Mobile Data Traffic Offloading over Passpoint Hotspots

Sahar Hoteit, Stefano Secci, Guy Pujolle, Adam Wolisz, Cezary Ziemlicki, Zbigniew Smoreda

Mobile Data Traffic Offloading over Passpoint Hotspots

Sahar Hoteit[a], Stefano Secci[a], Guy Pujolle[a], Adam Wolisz[b], Cezary Ziemlicki[c], Zbigniew Smoreda[c]

[a] *Sorbonne Universités, UPMC Univ. Paris 06, UMR 7606, LIP6, F-75005, Paris, France (e-mails: sahar.hoteit@upmc.fr, stefano.secci@upmc.fr, guy.pujolle@upmc.fr)*
[b] *Technical University Berlin, 10587 Berlin, Germany (e-mail: wolisz@tkn.tu-berlin.de)*
[c] *Orange Labs, 92794 Issy les Moulineaux, France (e-mails: cezary.ziemlicki@orange.com, zbigniew.smoreda@orange.com)*

Abstract

Wi-Fi technology has always been an attractive solution for catering the increasing data demand in mobile networks because of the availability of Wi-Fi networks, the high bit rates they provide, and the lower cost of ownership. However, the legacy WiFi technology lacks of seamless interworking between Wi-Fi and mobile cellular networks on the one hand, and between Wi-Fi hotspots on the other hand. Nowadays, the recently released Wi-Fi Certified Passpoint Program provides the necessary control-plane for these operations. Service providers can henceforth look to such Wi-Fi systems as a viable way to seamlessly offload mobile traffic and deliver added-value services, so that subscribers no longer face the frustration and aggravation of connecting to Wi-Fi hotspots. However, the technology being rather recent, we are not aware of public studies at the state of the art documenting the achievable gain in real mobile networks. In this paper, we evaluate the capacity and energy saving gain that one can get by offloading cellular data traffic over Passpoint hotspots as a function of different hotspot placement schemes and of access point selection policies (two enabled by the Passpoint control-plane and one independent of it). We compare the policies using real mobile data from the Orange network in Paris. We show that offloading using Passpoint control-plane information can grant up to 15% capacity gain and 13% energy saving gain with respect to Passpoint-agnostic ones based on signal quality

A preliminary version of this paper has appeared in the proceedings of the ACM International Workshop on Wireless and Mobile Technologies for Smart Cities WiMobcity, PA, USA, 2014 [1].

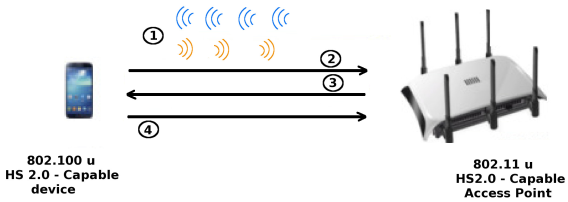


Figure 1: Passpoint hotspot association.

information. As of placement strategy, installing Passpoint hotspots in the outer annulus of the macrocell coverage grants the maximum capacity gain.

Keywords: Mobile Data Traffic, Passpoint, Traffic Offloading.

1. Introduction

Mobile data traffic continues its tremendous growth path, with an increasing number of smartphones, tablets and high-end handsets requiring ubiquitous Internet access. As a side effect of this mobile data explosion, we face nowadays the challenge of managing traffic overloads in cellular networks. According to the technical report [2], mobile data traffic will grow at a compound annual growth rate of 66% from 2012 to 2017, reaching 11.2 Exabytes per month by 2017. In order to meet mobile Internet demand while addressing the lack of available mobile spectrum and the expense of new infrastructure, service providers are severely challenged. They need to master the needed capacity expansion in their backhauling network, otherwise the data traffic will sooner or later clog their networks. Next-generation network deployments promise to deliver higher bandwidth and speed, but they often imply high capital and operational expenditures [3].

An alternative economically and technically viable way is represented by mobile data offloading solutions. Such solutions aim to optimize the resource utilization reducing the traffic on operator's licensed spectrum, and lowering the traffic load on base stations. Wi-Fi technology has always been an attractive solution for data offloading because of the ubiquity of Wi-Fi networks, the high bit rates they provide, the simplicity in deployment and maintenance, and the lower CAPEX [4]. Until the Wi-Fi Certified Passpoint Program (also known as 'Hotspot 2.0' and referred to in the following shortly as 'Passpoint') [5], the WiFi technology was lacking of seamless interworking

Table 1: Beacon and probe response information elements in Passpoint.

Access Network Type	identifies whether hotspot is for public, private or guest access.
Internet Bit	indicates if the hotspot can be used for Internet access.
Advertisement Protocol	indicates if the hotspot supports Generic Advertisement Service (GAS) and Access Network Query Protocol (ANQP)
Roaming Consortium element	provides a list of up to 3 names of reachable service providers.
Venue Information	describes the type of venue (i.e., whether it is a restaurant, a stadium, a library, etc.) where the hotspot is situated.
Load Element	provides information on channel utilization and the current number of associated devices.

between Wi-Fi and mobile cellular networks on the one hand and between Wi-Fi hotspots on the other hand. The new Passpoint program aims to make the WiFi network a "true extension of service provider networks", letting users roam from one hotspot to another with no manual effort, just like cell phone network that already switches seamlessly from one cell tower to another. The Passpoint technology provides all control-plane functionalities for automated and seamless connectivity to Wi-Fi hotspots. With Passpoint, service providers can look to such advanced Wi-Fi systems as a viable way to offload traffic and deliver high-bandwidth services. At the same time, subscribers no longer have to face the frustration and service degradation typically experienced when connecting to legacy Wi-Fi hotspots.

As a matter of fact, Passpoint can work in any network and overcomes the limitations of proprietary, non-interoperable solutions offered by some providers today. Devices certified in the Passpoint program will be able to manage network association, authentication, sign-up, and security in the background, in a way that is completely transparent to the subscriber and that consistently works in any Passpoint network [6] [8]. When a user with a "Hotspot 2.0" (HS2.0) capable mobile device (i.e., based on IEEE 802.11u) comes within the range of a HS2.0 capable hotspot, it will automatically open up a dialog with that hotspot to determine its capabilities before proceeding to authentication. It is worth noting that Passpoint logic is already implemented in many mobile devices, such as Android-based ones. Moreover, since Passpoint discovery is based on pre-authentication, there are considerable savings of time and battery life compared to existing methods [5].

In this paper, we evaluate mobile data traffic offloading over Passpoint hotspots by determining the obtainable capacity gain and energy saving gain in dense urban environment.[2] For the assessment, we use real Orange cellular network dataset retrieved by probes capturing mobile data sessions' details, and we compare different hotspot selection policies enabled by Passpoint with each other and with a Passpoint-agnostic policy based on signal quality metrics. Basic Passpoint policies can be based on the least utilized channel or the least number of attached users. The Passpoint-agnostic policy is one selecting the hotspot with the highest signal to noise ratio. We find out that offloading using Passpoint control-plane information can grant up to 15% capacity gain and 13% energy saving gain with respect to Passpoint-agnostic ones based on signal quality information. Moreover, we show that installing Passpoint hotspots in the outer annulus of the macrocell coverage permits to increase the offloading system capacity and system performance. The paper is organized as follows. Section 2 presents Passpoint and gives an overview of related works. Section 3 synthetically presents the available dataset and reports data traffic consumption and users characteristics. Section 4 describes the offloading over Passpoint approach, followed by a presentation of simulation results in Section 5. Finally, Section 6 concludes the paper.

2. Background

In the following, we first give an insight on the hotspot-device signaling information exchanged with Passpoint, and then we provide an overview of relevant work on the matter at the state of the art.

2.1. Passpoint Hotspot-Device Signaling

Figure 1 illustrates the four different required steps for Passpoint hotspot association. The Access Network Query Protocol (ANQP) is used for device-hotspot signaling [5].

[2]With respect to [1], this paper gives a more detailed modeling, more details on the algorithmic and protocol frameworks, and describes new simulation results, also evaluating mixed offloading policies, comparing the different solutions in terms of fairness and of energy gain.

1. The 802.11u-capable access point broadcasts its HS2.0 support, so that HS2.0-enabled devices can recognize such support.
2. The 802.11u-capable device is able to process ANQP messages, containing useful information such as the 'reachable' authenticators, and various hotspot capabilities. The 802.11u-capable device requests full authenticators list.
3. The hotspot responds to the ANQP query with the requested information.
4. Device compares provisioned network-selection policy with HS2.0 data from hotspots and associates itself to the best hotspot suitable for its needs.

Table 1 shows some of the information elements provided by the hotspot to the mobile devices. In the specifications, those six elements are mentioned. Most elements provide simple configuration and network reachability and locality information. The most interesting element for efficient Passpoint selection is the Load Element, which allows a mobile device to be informed about hotspot channel utilization and the current number of associated devices to a Passpoint hotspot.

We note that it may be possible for a mobile device to decide whether to use a hotspot based just on the information in beacons and probe responses. A quick scan allows the device to build a list of Passpoint-capable access points, whether they provide Internet access and a list of service providers available via that hotspot. It is worth mentioning that passive radio use (i.e., listening for beacons) is less battery-consuming than active probing where frames are transmitted, but the long interval between beacons (usually around 100msec) means that in practice, devices follow an active-scan regime, with an interval of 15 seconds or more. Passpoint allows probe requests to be directed: for instance, if a flag is set in the probe request, only those access points supporting Internet access will respond. This reduces frames on the air and potentially means the mobile device can spend less time listening for responses.

