Improving Cellular Capacity with White Space Offloading

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***Abstract*—With growing data demand and the current dearth of spectrum, mobile operators are looking for new frequency bands to satisfy data-hungry users. One promising avenue of expansion is TV white spaces, which are currently available to secondary users as long as they do not interfere with primary (i.e., incumbent) users. In this work, we explore the benefits of offloading cellular traffic onto TV white spaces. We develop an analytical model and efficient algorithms to assign users to the cellular network or white space channels by considering their channel gains, multi-user interference on white space channels, and the cost of switching between different networks. We perform extensive data-driven simulations in two representative urban scenarios based on publicly available datasets. Our results show that white spaces can increase capacity by 16-62%, depending on the environment, but careful network selection is necessary to ensure that maximum capacity gains are realized. Moreover, we show that white spaces provide a significant benefit in serving indoor users where cellular channel conditions are poor. Specifically, our algorithms can offload up to 40% of cellular traffic to white spaces for indoor scenarios.**

I. Introduction

The increasing diffusion of embedded devices, including not only smartphones and tablets but also Internet-of-things objects, has led to an exceptional growth in mobile data traffic. Despite technological advances in cellular communications, the rapid increase in demand has strained the cellular infrastructure, especially in the downlink, due to the proliferation of mobile applications. A viable option to reduce the traffic on the cellular network is *offloading*, i.e., migrating some of the traffic from the cellular infrastructure to supplementary networks using different communication technologies. A conventional approach is to employ WiFi networks such as wireless hotspots [1]. A newer approach is to use opportunistic device-to-device (D2D) communications [2], wherein mobile nodes directly exchange data when they are in proximity. However, offloading cellular traffic to WiFi and opportunistic networks has several limitations [3]: WiFi hotspots may not be deployed densely enough to guarantee adequate coverage under node mobility. Similarly, opportunistic contacts between nodes may be relatively infrequent and unpredictable in the D2D scenario.

A more promising approach consists of using *white spaces*, namely, frequencies that are spatio-temporally unused despite being allocated to primary users (PUs) such as television broadcasters. Secondary users (SUs) are allowed to reclaim these white spaces as long as they limit interference. This access scheme, known as *dynamic spectrum access*, has gained momentum in recent years as a method to address the scarcity of spectrum for wireless communications, largely due to initiatives taken by the Federal Communications Commissions (FCC) in the United States [4]. The white space databases used in practice describe the spatio-temporal availability of unused spectrum, thus assisting SUs to select suitable frequencies without affecting the operations of the PUs.

The goal of this work is to improve users' network quality (i.e., the maximum overall throughput for all users) by offloading mobile traffic from the cellular network to white spaces. To achieve this goal, one must consider the properties of these two interfaces: white space performance can be harmed by multi-user interference, different from cellular transmissions where bandwidth is divided between all users. Therefore, a naive greedy assignment of users to white spaces could result in significant interference and harm the overall system performance. Two main questions arise: *the traffic of which users should be offloaded to white spaces? How much white space capacity can be harnessed to complement cellular networks?*

Previous works on utilizing the cellular network and white spaces have mainly focused on measurements [5], energy minimization [6], or network selection [7], [8]. To the best of our knowledge, our work is the first to quantify the white space capacity in realistic network settings using real-world spectrum data, so as to evaluate the viability of white space offloading for cellular networks. In particular, we establish the following main contributions in our article:

- **Efficient algorithms** for assigning users to white space channels or the cellular network. Users must connect to a network not only to increase their own throughput, but also to reduce the impact on other users, so as to maximize total network throughput. We derive necessary conditions for network selection and efficient algorithms that capture both the needs of individual users and the network performance.
- **Data-driven simulations** to understand the benefits in using white spaces for different real-world environments. We use public crowd-sourced datasets for the location of cellular base stations (BSs) and spectrum databases for querying available white space channels. We consider two urban scenarios, a highly-populated (New York City) and a moderately-populated (Boulder, Colorado) setting.

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In particular, our results show that there is at most one white space channel that can be used in New York City, while the availability is much higher in Boulder (i.e., about 3-4 channels). As such, the fraction of users connecting to white spaces highly depends on the considered scenario: about 5% in New York City and 8-28% in Boulder. Nevertheless, our efficient network selection algorithms increase the cellular capacity by up to 16% in New York City and 62% in Boulder. Finally, we find that white spaces can significantly benefit indoor users, since their frequencies can better penetrate walls.

The rest of the article is organized as follows. Section II overviews the related work. Section III introduces the system model of network settings and key performance metrics. Section IV formulates the problem of maximizing the total capacity of the network and introduces different offloading strategies. Section V presents a performance evaluation. Finally, Section VI concludes the article.

II. Related Work

Using white spaces for cellular communications has been considered in the literature from different perspectives [5]–[7], [9]. Cui et al. [6] propose a tiered architecture called WhiteCell where existing cell towers are extended with both white space and WiFi capabilities. However, we show that white space alone is enough to increase the total network capacity even in densely populated urban scenarios. Madhavan et al. [9] consider supplementing cell towers with white space capabilities, but target the design of antenna arrays with beamforming, whereas we focus on offloading mechanisms.

Bayhan et al. [7] consider offloading mobile data to white spaces assisted by a spectrum database or to unlicensed frequencies (e.g., 2.4 GHz) via opportunistic D2D communications. In contrast to an opportunistic scenario, our analysis aims at maximizing the overall network capacity by connecting users to either cellular or white space channels.

