A Mechanism for Mobile Data Offloading to Wireless Mesh Networks

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***Abstract*— As the growth of mobile data traffic places significant strain on cellular networks, plans for exploiting underutilized network resources become increasingly attractive. In this paper, we propose, design, and evaluate a data offloading architecture, where mobile users are offloaded to mesh networks, which are built and managed by residential users. Such networks are often developed in the context of community networks or, recently, as commercial services. Mobile network operators can lease capacity from these networks and offload traffic to reduce their servicing costs. We introduce an analytical framework that determines the offloading policy, i.e. which mobile users should be offloaded, based on the energy cost induced to the cellular base stations. Accordingly, we design a minimum-cost servicing policy for the mesh networks. Clearly, such architectures are realizable only if the mesh nodes agree with each other to jointly serve the offloaded traffic. To achieve this, we employ the Shapley value rule for dispensing the leasing payment among the mesh nodes. We evaluate this paper by simulating the operation of the LTE-A network, and conducting test bed experiments for the mesh network. The results reveal significant savings for eNBs power consumption and reimbursements for mesh users.**

***Index Terms*— Mobile data offloading, mesh networks, network economics, Shapley value.**

I. Introduction

TODAY we are witnessing an unprecedented growth of mobile data traffic [2] 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 Wi-Fi networks are gaining increasing interest from industry, academia, and policy-making agencies [3]. At the same time, recent technological advances and standardization efforts, such as Hotspot 2.0 [4], and the 3GPP ANDSF service [5], render these offloading solutions highly attractive by enabling secure and seamless handover, and allowing co-existence and inter-working on single user's devices, among networks of different radio access technology. In this context, a disruptive and forward-looking idea is for the operators, apart from deploying expensive proprietary Wi-Fi networks, to lease the idle network capacity of residential users in order to offload cellular traffic on the spot and on demand. This solution has been proposed for femtocell and Wi-Fi access points (APs) [6], [7]. We make here a further step and propose the employment of Wi-Fi mesh networks that are managed collaboratively by residential users, for building carrier-grade offloading architectures.

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. Reference [8] provides a list with such networks in Europe, some of which exceed 25,000 nodes, while similar networks have been deployed also in USA with great success, e.g., see [9]. CNs complement conventional cellular network infrastructures, mainly in areas where coverage is poor, and/or access is expensive. Similar models have been also commercially launched[1] either by major network operators, e.g., by Telefonica [11], or by alternative Internet service providers, e.g., Netblazr [12]. For example, the BeWifi service of Telefonica [11] enables residential users in proximity to create mesh networks and share their Internet access. These mesh networks can serve as an offloading solution under a monetary compensation offered by the MNOs.

This promising *collaborative data offloading architecture* inevitably raises many questions for which we currently lack answers. First, we need to explore how such non-3GPP networks can be properly integrated in cellular systems. Existing offloading solutions are mainly opportunistic and best-effort services, operate independently from the infrastructure networks and do not provide any quality of service (QoS) guarantees to the offloaded users. For the next generation carrier-grade offloading architectures this approach is not suitable. Thus, we need to devise the technical solutions that can support QoS-enhanced offloading offered by the cellular network. Moreover, it is crucial to explore methods for assessing the performance and accordingly optimizing these *network-initiated offloading* schemes. How much traffic should be offloaded and which mobile users should be selected? And, more importantly, what are the cost savings for

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[1]Besides, there are many Wi-Fi communities, e.g., FON [10], where users coordinate and provide similar offloading services.

the operators? While we already know that offloading is beneficial for users (e.g., it provides energy-prudent wireless links) there is no systematic study of the operators' benefits. Besides, the hitherto offloading motivation was to alleviate congestion in heavy-duty cellular traffic situations. How useful is offloading for moderate load situations?

At the same time, there are many questions for the mesh node owners (e.g., the residential users) who have to collaborate with each other to serve the cellular traffic. For example, some nodes may need to offer more network resources (e.g., bandwidth or energy) than others, and some of them may not be willing to participate. Is there a way to facilitate their agreement on this joint offloading task? Before answering this incentive design question, we need to assess the impact of offloading both in energy costs and in terms of delay induced to the internal traffic of the mesh network. Are nodes which do not participate in offloading immune to these costs or they also experience negative externalities? Finally, this carrier-grade offloading architecture must ensure that the offloaded traffic will be served with proper quality criteria (at least in terms of rate). This is crucial to motivate the participation of mobile users. Which servicing policy at the mesh network satisfies this constraint?

A. Methodology and Contributions

It is clear from the above that the realization of next generation carrier-grade and network-initiated offloading solutions requires architectural advancements, optimization mechanisms, and practical tests to assess their performance. This is exactly the goal of our study. In particular, we consider the scenario depicted in Fig. 1, where the base stations (eNBs) of an LTE-A network[2] serve mobile users (MUs)[3] in a certain area. Every MU device is equipped with LTE and Wi-Fi interfaces. The LTE-A macrocells overlap partially with a Wi-Fi mesh network managed by a group of residential users (other than the MUs). First, we design the offloading mechanism which aims at reducing the costs of the MNO. The main operating expenditure of the cellular network is the eNBs' energy consumption [13], [14]. Minimizing this cost is the main goal and the key criterion for selecting which users to offload. We propose an offloading method that leverages the information from the eNB scheduler, namely the allocation of spectrum resource blocks and transmission power to each MU. This scheduling policy is devised at each eNB and independently of the offloading decisions, often with the objective to minimize the base station power consumption [15], [16]. Based on the energy impact and the demands of the MUs, the mechanism decides which of them should be offloaded. This decision is constrained by the Internet access availability of the mesh network, which is usually the servicing bottleneck in these systems [8], [9], [11], [12]. The offloading mechanism is optimized and tailored to the operation of the LTE network and can be adjusted to different offloading criteria

[2]Our methodology is also backwards compatible and directly applicable to LTE networks. It can also support other network technologies (e.g. WiMAX), as it is based on the broadly employed OFDM scheme.

[3]We use this notation as a complementary term of the user equipment (UE) used in 3GPP terminology.

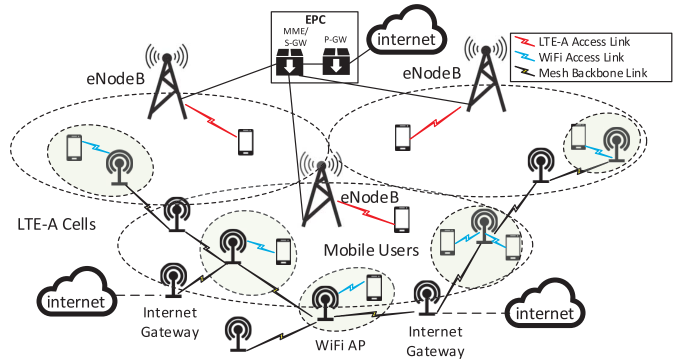

Fig. 1. A multicellular LTE-A network serving mobile users that are partially covered by a Wi-Fi mesh network.

(e.g., selecting the users with highest demands), or different eNB scheduling objectives (e.g., maximizing throughput).

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, taking into account the mesh network available resources and servicing 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, e.g., by utilizing Software Defined Networking (SDN) solutions [17]. The offloading architecture employs the LTE QoS mechanism and ensures that the offloaded users will enjoy comparable servicing rates in the mesh network. This is a hard constraint in the above problem. Accordingly, we design a mechanism for dispensing the profit of the mesh network, i.e., the compensation from the operator minus the servicing cost, among the Wi-Fi mesh nodes. It is based on the concept of the Shapley value [18], [19] which, under certain conditions, ensures that the cooperating mesh nodes will agree to participate in the offloading service. A node that abstains from servicing offloaded traffic might still incur indirect costs (e.g., in terms of interference) which however are substantially different than the direct energy and delay costs when it serves mobile data. The proposed incentive mechanism is proved to satisfy all the nodes and ensure their collaboration.