2.2. Related works

The increasing need of offloading solutions is caused by the explosion of Internet data traffic, especially the growing portion of traffic going through mobile networks. For these reasons, different studies and researches tackling mobile data offloading have been conducted in the past few years to alleviate the traffic load on cellular networks. We present in the following some of the offloading approaches proposed thus far. Wi-Fi and femtocell technologies are considered the primary offload technologies considered today by the industry stakeholders.

2.2.1. Horizontal data offloading

The femtocell technology [9] [10], also referred to as small-cells technology, aims to offer better indoor voice and data services for cellular networks via the deployment of tiny cellular repeaters, differently backhauled and synchronized. Femtocell services are already commercialized to expand cell coverage and improve radio resource management [11]. Femtocells work on the same licensed spectrum as the macrocells of cellular networks and thus do not require special hardware support on mobile phones, thus simplifying data offloading procedures. But, despite the benefits of femtocells networks in offloading data traffic via horizontal handovers from macro to femto cells and vice versa, one should not forget the inherent constraints of such networks due to cross-tier and co-tier interferences that should be taken into account when installing femtocells [12].

The cross-tier interference [13] is defined as the decrease in signal quality of macrocell users due to the presence of femto users sharing the same spectrum and vice versa, and the co-tier interference occurs when all femtocells share the same spectrum. Advanced resource scheduling and allocation techniques have been defined for both spectrum management situations, such as [14] for cross-tier and [15] [16] for co-tier interference. Despite the promising results therein in terms of achievable performance, those approaches either require a form of explicit coordination and signaling among femtocells or group of femtocells, or some sort of centralization to collect necessary multi-cell information at one computing place (e.g., using Cloud Radio Access Network, C-RAN, solutions [17]). In either case, an important level of complexity and significant investments need to be undertaken to implement this type of offloading management.

2.2.2. Vertical data offloading

A much simpler, inexpensive and lightweight solution consists of using Wi-Fi hotspots for data offloading. The key advantage of offloading to Wi-Fi hotspots is that they operate over unlicensed spectrum, thus no interference management is required between macrocell and Wi-Fi hotspots. In addition, the installation of Wi-Fi hotspots is easier and more cost effective than large cellular network deployments and upgrades. The main problem that was facing the industry with Wi-Fi is that it is used only for fixed access. Nevertheless, nowadays with the Passpoint program this problem is overcome; in other terms, this new standard enables seamless hopping from hotspot to hotspot and even vertical handoffs across cellular and Wi-Fi networks without the user being aware of it [5] [6]. Overall, we can say that the Passpoint technology combines the advantages of both Femtocell technology (in terms of simplifying data traffic offloading) and WiFi technology (in terms of mobility management), thus it helps the operators to facilitate data traffic offloading.[3]

Likely because of its recent specification, the scientific papers discussed from the literature do not consider the Passpoint technology explicitly along with its hotspot selection capabilities. We present thereafter a selection of Wi-Fi offloading strategies available in the literature.

Authors in [7] quantify city-wide Wi-Fi offloading gain. They show that even a sparse Wi-Fi network improves performance. Similarly, authors in [18] measure the offloading potential of the public WiFi based on city wide vehicular traces. Compared to the vehicle based high mobility scenario in [18], the authors in [19] study the performance of 3G mobile data offloading through Wi-Fi networks in a more general mobile scenario with empirical pedestrian traces. They distinguish two different types of Wi-Fi offloading: *on-the-spot* and *delayed* offloading. The first type consists of spontaneous connectivity to Wi-Fi and transfer data on the spot; when users move outside the Wi-Fi coverage area, the offloading is stopped and all the unfinished transfers are transmitted back to cellular networks. In the delayed offloading, each data transfer is associated with a deadline and as users come in and out of Wi-Fi coverage areas, their data transfer is repeatedly resumed until the transfer is complete or the deadline is reached. Based on a study done over some smartphones users and on the statistical distributions of their Wi-Fi connectivity, the authors evaluate the Wi-Fi offloading efficiency for various amount of Wi-Fi deployment, different deployment strategies, different traffic intensity and delay deadlines, showing that Wi-Fi in such configurations can offload up to 65% of the total mobile data traffic. Authors in [20] consider

[3]It is worth-mentioning that a WiFi access point can be simply transformed into a Passpoint-enabled access point by an operating system or firmware upgrade and does not require special hardware support.

the traffic flow characteristics and types when deciding to offload data traffic to Wi-Fi networks. They check the suitability of traffic to be offloaded over WiFi access points as a function of four different selection schemes: the received signal strength indicator that consists of offloading those users having the lowest signal strength, random selection that selects terminals randomly, inefficiency where we select the users or traffic flows that contribute significantly to the load in the access network but benefit only marginally from these expenditures and finally the equal weight selection scheme that takes into account both the inefficiency and the channel utilization factors. They show that the last two schemes outperform the others in terms of offloaded data traffic volume and number of traffic flows for different network cases. Authors in [21] explore the benefits in terms of energy savings that can be achieved by offloading traffic loads to Wi-Fi networks. Using different traffic types, they show that a saving of up to 70% is reached by opportunistically powering down cellular radio network equipment to offload users traffic to Wi-Fi hotspots.

In [22], a WiFi offloading scheme is proposed from a transport layer perspective. A multipath protocol called oSCTP is proposed to offload the 3G traffic via WiFi networks and maximize the user's benefit. The philosophy of oSCTP is to use WiFi and 3G interfaces simultaneously if necessary, and schedule packets transmitted in each interface every schedule interval. By modeling user utility and cost both as a function of the 3G and WiFi network usage, the user's benefit, i.e., the difference between the utility and the cost, is maximized through an optimization problem. Following the same direction, the authors in [23] propose a framework for 3G traffic offloading based on the idea of motivating mobile users with high delay tolerance to offload their traffic to Wi-Fi networks. A feasible approach consists of delaying all delay tolerant applications until their maximum delay tolerance, and then resorting to the cellular networks if the applications cannot finish. However, this approach does not appear much effective, considering that the user has to wait even when there is actually no available Wi-Fi connection. To solve this problem, the authors in [24] propose an adaptive approach that computes an offload handing-back time, after which the user stops waiting for offloading through Wi-Fi connections, hence resorting to the cellular network service. This allows achieving a better trade-off between offloaded volume and user satisfaction. A combination of different radio access technology is applied in [25] in which several radio access technology selection principles based on the signal strength (coverage) and instantaneous load are suggested.

3. On Mobile Data Characteristics

It is of paramount importance to have a realistic insight on real mobile data characteristics to understand the potential impact of offloading techniques at large. In this section, after a brief description of the available dataset, we synthetically describe mobile data consumption characteristics.

3.1. Cellular Network Dataset

The dataset used in our study consists of network probe's data, generated each time a mobile device uses the wireless mobile network for Internet data exchange (not for voice calls and SMS), i.e., what is commonly referred to as "mobile Internet" service. The probe is able to distinguish the transport protocol used for the communication (Transport Control Protocol, TCP, or User Datagram Protocol, UDP) and to categorize the traffic by application typology. All user identifiers and sensible information were irreversibly anonymized by Orange Labs before analysis. The probe collects data with 6-minute interval sessions, assigning the session to the cell identifier of the last used antenna. In other terms, we determine in each 6-minute interval the position of each user (i.e., the position of the last antenna to which the user is

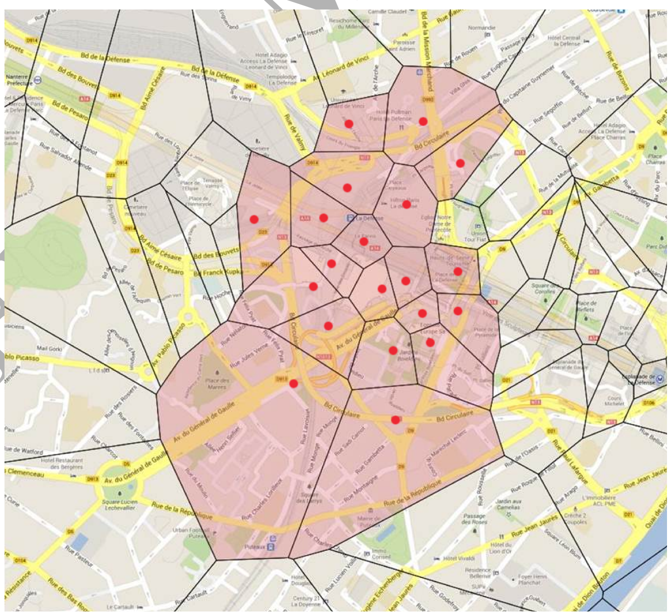


Figure 2: The dataset region.

connected) as well as the data traffic consumption (i.e., data traffic volume in MB for each used application during the 6-minute interval). The data are recorded on a per user basis and cover more than 1,5 million of French mobile phone users in the Parisian metropolitan area, the "Ile-de-France", giving about 100 million records per day.