Other works have also addressed white space offloading from a systems perspective. For instance, Dudda et al. [5] consider two cellular network scenarios: one deployed exclusively by using white spaces and the other one by offloading traffic in the mobile network to white spaces. They perform detailed system-level simulations and observe that offloading to white spaces is more favorable in urban settings than in rural areas. Although [5] proves the feasibility of such an approach based on geographically distributed spectrum availability, it does not explicitly quantify the benefits of offloading cellular traffic to white spaces with improved network selection algorithms.

III. System Model

We consider downlink transmissions in a cellular network with K cells and L white space channels.[1] We assume that the cellular and white space BSs are co-located by equipping each of the K BSs with antennas that also support white space communications. The networks consist of N users, denoted by $\mathcal{U}$ ($N = |\mathcal{U}|$), and K BSs (i.e., one for each cell). Each user communicates with the closest BS, and all BSs coordinate with a central controller that has full knowledge of users' locations and channel states. The controller obtains the availability of white space channels by querying a public spectrum database then makes a global decision on whether a user should use white spaces and, if so, which channel. Users can then be partitioned in two sets: the set $\mathcal{U}_c$ of those connected to the cellular network and the set $\mathcal{U}_w$ of those communicating over the available white space channels. We use $\mathcal{U}_w$ to denote the *offloading decision* performed by the central controller. We further define u_i^k as the i-th user among all U_c^k users on cellular BS k ($u_i^k \in U_c^k \subset \mathcal{U}_c$) and u_j^l as the j-th user among all users U_w^l on white space channel l ($u_j^l \in U_w^l \subset \mathcal{U}_w$).

We assume that the distance d_n from receiver n to the closest BS follows a uniform distribution with a probability density function $f(d_n) = 1/\bar{d}$ where $\bar{d}$ is the coverage radius of the BSs. We model the channel gain from transmitter m to receiver n under Rayleigh fading as $g_{nm} = d_n^{-a}\sigma_{nm}$, where d_n^{-a} is the path loss with power fall-off factor $a > 1$ and $\sigma_{mn} \sim \exp(1)$ is an independent and exponentially distributed random variable with unitary mean. Moreover, we define the noise spectral density η_0 as noise power per unitary bandwidth.

We now define the throughputs based on different medium access schemes for both cellular and white spaces [10].

Cellular throughput. We assume that frequency re-use has effectively ruled out inter-cell interference; e.g., in OFDMA, each user is assigned to a subset of subcarriers. Therefore, we define the Signal-to-Noise Ratio (SNR) of user i receiving downlink cellular transmissions as:

$$\mathsf{SNR}_i^k(p_i^k) = \frac{g_{ii}^k p_i^k}{\eta_0 (B_c/N_c^k)}, \tag{1}$$

where p_i^k is the transmit power, B_c is the cellular bandwidth, and $N_c^k = |U_c^k|$ is the number of cellular users connecting to BS k [10]. Each user is allocated an equal share of the channel bandwidth, i.e., B_c/N_c^k. Then, according to the Shannon capacity formula, the throughput r_i^k of user i on BS k is:

$$r_i^k(p_i^k) = (B_c/N_c^k) \log\left(1 + \mathsf{SNR}_i^k(p_i^k)\right). \tag{2}$$

White space throughput. If multiple users transmit simultaneously on a shared white space channel, the transmission quality is significantly affected by multi-user interference. We denote the transmit power of all users on white space channel l as a vector $\mathbf{p}^l$, and define the Signal-to-Interference-and-Noise Ratio (SINR) of user j on white space channel l as:

$$\mathsf{SINR}_j^l(\mathbf{p}^l) = \frac{g_{jj}^l p_j^l}{\sum\limits_{u_n^l \in \{U_w^l \setminus u_j^l\}} g_{jn}^l p_n^l + B_w \eta_0}, \tag{3}$$

where B_w is the bandwidth of the white space channel, and $g_{jn}^l p_n^l$ is the interference to user j due to the transmission of user n. Then, the throughput $r_j^l(\mathbf{p}^l)$ of user j on white space channel l is given by:

$$r_j^l(\mathbf{p}^l) = B_w \log\left(1 + \mathsf{SINR}_j^l(\mathbf{p}^l)\right). \tag{4}$$

[1] Unlicensed mobile devices can operate on white space channels 21-51 except channel 37. In such a case, we have $L = 30$. For fixed devices, permitted channels are channels 2–51, excluding channels 3, 4, and 37.

IV. User Selection for White space Offloading

The assignment of users to cellular or white space channels occurs over discrete time slots $t \in \{1, 2, \dots\}$. In particular, the controller makes its decision at the beginning of each time slot based on current channel conditions at user locations. We assume that the location of each user does not significantly change between two adjacent time slots.[2] A suitable setting of the time slot length allows modeling of practical scenarios when users are walking or driving.

We offload a subset $\mathcal{U}_w$ of users' data transmissions from the cellular network to white space channels by maximizing the overall throughput of all users:

$$\begin{aligned}\underset{\mathbf{p}^k,\mathcal{U}_w}{\text{maximize}} \quad & \sum_{U_c^k \subset \mathcal{U}_c} \sum_{u_i^k \in U_c^k} r_i^k(p_i^k) + \sum_{U_w^l \subset \mathcal{U}_w} \sum_{u_j^l \in U_w^l} r_j^l(p_j^l) \\ \text{subject to} \quad & \sum_{u_i^k \in U_c^k} p_i^k \le \bar{p}_c, \ \ \forall U_c^k \subset \mathcal{U}_c \end{aligned} \tag{5}$$

where, without loss of generality, we consider the total power constraint in a multi-user downlink system for all cellular users with an upper bound $\bar{p}_c$. Following the given regulations,[3] data transmissions on white space channels use a fixed power level $\bar{p}_w$, i.e., $p_j^l = \bar{p}_w, \ \forall u_j^l \in \mathcal{U}_w$. We assume that this maximum allowed power for each unlicensed user has effectively limited the interference to licensed users. The optimal solution for Eq. (5) is denoted by $\mathbf{p}^{k\star}$ and $\mathcal{U}_w^\star$.

