Interference Coordination Strategies for Content Update Dissemination in LTE-A

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Abstract—**Opportunistic traffic offloading has been proposed to tackle overload problems in cellular networks. However, they only address the problem of deadline-based content propagation in the cellular system, given wireless environment characterization. In contrast, we cope with the traffic offloading issue from another perspective: the base station interference coordination problem. In particular, we aim at the minimization of the total transmission time spent by the base stations in order to inject contents into the network, and we leverage the recently proposed ABSF technique to keep under control intercell interference. We formulate an optimization problem, prove that it is NP-Complete, and propose a near-optimal heuristic. Our proposed algorithm substantially outperforms classical intercell interference approaches proposed in the literature, as we evaluate through the simulation of dense LTE-A network scenarios.**

I. INTRODUCTION

A number of web and smartphone applications have recently appeared, which cause the generation of a huge volume of traffic for mobile devices. A large fraction of the traffic generated by such applications consists in the distribution of content updates such as social network updates and notifications, road traffic updates, map updates, and news feeds (e.g., *waze*, an *app* for a social network for navigation, includes all the above mentioned features).

Along with the appearance of such applications, some schemes have been recently proposed to offload the traffic generated by them in the cellular network. In particular, the device-to-device (D2D) paradigm has been proposed to assist the base station in the content distribution [1], [2], [3]: with D2D communications enabled, the base station delegates a few mobile users (*content injection*) to carry and spread content updates to the other users (*content dissemination*). Although the content dissemination phase introduces delays, D2D-based content update distribution is possible since it carries traffic with no strict real-time constraints, and whose content's lifetime lasts for a few minutes.

Most of the currently available offloading proposals, e.g., [2], [4], focus on the characterization of content dissemination and the design of content injection strategies, but largely neglect the optimization of radio resources in the *injection phase*, i.e., the process of injecting a content in a subset of the mobile user population, which produces bursty and periodic traffic. While this has been partially addressed, e.g., in [2], which has considered the impact of opportunistic resource utilization in the content injection strategies, their analysis is restricted to a single cell and does not consider the interference caused by other cells.

We tackle the traffic offloading issue from a different and unexplored perspective: the intercell interference coordination problem. The rationale behind our approach is twofold: (i) interference is a key factor in dense networks, where the single cell study case is not representative of a real network; (ii) content injection operations are impacted by network speed, which, in turn, strongly depends on intercell interference.

To address the intercell interference coordination problem, in this paper we adopt the the Almost Blank Sub-Frame (ABSF) mechanism recently defined for LTE-A [5]. This mechanism assigns resources in such a way that a subframe be *blanked* for some base stations, thus preventing their activity when the interference exceeds a threshold. A key advantage of this technique is that, by adopting a semi-distributed intercell interference coordination (ICIC) paradigm in which a central server simply announces to base stations the pattern of resources to be used, it greatly reduces the complexity of intercell interference coordination operations. While ABSF has only been proposed very recently and hence has not been thoroughly evaluated, some early studies (like our recent work in [6]) have shown its potential to improve performance.

When scheduling the transmission of content updates at base stations, our main objective is to minimize the time required for these transmissions, since (i) the faster contents are injected, the sooner they can be disseminated, and thus offloading performance is optimized; and (ii) the less time required for the transmissions, the more resources are freed for other applications. We show that the problem of finding an ABSF-based scheduling algorithm that minimizes the time required for content update transmissions while satisfying the content deadlines is NP-Complete and NP-Hard to approximate. Thus, we design BSB, an algorithm that runs in polynomial time and

achieves sub-optimal network performance, yet it outperforms the state of the art mechanisms proposed in the literature. In particular, our simulations show that BSB allows to abate the base station time devoted to content distribution by a factor 3 or larger, while boosting the ability of D2D schemes to reach the full set of content subscribers.