We limit the study in the paper to the "La Defense" region, a major business district in the northwest of Paris. The region of 1 km^2 area, is decomposed as shown in Figure 2 at base station level, where red dots represent the base stations and the surrounding polygons represent the Voronoi cells.[4] We analyze the data in a normal working day from 8 am to 10 am when people make their regular home-to-work travel. We choose this period to capture users mobility in the chosen region. Upon this selection, we extract mobility patterns and data consumption of about 20000 users. It is worth mentioning that since we are working on a cell-based data set with 6-minute interval sessions and in order to capture user's position at each instant of time, we use the following strategy: if the user remains in the same cell in two consecutive sessions, he is considered as a non-moving user (its position is chosen randomly in the cell), however if the user changes its cell from one session to another, he is considered as moving along a linear trajectory from its position in the first cell to its position in the second cell. The latter property was indeed established based on an in-depth analysis about human trajectories by the authors of [26], where they show that for users moving short distances, the linear trajectory is the best estimation of their real trajectories. This property applies strongly in our model, as the region of study is relatively small.

3.2. Data Consumption Characteristics

Before delving into the different offloading over Passpoint policies we define and analyze, we provide in this section some useful information about data consumption trends. First, we clearly highlight the most widely used applications and communication protocols. Then, we compare users consumption and demands. Figure 3 represents the proportion of traffic generated from each application (i.e., the traffic volume generated from each application to the total volume generated by all applications). We can clearly see

[4] The Voronoi cell can be determined based on the geographical position and the coverage area (determined according to power level) of the corresponding base station.

that video streaming applications occupy the highest consumption portion (38%) among other applications. These habitudes have taken place thanks to computing enhancements in mobile handheld devices and the increasing bandwidth from high-speed mobile networks in urban environments. This trend is also expected to increase at rapid paces in the coming years with the deployment of 4G networks. By classifying the data with respect to the transport-level protocol only (i.e., TCP and UDP, used for applications needing or not, respectively, flow control and packet retransmissions upon loss, so roughly corresponding to non-interactive and interactive real-time services), we find out that TCP based applications are much more used than UDP ones (i.e., 97% of the traffic is TCP-based whilst only 3% is UDP based). It is worth noting that video streaming applications are nowadays mostly based on HTTP Live Streaming protocol (also known as HLS) [27].

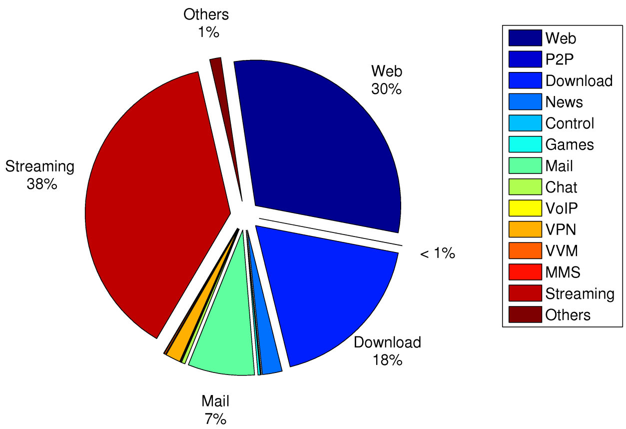


Figure 3: Traffic consumption by application type (3% UDP, 97% TCP; video streaming is mostly over TCP).

Comparing users' demands separately instead of collectively, Figure 4 plots the user demand distribution given the 6-minute aggregation intervals (i.e., one cannot know through the data the instantaneous user demands because the collected data are aggregated as mentioned above). We can notice that while 97% of users have a very low demand of less than 1 MB during the 6 min session (i.e., roughly 30 kb/s on average), we have only 1% of them with a demand of more than 100 MB (i.e., roughly 3 Mb/s on average) and the maximum demand is about 325 Megabytes that corresponds to a mean bit rate of roughly 7.2 Mb/s.

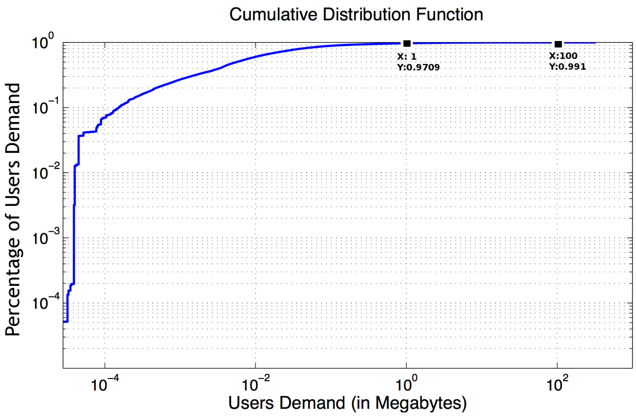


Figure 4: Cumulative Distribution Function of users demands.

4. Evaluation Methodology of Offloading over Passpoint

In this section, we describe the methodology we adopted to evaluate mobile data traffic offloading over Passpoint hotspots. We draw the whole offloading procedure in the flow chart presented in Figure 5.

Given a sample geographical distribution of Passpoint hotspots, we extract user displacement information from the Orange data traces. When a mobile device, connected already to the cellular network, encounters along its trajectory a Passpoint hotspot or a number of Passpoint hotspots, it starts up a dialog with these hotspots to learn about the service providers available via each of them, as well as other characteristics of the hotspots via the ANQP protocol. Thanks to this signaling, the mobile device can discover a comprehensive profile of the hotspot before association, so it can quickly identify, prioritize hotspots suitable for its needs and select the best match while still in the user's pocket. We should note that this procedure is done only when there is at least one Passpoint hotspot near the user's location and if the user, at any time, does not enter the coverage of at least one hotspot, it remains connected to the cellular network.

The hotspot selection policy is therefore of paramount importance for both the user, able to associate to the best access point, and the network, which should avoid hotspot and backhauling link congestion. We compare in this paper three different hotspot selection policies, each taking into consideration one different parameter, as described in the following

1. *Number of Associated Devices*: the user is attached to the hotspot with

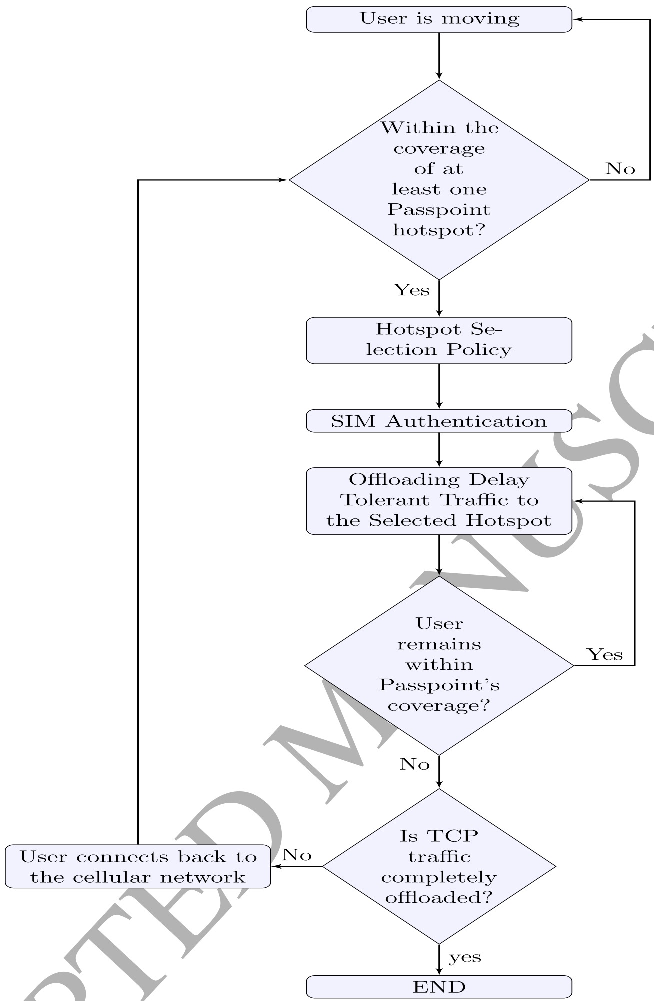


Figure 5: Offloading algorithm.

the least number of associated devices (this information is provided by the hotspot in its response to the ANQP query as presented in Table 1).

2. *Channel Utilization*: the user is attached to the hotspot with the least Channel Utilization defined as the percentage of time the hotspot senses the medium busy (i.e., this information is also provided by the hotspot

in its response to the ANQP query).[5] In the simulations, we compute this value for each 6-minute time interval using the dataset described in Section 3. It is worth noting that this metric takes into account the traffic volume of the users.

3. *Signal Quality*: the user is attached to the hotspot with the best received signal power.

While the first two are retrievable information via the ANQP Passpoint signaling, the latter instead does not strictly depend on Passpoint and can be considered as a policy that could easily be implemented with a relatively limited programming of mobile device's drivers ignoring hotspot capabilities.

After selecting the suitable hotspot, the mobile device is automatically authenticated. In Passpoint, this is done using Extensible Authentication Protocols (EAP) based on a Subscriber Identity Module (SIM) authentication, an authentication that is widely used in cellular networks today [6]. This procedure is specified in such a way that the process is completely transparent to the subscriber and that consistently works in any Passpoint network.

Then, the offloading process starts; only delay-tolerant traffic is offloaded to Passpoint hotspots, while retaining delay-sensitive traffic in mobile cellular networks. We consider as delay-tolerant the TCP traffic that can tolerate some delays. The UDP traffic is considered as the delay-sensitive traffic (i.e. real time traffic) that does not tolerate delays. We use a fixed delay tolerance Th_{max} to qualify TCP traffic: if the user reaches such delay tolerance, or moves out of the coverage of the Passpoint hotspot and finds no other hotspots in the environment, it returns back to the cellular network transparently. In the simulations, we fix the Th_{max} to 1 minute, but we evaluate the influence of varying this threshold on the performance in Section 5.5.