In the following, we first design an offloading strategy based on Eq. (5). We then discuss the stability of the offloading strategy. All proofs are provided in the technical report [12].

A. Offloading Strategy

Suppose that the offloading decision $\mathcal{U}_w$ is given. We can then discuss the optimal power allocation for cellular users. Although solving the optimization problem in Eq. (5) requires the power allocation and offloading decision to be jointly optimized, in this section we will show that the offloading decision depends only on the users' channel conditions in some special cases. First, we use the Karush-Kuhn-Tucker (KKT) conditions [13] for Eq. (5) to obtain the optimal transmit powers for the cellular users, as stated in the following proposition.

Proposition 1. *Given the offloading decision $\mathcal{U}_w$, the optimal transmit powers for all cellular users are given by*

$$p_i^{k\star} = \frac{1}{N_c^k}\bar{p}_c + \frac{B_c}{{N_c^k}^2} \sum_{u_n^k \in U_c^k} \left(\frac{\eta_0}{g_{nn}^k} - \frac{\eta_0}{g_{ii}^k}\right), \ \ \forall u_i^k \in U_c^k \subset \mathcal{U}_c. \tag{6}$$

The first term in Eq. (6) indicates that the power of cellular users is distributed mostly equally between users. The second term can be viewed as normalization, signifying that slightly less power is assigned to users with a poorer cellular channel quality, i.e., with a smaller g_{ii}^k. Thus, users with relatively poor cellular channel conditions may wish to switch to white space.

The offloading strategy has two decisions: which users should leave the cellular network, and which white space channel they should connect to. We address the first question by examining a necessary offloading condition, and we address the second question through a heuristic that ensures an increase in total throughput after switching a user.

Before doing so, we introduce two $(0, 1)$-matrices. Specifically, we define $\mathbf{Q} = [\mathbf{Q}_c \ \ \mathbf{Q}_w]$ as the *coverage matrix*, where $\mathbf{Q}_c \in \mathbb{R}^{N\times K}$ refers to the users under coverage of BSs (i.e., the cellular network) and $\mathbf{Q}_w \in \mathbb{R}^{N\times L}$ to users with available white space channels (with columns $\mathbf{q}_c^k$ and $\mathbf{q}_w^l$). Similarly, we define $\mathbf{V} = [\mathbf{V}_c \ \ \mathbf{V}_w]$ as the *allocation matrix*, where $\mathbf{V}_c \in \mathbb{R}^{N\times K}$ and $\mathbf{V}_w \in \mathbb{R}^{N\times L}$ refer to the choices of BSs (i.e., the cellular network) and white space channels respectively (with columns $\mathbf{v}_c^k$ and $\mathbf{v}_w^l$). Entries with a unitary value signify that the corresponding users are covered by or assigned to that network. For instance, $(\mathbf{q}_c^k)_n = 1$ and $(\mathbf{v}_c^k)_n = 1$ if user n is under the coverage of BS k and is also connected to that BS. Users are always under the coverage of the closest cellular BS, but may not have white space coverage.

Given the coverage and allocation matrices and based on the optimal power allocation strategy in Proposition 1, we can rewrite Eq. (5) in the following equivalent form:

$$\underset{\mathbf{V}=[\mathbf{V}_c,\mathbf{V}_w]}{\text{maximize}} \quad \sum_{k=1}^{K}\sum_{n=1}^{N} (\mathbf{v}_c^k)_n r_n^k(p_n^{k\star}) + \sum_{l=1}^{L}\sum_{n=1}^{N} (\mathbf{v}_w^l)_n r_n^l(\bar{p}_w)$$

$$\text{subject to} \quad \sum_{k=1}^{K} \mathbf{v}_c^k + \sum_{l=1}^{L} \mathbf{v}_w^l = \mathbf{1}_N, \tag{7a}$$

$$\mathbf{V}_c \le \mathbf{Q}_c, \ \mathbf{V}_w \le \mathbf{Q}_w, \tag{7b}$$

$$(\mathbf{v}_c^k)_n \in \{0,1\}, (\mathbf{v}_w^l)_n \in \{0,1\}, \quad \forall k,l,n, \tag{7c}$$

The constraints in Eqs. (7a) and (7b) ensure the feasibility of the offloading decision: a user can only be assigned to one interface (either white space or cellular) that covers the user's location. The constraints in Eq. (7c) ensure that all entries of $\mathbf{V}$ are binary. The optimal offloading decision for Eq. (7) is denoted by $(\mathbf{v}_c^k)_n^\star, \ \forall k, n$ and $(\mathbf{v}_w^l)_n^\star, \ \forall l, n$.

Since Eq. (7) is a hard combinatorial problem, we solve it by equivalently replacing the constraints in Eq. (7c) with $((\mathbf{v}_c^k)_n - 1)(\mathbf{v}_c^k)_n)^\alpha \ge 0 \ \forall k, n$ and $((\mathbf{v}_w^l)_n - 1)(\mathbf{v}_w^l)_n)^\alpha \ge 0 \ \forall l, n$, given $\alpha \ge 1$ and odd. This substitution allows us to verify the KKT conditions for Eq. (7) and find necessary conditions for optimality based on complementary slackness [13]:

Proposition 2. *Suppose that user n is under the coverage of cellular BS k, i.e., $(\mathbf{q}_c^k)_n = 1$. If user n is optimally connected to cellular network, then the following condition holds:*

$$\begin{aligned} r_n^k(p_n^{k*}) - r_n^l(\mathbf{p}^l) \ge & \frac{1}{N_c^k}\sum_{m=1}^{N} (\mathbf{v}_c^k)_m^\star r_m^k(p_m^{k*}) \\ & - \sum_{m=1}^{N} (\mathbf{v}_w^l)_m^\star \frac{g_{mn}^l}{\sum_{j\ne m} (\mathbf{v}_w^l)_j^\star g_{mj}^l + B_w\eta_0/\bar{p}_w} r_m^l(\mathbf{p}^l). \end{aligned} \tag{8}$$

[2] Entries in the white space database have temporal and spatial validity, implying that the availability or assignment of a channel is valid unless the users move more than the value associated with the entry.