The proposed architecture takes into consideration the particular characteristics of such systems. For example, user association (and hence offloading decisions) cannot be derived in a very small time scale as eNB re-selection requires several seconds [15], [20]. On the other hand, the eNBs' resource allocation decisions can be made in *msecs*, i.e., every transmission time interval (TTI), but channel quality feedback information (CQI) from the devices to the eNB are available every tens of ms. We explicitly model these limitations and discuss in detail how such a scheme can be incorporated into LTE-A architectures. Finally, we conduct a detailed simulation to evaluate the energy savings that an eNB may obtain in practice from offloading. We also set up in the NITOS wireless testbed [21] an actual mesh network that resembles a residential mesh network similar to BeWiFi networks [11]. This allowed us to quantify the delay the offloaded users experience, and measure the impact of offloading on the energy consumption and the internal traffic of the mesh network, under different loads. To this end, our contributions can be summarized as follows:

- *Offloading Architecture*. We propose a new carrier-grade architecture for offloading mobile data to mesh networks. We discuss the necessary details for integrating this architecture into the emerging 4G/5G networks. In doing so, we take into account the latest 3GPP advancements about LTE and Wi-Fi inter-working so as to handle the data traffic efficiently.
- *Offloading Optimization Framework*. We introduce an analytical framework for maximizing the cellular offloading benefits and minimizing the respective energy and Internet usage costs for the mesh network. This framework identifies the most preferable to be offloaded users, based on the possibly different cost criterion of each operator, and devises the minimum-cost servicing policy for the mesh network. Our analysis can be used for different mesh network architectures, such as small residential or larger community mesh networks [8], [11], [12].
- *Game-theoretic Analysis*. We provide a profit-sharing rule, based on the Shapley value, and prove that it ensures the participation of all mesh nodes. That is, we formulate the joint offloading task of the mesh nodes as a coalitional game and show that it has a non-empty core, which ensures the voluntareer participation of all mesh nodes.
- *Performance Evaluation*. We evaluate the above decision framework using a detailed simulation analysis and extensive experiments conducted in a residential small mesh network that is deployed in NITOS heterogeneous experimental facility [21]. We found that the power savings for an eNB that consumes 19.3308 Watt (in one slot) range from 0.88 Watt (or 4.56%) up to 10.39 Watt (or 53.75%), based on its load, and can be achieved by offloading 25% of its mobile users. Moreover, we showed that a small mesh network can serve these offloading requests without introducing practically any additional delay. Finally, we explored the aggregate energy cost of the mesh nodes and the delay induced in the local traffic due to offloading. We found that under heavy local load the delay increment can reach 19.86% and the corresponding energy consumption 8.13%, for offloading large amounts of cellular traffic.

The rest of this paper is organized as follows: Section II introduces the system model for the cellular and the Wi-Fi mesh network. We formulate the respective optimization decision frameworks in Section III. Section IV introduces the profit-sharing policy. In Section V we present the numerical and experimental setup, and the respective results. We discuss related works in Section VI and summarize our findings and conclusions in Section VII.

II. Model

A. LTE/LTE-A Network

We consider the downlink operation[4] of a multicellular network that consists of a set $\mathcal{K}$ of K base stations (eNBs) for a time period of T subframes, possibly expanding over multiple frames. We denote with $\mathcal{N}_k$ the set of mobile users that are associated with eNB $k \in \mathcal{K}$, and with $\mathcal{N} = \cup_{k\in\mathcal{K}}\mathcal{N}_k$ the total users. Each user n is assigned by the LTE QoS mechanism a data rate of $D_n/T \geq 0$ bps for the current period, based on the class of service she uses, her subscription status, etc. Some mobile users may be in range with a node of the mesh network, while some others may not. Each base station k has a set $\mathcal{M}_k$ of M_k resource blocks (RB) that can be allocated to users in each subframe $t = 1, 2, \ldots, T$. Hence, there are in total $M_k \cdot T$ RBs. We assume that proper enhanced Inter-Cell Interference Coordination (eICIC) techniques are applied, each base station operates on a different frequency domain in its cell, and orthogonal RBs allocation is performed [20]. 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). Besides, such offloading mechanisms are appropriate for static or slowly moving users. Note that, even if channels change rapidly, the eNB cannot be aware of this fact, as mobile users transmit their channel quality indicator (CQI) measurements only once during this time period (typically every 8 ms).

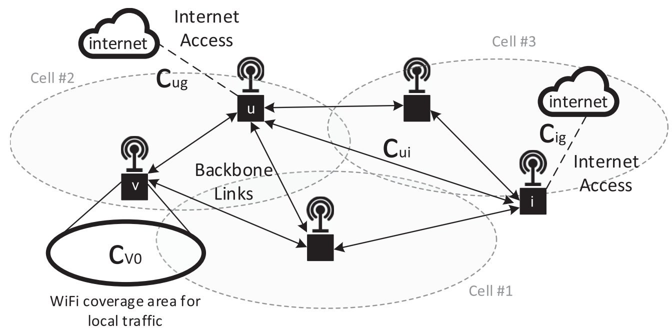

Fig. 2. A Wi-Fi mesh network architecture that its coverage range expands over multiple eNB cells of an LTE-A network. Some of the Wi-Fi nodes are (i) equipped with an AP for serving local traffic and/or (ii) used to provide Internet access to the mesh network (gateways).

Each eNB $k \in \mathcal{K}$ devises the resource block assignment and power allocation policy for serving its users. Let $x_{nm}(t) \in \{0, 1\}$, $n \in \mathcal{N}_k, m \in \mathcal{M}_k$, denote whether RB $m \in \mathcal{M}_k$ is allocated to user $n \in \mathcal{N}_k$ during subframe t. Let $P_{nm}(t)$ denote the respective transmission power. For each RB the base station can determine a different transmission power. The rate (in bps) for each user $n \in \mathcal{N}_k$ is:

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

where W_b is the symbol rate per RB,[5] and $h_{nm}(t)$ the channel gain of user $n \in \mathcal{N}_k$ in RB $m \in \mathcal{M}_k$ during slot t. These parameters are estimated through the CQI feedback. Hence, the scheduling policy of eNB $k \in \mathcal{K}$ consists of the RB

[4]The analysis for uploading is similar (architecture, mechanism), although one should take into account the differences that arise in the physical layer and the respective radio resource management (RRM) techniques.

[5]In LTE-A systems, OFDM symbols are grouped into RBs, each one having bandwidth of 180 KHz, consisting of 12 subcarriers. In the time domain, one RB slot contains 7 symbols of 0.5 ms, each one carrying 2 to 6 bits based on the modulation scheme. Each time transmission interval (TTI) lasts for 1 ms and constitutes a subframe of two RB slots.

TABLE I
SYSTEM MODEL PARAMETERS

Symbol	*Description*	*Symbol*	*Description*
$\mathcal{K}$	Set of eNBs in Multi Cellular Network	$P^k_{\max}$	Maximum TX Power of eNB k
$\mathcal{N}$	Set of Mobile Users in Multi Cellular Network	$\boldsymbol{P}_k$	TX Power Vector of eNB k
$\mathcal{N}_k$	Set of Mobile Users associated with eNB k	$P_{nm}(t)$	TX Power of User $n \in \mathcal{N}_k$ in RB $m \in \mathcal{M}_k$
$\mathcal{N}_o$	Set of Offloaded Mobile Users	$\boldsymbol{x}_k$	RB Assignment Vector of eNB k
$\mathcal{M}_k$	Set of available RBs in eNB k	$x_{nm}(t)$	RB $m \in \mathcal{M}_k$ assignment to User $n \in \mathcal{N}_k$
$\mathcal{V}$	Set of Wi-Fi AP Nodes in the Mesh Network	$h_{nm}(t)$	Channel Gain of User $n \in \mathcal{N}_k$ in RB $m \in \mathcal{M}_k$
$\mathcal{E}$	Set of available Links among Wi-Fi APs	W_b	Symbol Rate per RB $m \in \mathcal{M}_k$
σ	Noise Standard Deviation	$r_n(t)$	Instant Physical Rate in (bps) of User $n \in \mathcal{N}_k$
C_{uv}	Capacity of Mesh Link $(u, v) \in \mathcal{E}$	C_{vg}	Wi-Fi Node $v \in \mathcal{V}$ Internet Gateway Capacity
C_{v0}	Local Capacity of Mesh Node $v \in \mathcal{V}$	$f^{(n)}_{v0}$	Wi-Fi Flow of Node $v \in \mathcal{V}$
$f^{(n)}_{uv}$	Flow over Mesh Link (u, v) for user n	$f^{(n)}_{vg}$	Internet Flow at Node $v \in \mathcal{V}$ for User n
Q	Wi-Fi Network Policy Period	T	Cellular Network Policy Period
p_u	Internet Cost for Mesh Node $u \in \mathcal{V}$ ($/bit)	T_0	Subframe Duration
e^{TX}_{uv}	TX Energy Consumption of Mesh Node u (J/bit)	e^{RX}_{uv}	RX Energy Consumption of Mesh Node $u \in \mathcal{V}$ (J/bit)
e^{TX}_{u0}	TX Energy Consumption of Mesh Node $u \in \mathcal{V}$ for Local Traffic (J/bit)	e^{RX}_{u0}	RX Energy Consumption of Wi-Fi Node $u \in \mathcal{V}$ for Local Traffic (J/bit)

assignment vector:

$$\boldsymbol{x}_k = \big(x_{nm}(t) : n \in \mathcal{N}_k, m \in \mathcal{M}_k, t = 1, \ldots, T\big), \quad (2)$$

and the power allocation vector:

$$\boldsymbol{P}_k = \big(P_{nm}(t) \geq 0 : n \in \mathcal{N}_k, m \in \mathcal{M}_k, t = 1, \ldots, T\big). \quad (3)$$

Notice that this policy is derived by each eNB - independently of the offloading mechanism - so as to serve the user requests. Based on this policy the operator determines which users are expected to consume the largest amount of energy, and hence they are more costly and they should be offloaded. We define the set of offloaded users as $\mathcal{N}_o \subseteq \mathcal{N}$.