The contribution of our work can be summarized as follows: (i) we formulate a base station scheduling problem and we show that it is NP-Complete; (ii) we design and validate a practical algorithm for the computation of ABSF patterns; (iii) while available works on intercell interference coordination assume that a few interferes dominate the overall received interference experienced by a device, we show that, in a dense network scenario, a much broader set of interferes needs to be taken into account for interference coordination; (iv) we show that channel-opportunistic D2D schemes are seriously impaired by non-ideal content injection operations.

II. D2D-ASSISTED CONTENT UPDATE DISTRIBUTION

In this section, we present the scenario addressed by this paper as well as the overall framework of our system and its building blocks.

A. Content distribution scenario

The scenario addressed by this paper consists in a LTE cellular network with N base stations, each of which covers a user set U_b, where b is the base station index. Each user subscribes a content $c_i \in C$, with content length L_c and a deadline T_c by which the content needs to reach all subscribed users. Multiple users can request the same content, and a dynamic scenario is considered, where users join and leave. In order to distribute a content to multiple users in a scenario like this, while offloading the base station as much as possible, we exploit D2D: the base station delivers the content to a subset of the subscribed users, which then opportunistically share this content with other users via short-range communication technologies such as WiFi-Direct, WiFi or Bluetooth.

The main objective of this paper, in the context of the above scenario, is to design a strategy to deliver content to users that minimizes the total resources required by the base stations, as this frees resources that can used by other applications. An additional benefit of our approach is that power consumption of base stations decreases, since it depends on the total activity time of base stations. In order to achieve the objective, we need to address the following two challenges:

Intra-BS optimization: we need to select the optimal set of users in a cell that receive the content from the base station, to ensure that (i) the content reaches all subscribers in the cell by the deadline; and (ii) resources required from the base stations are minimized.

Inter-BS optimization: in addition to determining the transmissions that need to be performed by each base station, we also need to schedule each of these transmissions among base stations, taking into account the interference between base stations in such a way that the total time required by these transmissions is minimized.

While the issue of *intra-BS optimization* has already been addressed by a number of works in the literature [4], [6], [7],

our focus here is on the *inter-BS optimization*. To address this, we use ICIC techniques that, by improving the spectral efficiency of the celluar network, reduce the transmission times required by base stations to distribute the content. In the following, we present the mechanism that we use for the intra-BS part, and the assumptions for the inter-BS optimization problem that we tackle in this paper.

B. Intra-BS content distribution

The transmission process for a particular content in a base station is divided into the following two phases:

1) *Content injection:* Initially, when a new content update is available, base stations immediately send it to a subset of the content-subscribed users. To do this, a multicast group transmission is used since this is a very efficient strategy to reach multiple users in just one transmission. As multicast requires a transmission at the least user rate of all multicast receivers [8], for a given multicast rate, only a part of the users in the group will be able to decode the message (i.e., those whose channel condition enables them to receive at the chosen rate).

2) *Content dissemination:* In order to reach those users that do not receive the content in the injection phase described above, in the dissemination phase, the content is spread opportunistically in the group.

It follows from the above description that the choice of the multicast rate for the initial injection involves the following trade-off: (i) if the selected multicast rate is too low, the number of bits injected will be small and thus efficiency will be low, (ii) however, if the selected rate is too high, the initial injection will only involve few users and hence content is unlikely to spread to all subscribed users by the deadline.

To address the above trade-off, in this paper we adopt the solution proposed in [2] to select the optimal rate for the multicast transmission while ensuring that the content reaches all users by the deadline. In particular, by solving the corresponding optimization problem, [2] proposes to the tune the rate at which base station b performs the multicast transmission to subscribed-user group a interested in the content c_i at time t, according to the following expression:

$$r_a^b(t) = \underset{y \in [r_1, r_2, \dots, r_{s_i^b}]}{\operatorname{argmax}} \varphi_a(t, y), \quad \forall a \in \mathcal{G}^b; \qquad (1)$$

where r_u is the rate of a generic user u, s_i^b is the total number of users interested in content c_i, i.e., the subscriber group size, $\mathcal{G}^b$ is the set of groups active under base station b, and $\varphi_a(t, y)$ is defined as

$$\varphi_a(t, y) = \sum_{u=1}^{s_i^b} y \cdot 1_{y \le r_u(t)} + \frac{\chi_a(t, y) - \kappa_a(t, y)}{s_i^b - \kappa_a(t, y)} \cdot 1_{y > r_u(t)}. \quad (2)$$

