i.e., the maximum transmission power and the available spectrum, are sufficient to serve the users.[6]

The benefits from offloading the traffic of a user $n \in \mathcal{N}$, can be calculated by taking into account the energy consumption cost of the eNB as well as the charged energy prices. Clearly, the operator will decide to offload as many users as possible, based on the available mesh network capacity. Notice that we assume that the offloaded users are those that do not receive a guaranteed bit rate service (GBR) from the eNB, and hence there are no quality of service concerns.

Once the servicing policy of the eNB has been devised, the offloading decisions can be determined directly based on the eNB's resource allocation solution. In this context, every MU is described by the amount of energy she will consume according to the solution $(\boldsymbol{x}^*, \boldsymbol{P}^*)$, the amount of data she requests, and whether she is covered or not by a mesh AP. The eNB sorts the users in a decreasing order of energy consumption and selects the most energy-consuming that are eligible, i.e., within the coverage area of one AP. The exact amount of offloaded mobile data depends on the actual energy cost, which in turns is shaped by the energy prices. We emphasize here that this is a greedy method for determining the most energy consuming nodes as it leverages the results/policy that the eNB has to devise for serving its MUs. Finding the exact energy cost incurred by serving each user requires to solve combinatorially the problem (3)-(6) in a very small time scale. This would induce huge computational complexity into the problem, especially for this small time scale. Hence, we opted to use the already devised eNB's resource allocation policy.

Mesh Network Servicing Policy. Once the eNB has determined the set of users $\mathcal{N}_o$ to offload, the mesh network determines the routing policy $\boldsymbol{f}$ so as to meet the data delivery requirements. We study the mesh network for a time period of Q seconds. Our experimentation results indicate that Q is comparable with the respective period T. Clearly, this depends on the mesh network available resources and its architecture, e.g., the number of links/hops connecting each AP to an Internet gateway. During this period, the data that will be downloaded from all the node-gateways and delivered to each user $n \in \mathcal{N}_o$ should satisfy her demand:

$$\sum_{v\in\mathcal{V}} f_{vg}^{(n)}Q \geq D_n,\ \sum_{v\in\mathcal{V}} f_{v0}^{(n)}Q \geq D_n. \tag{7}$$

For each node v, and each commodity $n \in \mathcal{N}_o$, the flow conservation constraints should be satisfied [27]:

$$f_{vg}^{(n)} + \sum_{q\in In(v)} f_{qv}^{(n)} = f_{v0}^{(n)} + \sum_{u\in Out(v)} f_{vu}^{(n)} \tag{8}$$

where $f_{vg}^{(n)}$ is the flow node v downloads from the Internet, $f_{qv}^{(n)}$ is the incoming flow from each incoming node $q \in In(v)$ that has link to node v, f_{v0} is the flow for data delivery from v to user n, and f_{vu} is the flow delivered to each one of the outgoing neighbors of node v, $u \in Out(v)$.

The objective of the mesh network is to deliver the requested content, within the time period[7] Q, while incurring the minimum possible cost. This will ensure that the community mesh network will have the largest possible net benefit which consists of the reimbursement given by the operator minus the incurred cost. The policy of the mesh network can be derived by solving the minimum cost flow optimization problem (MFP):

$$\min_{\boldsymbol{f}} \quad \alpha\sum_{v=1}^{V}\sum_{n\in\mathcal{N}_o} e_{v0}^{\mathsf{TX}}\ f_{v0}^{(n)} + \alpha\sum_{(v,u)\in\mathcal{E}}\sum_{n\in\mathcal{N}_o}\left(e_{vu}^{\mathsf{TX}} + e_{vu}^{\mathsf{RX}}\right)\ f_{vu}^{(n)}$$

$$+\sum_{v=1}^{V}\sum_{n\in\mathcal{N}_o} p_v\ f_{vg}^{(n)} \tag{9}$$

s.t. (2), (7), (8),

$$0 \leq \sum_{n\in\mathcal{N}_o} f_{vu}^{(n)} \leq C_{vu},\ \forall\,(v,u) \in \mathcal{E}, \tag{10}$$

$$0 \leq \sum_{n\in\mathcal{N}_o} f_{vg}^{(n)} \leq C_{vg},\ 0 \leq \sum_{n\in\mathcal{N}_o} f_{v0}^{(n)} \leq C_{v0},\ \forall\, v \in \mathcal{V}, \tag{11}$$

where parameter $\alpha \geq 0$ is properly selected so as to transform the energy cost to monetary cost (i.e., based on the charged energy prices or a stipulated compensation agreement between the operator and mesh network users). This is a linear programming problem, with closed, compact and convex constraint set [28]. Hence, it can be solved optimally in polynomial time.