B. Mesh Network

The mesh network is modeled by a directed graph $G = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V}$ is the set of the $V = |\mathcal{V}|$ mesh nodes, and $\mathcal{E}$ the set of the backbone point-to-point links, (see Fig. 2). The Wi-Fi mesh network expands over multiple eNBs coverage areas. Each node $v \in \mathcal{V}$ comprises a wireless mesh router for the backbone links, and possibly a Wi-Fi AP for serving local traffic (hereafter called *local AP*). Moreover, some nodes may have Internet connections, thus acting as gateways for the mesh network. The channel fading gains for the backbone links, and the network configuration are considered constant during T.[6]

The mesh network dedicates certain amount of link capacities to the offloading mechanism. Such a segregation can be achieved in practice with tools such as AFFIX and Click [22], [23], or with SDN architectures [17]. In particular, every mesh link $(v, u) \in \mathcal{E}$ has an average available capacity of $C_{vu} \geq 0$ bps, and each node $v \in \mathcal{V}$ a capacity of $C_{v0} \geq 0$ bps for delivering mobile data and Internet access of $C_{vg} \geq 0$ bps. In most network deployments [8], [11], [12], this Internet capacity is the actual bottleneck of the mesh network, as it is much smaller than the capacity of the backbone links or the local AP capacity. In other words, it holds $C_g = \sum_{v\in\mathcal{V}} C_{vg} \leq \sum_{v\in\mathcal{V}} C_{v0}$.

The servicing policy of the mesh network comprises the routing and flow decisions for the set $\mathcal{N}_o \subseteq \mathcal{N}$ of the offloaded mobile users. Let $f^{(n)}_{vu} \geq 0$ denote the average flow (bps) of data transfer over the wireless link (v, u) for the offloaded user $n \in \mathcal{N}_o$, i.e., commodity (n). Also, $f^{(n)}_{v0} \geq 0$ denotes the Wi-Fi flow of node v for delivering the offloaded traffic (n), and $f^{(n)}_{vg} \geq 0$ the respective Internet flow. The mesh network policy is:

$$\boldsymbol{f} = \big(f^{(n)}_{vu}, f^{(n)}_{v0}, f^{(n)}_{vg} : (v, u) \in \mathcal{E}, v \in \mathcal{V}, n \in \mathcal{N}_o\big), \quad (4)$$

and it 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 of traffic with maximum rate to all her neighbors. Moreover, the performance of each node is limited by the concurrent packet transmissions that occur within its range and use the same channel. Then, according to the interference protocol model as it is applied for the backbone links of the mesh network [24], [25] the policy should satisfy the following set of constraints:

$$\Big(\sum_{i\in In(u)} \frac{f^{(n)}_{iu}}{C_{iu}} + \sum_{i\in Out(u)} \frac{f^{(n)}_{ui}}{C_{ui}} + \sum_{i\in In(v)} \frac{f^{(n)}_{iv}}{C_{iv}} + \sum_{i\in Out(v)} \frac{f^{(n)}_{vi}}{C_{vi}} \Big) \leq 1, \quad \forall\, (u, v) \in \mathcal{E}, \quad (5)$$

where $Out(u) = (j : (i, j) \in \mathcal{E})$, $In(u) = (j : (j, i) \in \mathcal{E})$ are the set of outgoing and incoming one-hop neighbors of node u in the mesh network. Note that the above constraint refers to the case where the mesh backbone links use a single channel. Nevertheless, the model can be directly extended for cases where multiple different channels are used, (e.g., [24]). We assume the local transmissions are realized over different channels and do not interfere with the mesh backbone links.

[6]Tasks such as channel re-allocation and AP deployment that may change the properties of the mesh network, involve many different entities. Thus, it is not reasonable to assume that such a re-configuration is accomplished very often.

It is clear from Eq. (5) that even if a mesh node does not participate in the offloading task, it will still experience interference and thus delay and energy cost for its local traffic.

The energy cost in particular can be very important. $e_{uv}^{\mathsf{TX}} \geq 0$ and $e_{uv}^{\mathsf{RX}} \geq 0$ (Joules/bit) denote 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 wireline Internet connections. Finally, we denote with $p_v \geq 0$ the price node v pays per bit that she downloads from Internet. Some mesh networks may be charged for their Internet access with usage-based schemes, while others with flat-pricing schemes (e.g., in Australia) and we set the price to zero for them. Finally, Table I summarizes the system model parameters.

III. Offloading Decision Framework

In this Section, we analyze the offloading decision framework which implements and enforces two policies: the offloading policy of the LTE-A multicellular network, and the routing and servicing policy for the offloaded traffic that is employed by the Wi-Fi mesh network. We also discuss the practical aspects of incorporating such a mechanism into a 3GPP architecture.

A. Practical Considerations

The first step for offloading is the mobile user to explore if she is in range with any node of the Wi-Fi mesh network, and then to initiate the connection establishment procedure with it. 3GPP has introduced the ANDSF mechanism [5] in order to assist mobile users to discover and access non-3GPP radio networks. Additionally, in [26] and [27] 3GPP has specified two different types of Wi-Fi access modes (trusted and non-trusted) and the corresponding methods to ensure IP-persistence, and maintain seamless flow mobility while offloading users. Our offloading framework extends the 3GPP architecture for inter-working between an LTE-A and a *trusted* Wi-Fi network, Fig. 3. To enable carrier-grade mobile data offloading to/from the Wi-Fi mesh network, certain components of EPC should be involved as described in the sequel.

The *Mobility Management Entity* (MME) processes the control signaling between eNBs and the core network. During the offloading process, its role is to collect specific measurement information (i.e., metrics about energy consumption and traffic requests) which is sent by eNBs. Moreover, it is informed about the capacities offered by the complementary networks. The MME determines the offloaded users and triggers the process for shifting them to the complementary network. The offloading process is then forwarded to the P-GW as it offers the means to support dynamic network-based traffic optimization.

The *PDN Gateway component* (P-GW) serves as the mobility anchor between 3GPP and non-3GPP networks, and it is the entry/exit point of traffic with the latter. Its role is to

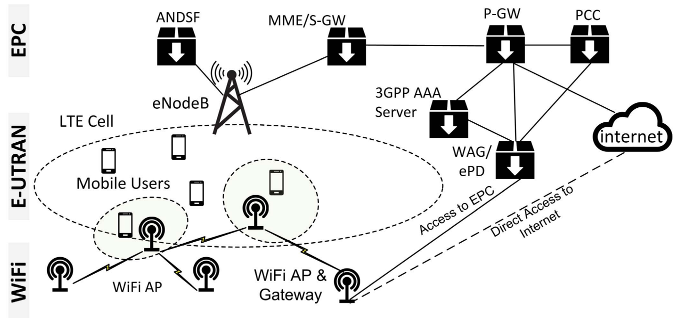

Fig. 3. Non-roaming architecture for mobile data offloading. The architecture is based on 3GPP specifications TS 23.402 [26] & TS 23.234 [27] for offloading and WLAN-3GPP networks interworking.

provide a mobile user with connectivity to external packet data networks. Finally, the *WLAN Access Gateway* (WAG) purpose is to enable access and packet filtering to traffic that is destined to the WLAN network. It takes the role of a router for the Wi-Fi mesh network and also enforces routing of packets through the P-GW. The WAG implements certain policies for offloading enforcement and also supports QoS mechanisms.

B. LTE-A Offloading Policy

The first step in devising the offloading policy is to calculate the expected servicing cost for every user n that is served by each eNB $k \in \mathcal{K}$. In order to do so, we need to quantify the power and the spectrum that she will consume, based on her location in the cell and her traffic rate demands. It is important to emphasize here that eNBs while adopting the proposed offloading framework are not encumbered with extra computational cost. Instead, the determination of the costly users stems from the power allocation and RB assignment policy the eNB scheduler has to devise in order to serve its users. Moreover, the offloading mechanism can work in conjunction with different schedulers, e.g., maximizing throughput, ensuring fair rate allocation, etc, (please see [15] for a survey) as it only requires the spectrum and power allocation results.

In this work we assume that the MNO aims at minimizing its OPEX costs, and hence it enables the eNB scheduler to apply a policy that minimizes the aggregate transmission power. This policy is derived from the solution of the following cost optimization problem that each eNB $k \in \mathcal{K}$ solves in the beginning of every time period T:

$$\mathbf{COP}_{\boldsymbol{k}}: \min_{\boldsymbol{P}_k, \boldsymbol{x}_k} \sum_{m=1}^{M} \sum_{n=1}^{N} \sum_{t=1}^{T} x_{nm}(t) P_{nm}(t) \tag{6}$$

$$\text{s.t.} \sum_{t=1}^{T} r_n(t) T_0 \geq D_n, \quad \forall n \in \mathcal{N}_k, \tag{7}$$

$$x_{nm}(t) \in \{0, 1\},\ P_{nm}(t) \geq 0 \quad \forall n \in \mathcal{N}_k,\ m \in \mathcal{M}_k, t, \tag{8}$$

where $T_0 = 1ms$ is the duration of the LTE subframe, and $r_n(t)$ is given by Eq. (1). We assume that this problem has a feasible solution [16] that is denoted by $(\boldsymbol{x}_k^*, \boldsymbol{P}_k^*)$, i.e., we consider that the maximum transmission power and the available spectrum are sufficient to serve the mobile users in cell $k \in \mathcal{K}$.[7] Clearly, this is an NP-hard problem that cannot be solved optimally in polynomial time [28]. However, there have been proposed various heuristic or approximation methods [29], while it is possible to employ brute-force solutions (e.g., branch-and-bound) to reduce computing cost and delay when enough computational power is available.