[3] The maximum power depends on the device class: fixed devices such as BSs can transmit up to 4 W, whereas power limit for mobile devices is 100 mW or 40 mW if an adjacent channel is occupied by a TV signal [11].

If $g^l_{mj} \simeq g^l_{ni} \simeq B_w\eta_0/\bar{p}_w$, $\forall j \neq m, i \neq n$, we would have $\frac{g^l_{mn}}{\sum_{j\neq m}(\mathbf{v}^l_w)^\star_j g^l_{mj} + B_w\eta_0/\bar{p}_w} \simeq \frac{1}{N^l_w}$ in Eq. (8). This suggests that, for a user connecting to the cellular network, the difference of this user's throughput under cellular and white spaces should be higher than the difference of the average cellular throughput and the average of white space throughput of all the other users. If we further assume that interference power is much less than the received signal power for all white space users, i.e., $g^l_{mj}\bar{p}_w \ll g^l_{mm}\bar{p}_w$, $\forall m \neq j$, we find a simplified version of Eq. (8) for this special case.

Corollary 1. *If $g^l_{mj} \simeq g^l_{ni} \simeq B_w\eta_0/\bar{p}_w$, $\forall j \neq m, i \neq n$, and $g^l_{mj}\bar{p}_w \ll g^l_{mm}\bar{p}_w$, $\forall m \neq j$, Eq.* (8) *can be reduced to:*

$$\begin{aligned}&(B_c/N^k_c)\left(\log g^k_{nn} - \frac{1}{N^k_c}\sum_{m=1}^{N}(\mathbf{v}^k_c)^\star_m \log g^k_{mm}\right)\\ &\geq B_w\left(\log g^l_{nn} - \frac{1}{N^l_w}\sum_{m=1}^{N}(\mathbf{v}^l_w)^\star_m \log g^l_{mm}\right)\end{aligned} \tag{9}$$

Intuitively, users with cellular channel conditions worse than the channel conditions that they would experience under white space are more likely to be switched to white space channels. The condition in Eq. (9) mathematically formulates this intuition. We can also observe from Eq. (9) that the switching decision also depends on the number of users in the cellular network since the bandwidth is divided by all users: when too many users in the cellular network experience a too low individual throughput, some of them will be offloaded to available white space channels.

We recall that the offloading decision has to be made by maximizing the overall network performance. Even though the throughput of an individual user may increase or decrease, the aggregate increase in the throughputs of some users should exceed the aggregate decrease in the throughputs of the other users. To enforce this condition, we introduce the *Positive Gain* (PG) heuristic that explicitly considers how the assignment of a given user n to a specific channel affects the throughput of the users already allocated to that channel. For instance, user n on white space channel l may significantly interfere with existing users $\mathcal{U}^l_w$, eventually decreasing the aggregate throughput. Therefore, assigning user n to white space channels must ensure that the decrease in the aggregate throughput is compensated by the throughput increase after switching user n to channel l. Accordingly, PG first checks if user n satisfies the following condition:

$$\begin{aligned}\log(1+\mathsf{SINR}^l_n) \geqslant &\sum_{m\in\mathcal{U}^l_w}\log(1+\mathsf{SINR}^l_m(\mathcal{U}^l_w))\\ &-\sum_{m\in\mathcal{U}^l_w}\log(1+\mathsf{SINR}^l_m(\mathcal{U}^l_w\cup n)),\end{aligned} \tag{10}$$

where $\mathsf{SINR}^l_m(\mathcal{U}^l_w \cup n)$ denotes the SINR of user m when the interfering set of users includes those in $\mathcal{U}^l_w$ plus user n.

Whereas Eq. (10) only considers switching between white space channels, the offloading decision must also consider the user's throughput on the cellular network. PG also compares the throughput of the cellular network and white spaces as follows:

$$B_w\log(1+\mathsf{SINR}^l_n) \geqslant \frac{B_c}{1+N^k_c}\log(1+\mathsf{SNR}^k_n) \tag{11}$$

Users satisfying both conditions above are assigned to white space l, whereas the remaining ones stay in the cellular network. If multiple white space channels satisfy Eq. (10) and Eq. (11), users are assigned to the channel with the highest throughput.

B. Stability and Switching Cost

Thus far, we have developed an offloading strategy that targets maximizing the total throughput across all users. However, such an approach neglects the impact of time dynamics on end users: if users are forced to frequently switch between cellular and white spaces, user experience is affected by the delay and extra cost from connection setup and teardown times. In this section, we derive a probabilistic characterization of the switching frequency, based on Corollary 1, assuming that the number of users in the cellular network and white space channels are substantial.

Proposition 3. *If N^k_c and N^l_w are large, the probability that Eq.* (9) *in Corollary 1 asymptotically holds is:*

$$\rho_c \asymp \frac{1}{a}e^{\frac{\gamma}{a}-1}\varphi\Big(\frac{1}{a}, e^{-\gamma+a}\Big) \tag{12}$$

where $\gamma \approx 0.5772$ is the Euler's constant, and $\varphi(s,z) \equiv \int_0^z x^{s-1}e^{-x}\mathrm{d}x$ is the lower incomplete gamma function.