5. Simulation Results

In this section we describe the simulation framework we adopted to evaluate different offloading policies in MATLAB. We note that we use the Orange

[5] A user having higher traffic volume than another one makes the medium busy for a longer time.
Due to the limitation of details, in the public documentation about the Passpoint standard, on how to compute the channel utilization exactly, we use only this small definition without taking the complexity into account.

network dataset described in Section 3 for mobility patterns and traffic consumption. For each simulation, the Passpoint hotspots are distributed in the selected region presented in Figure 2 of approximately 1 km^2. The results are obtained over many simulation instances, with a margin error lower than 3%; we do not plot corresponding confidence intervals for the sake of presentation. In the following, we first present the radio model then we compare different offloading policies and hotspot placement strategies.

5.1. Radio Model

The macrocells are assumed to operate using the OFDMA technology (e.g., in LTE) whose frame structure is based on time-frequency slots, also called tiles or resource blocks (RBs). A set of parameters for typical transmission bandwidths for LTE in the downlink is shown in Table 2, where the subcarrier spacing is $\Delta f = 15$ kHz. We select 20 MHz as the transmission bandwidth, therefore the number of resource blocks per frame is equal to 100 RBs, e.g., allowing a max throughput of 100.8 Mb/s for the 64 QAM modulation.

These parameters are used to compute user demands in terms of RBs knowing only the volume in bytes. We note here that the modulation used by each user depends on its Signal to Noise plus interference (SINR) level.[6] We use the COST-231 Hata path loss model [28], devised as an extension to the Okumura-Hata model, which is the most widely used radio frequency propagation model for predicting the behavior of cellular transmissions in urban areas [29]. Moreover, we model the non-deterministic part of the channel using a Rayleigh fast fading model according to a Rayleigh distribution of expectancy equal to 1.

For the Passpoint hotspots, we employ a SINR interference model. Each hotspot is assigned randomly one channel from the 13 available channels in France on the 2.4 GHz frequency range. If the hotspot j transmits signals to user i, the SINR computed by user i is expressed as follows:

$$SINR_i = \frac{Pd(i,j)^{-\alpha}}{N + \sum_{k \in A, k \neq j} P\lambda(i,k)d(i,k)^{-\alpha}} \quad (1)$$

where:
P is the transmission power of the hotspot (i.e., for simplicity we assume all

[6]For each SINR level, a modulation is selected from those presented in Table 2.

hotspots use the same transmission power P of 20 dBm);
$d(i, j)$ is the distance between user i and the hotspot j;
α is the path loss index (a value typically between 2 and 4);
N is the background noise (i.e., we set this value to -96 dBm);
A is the group of the hotspots existing in the network;
$\lambda(i, k)$ is the channel overlapping degree between the channels used by i and k; it decreases when the channel distance between i and j increases. The channel overlapping degree is computed by [30] and shown in Table 3. We note that when the channel distance is 5 or above, the overlapping degree becomes negligible. The access points are compliant to the 802.11g standard thus the maximum achievable capacity is set to 54 Mbps. The data rates of the 802.11g standard are 6, 9, 12, 18, 24, 36, 48, and 54 Mbit/s.[7] Moreover, we suppose a sharing access to the medium based on the CSMA/CA protocol.[8] We note that the access points have a circular coverage radius of 100 meters.

In the following, we compare various scenarios with respect to the capacity gain (CG) that we can get by offloading users traffic to Passpoint hotspots. The CG is defined as:

$$CG = RB_{freed}/RB_{total} \tag{2}$$

where RB_{freed} is the total number of RBs freed from the cellular mobile by offloading data traffic over Passpoint hotspots, and RB_{total} is the total number of RBs required by users without offloading data traffic over Passpoint hotspots.

5.2. Achievable gain with different hotspot selection policies

Figure 6 illustrates the capacity gain (in percentage) that we get for the three different selection policies with a random distribution of hotspots in the selected region. We can clearly notice that:

- the capacity gain increases with the Passpoint density, as the probability of encountering a Passpoint while moving increases;
- the capacity gain with the Passpoint-agnostic Signal Quality policy gives results similar to those at the state of the art only for very high hotspot density, over 120 hotspots per square km;

[7]The data rate is chosen depending on the SINR level of the user.
[8]The channel access parameters (i.e., DIFS, SIFS, etc.) are defined in the CSMA/CA MAC protocol for the 802.11g standard.

Table 2: Typical parameters for downlink transmission.

Transmission bandwidth [MHz]	20
Number of resource blocks	100
OFDMA symbols per 1 ms	14
Modulation symbol rate (Mb/s)	16.8
QPSK Bit Rate (Mb/s)	33.6
16QAM Bit Rate (Mb/s)	67.2
64QAM Bit Rate (Mb/s)	100.8

Table 3: Channel overlapping degree.

Channel Distance	0	1	2	3	4	5	6	≥7
Overlapping Degree	1	0.7272	0.2714	0.0375	0.0054	0.0008	0.0002	0

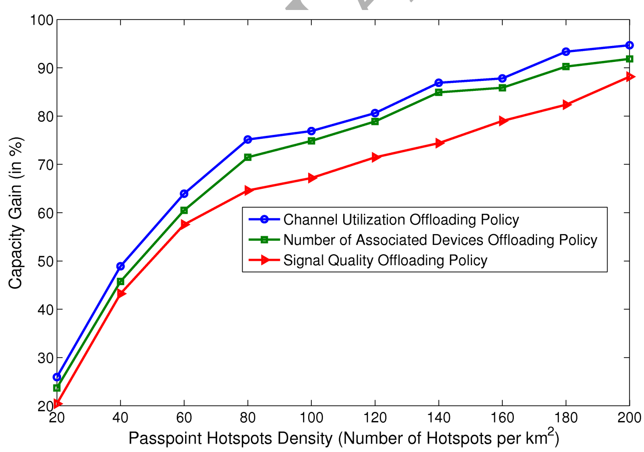


Figure 6: Capacity gain for different Passpoint hotspot selection policies.

- the *Channel Utilization* offloading policy outperforms the other ones and offers the highest capacity gain. A reasonable justification of this behavior is that this policy equally distributes the users to hotspots taking into account traffic volume and hence allowing hotspot resources to be efficiently utilized;

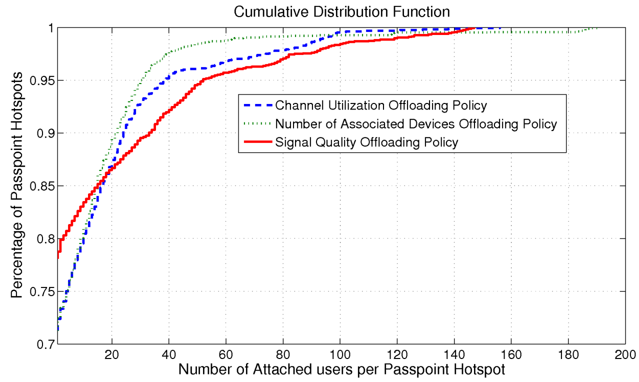


Figure 7: CDF of the number of attached users per Passpoint hotspot (density of 80 hotspots/km^2).

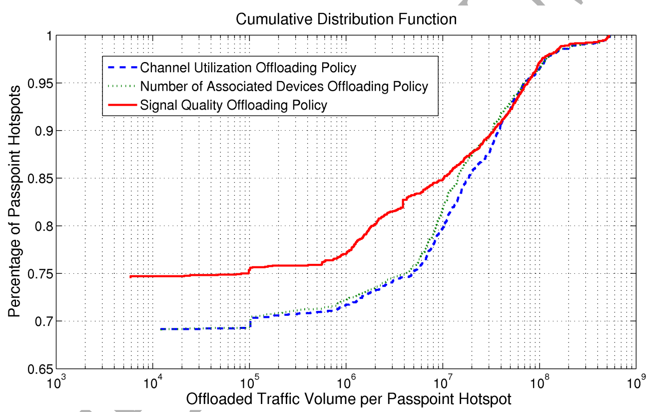


Figure 8: CDF of offloaded traffic volume per Passpoint hotspot (density of 80 hotspots/km^2).

- with the *Signal Quality* offloading policy, all users in a close location are assigned to the same hotspot because they will all receive AP signals with the same power. As a result, there will be a larger number of users competing for limited resources in the unilaterally best hotspot whereas the resources in the other hotspots remain free and hence wasted;
- The *Number of Associated Devices* offloading policy does not take into account the traffic volume required by each user and thus inefficiently distributes the users to hotspots.
- We can clearly see that the slope of the curve corresponding to the

Signal Quality offloading policy is higher than the other two policies. For instance, for a density of 200 hotspots per km2, we notice that the difference between the different policies decreases. This means that the advantages of using the SINR as an offloading metric increase with the hotspot density but it remains lower than those obtained by the other metrics.