The value $\kappa_a(t, y)$ is the total number of users in group a which can decode the multicast message, while $\chi_a(t, y)$ is the total number of users which will have the content when the content deadline expires (it includes also $\kappa_a(t, y)$). Note that $\chi_a(t, y)$ depends on the average inter-contact rate amongst the users in the network and the content dissemination deadline,

which corresponds to the content deadline T_c according to [2], where the injection time is neglected. In contrast, in our simulations, we assume a reasonable value for the content dissemination deadline equal to 50 seconds, that is 50% of the total content deadline T_c.

C. Inter-BS scheduling

Following the previous explanation, during *content injection*, base stations schedule the multicast transmissions to inject the content to a subset of users. In a scenario with multiple base stations like the one considered here, we need to cope with the intercell interference (ICI) problem when scheduling these transmissions.

To address the above problem, in this paper we adopt the ABSF paradigm. In order to schedule the content transmissions following this paradigm, we need to allocate them to different subframes in each base station. Since a single transmission does not suffice to transmit an entire content, we need to divide the content in different chunks, and transmit as much chunks as possible in each subframe. Following the strategy of [2], only one group is opportunistically scheduled in each subframe and the transmission rate used is r_a^b given in (1). We denote by $a \in \mathcal{G}^b$ a group formed by the set of users interested in a specific content under base station b. Thus, $d_b = |\mathcal{G}^b| \leq |C|$ groups are placed in each cell, and each base station is loaded with d_b content update transmissions.

In a subframe i, the maximum rate that can be decoded by a user u is given by the Shannon capacity limit:

$$r_u(i) = B_T \log_2 \left(1 + \frac{S_u^b(i)}{N_0 + \sum_{j \neq b} I_u^j(i) x_{ij}} \right) \qquad (3)$$

where B_T is the bandwidth, N_0 is the noise power, S_u^b is the power of the signal received by user u from base station b, I_u^j is the power of the interference from base station j and x_{ij} is a binary value which indicates whether station j is scheduled in subframe i. Since the subframe i can be seen as the base station allocation *round*, as explained in the next section, hereafter the two terms *subframe* and *round* are used interchangeably.

According to the explanation provided before, the content chunks for group a are transmitted at a rate r_a^b, which implies that those users whose transmission rate satisfies $r_u(i) \geq r_a^b$ will be able to decode while the others will not be able to decode them. Note that, since r_a^b is the smallest transmission rate among those mobile users that can decode the transmission, we can express it as follows:

$$t_a(i) = r_a^b = B_T \log_2 \left(1 + \frac{S_{u^*}^b(i)}{N_0 + \sum_{j \neq b} I_{u^*}^j(i) x_{ij}} \right) \qquad (4)$$

where u^* is the user in group a with the worst channel conditions among the ones that can decode the transmission, i.e., $u^* = \underset{j \in a}{\operatorname{argmin}} \{\text{SINR}_j : r_a^b \leq r_j\}$.

III. BASE STATION TRANSMISSION TIME MINIMIZATION

Here, we formulate the inter-BS scheduling introduced before as an optimization problem, and show that it is NP-Complete and NP-hard to approximate. Then, we provide

a sufficient condition to solve the problem, which we will leverage to generate ABFS patterns (see Section IV).