The benefits from offloading the traffic of a mobile user can be calculated by taking into account the energy consumption cost of the serving eNB k. Clearly, the operator will decide to offload as many users[8] as possible based on the available mesh network capacity (that is upper bounded by the capacity of the Internet access in the gateway nodes). Note that the total power consumption of a base station is generally a linear function of the total transmission power [13], [14]. Yet, we explain below, and verify in Section V through experiments, that the offloaded users experience a comparable service from the mesh network.

Once the servicing policy of the eNB has been devised, the offloading decisions can be determined directly based on the eNB's resource block assignment and power allocation solution, i.e., without requiring the eNB to perform additional computations specifically for the offloading mechanism. In this context, every MU is described by the amount of energy she would consume, the amount of data she requests, and whether she is effectively covered or not by a mesh AP. In particular, every eNB $k \in \mathcal{K}$, after solving the respective $\mathbf{COP_k}$ problem, creates the set[9] $\mathcal{L}_k = \big((e_n, D_n) : n \in \mathcal{N}_k\big)$, where e_n denotes the energy that user $n \in \mathcal{N}_k$ consumes according to the solution $(\boldsymbol{x}_k^*, \boldsymbol{P}_k^*)$:

$$e_n = \sum_{m=1}^{\mathcal{M}_k} \sum_{t=1}^{T} x_{nm}^*(t) P_{nm}^*(t). \tag{9}$$

At this point, we need to emphasize that this is the *expected* energy consumption for every mobile user $n \in \mathcal{N}_k$ during the period of interest T, since: (i) problem $\mathbf{COP}_k$ is solved using estimations for the channel gains $\tilde{h}_{nm}(t)$ as the MUs cannot in practice provide feedback in every subframe t, (ii) in some cases the eNB may update its scheduling policy during T by solving again its resource allocation problem; this might change the energy consumption of the MUs as the new decisions will be made based on the updated CQI values. However, when one takes into account the practical limitations of user association [30], [31], which cannot be realized very fast, and the computational cost of solving the scheduling problem, it is reasonable to assume that in practice these expected values should be used for making the offloading decisions.

Every eNB $k \in \mathcal{K}$ communicates the set $\mathcal{L}_k$ to the EPC core where the central offloading decisions are made. In particular, the MME unit receives these sets $\mathcal{L} = \cup_{k\in\mathcal{K}}\mathcal{L}_k$ and, based on the mesh network coverage information which is provided by the ANDSF service, devises the overall set $\mathcal{N}_L$ of users that are eligible for offloading. Accordingly, the MNO selects the users that will be offloaded, considering also the criterion of the Wi-Fi channel quality. This decision depends on the energy consumption and on the data demand of each user, as it is assumed that the mesh network has limited Internet access. Technically, this is a knapsack problem, where the knapsack size is the available total Internet access of the mesh network C_g, the value of each item $n \in \mathcal{N}$ is the energy cost, and the size is the respective data usage D_n, and thus can be solved in pseudo-polynomial time [32].

C. Mesh Network Servicing Policy

Once the MME has determined the set of users $\mathcal{N}_o$ to offload, the WAG network determines the routing policy $\boldsymbol{f}$ so as to meet the user traffic demands and the traffic delivery requirements. We study the mesh network for a time period during which the data that will be delivered to every user $n \in \mathcal{N}_o$ should satisfy the respective demand:

$$\sum_{v\in\mathcal{V}} f_{vg}^{(n)} Q \geq D_n, \quad \sum_{v\in\mathcal{V}} f_{v0}^{(n)} Q \geq D_n. \tag{10}$$

The flow conservation constraints must be also satisfied [24]:

$$f_{vg}^{(n)} + \sum_{q\in In(v)} f_{qv}^{(n)} = f_{v0}^{(n)} + \sum_{u\in Out(v)} f_{vu}^{(n)}, \;\; v \in \mathcal{V}, n \in \mathcal{N}_o, \tag{11}$$

where $f_{vg}^{(n)}$ is the flow v downloads from Internet, $f_{qv}^{(n)}$ is the incoming flow from each node $q \in In(v)$, f_{v0} is the flow from node v to user n, and f_{vu} is the outgoing flow to $u \in Out(v)$.

The objective of the mesh network is to deliver the requested content within the time period Q, while incurring the minimum possible cost. This will ensure that the Wi-Fi mesh network will have the largest possible net benefit, which consists of the reimbursement given by the operator minus the incurred cost. Clearly, the mesh network needs to allocate to each offloaded user only those resources that are necessary so as to satisfy the QoS level D_n that has been determined by the MNO. Please note also that this servicing policy does not need to consider the local internal mesh traffic since the link capacities are segregated (between offloading and internal traffic).

Given the above, the policy of the mesh network can be derived by solving the minimum cost flow optimization

[7]If the eNB $k \in \mathcal{K}$ cannot serve all the users, some of them will be dropped. This case does not affect our analysis. Besides the framework is applicable for different formulations of the COP_k problem and it can be adapted to other performance-cost optimization criteria such as throughput maximization, as the eNB scheduling objective is not specified in 3GPP standards.

[8]More specifically, not only the users but their services require individually priority handling. As every mobile user traffic in LTE is differentiated by bearers of different QoS constraints, one mobile user may have multiple bearers of traffic with diverse demands. The proposed analysis can be directly extended to the above case and hence it is more reasonable to assume that part or the whole traffic of a user is offloaded. However, without loss of generality we say that a user is being offloaded.

[9]The eNB takes into account the *effective coverage* of its users in the mesh network. That is enabled by ANDSF service which allows each MU to map from its current location a list of the Wi-Fi networks and the eNB to identify the eligible users to offload. MUs detect the presence of any Wi-Fi network and advertise this discovery information to the ANDSF server reporting (i) a list of available WLANs to each MU, (ii) channel quality indicators and reference signals (RSSI for strength, RSRP for received power and RSRQ for received quality), (iii) the MUs geographical coordinates, and (iv) the eNB's cell id.

problem (**MFP**):

$$\min_{f} \ \alpha\bigg(\sum_{\upsilon=1}^{V}\sum_{n\in\mathcal{N}_o} e_{\upsilon 0}^{\mathsf{TX}} f_{\upsilon 0}^{(n)} + \sum_{(\upsilon,u)\in\mathcal{E}}\sum_{n\in\mathcal{N}_o}\big(e_{\upsilon u}^{\mathsf{TX}}+e_{\upsilon u}^{\mathsf{RX}}\big) f_{\upsilon u}^{(n)}\bigg) + \sum_{\upsilon=1}^{V}\sum_{n\in\mathcal{N}_o} p_\upsilon f_{\upsilon g}^{(n)} \quad (12)$$

$$\text{s.t.} \ \sum_{\upsilon\in\mathcal{V}} f_{\upsilon g}^{(n)} Q \geq D_n, \quad \sum_{\upsilon\in\mathcal{V}} f_{\upsilon 0}^{(n)} Q \geq D_n, \quad \forall n\in\mathcal{N}_o, \quad (13)$$

$$f_{\upsilon g}^{(n)} + \sum_{q\in In(\upsilon)} f_{q\upsilon}^{(n)} = f_{\upsilon 0}^{(n)} + \sum_{u\in Out(\upsilon)} f_{\upsilon u}^{(n)}, \quad \forall n\in\mathcal{N}_o, \quad (14)$$

$$\bigg(\sum_{i\in In(u)}\frac{f_{iu}^{(n)}}{C_{iu}} + \sum_{i\in Out(u)}\frac{f_{ui}^{(n)}}{C_{ui}} + \sum_{i\in In(\upsilon)}\frac{f_{i\upsilon}^{(n)}}{C_{i\upsilon}} + \sum_{i\in Out(\upsilon)}\frac{f_{\upsilon i}^{(n)}}{C_{\upsilon i}}\bigg) \leq 1, \quad \forall(\upsilon,u)\in\mathcal{E}, \quad (15)$$

$$0 \leq \sum_{n\in\mathcal{N}_o} f_{\upsilon u}^{(n)} \leq C_{\upsilon u}, \quad \forall(\upsilon,u)\in\mathcal{E}, \quad (16)$$

$$0 \leq \sum_{n\in\mathcal{N}_o} f_{\upsilon g}^{(n)} \leq C_{\upsilon g}, 0 \leq \sum_{n\in\mathcal{N}_o} f_{\upsilon 0}^{(n)} \leq C_{\upsilon 0}, \quad \forall \upsilon \in \mathcal{V}, \quad (17)$$

where parameter $\alpha \geq 0$ is the electricity rate price that transforms the energy consumption cost to monetary units based on the retail electricity cost. We assume that the mesh network is a retail electricity consumer, where the flat rate prices are regulated by the Energy Regulatory Commission of each country. Indicatively, in US the rate is 0.025 USD/KWh or $6.94 \cdot 10^{-9}$ USD/J, and in Greece 0.054 EUR/KWh or $1.5 \cdot 10^{-8}$ EUR/J (note that 1KWh=3.6MJ). Also, recall that p_υ is the Internet access cost of node υ per bit, that may capture both a flat pricing scheme or a capped Internet access plan as explained in the previous section. This is a linear programming problem, with closed, compact and convex constraint set [33]. Hence, it can be solved optimally in polynomial time. Besides, we assumed that the bottleneck of the mesh network is the Internet access capacity (as this is motivated by real mesh network deployments, e.g., [8], [9]), and the latter has been taken into account in deciding the set $\mathcal{N}_o$. Hence, the MFP problem is feasible and the mesh servicing policy is realizable. The offloading decision framework is summarized in Algorithm 1.