Let us assume that ρ_l is the probability that white space channel l is available, and that ρ_l, $\forall l$ are independent. Then, $\rho_w = 1 - \prod_{l=1}^{L}(1-\rho_l)$ is the probability that one or more white space channels are available. Proposition 3 allows us to derive the continuous time spent by a user on the same interface:

Corollary 2. *The expected amount of time a user continuously connects to the cellular network is:*

$$t_c \asymp \frac{\tau}{\big(1-\frac{1}{a}e^{\frac{\gamma}{a}-1}\varphi(\frac{1}{a}, e^{-\gamma+a})\big)\rho_w}, \tag{13}$$

and the amount of time a user continuously connects to a white space channel is:

$$t_w \asymp \frac{\tau}{1-\big(1-\frac{1}{a}e^{\frac{\gamma}{a}-1}\varphi(\frac{1}{a}, e^{-\gamma+a})\big)\rho_w}, \tag{14}$$

where τ is the length of a time slot.

From Eq. (13) and Eq. (14), we observe that users stay longer on a white space channel and shorter in the cellular network with larger values of the path-loss factor a and more available white space channels. We also observe that very small or large $\big(1-\frac{1}{a}e^{\frac{\gamma}{a}-1}\varphi(\frac{1}{a}, e^{-\gamma+a})\big)\rho_w$ leads to a very short stay in either a cellular network or a white space channel.

These results establish the need of a mechanism to effectively stabilize the connections of users or, equivalently, to avoid frequent switches between the cellular network and white spaces. To do so, we introduce a *cost function* characterizing the switching latency, i.e., the time required to reconfigure the hardware when transmissions are switched from one frequency to another. We assume that mobile devices are equipped with two different interfaces, one for cellular communications and another for white space access, and represent these two cases in our cost function:

$$C(\zeta)=\begin{cases} c|\zeta(t)-\zeta(t+1)|, & \text{if } \zeta(t),\zeta(t+1)\in[\underline{f},\bar{f}],\\ \bar{c}, & \text{otherwise.}\end{cases} \tag{15}$$

The first case represents the cost of switching between white space channels, which we characterize as a linear function of the difference between the current white space frequency $\zeta(t)$ and the white space frequency $\zeta(t+1)$ to switch to. Specifically, c denotes the delay for switching unit bandwidth, and $\underline{f}$ and $\bar{f}$ are the extremes of the white space frequency ranges, typically corresponding to $\underline{f}=512, \bar{f}=698$ [14]. The second case represents the cost of switching between the cellular and white space interfaces, which we model as a constant and relatively large delay $\bar{c}\geq c(\bar{f}-\underline{f})$. Note that the cost function in Eq. (15) also accounts for user mobility, as the availability of white space channels is likely to change more when users move a longer distance. The expected switching latency for a certain user at time slot t is then $\mathbb{E}\left(C(\zeta)\right)=\sum_{l=1}^{L}c|\zeta(t)-\zeta_l|\rho_l(1-\rho_c)+\bar{c}\rho_c$, where ρ_c is derived according to Eq. (12) and ρ_l is the probability that white space channel l is available at a given time.

We now extend the offloading strategy by explicitly accounting for the switching cost. Accordingly, the controller decides whether to reconsider the network connection of user n or not based on the following cost function:

$$\omega_n(C(\zeta))=\left(1-\lambda_\beta\frac{\mathbb{E}\left(C(\zeta)\right)}{\bar{c}}\right)^\beta, \tag{16}$$

where $\beta>0$ is the relative significance of switching latency, and $\lambda_\beta\in(0,1)$ is a cost sensitivity parameter. A large λ_β indicates that the controller favors user experience: it does not switch users when the switching latency is high. If we expect users to stay in a network for T time slots, with $T>\frac{1}{\tau}\max\{t_c,t_w\}$, we choose λ_β such that $1/\big(1-\lambda_\beta\frac{\mathbb{E}(C(\zeta))}{\bar{c}}\big)^\beta=T$, so ω_n could represent the probability that users will switch after T time slots.

The Switching Cost-Aware (SCA) offloading strategy described above is detailed in Algorithm 1. Note that a user generally will not switch if the switching cost is high – i.e., if ω_n in Eq. (16) is small – to reduce temporal fluctuations until the steady state is reached. However, the user may occasionally switch even if the switching cost is high to allow some exploration of other channels. The decision to switch is based on the conditions in Eqs. (9), (10), and (11).

An important parameter that affects the performance of the SCA offloading strategy is the probability ρ_l, $\forall l$, that white space channels are available. In practice, these probabilities can be inferred by querying a white space database for real-time channel availability, as simulated in the next section.

Algorithm 1 Switching Cost-Aware (SCA) offloading strategy

```
for Each user u_n do
  Generate a random variable ω̂_n
  Update E(C(ζ)) based on ρ_c and ρ_l, ∀l at u_n's location
  if ω̂_n ≤ ω_n(C(ζ)) in Eq. (16) then
    if Condition in Eq. (9) is satisfied then
      Choose the cellular network k for user n
    else
      if Conditions Eq. (10) and Eq. (11) are satisfied then
        Choose white space channel l for user n
      else
        User n remains in the currently selected network
  else
    User n remains in the currently selected network
```

V. Performance Evaluation

A. Methodology and Experimental Setup

Since white space availability highly depends on population density [15], we consider two cities, New York City (NYC) and Boulder in Colorado (BC), as representative examples of a densely-populated and a relatively less-populated setting. For both scenarios, we consider an area of 4 km×4 km. We query the Google Spectrum Database (GSDB)[4] to obtain the white space availabilities in these cities. Specifically, we generate one query per hour for multiple locations and calculate the probability of a given white space channel being available at a certain time and location. We regard each BS as a fixed device using the maximum transmit power of 4 W and assume each cell tower to be 20 m high. As the GSDB API limits the daily number of queries to 1,000, we select 40 locations and analyze the collected data accordingly.