A. Cost Sharing Policy

Each node of the mesh network will agree to cooperate in this offloading task only if she receives a fair portion of the net profit the network makes. The latter is determined from the payment of the operator, which is constant for a certain amount of offloaded traffic, minus the cost induced by serving this traffic. In game theoretic terms, the mesh nodes participate in a cooperative game with transferable utilities (TU game) [14], as the profit can be shared in an arbitrary fashion among them. In this game, each node decides whether to participate or not in the offloading service. This decision affects the servicing cost of the mesh network, as each participating node contributes

[6] If the eNB cannot serve all the users, some of them will be dropped. This case does not affect our analysis.

[7] Notice that depending on the value of Q the network can decide about the QoS Class Identifier (QCI) to specify the offloading treatment. Assuming that $Q = T$, requires a full convergence between WiFi and LTE-A cellular network. For values of Q close to T, i.e. $Q \simeq T$, the considering time period is adequate for offloading, as it is justified by our experimentation results. In the case where $Q >> T$ and hence $Q >> D$ the problem is relaxed and delay tolerance is implicitly inserted, which should be clarified.

new resources to the network and hence changes the solution space of the MFP problem.

In particular, we define the cooperative TU game $\mathcal{G}_M = (\mathcal{V}, I(\cdot))$ among the $\mathcal{V}$ nodes of the mesh network, where $I : \mathcal{S} \rightarrow \mathbf{R}^+$ is the so-called *characteristic function* that assigns a positive scalar value to each coalition $\mathcal{S} \subseteq \mathcal{V}$. That is, each subset of nodes $\mathcal{S}$ that decide to cooperate, achieves a net profit:

$$I(\mathcal{S}) = H_{op} - J(\boldsymbol{f}^*(\mathcal{S})), \tag{12}$$

where H_{op} is the payment of the operator, which is constant as long as the service offloads all the agreed traffic, and $\boldsymbol{f}^*(\mathcal{S})$ is the solution of the MFP problem when the subset $\mathcal{S}$ of the mesh nodes participate in this task. The critical issue in this context is how the value of each coalition will be allocated to its members. In turn, this determines the coalitions that will be formed, i.e., which nodes will cooperate with each other. A particularly important question is whether the *grand coalition* $\mathcal{S} = \mathcal{V}$ will be formed and if it will be stable.

We employ the concept of Shapley value [13], which is an axiomatic fairness criterion, for allocating the profit among the mesh nodes. In detail, for each player v participating in a coalition $\mathcal{S} \subseteq \mathcal{V}$, the Shapley value $\phi_v(\mathcal{S}, I)$ is the portion of the net profit that should be allocated to v. The Shapley value has certain desirable properties that render it self-enforcing [13], [14]. Moreover, there exists a closed form expression for finding this value for each player:

$$\phi_v(\mathcal{S}, I) = \sum_{S \subset \mathcal{V}} \frac{|S|!(|\mathcal{V}| - |S| - 1)!}{|\mathcal{V}|!} (I(\mathcal{S} \cup \{v\}) - I(\mathcal{S}))$$

When the coalition game is super-additive and super-modular [14], then allocating the Shapley values to each player ensures that the grand coalition is formed and it is stable. That is, all nodes will participate in the offloading service and each one of them will receive a payment that is larger than his cost (in terms of energy consumption and Internet usage). Interestingly, the game $\mathcal{G}_M$ poses both of these properties which are quite intuitive, as there is no participation cost for the mesh nodes, nor conflicting objectives among them. The detailed proof is provided in our technical report [29].

V. PERFORMANCE EVALUATION

In this Section, we present: (*i*) the simulation results for the performance evaluation of the LTE-A cellular network that indicates how costly users are being offloaded, (*ii*) the testbed experimentation results and the assessment for the WiFi mesh network that will host the offloaded users, and (*iii*) the profit sharing results for the offloading monetary study.