Algorithm 1 Offloading Decision Framework

Executed every T subframes;

1. Each eNB $k \in \mathcal{K}$ solves the **COP**$_k$ problem and finds the servicing policy $\boldsymbol{x}_k^*$, $\boldsymbol{P}_k^*$;
2. Each eNB $k \in \mathcal{K}$ calculates the expected energy consumption e_n for every user $n \in \mathcal{N}_k$ and creates the set $\mathcal{L}_k = \big((e_n, D_n) : n \in \mathcal{N}_k\big)$;
3. Each eNB $k \in \mathcal{K}$ communicates this information $\mathcal{L}_k$ to the MME;
4. The MME is informed by the WAG (through the P-GW) about the link capacities of the mesh network; The MME finds the set of eligible to be offloaded users $\mathcal{N}_L$ by selecting from the union set $\cup_{k\in\mathcal{K}}\mathcal{L}_k$ all the MUs that are in *effective coverage* range with some node of the mesh network based; This information is provided by the ANDSF;
5. The MME solves a 0-1 knapsack problem with items the elements of $\mathcal{N}_L$, value for each item equal to e_n, cost of each item D_n, and Knapsack size C_g, and finds the set of users to be offloaded $\mathcal{N}_o$;
6. The information $(e_n, D_n) : n \in \mathcal{N}_o$, is used as input to the **MFP** problem which is solved by the WAG, in order to find the optimal mesh servicing policy;
7. The WAG imposes the servicing policy $\boldsymbol{f}^*$ on the mesh network nodes;

IV. Profit 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 profit that the network makes due to the payment of the operator. Our focus here is on the strategic interactions among the mesh nodes and we assume that the value of the reimbursement has already been agreed among them and the MNO. Therefore we focus on how H_{op} has to be dispensed to the mesh nodes. In game theoretic terms, the mesh nodes participate in a cooperative game with transferable utilities (TU game) [19], as the profit can be shared in an arbitrary fashion among them. In this game, each node which is considered a distinct player, 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 new resources to the network, and it changes the feasible solution space of the MFP problem. Note that unlike other routing settings with strategic decision makers, here the mesh nodes route a third-party's traffic and are compensated for their joint effort. Thus, a cooperative game model is a more precise framework than a non-cooperative approach.

Particularly, we define the cooperative TU game $\mathcal{G}_M = \big(\mathcal{V}, I(\cdot)\big)$ among the $\mathcal{V}$ nodes of the mesh network, where $I : \mathcal{S} \to \mathbf{R}^+$ 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 decides to cooperate, achieves a net profit $I(\mathcal{S}) = H_{op} - J\big(\boldsymbol{f}^*(\mathcal{S})\big)$, where H_{op} is the payment of the operator which is constant based on the agreement of the MNO and the mesh nodes for the offloaded traffic that is upper bounded by the provided mesh link capacities. This parameter is given as input to our study and it is clear that it has to be lower than the energy saving benefits of the MNO and higher than the incurred costs by the mesh nodes. Also $\boldsymbol{f}^*(\mathcal{S})$ is the solution of the MFP problem when the subset $\mathcal{S}$ of the mesh nodes $\mathcal{V}$ participate in this task, and $J(\cdot) \geq 0$ the mesh cost function given in Eq. (12). The critical issue in this context is how the worth of the net profit of each coalition will be allocated to its members. In turn, this determines the coalitions that will be formed, i.e., which mesh nodes will cooperate with each other. The key question is whether the *grand coalition* $\mathcal{S} = \mathcal{V}$ will be formed and if it will be stable. Technically, this means that all nodes $\upsilon \in \mathcal{V}$ have an incentive to join the offloading service.

We employ the concept of Shapley value [18], which is an axiomatic fairness criterion, for allocating the profit among the mesh nodes. In detail, for each player υ participating in a coalition $\mathcal{S} \subseteq \mathcal{V}$, the Shapley value $\phi_\upsilon(\mathcal{S}, I)$ is the portion

TABLE II
LTE-A FDD SYSTEM CONFIGURATION

Parameter	*Value*	*Parameter*	*Value*
Carrier Freq. fc	1800 MHz	*max eNB TX Power*	20 W [43 dBm]
Bandwidth	10 MHz	*Shadowing*	Log-normal
Frame Duration	10 ms	*Fading*	Rayleigh
T_{slot} / *TTI*	0.5 ms / 1 ms	*Pathloss Model*	Hata/COST 231 Eq. (18)
MUs (Uniform Distr.)	40	*eNB Radius* d	2 km
RBs per T_{slot}	50	*eNB Height* h_t	50 m
RBs per TTI	100	*UE Height* h_r	[1 m-10 m]
Subcarriers per RB	12	*Symbols per RB*	7

$$PL_{[dB]} = 46.3 + 33.9\log_{10}(fc) - 13.82\log_{10}(h_t) + (44.9 - (6.55\log_{10}(h_t))\log_{10}(d)) - a(h_r) + C \quad (18)$$

$$\text{where} \quad a(h_r) = (1.1\log_{10}(fc) - 0.7)h_r - (1.566\log_{10}(fc) - 0.8) \quad (19)$$

$$\text{and} \quad C = 3\,\text{dB}, \text{ for metropolitan areas}, \quad C = 0\,\text{dB}, \text{ for medium cities and suburban areas}$$

of the net profit that should be allocated to every participating node v. Indeed, the Shapley value has certain desirable properties that render it self-enforcing [18], [19], [34]. Moreover, there exists a closed form expression for finding this value for each player:

$$\phi_v(\mathcal{S}, I) = \sum_{S \subset \mathcal{V}} \frac{|S|!(|\mathcal{V}| - |S| - 1)!}{|\mathcal{V}|!} \big(I(\mathcal{S} \cup \{v\}) - I(\mathcal{S})\big). \quad (20)$$

When the coalition game is super-additive and super-modular [19], 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 her cost that is induced by the energy consumption and Internet usage. Interestingly, the game $\mathcal{G}_M$ poses both of these properties which are quite intuitive, as there is neither participation cost for the mesh nodes, nor conflicting objectives among them:

Lemma 1: The characteristic function $I(\cdot)$ of the game $\mathcal{G}_M$ has the following properties:

1) *It is* super-additive*, i.e.:* $I(\mathcal{S}_1 \cup \mathcal{S}_2) \geq I(\mathcal{S}_1) + I(\mathcal{S}_2)$, $\forall \mathcal{S}_1, \mathcal{S}_2 \subset \mathcal{N}$, $\mathcal{S}_1 \cap \mathcal{S}_2 = \emptyset$
2) *It is* super-modular*, i.e.:* $I(\mathcal{S} \cup \{v\}) - I(\mathcal{S}) \leq I(\mathcal{Q} \cup \{v\}) - I(\mathcal{Q})$, $\forall \mathcal{S} \subseteq \mathcal{Q} \subseteq \mathcal{V} \setminus \{v\}$

Proof: The super-additivity property can be easily verified if we consider that cooperation does not entail any additional cost to the mesh nodes, e.g., they do not have capital to invest for buying additional equipment. Therefore, when two disjoint sets of mesh nodes cooperate, in the worst case scenario they can achieve the same performance as their previous disjoint operation. Regarding the super-modularity property, we have the following:

$$I(\mathcal{S}) = H_{op} - J(\boldsymbol{f}^*(\mathcal{S})),\ I(\mathcal{S} \cup \{v\}) = H_{op} - J(\boldsymbol{f}^*(\mathcal{S} \cup \{v\})),$$
$$I(\mathcal{Q}) = H_{op} - J(\boldsymbol{f}^*(\mathcal{Q})),\ I(\mathcal{Q} \cup \{v\}) = H_{op} - J(\boldsymbol{f}^*(\mathcal{Q} \cup \{v\})).$$

Substituting the above to the definition of the super-modularity property, we get:

$$J(\boldsymbol{f}^*(\mathcal{S})) - J(\boldsymbol{f}^*(\mathcal{S} \cup \{v\})) \leq J(\boldsymbol{f}^*(\mathcal{Q})) - J(\boldsymbol{f}^*(\mathcal{Q} \cup \{v\})). \quad (21)$$

It is easy to see that the above inequality holds. The critical observation is the following: when optimizing the policy $\boldsymbol{f}$ for a larger mesh network, e.g., $\mathcal{Q}$, then the value of the minimum cost is upper bounded by the respective (minimum) cost for a smaller coalition $\mathcal{S}$ plus the additional costs that incurred by $\mathcal{S}$ for not having the additional resources that the nodes $\mathcal{Q} \setminus \mathcal{S}$ contribute to the network. You should notice that any coalition can achieve the minimum cost of a smaller coalition by adopting exactly the same servicing policy. Moreover, the benefits that are derived from adding one more node to the network, increase with its size, as there are more options for exploiting the additional node resources. □

V. PERFORMANCE EVALUATION

The objective of the performance evaluation is threefold: (i) study the eNB energy consumption savings, (ii) investigate the offloading costs incurred by the mesh network in terms of node energy consumption and delay for the local traffic, and (iii) assess the performance impact - if any - on the offloaded users. We used for the LTE-A network a detailed simulator fully compliant with the respective 3GPP specs [35], and for the mesh network an actual small-scale residential setup (such as the Telefonica BeWiFi service) that was built in the NITOS wireless testbed [21].