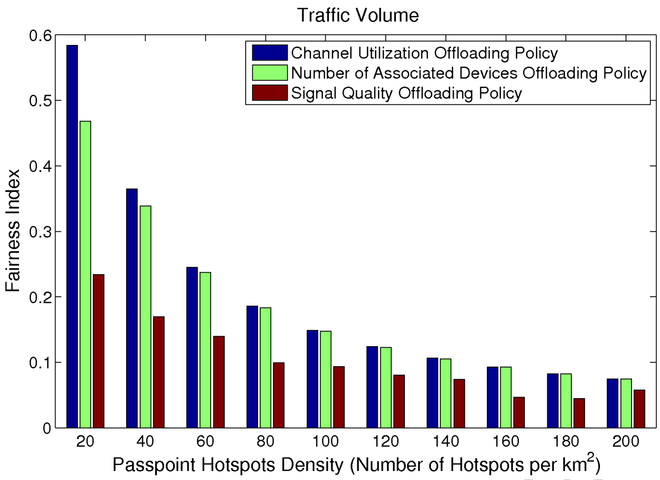
- The differences between the *Channel Utilization* and the *Number of Associated Devices* offloading policies are not so remarkable; this is due to the more or less homogenous data traffic distribution among the users in the considered region. As a matter of fact, as we have seen in Figure 3, only 3% of users have high data traffic volume whereas the rest of 97% of users have a very low data traffic. With a more heterogeneous data traffic distribution, we could expect a higher difference between the two policies.

Furthermore, Figure 7 and 8 show, respectively, the cumulative distribution function of the number of users attached as well as the traffic volume per Passpoint hotspot using the three offloading policies (for a hotspot density of 80 hotspots/km^2). We notice that the percentage of low-loaded hotspots is higher for the *Signal Quality* offloading policy than for the other two policies (e.g., in the *Signal Quality* offloading policy, approximately 80% of Passpoint hotspots have less than four attached users while 73% of hotspots have this value in the other two policies). Also 77% of hotspots offloading each less than 1 MB of traffic in *Signal Quality* while 71% and 72.5% in *Channel Utilization* and *Number of Associated Devices* respectively. Moreover, the percentage of highly-loaded hotspots is bigger in *Signal Quality* offloading policy than the other two policies. This means that the users are more concentrated in a small selection of hotspots in the *Signal Quality* offloading policy whereas in the other two policies, the users are distributed among more hotspots.

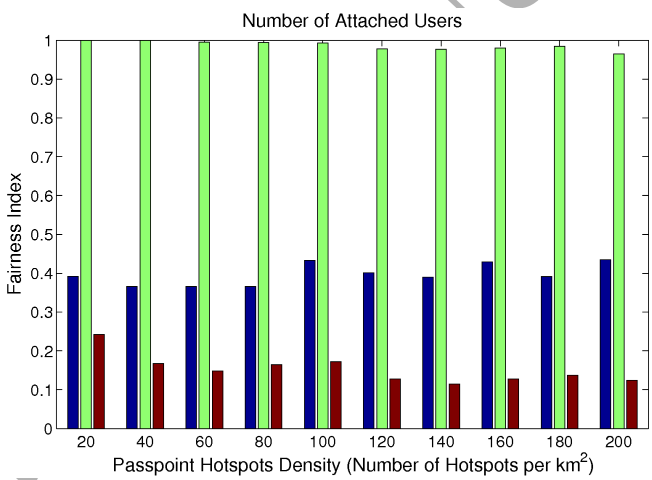
To ensure the latter property, we evaluate the fairness distribution of the three policies in terms of number of attached users and traffic volume, using the Jain's fairness index J_I [31], defined as:

$$J_I = \left(\sum_{i=1}^{N} x_i \right)^2 / \left(N \sum_{i=1}^{N} x_i^2 \right) \tag{3}$$

where N represents the total number of hotspots in the region and x_i is either the number of attached users to hotspot i or the offloaded traffic



(a)



(b)

Figure 9: Jain's Fairness Index of the three offloading policies as a function of the traffic volume and the number of users.

volume to hotspot i. These results are reported in Figure 9, we can clearly see that while the *Number of Associated Devices* offloading policy offers the highest fairness in terms of number of attached users, the *Channel Utilization* outperforms the others in terms of traffic volume. Moreover, we can notice that the *Signal Quality* policy offers the most unfair distribution of users and resources among the different hotspots. Furthermore, we can easily see that the fairness indexes in terms of number of attached users and traffic volume decrease with the increase of hotspots density. This can be interpreted by the fact that, as the hotspot density increases, the user will have more choices for the selection of hotspots and this leads to higher unfairness. For example, suppose we have a user that enters the coverage zone of:

- Scenario A: N different hotspots.
- Scenario B: N' different hotspots such that $(N' \geq N)$.

By applying Formula (3), the fairness index of the distribution of users among the N hotspots is equal to $\frac{1}{N}$ in Scenario A, while it decreases to $\frac{1}{N'}$ in Scenario B. The same reasoning applies for the traffic volume distribution.

It is worth mentioning that the decrease of the fairness index with the hotspots density does not happen at the same rate for both the number of attached users and the traffic volume. This is due to the higher standard deviation of the traffic compared to the number of attached users (e.g., for a density of 60 hotspots/km^2, the *Channel Utilization* offloading policy leads to a distribution of traffic among the hotspots in which the standard deviation is equal to $6.24e + 07$, while the distribution of the users has a standard deviation equal to 10.14).[9] All these results confirm the previous findings and emphasize the more efficient usage of resources and distribution of traffic among different hotspots in the *Channel Utilization* offloading policy.

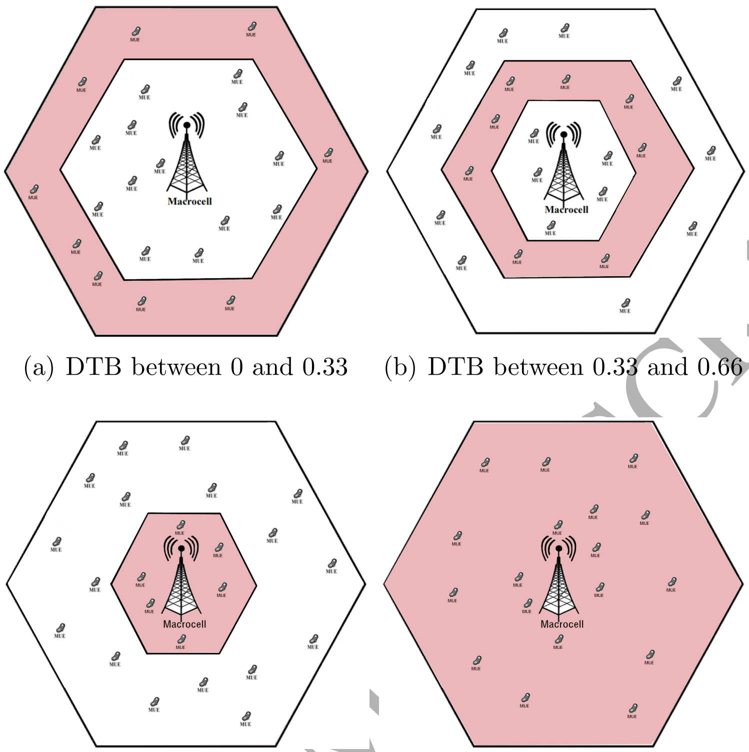
All in all, starting from a discrete Passpoint hotspot density, the gain of using the best among Passpoint offloading policies (i.e., the Channel Utilization one) and the offloading policy implementable without Passpoint (the Signal Quality one) is of roughly 15%.[10] These results are obtained for a random distribution of Passpoint hotspots, so the next question to answer is what is the most appropriate hotspot placement scheme.

5.3. Passpoint placement schemes

We compare different Passpoint placement schemes in order to assess the impact of Passpoint positions on the offloading system performance. Given

[9] The higher the standard deviation is, the higher the inequity of the distribution becomes.

[10] It is worth mentioning that besides capacity gain, we can compare the offloading policies in terms of throughput, delay, etc. However the results of fairness analysis, presented previously, allow us to expect the behavior of the different offloading policies.



(a) DTB between 0 and 0.33 (b) DTB between 0.33 and 0.66

(c) DTB between 0.66 and 1 (d) DTB between 0 and 1

Figure 10: Illustration of different hotspot placement schemes.

the base station antenna-centric nature of cellular access, and more generally of wireless access, we consider different placement schemes depending on a parameter expressing the Distance To Borders (DTB) defined as:

$$DTB_{i,j} = \frac{distance(P_i, \Diamond_j)}{distance(M_j, \Diamond_j)} \tag{4}$$

where:
P_i is the i^{th} Passpoint and M_j is the j^{th} macrocell in the region.
$\Diamond_j$ is the polygon that surrounds the coverage area of Macrocell j.
$distance(P_i, \Diamond_j)$ is the minimal distance from the Passpoint P_i to all ribs of $\Diamond_j$.