A. Problem formulation

As explained in the previous section, the efficiency of the content dissemination depends on the speed of the content injection process, and therefore our goal when designing the inter-BS scheduling is to minimize the time needed to inject the content. In view of this, we formulate the following optimization problem, which aims to minimize the sum of subframes used by the base stations to serve the traffic demand, subject to being able to send the entire content within its lifetime T_c.

Problem BS-SCHEDULE

Input:
A collection of N base stations $B = \{1, 2, \cdots, N\}$, and distinct multicast groups $A = \{a_1^b, a_2^b, \cdots, a_{d_b}^b\}$ associated with base station $b \in B$. Positive constants N_0, τ, Θ, L_c, B_T. Integer $Z > 0$. For a multicast group a associated with base station b: $S_a^b(i)$, $w_a(i)$ and $I_a^j(i)$ for every $j \in B \setminus \{b\}$ and every $i = 1, 2, \cdots, Z$.

Question: Is there a scheduling of the base stations in at most Z rounds, such that

$$\Psi_a^b(Z) = \tau B_T \sum_{i=1}^{Z} x_{ib} w_a(i) \log_2 \left(1 + \frac{S_a^b(i)}{N_0 + \sum_{j \neq b} I_a^j(i) x_{ij}} \right) \geq L_c,$$

$\forall a \in \{1, .., d_b\}$, $b \in \{1, .., N\}$, and

$$\sum_{b=1}^{N} T_{TOT}^b = \tau \sum_{b=1}^{N} \sum_{i=1}^{Z} x_{ib} \leq \Theta \ ?$$

In Problem **BS-SCHEDULE**, each term $T_{TOT}^b = \tau \sum_{i=0}^{Z} x_{ib} = \tau Z_b$ represents the activity time of base station b (τ is the subframe duration). The term $w_a(i)$ represents the amount of resources allotted to group a in subframe i. Given that only one group can be scheduled in one subframe, we have $w_a(i) = 1$ if the subframe is completely devoted to this group and 0 otherwise. $I_a^j(i)$ is defined as the power of interference from base station j, experienced in subframe i by the user having the worst channel condition in the multicast group a. Z is the number of subframes that correspond exactly to the content lifetime interval T_c, while Θ is the upper bound for the aggregate transmission time of the system. Transmission rates are computed using Shannon capacity formula.

B. Complexity of Problem **BS-SCHEDULE**

Classical wireless scheduling problems, e.g., scheduling and channel assignment, have been shown to be NP-Hard [9], [10]. However, we are the first to address the complexity of base station resource allocation with deadlines and multicast transmissions using variable rates. Specifically, we show that problem **BS-SCHEDULE** is NP-Complete when $Z \geq 3$ for bounded interferences, and for $Z = 2$ for unbounded interferences. These NP-Completeness results apply to very special instances of the problem ($d_b = 1$ for every base station b).

Theorem 1. *Problem **BS-SCHEDULE** is NP-Complete, for any $Z \geq 3$, even when all interferences are $\in \{0,1\}$.*

Sketch of Proof: It is clear that the problem is in NP. For the NP-Hardness we use a reduction from the problem **GCk** of graph k-coloring (see [11]). We are given an instance $I_{\mathbf{GCk}} = H(V, E)$ of Problem **GCk**, and construct an instance $I_{\mathbf{BS\text{-}SCHEDULE}}$ of Problem **BS-SCHEDULE**. Assume $V = \{1, 2, \cdots, n\}$. The base stations are $B = \{b_1, b_2, \cdots, b_n\}$, and the users $U = \{u_1, u_2, \cdots, u_n\}$, where for every t base station b_t is serving user u_t. In addition, $Z = k$, $N_0 = \tau = B_T = L_c = 1$, $\Theta = n$, and $S_{u_t}^{b_t}(i) = w_a(i) = 1$ for every $i = 1, 2, \cdots, Z$, $t = 1, 2, \cdots, n$. Last, for every $t = 1, 2, \cdots, n$, every $j \neq t$ and every $i = 1, 2, \cdots, Z$, $I_{u_t}^{b_j}(i) = 1$ if $(i, j) \in E$ and is 0 otherwise.