A. Methodology and Offloading System Setup

1) LTE-A Simulation: We consider an LTE-A FDD system for one eNB cell operating in 1800 MHz with 10 MHz available bandwidth. Table II summarizes the operational system characteristics. There are 40 MUs randomly placed (uniform distribution) within the eNB's coverage area of $d = 2$ km radius. We have modeled the path loss (PL) that each mobile user experiences in a metropolitan network topology, according to Eq. ((18)) of the - widely adopted for cellular networks [35] - empirical Hata Cost 231 model [36]. Moreover, we model slow shadow fading SH as log-normal with zero mean and 8dB standard deviation. FD models a Rayleigh fast fading channel with 5 Hz Doppler. Therefore, the channel gains are $h = 10^{\frac{(SH+PL+FD)}{10}}$.

Every TTI, the eNB makes a scheduling decision to dynamically assign the available RBs to MUs and determine the transmission power in each one of them. The scheduler devises the servicing policy $(\boldsymbol{x}_k^*, \boldsymbol{P}_k^*)$ based on the solution of the COP_k problem. Following [15], the minimum size of radio resources that the eNB scheduler can assign is the minimum TTI which corresponds to 2 consecutive RBs. The size of

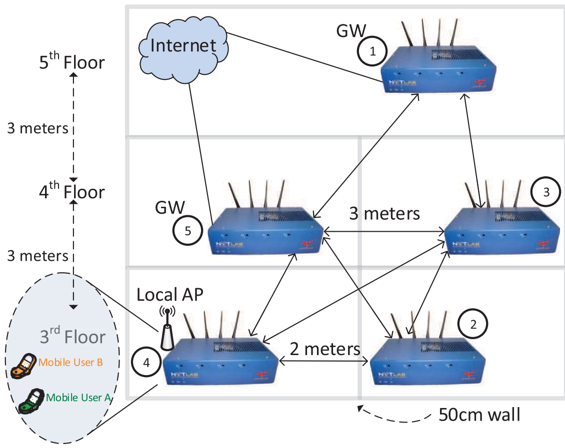

Fig. 4. Mesh Experimentation Topology.

each RB is the same for all bandwidths which is 180 KHz. 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} (0.5 ms) is $0.9\frac{10\ MHz}{180KHz} = 50$ and per TTI (1 ms) is 100. Every $T = 20$ subframes each eNB $k \in \mathcal{K}$ reports a list of the most costly users in terms of power-consumption along with their demands to the MME in order to determine the offloaded users.

2) Wireless Mesh Network Testbed Experimentation: The NITOS nodes [21] that were used for the mesh network are equipped with both wireless and wired network interfaces. We employed the wired interface to provide Internet access for the gateway nodes (nodes 1 and 5), while the Atheros 9380 wireless cards were used to implement the wireless mesh network. In Fig. 4, we illustrate the experimental topology, which spans three different floors of the same concrete building. For all experiments we fixed the upper limit for the physical layer bit rate to 12 Mbps.

Based on the configured setup, we assess the actual achieved throughput per link in the worst case scenario, i.e., when all nodes transmit concurrently saturated traffic to all their one-hop neighbors. To do so, we leveraged a topology and link assessment protocol [37] to inspect link quality among NITOS testbed nodes. Application layer traffic was generated through the Iperf command [38]. Table III summarizes the results. 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 [39]. Using the measurements from the NITOS online energy monitoring tool [40], we found that the Atheros 9380 energy consumption (when it's physical throughput is upper-bounded at 12 Mbps) is $e^{\mathrm{TX}} = 10.2083$ nJ/bit for transmission and $e^{\mathrm{RX}} = 7.7083$ nJ/bit for reception. Moreover, we set $\alpha = 6.94 \cdot 10^{-9}$ USD/J.

B. Experimentation

In this subsection we ask and answer practical questions about the actual costs and performance of this offloading architecture.

TABLE III
MESH NETWORK LINK CAPACITIES (Mbps)

C_{vu}	①	②	③	④	⑤	*AP*
①	0	0	11.8	0	3.719	-
②	0	0	10.452	11.182	10.713	-
③	10.537	10.445	0	10.482	10.635	-
④	0	10.649	10.488	0	5.304	12
⑤	3.936	10.28	10.263	5.263	0	-
GW	12	-	-	-	2	-

Q_1: How many users should be offloaded by the eNB?

The answer depends on (i) the eligibility of the mobile users to be offloaded, i.e., their coverage by the Wi-Fi mesh network, (ii) the QoS that the mobile users can receive by the mesh network, and (iii) the energy cost savings that the eNB would gain by offloading them. As the first two criteria cannot be fully controlled by the MNO, the latter one is the key indicator that is used to index which users should be offloaded when the first two criteria are met. In addition, the energy costs for servicing the mobile users are directly related to the induced load that they induce to the cellular network. In Fig. 5, we illustrate the power saving costs for the eNB as the number of offloaded users increases. The eNB's total power consumption (in one slot) for servicing 40 MUs is measured to be $P = 19.3308$ Watts. The total users' demand is uniformly distributed and saturates (and also is greater than) the eNBs servicing capacity that equals to 25.2 Kbits per slot, which is 50 (RBs per slot) $\times 12$ (subcarriers per RB) $\times 7$ (symbols per subcarrier) $\times 6$ (bits per symbol) $= 25.2$ Kbits for a 64QAM scheme per slot or ($\frac{25.2\text{Kbits}}{0.5\text{ms}} = 50.4$ Mbps). An LTE-A frame is 10 ms comprising 20 slots. The savings in power consumption is expected to grow as the number of offloaded users increases and reach up to 54% by offloading the 25% of its traffic (10 out of 40 MUs). In addition, the average power consumption per served user reduces as their number decreases. An important finding, depicted in Fig. 6, is that the total gain per offloaded user is high for a small number of offloaded users ($|\mathcal{N}_0| \leq 4$), but becomes lower as the number of offloaded users increases ($|\mathcal{N}_0| > 4$). The reason is that as the eNB scheduler tends to select the most power costly users, the remaining mobile users have lower energy and data demands.

Q_2: Does the mesh network induce significant delays to the offloaded users?

Although the offloading decisions are taken so as to satisfy the available Internet access capacity of the mesh network, it is possible to have additional delays introduced, for example, by the various processing tasks (e.g., for routing) in each mesh node, or because of the long-range links connecting the mesh network with the EPC. If these delays are large, they may deteriorate significantly the user-perceived network performance. To investigate this issue, we considered a setup with two different users A and B being offloaded from the cellular network, and we assess the servicing region of the mesh network, i.e., the geometric area of the supported values for these two offloaded commodities, (see Fig. 7). Outside the grey-shaded line, there is no solution that satisfies the QoS constraints of the MUs.

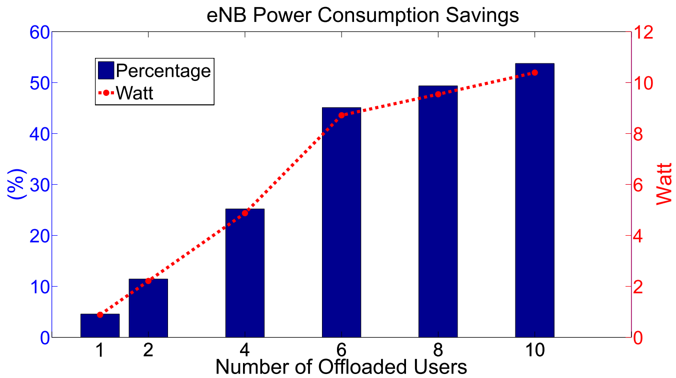

Fig. 5. Power consumption savings due to offloading.