Based on the DTB parameter, we select four different placement schemes, presented in Figure 10 where the colored zone represents the region of in-

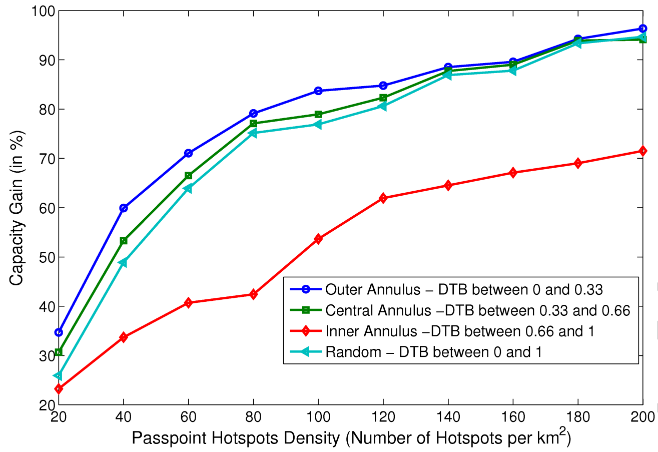


Figure 11: Capacity gain for different hotspot placement schemes under the best hotspot selection policy.

stalling the Passpoint hotspots. We consider the placement of Passpoint hotspots in the:

- outer annulus (i.e., zone close to the edge) of the macrocell coverage, with a DTB between 0 and 0.33, as in Figure 10(a);
- middle annulus (i.e., central zone) of the macrocell coverage, with a DTB between 0.33 and 0.66, as in Figure 10(b);
- inner annulus (i.e., zone closest to the base station) of the macrocell coverage, with a DTB between 0.66 and 1, as Figure 10(c);
- whole macrocell zone, randomly distributed, with a DTB between 0 and 1, as in Figure 10(d).

Figure 11 illustrates the results obtained by varying the hotspot placement schemes. We consider here the *Channel Utilization* policy which appears as the best Passpoint offloading policy. We can clearly notice that:

- the hotspot placement with DTB between 0 and 0.33 (i.e., installing Passpoint hotspots in the outer annulus of the macrocell coverage) is the best placement scheme, which guarantees the highest capacity gain. The interpretation is straightforward as users located at the edge of the macrocell base station suffer from a low SINR; therefore, the

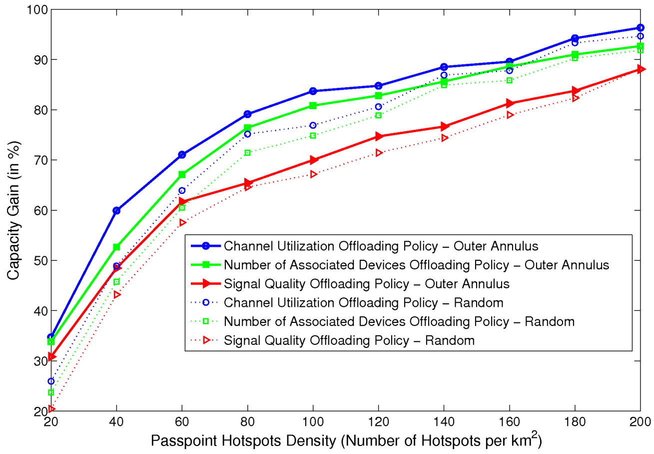


Figure 12: Capacity gain for different Passpoint hotspot selection policies under the best placement scheme.

modulation chosen for those users is the one that requires the least number of bits per symbol (i.e., QPSK modulation in our case) to reduce the symbol error rate. Those users have low bit rates and thus require more time and more RBs to transmit their traffic. By offloading their traffic to Passpoint hotspots, we free a big number of RBs from the cellular networks.

- The topology corresponding to DTB between 0.66 and 1 (i.e., inner annulus) is the worst among others. Differently than for the outer annulus case, users close to the macrocell base station use the modulation that requires the highest number of bits per symbol: those users have a high bit rate and require less time and RBs. So offloading their traffic is not very beneficial for cellular networks.

- The topology corresponding to DTB between 0 and 0.33 overcomes the random one (DTB between 0 and 1) with a mean capacity gain of roughly 5%, and that with DTB between 0.33 to 0.66 (i.e., central annulus) with a mean gain of roughly 3%.

It is worth mentioning that the results of the best placement study are not quite surprising. However, as we try to compute the highest capacity gain that one can get using this Passpoint program and since this gain depends strongly on the hotspots' positions, the latter study enables a further analysis on the comparison of different offloading policies under the best hotspot placement scheme, i.e., the case where Passpoint hotspots are placed only in the outer annulus. Figure 12 illustrates the obtained results, where the dotted lines refer to the random hotspot placement replicated from Figure 6. The figure shows that the gap between Passpoint policies and the signal quality policy is further increased when placing the hotspot in the outer annulus only. We notice a mean difference between the outer and random placement schemes of around 11% for low hotspots density and this difference decreases for high hotspots density with a mean difference of around 3%. Overall, with hotspot placement in the outer annulus, the gain increases when using the Passpoint-enabled offloading policies rather than the signal quality one and this gain is around 15%.

5.4. Sensibility Analysis

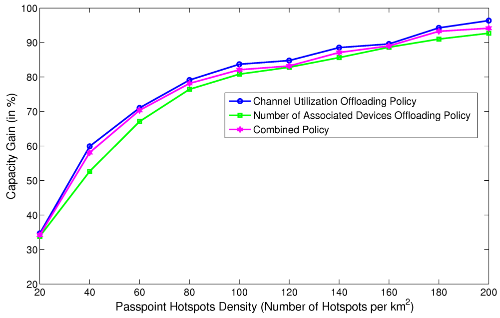
The results obtained so far, proved that the usage of the *Channel Utilization* metric as an offloading policy shows the best overall performance in terms of fairness and capacity gain. An important research question may arise here, does the combination of some metrics together permit further benefits in terms of capacity? To answer this question, we are interested in evaluating the capacity gain obtained from the combination of different offloading policies. The combined policy can be seen as follows:

$$C(P_i, P_j) = \alpha * P_i + (1 - \alpha) * P_j \tag{5}$$

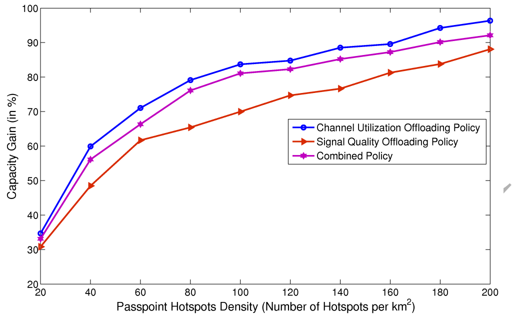
where P_i and P_j are the policies to combine; $C(P_i, P_j)$ is the result of the combination between $policy_i$ and $policy_j$. Moreover, α and (1-α) are the weights of $policy_i$ and $policy_j$, respectively. In our study, we take an equal weight for the two combined policies (i.e., $\alpha = 1 - \alpha = 0.5$). Since, we have three different policies (*Channel Utilisation*, *Number of Associated Devices* and *Signal Quality*), we can obtain three different combined policies. We note that in the combined policy, the selected hotspot for offloading user's data traffic is the one having the highest value in Equation 5.

Figure 13 shows the obtained results for the different cases under the best placement scheme (i.e., the outer annulus). We can clearly notice that the capacity gain resulting from the combination of the different policies sits in-between those obtained by the two separated policies.

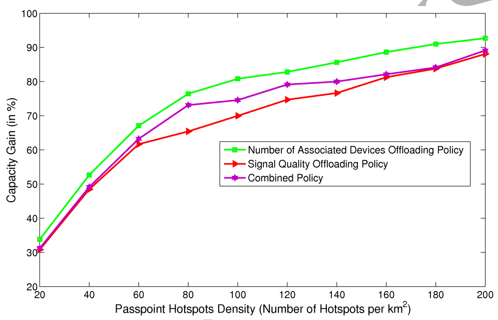
Furthermore, we evaluate the sensibility of the offloading policies by varying the weights attributed to the combined policies, Figure 14 shows the result



(a) Combination between *Channel Utilization* and *Number of Associated Devices* offloading policies



(b) Combination between *Channel Utilization* and *Signal Quality* offloading policies



(c) Combination between *Number of Associated Devices* and *Signal Quality* offloading policies

Figure 13: Combination of the different policies under the best placement scheme (for a weight = 0.5)

of combining the *Channel Utilization* and the *Number of Associated Devices* offloading policies using different weights (i.e., α) under the best placement scheme (i.e., the outer annulus) and for a hotspot density of 80 hotspots per km^2. We can clearly see that the capacity gain of the combined policy varies between those of the *Channel Utilization* and the *Number of Associated Devices* policies. When α=0; the combined policy has a capacity gain equal to that of the *Number of Associated Devices* offloading policy while for α=1; the combined policy offers a gain equal to that of the *Channel Utilization* policy. We note that a quite similar behavior can be seen for the other combined policies. All in all, we can say that the combination of some metrics together

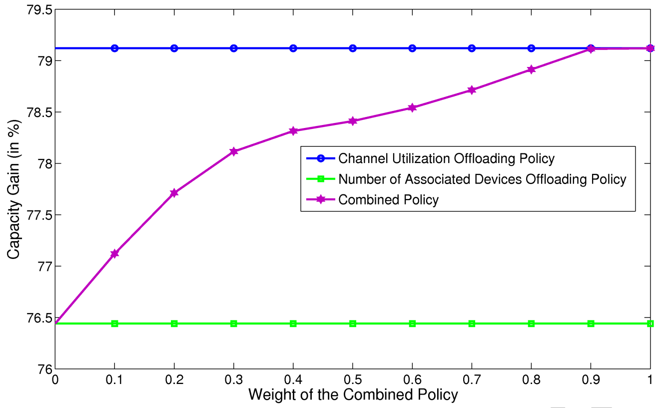


Figure 14: Capacity gain for different weights under the best hotspot placement scheme (for a density of 80 hotspots/km^2).