We have to show that there is a k-coloring of $I_{\mathbf{GCk}}$ if and only if for $I_{\mathbf{BS\text{-}SCHEDULE}}$ there is a scheduling of the base stations in at most k rounds, with $\Psi_{u_t}^{b_t}(Z) \geq 1 = L_c$, and $\sum_{t=1}^{n} T_{TOT}^{b_t} \leq n$.

Given a graph k-coloring of $I_{\mathbf{BS\text{-}SCHEDULE}}$, with colors $1, 2, \cdots, k$. If a node t is colored p, then we schedule station b_t in round p, for $p = 1, 2, \cdots, k$.

$\Psi_{u_t}^{b_t}(Z) = \sum_{i=1}^{Z} x_{ib} \log_2 \left(1 + \frac{1}{1 + \sum_{j \neq t} I_{u_t}^{b_j}(i) x_{ij}}\right)$ for every t. Since all base stations b_j scheduled with b_t are such that $(j, t) \notin E$, and since each base station is scheduled in exactly one round, therefore $\Psi_{u_t}^{b_t}(3) = \log_2 \left(1 + \frac{1}{1}\right) = 1$. $\sum_{t=1}^{n} T_{TOT}^{b_t} = n$ since each station is scheduled in exactly one round.

Conversely, assume that for $I_{\mathbf{BS\text{-}SCHEDULE}}$ there is a general scheduling of at most k rounds, such that for each user $\Psi_{u_t}^{b_t}(k) \geq 1$ and $\sum_{t=1}^{n} T_{TOT}^{b_t} \leq n$. $\Psi_{u_t}^{b_t}(k) > 0$ implies that each user—and thus each station—is scheduled in at least one round. $\sum_{t=1}^{n} T_{TOT}^{b_t} \leq n$ implies that each station—and thus each user—is scheduled in exactly one round. Moreover, if user u_i is scheduled with user u_j, then $(i, j) \notin E$ (otherwise $\Psi_{u_i}^{b_i}(Z) < 1 = L_c$). Therefore assigning color p to nodes associated with the stations in round p, for $p = 1, 2, \cdots, k$, results in a k-coloring of the graph $I_{\mathbf{GCk}}$. □

Theorem 2. *Problem **BS-SCHEDULE** is NP-Complete for $Z = 2$.*

Sketch of Proof: We use a reduction from a variation of the Partition problem. We term this Problem **MPAR**. In the Partition problem we are given integers $A = \{a_1, a_2, \cdots, a_n\}$, such that $\sum_{j=1}^{n} a_j = 2S$, and have to determine whether there exist $\{a_1', a_2', \cdots, a_k'\} \subseteq A$ such that $\sum_{j=1}^{k} a_j' = S$ (see [11]). In the modified version **MPAR** (that can be shown to be NP-Complete) we are given integers $A = \{x_1, x_2, \cdots, x_{2n}\}$, $S > 0$, $S < x_i < 2S$ for all i, such that $\sum_{j=1}^{2n} x_j = 2(n+1)S$, and have to determine whether there exist $\{x_1', x_2', \cdots, x_n'\} \subseteq A$ such that $\sum_{1}^{n} x_j' = F$, where $F = (n+1)S$.

We are given an instance I of **MPAR**, and construct an instance $I_{\mathbf{BS\text{-}SCHEDULE}}$ of Problem **BS-SCHEDULE** as follows. The base stations are $B = \{b_1, b_2, \cdots, b_{2n}\}$, and the users $U = \{1, 2, \cdots, 2n\}$; base station b_i is serving user i. $Z = 2$, $N_0 = F$, $\tau = B_T = L_c = 1$, $\Theta = n$, and $S_{u_t}^{b_t}(i) = 2F$, $w_a(i) = 1$ for $i = 1, 2$, $t = 1, 2, \cdots, n$. Last,

for every $t = 1, 2, \cdots, n$, every $j \neq t$ and every $i = 1, 2$: $I_{u_t}^{b_j}(i) = x_j + \frac{x_i}{n-1}$.