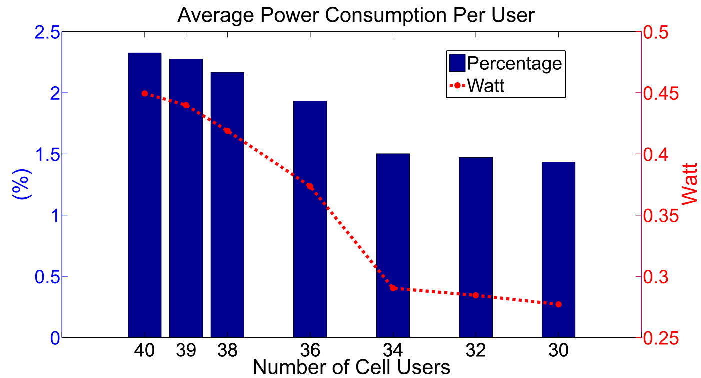

Fig. 6. Power consumption per cell. user due to offloading.

For various demands that lie within the servicing region, we solve the minimum cost flow optimization problem **MFP** by using optimization software tools [41] and estimate the minimum incurred cost, (see Fig. 8). To facilitate comparison of the offloading service with the LTE performance, the number of subframes after the eNB makes an offloading decision is set to $T = 20$ and the duration of each subframe is 1 ms. Therefore the total capacity in one time period of $T = 20 \times 2 = 40$ slots is $40 \times 25.2 = 1008$ Kbits. We chose a point on the border of the servicing region i.e $D_A = 4000$ Kbits and $D_B = 2100$ Kbits. Therefore, the MUs have a total demand which is approximately $\frac{4000+2100}{1008} \approx 6.05$ times greater of the total eNB capacity in an offloading period and it is $\frac{4000+2100}{25.2} \approx 242.06$ times greater than the eNBs capacity in one slot. We measured the delay that each user experiences from the service in the Wi-Fi mesh to be $d_A = 0.7495$ sec. for user A, and $d_B = 0.3861$ sec for user B. As a side note, recall that the offloading decisions occur sparser in time and not every TTI t. Clearly, 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).

Q_3: How much is the energy cost for each mesh node for routing the offloaded traffic?

Energy consumption is a critical line item in community wireless networks since it affects their operation costs. The energy consumption implications of data offloading have been studied before mainly for mobile users, e.g., see [42], ignoring its impact on the network infrastructure that admits this traffic. We focus on this latter aspect. The experimental setup consists of five nodes in a wireless mesh topology and it resembles the operation of a residential mesh network in small scale [11], [12]. Particularly, we leveraged the NITOS testbed [21] for the assessment of link throughputs (using [37]) and for conducting very detailed energy measurements (using the custom tool [40]). The latter can measure in real time and high accuracy the energy consumption of the wireless cards, both in transmission and reception mode, with a sample rate of 63KHz. Mini-PCIe adapters were used to intervene between the circuit board of the node and the wireless cards pins, so as to isolate and measure accurately the wireless card's energy consumption. Many of these tasks can be easily replicated using commercial and low-cost equipment (e.g., Atheros cards) by the mesh networks. Fig. 9.(a) presents the energy cost for the network nodes for servicing different volumes of offloaded traffic demand. The exact flows over each link, as they are devised by the MFP solution, are shown in Fig. 9.(b).

We observe that the energy consumption of node 4 (AP), which delivers the traffic to the mobile users, increases constantly with the offloaded volume. On the contrary, the energy cost of node 5 increases up to 2 Mbits of offloaded traffic, and remains constant afterwards as its Internet capacity has been exhausted. After that point, the other gateway is employed (mesh node 1) to satisfy the additional demand, and we can see that its energy consumption increases constantly. It is interesting also to note that, according to the network setup and due to interference, the traffic flows that a certain mesh node serves might even be reduced despite the increase of the offloaded volume as this can be triggered by the routing policy that considers the minimum energy consumption for the mesh network according to MFP. Observe in Fig. 9.(b) the reduction on the f_{54} when offloaded traffic demand surpasses the volume of 5400 Kbits.

Q_4: How much is the delay induced to the local (internal) traffic of the mesh network due to offloading? And how much is the energy consumption cost for a mesh node that does not actively participate in offloading?

A mesh node which does not route or deliver mobile data traffic still experiences *indirect* costs. The latter include the interference and opportunity cost because the mesh network has less available capacity for the internal traffic needs. We measure here the impact of offloading on (a) the delay of the local service (internal traffic of the mesh network) and (b) on the energy consumption of a node even if it does not actively offload traffic.

We use the setup shown in Fig. 10.(a), where the mesh network offloads the mobile users associated with node 4. We consider two different mesh network configurations that differ on the capacity of the Internet access gateways: (i) $C_{1g} = 12$ Mbps, $C_{5g} = 2$ Mbps, and (ii) $C_{1g} = C_{5g} = 12$ Mbps. We set node 2 to serve only its own local traffic of D_{2L} Kbits so as to better capture the impact of offloading on the local traffic. In Fig. 10.(b), we depict the delay of the local traffic (at node 2) for different amounts of offloaded volumes. We observe that node 2 (the local service) does not experience any additional delay when the offloaded traffic is small and the local demand D_{2L}

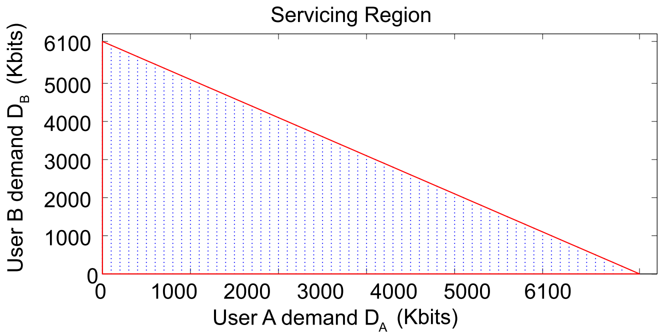

Fig. 7. Mesh Network Servicing Region for 2 Users.

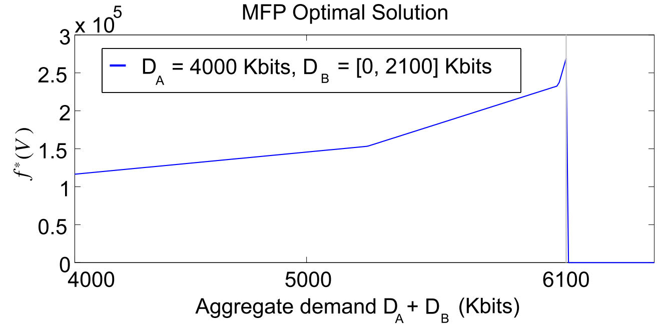

Fig. 8. MFP Solution, $D_A = 4000$, $D_B = \{0, 2100\}$ (KBits).

is also small. In other words, we find that there is a range of offloaded volumes that do not affect the servicing delay of the local traffic. Under heavy volume conditions, we find that the additional delay ranges from 8.76% up to 26.35% and decreases as the offloaded traffic demand increases. If the mesh network has larger Internet capacity, the 2nd configuration here, this no-impact region further increases as it is clear from Fig. 10.(c), and the the additional delay ranges from 19.86% up to 43.54%. However, it is interesting to observe that the offloading performance is less than the aggregate Internet capacity because it is bounded by the interference among the mesh links.

Similarly, in Fig. 11.(a) we show the additional energy consumption that node 2 incurs (when it serves the local traffic) due to offloading which can reach up to 11.08%. Similar results, that refer to the second configuration where $C_{1g} = C_{5g} = 12$ Mbps, are shown in Fig. 11.(b) for the energy consumption and can reach up to 17.15%. The above results reveal that a mesh node which does not actively participate in offloading may have indirect (delay and energy) costs, which depend on the offloaded traffic volume, the local demand, and of course the network setup. These parameters obviously impact the decisions of the mesh nodes to participate in offloading and affect their reimbursements.

Q_5: How is the H_{op} compensation split among the mesh nodes in practice?

Finally, we explore how the profit sharing rule works in practice. To motivate the nodes to participate in this offloading task their payment should be fair and reflect their contribution as well as their extra incurred cost. Therefore, the MNO compensates the mesh network with a fixed payment $H_{op} = 10^6$ ($ or non-restricted to any other currency) and this amount is split among the nodes based on the Shapley value formula which ensures fairness and rewards their contribution. In Table IV, we summarize the reimbursements ϕ_i, $(_{i=1,\ldots,5})$, for the mesh nodes of the experiment shown in Fig. 4. We reveal the impact of different volumes of offloaded data. Namely, we can see that for low values of aggregated offloaded traffic $D_A + D_B$, mesh node 2 does not receive any compensation, as it does not route any mobile data in these low-load cases. This becomes evident if one revisits Fig. 9.(b) that depicts the mobile data amounts that flow over each mesh node (under different conditions). Eventually, node 2 receives compensation when the aggregated demand is larger than 5400 Kbits, while, at the same time, the compensation of node 5 decreases. This example shows in a nutshell the profit sharing rule's agiity to adapt to the changing network conditions and offloading data volumes, ensuring this way the participation of the mesh nodes in the joint offloading task.