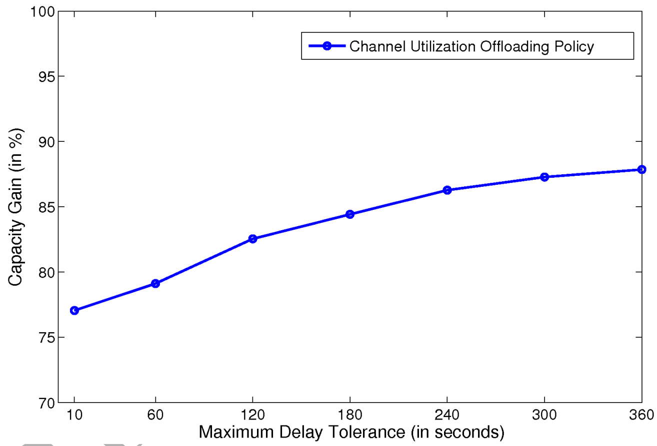


Figure 15: Capacity gain for the Channel Utilization Offloading Policy as a function of different delay tolerance thresholds under the best hotspot placement scheme (for a density of 80 hotspots/km^2).

increases the overall capacity gain but the latter remains bounded by the one obtained through the *Channel Utilization* offloading policy.

5.5. Delay Tolerance Sensibility

As a final analysis, we are interested in evaluating the effect of varying the traffic delay tolerance Th_{max} on the overall performance. For the simulations, we consider the *Channel Utilization* offloading policy under the best placement scheme for a density of 80 hotspots/km^2. We compute the capacity gain by varying the Th_{max} from 10 seconds to 6 minutes.[11] The results of this study are presented in Figure 15, we can clearly notice that the capacity gain increases with the increase of Th_{max} as the traffic has higher probability to be offloaded over a Passpoint hotspot when its delay tolerance increases. Overall, we notice an increase of the capacity by 17% when changing the maximum delay tolerance from 10 seconds to 6 minutes. We note that the same results are obtained for the different offloading policies, under different placement schemes.

5.6. Energy Saving Gain

Thus far, we have studied the capacity gain that an operator can get by offloading data traffic over Passpoint hotspots but what about the gain from users' point of view? Does this offloading solution increase the battery lifetime of mobile phones?

We therefore study whether offloading mobile data traffic over Passpoint hotspots is worthwhile, in terms of energy. The power consumption values for LTE and WiFi systems are computed based on local experiments done by the authors of [32] on an LTE phone. These values are presented in Table 4, where α_u represents the uplink power consumption per Mbps (i.e., the power needed in mW for sending data at a throughput of 1 Mbps), α_d is the downlink power consumption per Mbps (i.e., the power needed in mW for receiving data at a throughput of 1 Mbps) and β is the baseline power. For example, the power consumption of a given user in the LTE cellular network for the downlink transmission is given by:

$$P_d = \beta + \alpha_d t_d \tag{6}$$

where β is equal to 1288.04 mW, $\alpha_d = 51.97$ mW/Mbps, and t_d represents the downlink data rate (in Mbps) for the user over the LTE interface, which depends on the allocated RBs and the channel quality experienced by the user. The same formula holds for the power consumption in WiFi networks, we only replace the parameters β and α_d by the values in the second line of Table 4. We define the Energy Saving Gain (ESG) as follows:

[11]The maximum delay tolerance is upper bounded by the value of 6 minutes because the data used in our analysis are decomposed into 6-minute interval sessions as explained in Section 3.

Table 4: Power Consumption of a smartphone networking interfaces [32].

	α_u (mW/Mbps)	α_d (mW/Mbps)	β (mW)
LTE	438.39	51.97	1288.04
WiFi	283.17	137.01	132.86

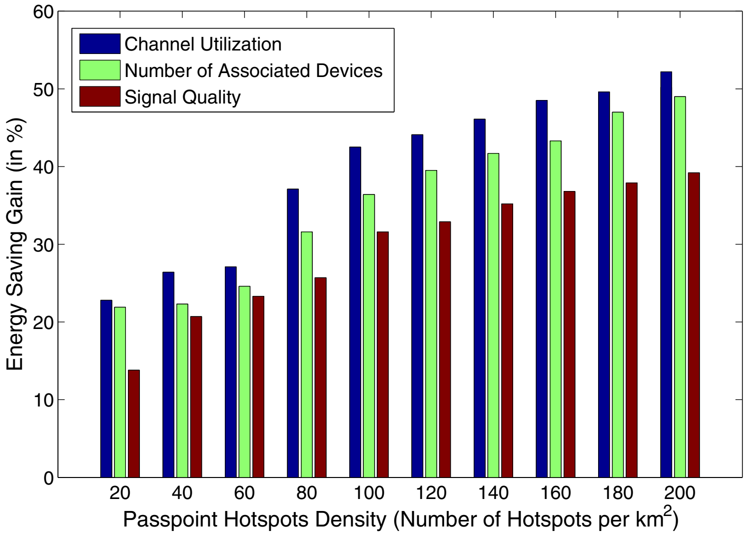


Figure 16: Energy saving of offloading mobile data traffic over Passpoint hotspots for different offloading policies.

$$ESG = 1 - \frac{Energy\ Consumption\ with\ Offloading}{Energy\ Consumption\ without\ Offloading} \tag{7}$$

Figure 16 shows the average energy saving in percentage (i.e., average energy saving of all users in the region) that one can get by offloading mobile data traffic over Passpoint hotspots for different offloading policies. The same dataset of the previous simulations is used. As before, the hotspots are randomly distributed. We can clearly notice that:

- The energy is better saved when the number of Passpoint hotspots increases, as the probability that a user encounters a Passpoint and thus offloads its data traffic over Passpoint increases.

- The *Signal Quality* offloading policy is less energy-efficient than the other two and its energy saving gain seems to increase at slower rates compared to the other two policies. This behavior can be explained by the higher percentage of highly-loaded hotspots in *Signal Quality* offloading policy compared to the other two policies as reported in Figure 7 and Figure 8. Thus with the *Signal Quality* offloading policy, users compete more with each other to get access to the selected hotspot and end up sometimes without being able to transfer their traffic over that hotspot, which results in a waste of energy.

- The *Channel Utilization* offloading policy outperforms the other policies in terms of energy consumption and saves from 23% of energy in low hotspots density to 52% in high hotspots density. It saves up to 3% and 13% of energy comparing to the *Number of Associated Devices* and *Signal Quality* policies.

All in all we can emphasize the strength of offloading mobile data traffic over Passpoint hotspots in terms of both user's device and spectrum capacity gain from the cellular network operator.

6. Conclusion

Traffic growth is outstripping the capacity of cellular mobile networks, especially in urban and densely populated zones. Moreover, operators are under pressure to find solutions to keep up with their customer's insatiable demand for data intensive applications. Data traffic offloading to Wi-Fi hotspots has always been an attractive solution for catering the increasing data demand in mobile networks, despite the existence of some drawbacks that limit their usage. Nowadays, with the advent of the Passpoint program [5], offloading data traffic to Passpoint hotspots is back to the forefront. The Passpoint program was created to address critical business needs for mobile data, streamline access and to help ease operator data traffic offload to these smart Wi-Fi networks in a completely transparent way for the user.

In this paper, we compare different conceivable mobile data traffic offloading over Passpoint hotspots to each other and to baseline approaches, using real mobile consumption data gathered from the Orange mobile network in Paris. First, we provide a brief analysis of mobile data consumption and characteristics. Then, we compute the capacity gain as well as the energy saving gain that one can get by offloading users traffic while taking into account different offloading policies and hotspot placement schemes.

In particular, we show that offloading using Passpoint control-plane information can grant up to 15% capacity gain and 13% energy saving gain with respect to Passpoint-agnostic ones based on signal quality information. As of our knowledge, our study is the first one quantifying the achievable cellular traffic offloading gain to Passpoint hotspots using the additional information given by Passpoint, via the ANQP protocol to mobile users, for hotspot selection.

As a future work, we aim to investigate new offloading policies by exploiting the additional information provided by the Passpoint hotspots to the end users.

Acknowledgment

This work was partially supported by the ANR ABCD project (Grant No: ANR-13-INFR-005), and by the EU FP7 IRSES MobileCloud Project (Grant No. 612212).

References

[1] S. Hoteit, S. Secci, G. Pujolle, S. Wietholter, A. Wolisz, C. Ziemlicki and Z. Smoreda "Quantifying the Achievable Cellular Traffic Offloading Gain with Passpoint Hotspots", *in Proc. of ACM International Workshop on Wireless and Mobile Technologies for Smart Cities*, Philadelphia, PA, USA, 2014.

[2] Cisco, San Jose, CA, "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2012-2017, `http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11-520862.pdf`, Feb. 2013.

[3] D. Srinivasan, J. Dey, S. Kumar and R.N. Mukherjee, "Data Offload Approches for Mobile Operators: Improving Network Efficiency And Strengthening Quality Of Service, Wipro Technologies 2012.

[4] W. Lehr and L.W. Mcknight "Wireless Internet access: 3G vs. WiFi?", *Telecommunications Policy, Vol. 27, pp. 351 - 370.*, 2003.

[5] "Wi-Fi Certified Passpoint Architecture for Public Access," *White Paper, Aruba Networks*, 2012.