The available white space channels in BC are {21, 22, 50, 51}. The corresponding lower edge frequencies are {512, 518, 686, 692} MHz. We found that these channels are always available under the footprint of a BS in the considered scenario. However, to introduce some variability in the simulation, we model the availability of these channels as a uniform distribution, i.e., $p_l\sim U(0.75,1),\forall l=\{512,518,686,692\}$. The GSDB reports that no white space channels are available in downtown NYC (i.e., in Manhattan). But, one channel (e.g., channel 5) is available in some less populated areas of NYC. Accordingly, we model the availability of one white space channel in this case as $p_l\sim U(0.95,1)$ to characterize how much traffic can be offloaded under such stringent conditions.

We simulate realistic cellular network topologies by extracting cell tower locations from the crowd-sourced OpenSignal[5] database. Specifically, we use the data for T-Mobile, as it has more cell towers in both NYC (4,097) and BC (35) compared to other major U.S. carriers. OpenSignal data are affected by crowd-sourced measurement errors that lead to overlapping or very close tower locations for a given operator. To circumvent these effects, we cluster cell towers that are closely spaced. The BC scenario has two such inaccurate BS locations that we manually merged. The data for the NYC scenario are more

[4]https://www.google.com/get/spectrumdatabase/
[5]http://opensignal.com/

inaccurate, as the cell towers are more densely deployed. In this case, we apply k-means clustering to merge the BSs into 100 cells, which is a reasonable coverage of the target area.

We use the following performance metrics for each cell.

- *Total capacity per cell* as the aggregate throughput in a cell achieved by assigning all users to different resources.
- *Per user throughput* as the average throughput per user.
- *Fraction of traffic* through each interface as the ratio of the traffic served through a particular interface (i.e., either cellular or white space) to the total capacity of a cell.
- *Probability of frequency (interface) switching* as the probability that a user will be assigned to a different frequency (interface) in the next time slot.
- *White space re-use distance* as the average minimum distance between users on the same white space channel.

For comparison purposes, we consider different schemes for making switching decisions.

- *Positive Gain* (PG): the offloading strategy introduced in Section IV-A with decisions made based on the conditions in Eqs. (10) and (11).
- *Switching Cost-Aware* (SCA): the offloading strategy described in Algorithm 1.
- *Cellular* (CELL): only the cellular channel is considered in resource allocation as in conventional networks that do not employ white spaces.
- *Greedy* (GR): the central controller sequentially assigns each user (e.g., user i under the coverage of BS k) to the channel with the highest throughput based on the current allocation in terms of $\mathcal{U}_c^k$ and $\mathcal{U}_w^l$. For cellular networks, we use Eq. (2) to calculate the new channel throughput given that the current $N_c^k - 1$ users will remain connected to the cellular interface, and assume that the BS shares its power budget equally among its users. Similarly, we calculate the white space channel throughput as in Eq. (4) under $\mathcal{U}_w^l$, assuming $p_i^l = \bar{p}_w, \forall i \in \mathcal{U}_w^l$. In contrast to PG and SCA, GR does not take into account how much throughput degradation other users will experience once the current user is switched to the white space channel.
- *Random Interface* (RI): each BS assigns its users randomly to the cellular or one of the available white space channels.

For all schemes and after the assignment, the BS allocates power for the associated downlink antenna according to Eq. (6) for cellular users. Moreover, we account for the switching cost $C(\zeta)$ in Eq. (16) by calculating channel capacities for all schemes as $r_i(C(\zeta)) = (1 - C(\zeta)/\tau)r_i$, where $C(\zeta)/\tau$ is the fraction of time spent for channel switching and r_i is the rate of the user in channel i.

Unless otherwise stated, we use the following parameters in our simulations [11], [16]: $B_w = 6$ MHz, $B_c = 10\,\mathrm{MHz}$, $p_c = 40\,\mathrm{W}$, $p_w = 4\,\mathrm{W}$, $\eta_0 = 3 \times 10^{-19}$, $\sigma_{nn} \sim \exp(1)$ for both cellular and white space links, $\sigma_{nm} \sim \exp(0.01)$, $c = 0.005\,\mathrm{s/6\,MHz}$, $a = 2.5$, $\bar{c} = 0.15\,\mathrm{s}$, $\beta = 1$, and $\lambda_\beta = 0.9$. We assume that users move with a speed $\upsilon \sim U(0, 10)$ m/s. Each simulation runs for 100 time slots, whose individual duration is 1 s. The reported values are the average of 10 runs.