VI. Related Work

Wi-Fi Offloading: Several recent studies have quantified the benefits of cellular data offloading to Wi-Fi networks [42], [43]. These benefits can be advantageous to both users and providers and can be further enlarged when the user needs are delay tolerant [44] as well as when monetary incentives are also provided [45]–[47]. But such techniques could be beneficial only when proper eICIC techniques are applied, due to performance degradation caused by interference [48]. In another work [49], LTE/Wi-Fi co-existence is supported by leveraging a coding scheme that supports decoding of two interfering OFDM signals that are not aligned in time or frequency. 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 Wi-Fi APs [7], [50], [51]. 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 [8], [9], [11], [12], [52]. 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 consumption of transmissions. This is particularly challenging for LTE-A networks since it requires the solution of a multi-variable optimization problem [15], [53]. Among the different possible policies, such as proportional allocation, the total power transmission minimization policy [15], [16], is of paramount importance for cost savings [13]. However, this is a well known NP-hard problem that can be either solved using exhaustive

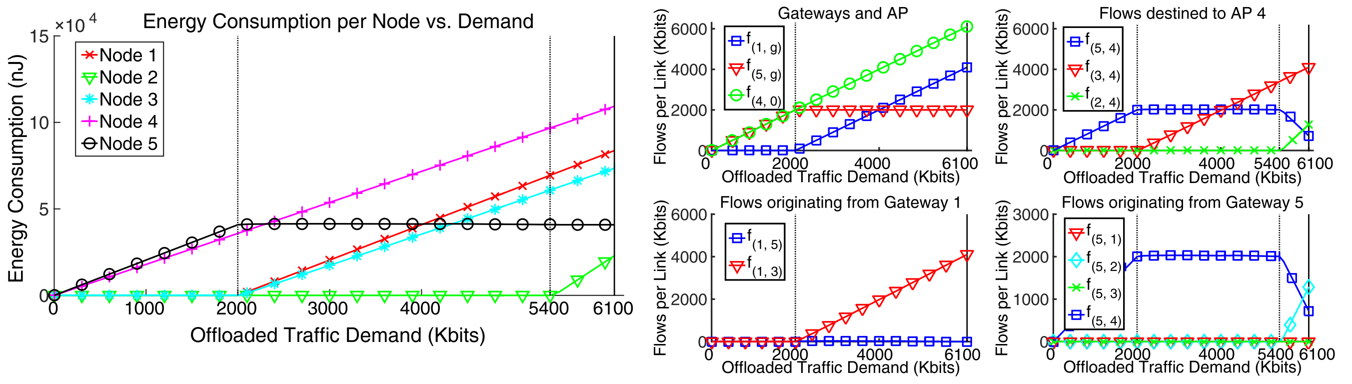

Fig. 9. The mesh network configuration is $C_{1g} = 12$ Mbps, $C_{5g} = 2$ Mbps and $C_{40} = 12$ Mbps. Subfigure (a) depicts the measured energy consumption per wireless mesh node for different amounts of offloaded traffic. Subfigure (b) depicts the respective traffic flow in each communication link.

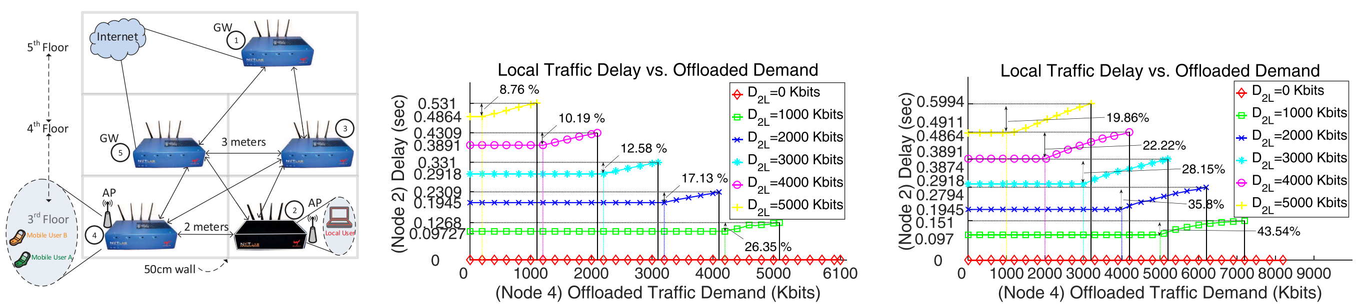

Fig. 10. A mesh network with 5 nodes and configuration $C_{20} = C_{40} = 12$ Mbps. Node 2 serves local traffic of different values, namely $D_{2L} = \{0, 1000, 2000, 3000, 4000, 5000\}$ Kbits. Subfigure (a) shows the experimentation setup. Subfigure (b) depicts the *local traffic delay* for different D_{2L} and volumes of offloaded traffic (x-axis), and for the configuration $C_{1g} = 12$, and $C_{5g} = 2$ Mbps. Subfigure (c) depicts the respective results for a different mesh network configuration, namely $C_{1g} = C_{5g} = 12$ Mbps.

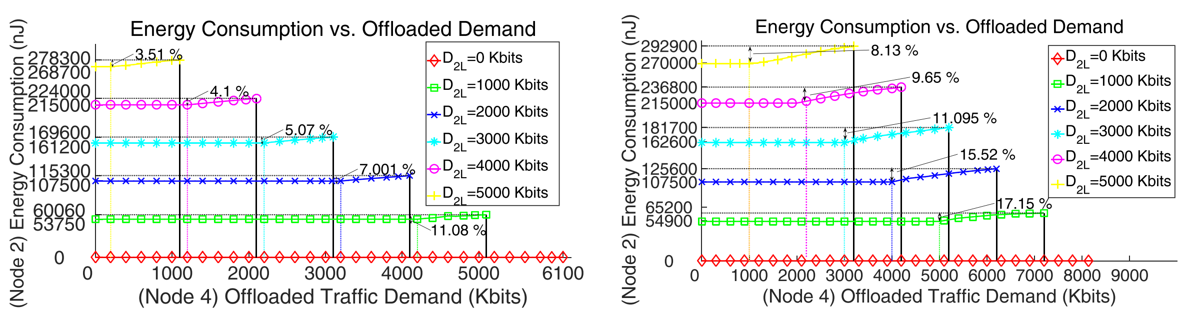

Fig. 11. Subfigure (a) depicts the *energy consumption (nJ)* of node 2, for different values of D_{2L} and volumes of offloaded traffic (x-axis), and for the configuration $C_{1g} = 12$, and $C_{5g} = 2$ Mbps. Subfigure (c) depicts the respective results for a different mesh network configuration, namely $C_{1g} = C_{5g} = 12$ Mbps.

search methods for small instances (e.g., branch-and-bound), or various approximation techniques [29]. 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.

Vertical Handover: Finally, offloading can be seen as a type of vertical handover. The handover policies vary from simple signal strength-based rules [54], to sophisticated schemes that consider the network load and the QoS requirements [55], [56]. The proposed offloading architecture here however, differs in that the Wi-Fi 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.

TABLE IV
SHAPLEY VALUES: PROFIT SHARING

Demand	***Cost ($)***	***Shapley Values ($)***				
D_A+D_B	$J(\boldsymbol{f}^*(\mathcal{V}))$	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5
$1000+900$	54625	75970	0	75970	548660	244770
$1000+2000$	103980	370390	0	71710	37039	83530
$1000+4500$	222190	255640	3380	255640	255640	7520

VII. Conclusions

Today it is clear that the surging mobile data traffic necessitates the employment of idle or underutilized network resources, i.e., managing in a more efficient fashion the existing wireless capacity. Motivated by the proliferation of community and commercial mesh networks, in this paper we proposed, designed, and evaluated a framework that enables the offloading of mobile data to Wi-Fi mesh networks. We presented a holistic study for this new idea that includes the architectural advancements and the detailed resource allocation decisions that are necessary to be made by the mobile network operators as well as the mesh nodes. Such solutions are fully aligned with the vision for the emerging 5G wireless systems where the integration of user-owned network infrastructure is expected to play a crucial role. Additionally, it departs significantly from previous generation opportunistic and best-effort offloading approaches.

Our approach captures the following aspects of the problem: (*i*) From the operators perspective, we enable eNBs to determine independently the power costly users that they serve aiming at reducing their power consumption. The proposed policy exploits the regular scheduling and resource block allocation decisions of the eNB scheduler and does not add any extra computational cost to identify the costly users. (*ii*) From the complementary wireless mesh networks perspective, we propose methods to minimize the servicing costs and the cooperation policies that entice all the mesh nodes to work jointly on the offloading task. We employed detailed and precise models which can be applied for different system setups, and rigorous optimization formulations. Moreover, we employed a hybrid experimentation methodology that combined extensive simulation with realistic system settings for an LTE-A FDD network, and thorough experiments using real hardware equipment in our NITOS testbed for the mesh network. The findings revealed that offloading reduces significantly the energy costs for the operators, and does not induce comparatively additional costs for the mesh networks.

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