[6] Wi-Fi Alliance, "Launch of Wi-Fi CERTIFIED Passpoint Enables a New Era in Service Provider Wi-Fi Austin, TX, June, 2012.

[7] S. Dimatteo, P. Hui; B. Han; V. Li, "Cellular Traffic Offloading through WiFi Networks," *in Proc. of IEEE International Conference on Mobile Adhoc and Sensor Systems (MASS)*, 2011.

[8] A. Schumacher and J. Schlien, "WLAN Traffic Offload in LTE White Paper, November 2012.

[9] Femto forum, "Femtocell - Natural Solution for Offload", *White paper,* June, 2010.

[10] Femto forum, "Challenges in Deployment of UMTS/HSPA Femtocell", *White paper,* Feb, 2008.

[11] J.G. Andrews, H. Claussen, M. Dohler, S. Rangan, M.C Reed "Femtocells: Past, Present, and Future", *IEEE Journal on Selected Areas in Communications ,* 2012.

[12] J. Roh , Y. Ji, Y.G. Lee, I. Rhee, T. Ahn "Femtocell Traffic Offload Scheme for Core Networks", *4th IFIP International Conference on New Technologies, Mobility and Security (NTMS)*, Paris, February 2011.

[13] D. Lopez-Perez , A. Ladanyi, A. Juttner, J. Zhang "OFDMA femtocells: Intracell Handover for Interference and Handover Mitigation in Two-Tier Networks", *in Proc. of Wireless Communications and Networking Conference WCNC* , April 2010.

[14] V. Chandrasekhar, J. Andrews, "Spectrum allocation in tiered cellular networks", *IEEE Trans. Communications, Vol. 57, No. 10, pp. 3059-3068*, Oct. 2009.

[15] S. Hoteit , S. Secci, R. Langar, G. Pujolle and R. Boutaba "Bankruptcy Game Approach for Resource Allocation in Cooperative Femtocell Networks", *IEEE Global Communications Conference (IEEE GLOBECOM 2012)*, Anaheim, CA, USA, December 2012.

[16] A. Hatoum, N. Aitsaadi, R. Langar, R. Boutaba, and G. Pujolle, "FCRA: Femtocell Cluster-based Resource Allocation Scheme for OFDMA Networks", *in Proc. of IEEE ICC 2011.*

[17] K. Sundaresan, M. Arslan, S. Singh, S. Rangarajan, and S. Krishnamurthy, "FluidNet: a flexible cloud-based radio access network for small cells", *in Proc. of the 19th annual international conference on Mobile computing and networking (MobiCom 2013)*, Miami, USA, October 2013.

[18] A. Balasubramanian, R. Mahajan, and A. Venkataramani "Augmenting mobile 3G using WIFI", *in Proc. of ACM MOBISYS, 2010.*.

[19] K. Lee , J. Lee, Y. Yi, I. Rhee, S. Chong, "Mobile Data Offloading: How Much Can Wi-Fi Deliver?", *IEEE/ACM Transactions on Networking*, Vol. 21, No. 2, April 2013.

[20] S. Wietholter, M. Emmelmann, R. Andersson, A. Wolisz, "Performance evaluation of selection schemes for offloading traffic to IEEE 802.11 hotspots", in *Proc. of IEEE International Conference on Communications*, ICC, 2012.

[21] A. Aijaz, O. Holland, P. Pangalos, H. Aghvami, "Energy savings for cellular access network through Wi-Fi offloading", in *Proc. of IEEE International Conference on Communications*, ICC, 2012.

[22] X. Hou, P. Deshpande, S.R. Das "Moving bits from 3G to metro-scale WiFi for vehicular network access: An integrated transport layer solution", *in Proceedings of IEEE ICNP, Vancouver, Canada (2011)*

[23] X. Zhuo, W. Gao, G. Cao, and Y. Dai, "Win-coupon: An incentive framework for 3G traffic offloading", *in Proc. IEEE ICNP*, 2011.

[24] D. Zhang, C.K. Yeo, "Optimal handing-back point in mobile data offloading," *IEEE Vehicular Networking Conference (VNC)*, 2012.

[25] O. Yilmaz, A. Furuskar, J. Pettersson, and A. Simonsson, "Access Selection in WCDMA and WLAN Multi-Access Networks, *in Proc. of IEEE Vehicular Technology Conf., VTC*, 2005.

[26] S. Hoteit, S. Secci, S. Sobolevsky, C. Ratti and G. Pujolle, "Estimating Human Trajectories and Hotspots through Mobile Phone Data, *Elsevier Computer Networks, Vol.4, pp. 296-307, 2014.*

[27] C. Mueller, S. Lederer and C. Timmerer "An Evaluation of Dynamic Adaptive Streaming over HTTP in Vehicular Environments," *in Proc. of the 4th Workshop on Mobile Video (MoVid12)*, 2012.

[28] COST Action 231, "Digital mobile radio towards future generation systems, final report," *tech. rep., European Communities, EUR 18957*, 1999

[29] M. Hata, "Empirical formula for propagation loss in land mobile radio services," *IEEE Transactions on Vehicular Technology, vol. VT-29, pp. 317-325*, 1981.

[30] M. Burton, "Channel overlap calculations for 802.11b networks," *White Paper, Cirond Technologies Inc.*, 2002.

[31] R. Jain, W. Hawe, D. Chiu, "A Quantitative measure of fairness and discrimination for resource allocation in Shared Computer Systems", *DEC Research Report TR-301*, 1984.

[32] J. Huang, F. Qian, A. Gerber, Z. Mao, S. Sen, and O. Spatscheck, "A close examination of performance and power characteristics of 4G LTE networks" *In Proc. of Mobysis*, 2012.

Author biography

Sahar Hoteit is currently a Postdoctoral Researcher at the LSS (Laboratoire de Signaux et Systmes) Centrale-SUPELEC, Gif sur Yvette, France. She received the Diploma in Electrical, Electronics, Computer and Telecommunications Engineering from Lebanese University, Beirut, Lebanon, in 2010; the M.S. degree in computer science from the University of Pierre and Marie Curie, France, in 2011 and the PhD degree in computer science and networks from University Pierre and Marie Curie in 2014. She was a visiting researcher at Senseable City Lab, Massachusetts Institute of Technology MIT, Cambridge, USA in 2012 and at the Telecommunication Networks group in the Technical University of Berlin, Germany in 2013. Her research interests include power and resource management in wireless networks, human mobility analysis and cloud computing.

Stefano Secci is an Associate Professor at the University Pierre and Marie Curie (UPMC - Paris VI, Sorbonne Universities). He received a " Laurea " degree in Telecommunications Engineering from Politecnico di Milano, in 2005, and a dual Ph.D. degree in computer networks from the same school and Telecom ParisTech, in 2009. He also worked as a Research Fellow at NTNU, George Mason University, Ecole Polytechnique de Montreal, and Politecnico di Milano, and as a Network Engineer with Fastweb Italia. His works mostly cover network modeling and optimization, protocol design, Internet traffic engineering. He is Vice-Chair of the IEEE Communications Society/Internet Society (ISOC) Internet Technical Committee (ITC).

Guy Pujolle is a Professor at Pierre et Marie Curie University - Paris 6. He spent the period 1994-2000 as Professor and Head of the computer science department of Versailles University. He was also Professor and Head of the MASI Laboratory at Pierre et Marie Curie University (1981-1993), Professor at ENST (1979-1981), and a member of the scientific staff of INRIA (1974-1979). Guy Pujolle is an editor for ACM International Journal of Network Management, Telecommunication Systems, and Editor in Chief of Annals of Telecommunications. Guy Pujolle is a pioneer in high-speed networking having led the development of the first Gbit/s network to be tested in 1980. He was participating in several important patents like DPI or virtual networks. Guy Pujolle is co-founder of QoSMOS (www.qosmos.fr), Ucopia Communications (www.ucopia.com), EtherTrust (www.ethertrust.com), Virtuor (www.VirtuOR.fr), and Green Communications (www.green-communications.fr).

Adam Wolisz received his degrees (Diploma 1972, Ph.D. 1976, Habil. 1983) from Silesian University of Technology, Gliwice, Poland. He joined TU Berlin in 1993, where he is a chaired professor in telecommunication networks and executive director of the Institute for Telecommunication Systems. He is also an adjunct professor at the Department of Electrical Engineering and Computer Science, University of California, Berkeley. His research interests are in architectures and protocols of communication networks. Recently he has been focusing mainly on wireless/mobile networking and sensor networks.

Cezary Ziemlicki is a R&D engineer at Orange Labs, in the laboratory Sociology & Economics of Networks and Services, Issy-les-Moulineaux, France. A graduate of the Warsaw University of Technology in automation of industrial processes, Cezary is a research engineer and joined Orange Labs in 2000. His work at Orange Labs is to develop methodologies of analysis of telco operator data for use in human sciences.

Zbigniew Smoreda is a senior researcher at Orange Labs, Sociology and Economics of Networks and Services (SENSE) department. Before integrating Orange Labs (CNET) in 1995, he worked as an Assistant Professor with Warsaw University, a Researcher and Lecturer with GRIFS (Universit de Paris 8), a Researcher with Group d'Analyse Sociologique des Tlcoms (France Tlcom) and with Observatoire Mondial des Systmes de Communication (OMSyC). His work in Orange Labs is related to sociology of communication and in particular to social uses of ITCs and social network forms and transformations associated with technologies.