A. LTE-A and WiFi Mesh Networks System Setup

LTE-Advanced Cellular Network Simulation: We consider an LTE-A FDD system for one eNB cell operating in 1800 MHz with an available bandwidth of 10 MHz. Table I summarizes the operational system characteristics. We assume the existence of 40 UEs that lie in the eNB's coverage area of a 5km radius. We have modeled the pathloss (PL) that each UE experiences in a metropolitan network topology, according to the empirical Hata Cost 231 model [30], which was built using collected experimental radio data so as to estimate radio propagation models. Our assumption is aligned with the 3GPP adopted models for cellular network performance evaluation according to [31]. Moreover, we model slow shadow fading SH as log-normal with zero mean and a standard deviation of 8 dB. FD models a Rayleigh fast fading channel with a Doppler of 5 Hz. Therefore, the corresponding channel gains are derived according to $h = 10^{(SH+PL+FD)}/_{10}$.

TABLE I: LTE-A FDD System Configuration.

Parameter	*Value*	*Parameter*	*Value*
Carrier Freq. fc	1800 MHz	*max eNB TX Power*	20W [43dBm]
Bandwidth	10MHz	*Shadowing*	Log-normal
Frame Duration	10ms	*Fading*	Rayleigh
T_{slot} / TTI	0.5ms / 1ms	*Pathloss Model*	Hata Cost 231
UEs	40	*eNB Radius*	5km
RBs per T_{slot}	50	*eNB Height h_t*	50m
RBs per TTI	100	*UE Height h_r*	[1m-10m]
Subcarriers per RB	12	*Symbols per RB*	7

Every TTI the eNB makes a scheduling decision to dynamically assign the available time-frequency resources blocks (RBs) to the 40 UEs. The eNB scheduler aims at power minimization while also at satisfying UEs demands (see problem def. in (3)). According to [10] the minimum size of radio resource that a scheduler can assign, is the minimum TTI in time domain which corresponds two 2 consecutive RBs. The size of each RB is the same for all bandwidths which is $180KHz$. We assume that 90% of the available spectrum is effectively utilized for data-carrying and the rest 10% for pilot and guard signaling. Therefore the total number of data-carrying available RBs per T_{slot} (0.5ms) is $0.9\frac{10MHz}{180KHz} = 50$ and per TTI (1ms) is 100. Every T subframes the eNB decides to offload the most power-consuming users, to the WiFi mesh network. We arbitrarily set $T = 20$ capturing the sparse time the eNB decides to offload. Given the problem definition in Eq. (3)-(6), the eNB needs to solve a mixed integer non-linear programming (MINLP) problem. For solving this NP-hard problem [23], we utilize OPTI [32], an embedded MATLAB optimization toolbox for attaining a feasible solution over the scheduling and power constraints.

Wireless Mesh Network Experimentation: In order to investigate the applicability of the proposed offloading approach in realistic environments, we deployed an indicative experimental setup in the NITOS indoor wireless testbed [16] for the wireless mesh part. NITOS nodes are equipped with both wireless and wired network interfaces. We employed the wired interface to provide Internet access for the gateway nodes, while the Atheros 9380 wireless cards were used to implement the wireless mesh network. In Fig. 2, we illustrate the experimental topology, which spans three different floors of the same building. In order to provide for a clearer interpretation of the collected results in this basic experiment, we decided to fix the physical layer data bit rate equal to 12 Mbps for all the wireless adapters.

Based on the configured setup, we assess the maximum achievable throughput per link in the worst case scenario, which considers that all nodes constantly transmit saturated traffic to all their one-hop neighboring nodes. Application layer traffic was generated through the Iperf command [33]. Table II summarizes the gathered throughput capacities per link. Moreover, deriving of precise energy consumption results requires the collection of real time low level statistics per node, such as frame retransmissions. We managed to collect such information, by enabling the ath9k debugging option in the Ath9k driver [34]. Relying on the results of the work in [35],

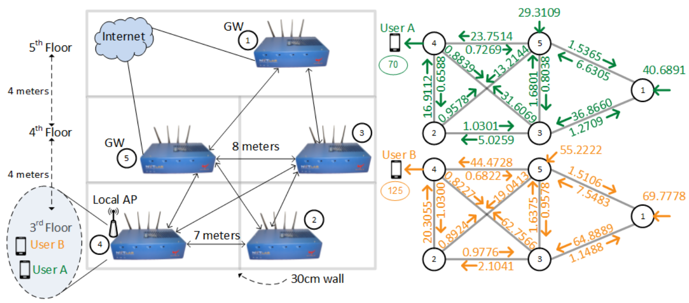

Fig. 2: Wireless Mesh Experimentation Topology: *(left)* NITOS interior building testbed setup. *(right)* Optimal flows for mobile users A and B (Kbits).