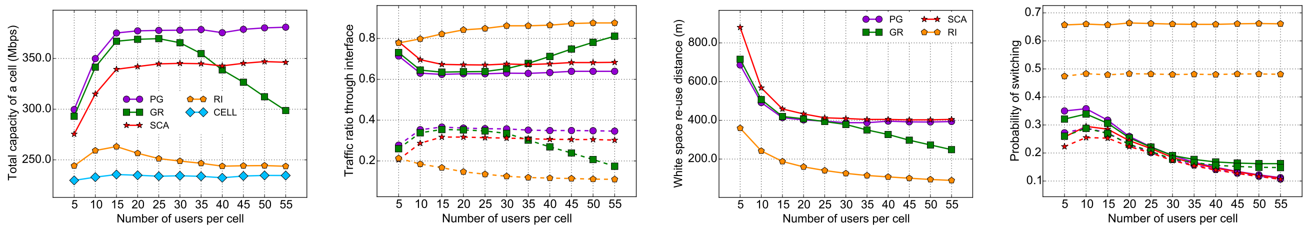
B. Impact of User Density

Fig. 1 and Fig. 2 show the performance of all schemes for BC and NYC, respectively. As illustrated in Fig. 1(a), there is a significant gap between CELL and the schemes using white spaces. For PG, this gap is 70 Mbps per cell and corresponds to around 15 Mbps gained per user (63.02 Mbps vs. 48.34 Mbps) when there are only five users (on average) in each cell. RI does not leverage channel diversity, thus the corresponding gap is only 3 Mbps/user. The figure clearly shows that a mobile operator in BC can harvest additional 70 Mbps of capacity per cell by adopting PG and capitalizing on four white space channels. The improvement of PG over CELL varies between 30–62%. PG performs well even when there are more users ($N = 55$), with an increase in capacity of 146 Mbps/cell over CELL. This behavior is due to the advantages in leveraging multi-user and multi-channel diversity, and does not occur in RI. The total cellular capacity remains roughly constant with increasing number of users, because users share the cellular bandwidth and power without interfering with each other.

As the number of users increases, we see that the performance of GR worsens due to its greedy nature: a new user joining white space l is more likely to degrade the performance of existing users in that channel compared to a sparse network. On the other hand, SCA trades off capacity for stability and, hence, performs worse than PG and GR. However, as opposed to GR, SCA still maintains its total cell capacity with increasing population density and is the second best scheme after PG for $N \geqslant 40$. The per-user rate follows similar trends, and there is a significant gap between CELL and PG, GR, SCA. For example, CELL achieves 4.45 Mbps/user while PG provides each user with 7.23 Mbps, GR with 5.67 Mbps, SCA with 6.58 Mbps, and RI with 4.63 Mbps for $N = 55$.

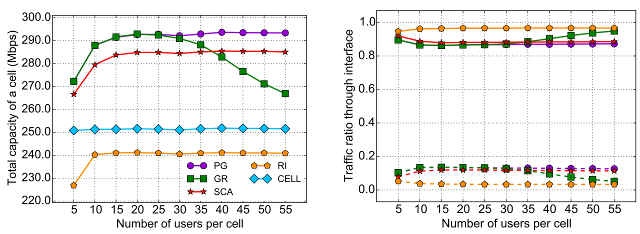
By comparing the capacity of BC in Fig. 1(a) and that of NYC in Fig. 2(a), we observe that the gap between CELL and the other schemes is narrower, due to the lower availability of white spaces in NYC. The capacity improvement enabled by PG varies between 21–42 Mbps/cell corresponding to an 8–17% improvement over CELL. Nevertheless, it is noteworthy to highlight that white spaces enable about 4.3 Mbps/user additional capacity for NYC setting for $N = 5$ and about 0.8 Mbps for $N = 55$ per cell under PG. In this setting with only one white space channel, the performance of GR is the same as that of PG for $N \leqslant 30$, while RI can not use white space efficiently and performs even worse than CELL.

Fig. 1(b) and Fig. 2(b) show that PG offloads between 27–37% of traffic to white spaces in BC, whereas it varies between 10–13% for NYC. For instance, fraction of offloaded traffic is around 35% for BC and 13% for NYC when $N = 55$. When there are many users, only some of them are assigned to white spaces, since the capacity drastically decreases due to interference from the users in the same channel. When there are few users, more traffic can initially be supported by white spaces, as illustrated in Fig. 1(b) and Fig. 2(b). However, when the network starts to become congested (i.e., with a large N), the white space capacity saturates. Thus, the fraction of



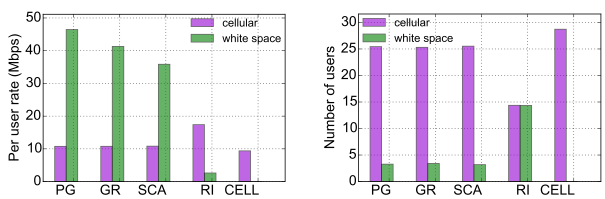
(a) Total cell capacity. (b) Traffic through each interface. (c) White space re-use distance. (d) Probability of switching.

Fig. 1. Results for the BC scenario. The same markers are used in (b) and (d) for each scheme listed in (a). In (b), solid lines (—) and dashed lines (- - -) represent the traffic through cellular and white spaces, respectively; in (d) solid lines stand for frequency switching and dashed lines for interface switching.



(a) Total cell capacity. (b) Traffic through each interface.

Fig. 2. Results for the NYC scenario.



(a) Per user throughput. (b) Number of users.

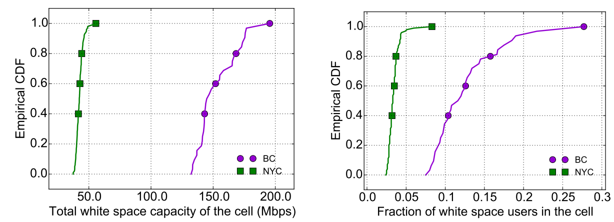
Fig. 3. BC scenario: comparison of algorithms for $N = 30$ users per cell.

offloaded traffic remains almost the same for PG and SCA, while it decreases for GR as N increases due to the capacity degradation observed in Fig. 1(a).

Fig. 1(c) shows the white space re-use distance with increasing N for BC. Interestingly, the behavior of PG and GR after $N = 30$ diverges: while the re-use distance of PG tends to stabilize, this distance of GR still decreases almost linearly. This can be explained by the different approaches taken by the two schemes. PG considers the performance degradation on existing users and may not assign new users to white space channels after some user density. Instead, GR greedily considers the performance of the current user and may still assign it to white space.

Fig. 1(d) illustrates the switching probability, which clearly shows how RI oscillates between the two interfaces. With increasing N, the switching probability of PG decreases from 0.27 to 0.12 for BC, whereas it decreases from 0.13 to 0.04 for NYC (not shown here). We also notice the lower switching probability of SCA compared to other schemes for low N as a result of its threshold-based switching decision. PG and SCA achieve similar levels of stability for high values of N, in terms of both interface and frequency switching probability.

Fig. 3 provides more details about white space and cellular capacities when $N = 30$ for the BC scenario. Fig. 3(a) shows that the throughput of the white space interface is 4 times



(a) Total white space capacity. (b) Fraction of white space users.

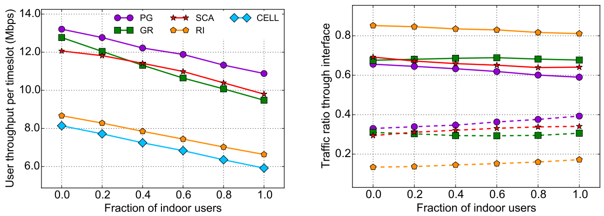
Fig. 4. Distribution of white space cell capacity and number of white space users for BC and NYC with $N = 30$ users per cell.

that of the cellular interface for PG. This large difference is surprising, as white space channels have lower bandwidth and power levels compared to the cellular network. However, as shown in Fig. 3(b), this result is due to the low number of users sharing the white space capacity. In fact, most users stay in the cellular network, while others are assigned to white spaces. Within the same cell, there is only one user at each white space channel because the co-channel interference is very high due to the close distance when one more user is assigned to the same white space channel.

Fig. 4(a) and Fig. 4(b) illustrate the distribution of white space capacity and the number of white space users in a cell for PG in the BC and NYC scenarios, respectively. As apparent from Fig. 4(a), the capacity harvested from white spaces in NYC is limited compared to BC. In fact, the capacity gap is proportional to the difference in the number of available white space channels. For NYC, almost every cell offloads only 5% of its users to white space, whereas for BC the offloaded fraction is in the range 8–28%. The corresponding per cell white space capacity varies between 37–56 Mbps for NYC and 133–195 Mbps for BC. We attribute this wider range of capacity variation to the higher degree of freedom resulting from more white spaces as well as the more heterogeneous network topology of BC compared to the NYC scenario.

C. Impact of Cellular Channel Quality

White spaces with good wall penetration capability offer advantages in indoor scenarios where network operators face challenges with coverage. Given that a significant share of the current data consumption is by indoor users [17], understanding the impact of poor cellular link quality is crucial. To this end, we model cellular channels using two σ_{nn} values, one for outdoor users with good channel conditions – i.e., the same channel gain as white spaces: $\sigma_{nn} \sim \exp(1)$ –



(a) Per user throughput. (b) Fraction of traffic.

Fig. 5. Impact of indoor users for the BC scenario with $N = 30$ users per cell. Dashed lines in (b) stand for the white space interface.

and one for indoor users with poor channel conditions, i.e., $\sigma_{nn} \sim \exp(0.01)$. We then vary the fraction of indoor users and examine the offloading behavior.

As Fig. 5(a) shows, for all schemes, throughputs decrease with the fraction of indoor users. However, there is a considerable performance gap between CELL and the other schemes in all cases. We observe in Fig. 5(b) that the fraction of traffic carried by white spaces increases with the fraction of indoor users and eventually reaches 40% for this setting. Interestingly, the number of white space users increases moderately with the fraction of indoor users. As discussed before, this behavior is due to the impact of interference on white space capacity. For high user density, a cellular interface with a poor channel may yield higher performance compared to a good white space channel whose capacity is limited by multi-user interference.

D. Impact of Switching Cost

Fig. 6 illustrates the change in throughput with increasing switching cost for BC. The values in the horizontal axis represent the fraction of a time slot that is needed for switching from one white space channel to another one separated by 6 MHz. We set the interface switching cost to $\bar{c} = 30c$ to reflect our assumption that switching interfaces is more costly than switching between white space channels. In our setup, the maximum separation between white spaces is 30 channels, each with a 6 MHz bandwidth. The results in Fig. 6 show that, when the switching cost is negligible (i.e., $c = 0$), all schemes outperform CELL, including the naive RI. The performance gap decreases with increasing c. Finally, the performance of SCA converges to that of CELL for $c \geq 0.015$, as SCA does not allow any switching to white spaces because of the ω threshold. At the same time, the performance of RI is lower than CELL due to its inefficient switching between interfaces. However, PG and GR can maintain their high performance despite very high switching costs, as they explicitly account for the capacity loss due to the switching overhead.

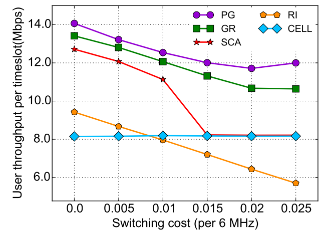


Fig. 6. Impact of the switching cost for the BC scenario with $N = 30$ users per cell.

VI. Conclusion

In this work, we introduced *white space offloading*, in which a mobile network operator can harness unused white spaces and migrate part of the cellular traffic on the corresponding spectrum. Since optimal power and resource allocation is a hard problem, we introduced several algorithms to allocate available white spaces that are retrieved from a white space database. We quantified the benefits of white space offloading in different scenarios (urban, indoors, densely and moderately populated) through an evaluation based on the Google Spectrum Database and crowd-sourced cellular tower locations.

As a future work, we will adopt existing white space power allocation schemes which can further boost the capacity improvement. We will also extend our framework to other emerging technologies in 5G, including LTE-U and mmWave. Finally, we will consider energy efficiency as a major criterion to decide on offloading.

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