[36], we estimated the energy consumption that the Atheros 9380 consumes while transmitting a single bit of information for all the available 802.11 a/g physical layer bit rates. Based on the above, we remark that when the AR9380 is configured to operate at 12 Mbps, it consumes $e^{\mathsf{TX}} = 10.2083$ nJ/bit for transmission and $e^{\mathsf{RX}} = 7.7083$ nJ/bit for reception.

B. Experiments

The experimentation part constitutes a feasibility study for data offloading. The number of users to be offloaded is determined by two parameters: a) the eNB's energy performance gain and b) the sufficient capacity of the WiFi mesh to service the offloaded users. Therefore, the eNB decides to offload the users for whom the WiFi mesh capacity can sustain their demand. Moreover, the WiFi mesh network users should be willing to assist and their incentives rely on the monetary compensation for their service which is paid by the MNOs.

LTE-A Network: Which users should be offloaded by the eNB? In this simulation setup, we determine the offloaded users by evaluating the power efficiency of an eNB for servicing them. The most costly users are those who require the greatest combination of power and resource allocation assignment during scheduling. Depending on the eligible mesh networks capacity, the eNB will decide to offload as many MUs as possible. As scheduling decisions are derived from the solution of the MINLP problem, the most costly users can be indicated directly to the eNB, so as to be offloaded in nearby WiFi mesh networks. In this context, an eNB performs resource allocation and in parallel determines the offloaded users based on their incurred energy cost for servicing them. The total UEs demand saturates the LTE capacity for the period of $T = 20$ subframes. For a different number of offloading users, we illustrate in Fig. 3 the power saving costs for the eNB as the number of offloaded users increases. The eNBs' total power consumption (in one slot) for servicing 40 UEs is measured $P = 19.3308$ Watts. The saving in power consumption is expected to grow as the number of offloaded users increases. In addition, the average power consumption per servicing user reduces as this number decreases. An important finding is that the total gain remains high for a low number of offloaded users ($|\mathcal{N}_o| \leq 4$), while this gain remains low as the number of offloaded users increases ($|\mathcal{N}_o| > 4$). The rationale behind this is that as the eNB scheduler tends to select the most power consuming users to rid, the servicing users left can be characterized as less consuming and less power divergent. Fig. 4 illustrates the above finding showing the average power consumption per servicing user when offloading.

Wireless Mesh Network: Can the mesh network capacity be sufficient for offloaded users? For any user being served in a LTE cell, we must guarantee that her demands will be satisfied in an adequate time while toggling in the WiFi network. Although offloading can benefit eNBs and improve their energy efficiency, this must not degrade roughly the users experience. For two different users A and B being offloaded from the cellular network, we assess the servicing region of the mesh (see Fig. 5). It is important to remark, that the servicing region illustrates the geometrical space of the feasible supported loads by the mesh network.

TABLE II: Wireless Mesh Network Link Capacities (Kbps).

C_{vu}	①	②	③	④	⑤	AP
①	0	0	1445	0	1380	-
②	0	0	363	949	572	-
③	431	357	0	387	510	-
④	0	521	392	0	244	1000
⑤	290	225	211	211	0	-
GW	4000	-	-	-	2000	-

For various demands that lie within the servicing region, we solve the minimum cost flow optimization problem (Eq. 9) by using optimization software tools [32] and estimate the minimum incurred cost. Fig. 6 illustrates the solution evaluation. After the grey shaded line, there is no solution to guarantee the constraints in MFP. Moreover, for the two mobile users A and B being offloaded and requesting $D_A = 70$ and $D_B = 125$ Kbits accordingly, the optimal routing solution is also depicted in the right-side of Fig. 2 showing the amount of data transported through each link. (Recall that, for the sake of comparison that the number of subframes after when the eNB makes an offloading decision is $T = 20$ and the duration of each subframe is 1ms.) We measured the delay that each user experiences from the service in the WiFi mesh to be $d_A = 0.34155ms$ for the A and for user B $d_B = 0.56198ms$. The delay is less than and comparable to the TTI duration of $1ms$ that the eNB schedules the resources. However, the offloading decisions occur sparser in time and this implies that the wireless mesh operation can afford offloading. Notice that, depending on the value of T, it may be required to make fast policy decisions in the mesh network (e.g., in the scale of several seconds). Currently, this is easily implementable using software-defined networking (SDN) techniques which are available and have been already considered for routing in mesh networks [12].

Profit sharing: Offloading the most costly users from the cell network is not a free of charge service for the MNOs. For the mesh users, in order to participate/aid in offloading process for servicing cellular users, a strong motivation is required, that is usually expressed in monetary gains. MNOs compensate mesh users for their service with a fixed H_{op} payment that is stipulated upon agreement. At the end the mesh users should be motivated so as to continue participating in such a coalition. Therefore, mesh users are getting reimbursed for their service according to their provided effort and they share their profits relying on the Shapley values. In Table III, we summarize the profit sharing values ϕ_i's' for the mesh nodes that participate in such a coalition for different values of H_{op} (virtual money) and aggregated user demands. The grand coalition is ensured by the Shapley value criterion for profit dispensing. We arbitrarily set $\alpha = 1$ and $p_u = 1$ to transform energy to monetary cost.

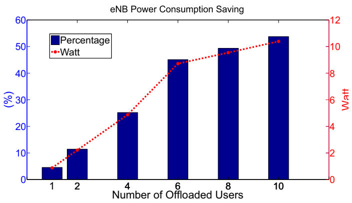

Fig. 3: Offloading power consumption savings.

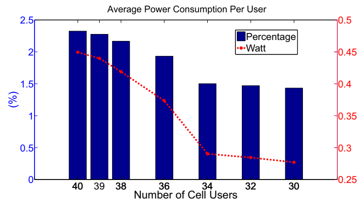

Fig. 4: Power consumption per cellular user due to offloading.

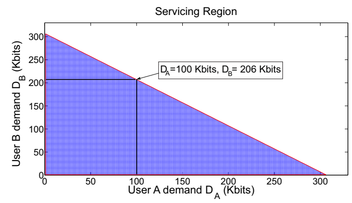

Fig. 5: Mesh Network Servicing Region, for users A and B.

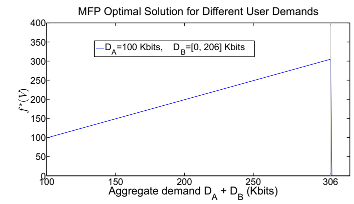

Fig. 6: MFP Solution, $D_A = 10, D_B = \{0, 206\}$ (KBits).

TABLE III: Shapley Values: Profit Sharing.

Demand	***Payment***	***Cost***	***Shapley Values***				
$D_A + D_B$	H_{op}	$J(\boldsymbol{f}^*(\mathcal{V}))$	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5
$10 + 200$	5000	2100	75	250	491.6	1525	558.4
$10 + 200$	10000	2100	325	500	1158.4	4275	1641.6
$70 + 125$	5000	1950	87.5	250	504.2	1612.5	595.8
$70 + 125$	10000	1950	337.5	500	1170.8	4362.5	1679.2
$150 + 50$	5000	2000	83.4	250	500	1583.2	583.4
$150 + 50$	10000	2000	333.4	500	1166.6	4333.4	1666.6

VI. Conclusions

As the rapid proliferation of the 4G technology will not alleviate the ever-increasing demand for capacity, alternative solutions for heterogeneous networking interplay seem quite attractive. In this paper we presented a framework for cellular to mesh (C2M) offloading. Our approach captures the following aspects of the problem: (*i*) From the operators perspective, we determine the power costly users aiming at reducing the power consumption. (*ii*) From the wireless mesh perspective, we motivate the participation in an interplay with cellular networks for servicing offloaded users. Mesh user stimulation relies on the monetary compensation provided by the operator and the final fair profit sharing.

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