We have to show that there is a solution to I if and only if there is a scheduling for $I_{\mathbf{BS\text{-}SCHEDULE}}$ in at most 2 rounds, such that for each user $\Psi_{u_t}^{b_t}(2) \geq 1 = L_c$, and $\sum_{t=1}^{n} T_{TOT}^{b_t} \leq n$.

Assume there is a solution to I. Thus we assume the existence of a $\{x_1', x_2', \cdots, x_n'\} \subset A$ such that $\sum_{1}^{n} x_j' = F$. Schedule the base stations $b_{x_1'}, b_{x_2'}, \cdots, b_{x_n'}$ in the first round and the other n base stations in the second round. Clearly $\sum_{t=1}^{n} T_{TOT}^{b_t} \leq n$.

Every user t is thus scheduled in exactly one round, and thus $\Psi_{u_t}^{b_t}(2) = \log_2 \left(1 + \frac{2F}{F + \sum \left\{x_j' + \frac{x_i'}{n-1} \middle| j=1,2,\cdots,n, j\neq i\right\}}\right) = \log_2 \left(1 + \frac{2F}{F + \sum_{1}^{n} x_j'}\right) = \log_2 \left(1 + \frac{2F}{F+F}\right) = 1$.

Conversely, assume a solution to $I_{\mathbf{BS\text{-}SCHEDULE}}$. Since each interference is positive, and since $\sum_{t=1}^{n} T_{TOT}^{b_t} \leq n$, it follows that each station is scheduled in exactly one round.

Assume the base stations at the first round are $b_1, b_2, \cdots, b_k$, and in the second round are $b_{k+1}, \cdots, b_{2n}$. If $k \neq n$ then one of these rounds has more than n base stations. Assume, with no loss of generality, that $k > n$. This means that $\sum \left\{x_j + \frac{x_i}{n-1} \middle| j = 1, 2, \cdots, k, j \neq i\right\} > nS + \frac{nx_i}{n-1} > F$, for every $i = 1, 2, \cdots, k$, thus $\Psi_{u_i}^{b_i}(2) < 1$, a contradiction. Therefore $k = n$. The interference of each of the users in the first (second) round is $\log_2 \left(1 + \frac{2F}{F + \sum_{i=1}^{n} x_i}\right)$ $\left(\log_2 \left(1 + \frac{2F}{F + \sum_{i=n+1}^{2n} x_i}\right)\right)$. So, $\sum_{i=1}^{n} x_i = \sum_{i=n+1}^{2n} x_i = F$, and all interferences are 1. □

When considering the minimization version of the problem (to determine a scheduling with smallest number of rounds), we use [12], which shows that for all $\epsilon > 0$, approximating the chromatic number of a given graph $G = (V, E), |V| = n$ within $n^{1-\epsilon}$, is NP-hard. Since coloring G with n colors is trivial, this means that this result is rather strong. Using it we show that Problem **BS-SCHEDULE** is rather difficult to approximate, as follows:

Theorem 3. *For all $\epsilon > 0$, approximating within $n^{1-\epsilon}$ the minimal number of rounds required to solve Problem **BS-SCHEDULE** with n base stations is NP-hard.*

Sketch of Proof: Following the same reduction from **GCk**, as done in the proof of Theorem 1, it is clear that the instance of **BS-SCHEDULE** can be scheduled in k rounds if and only if the given graph can be colored with k colors. Therefore the existence of an algorithm with approximation ratio $n^{(1-\epsilon)}$ for **BS-SCHEDULE** will imply the existence of an algorithm with the same approximation ratio for **GCk**. □

C. Sufficient condition for Problem BS-SCHEDULE

Since, as we have shown above, Problem **BS-SCHEDULE** is NP-complete and NP-hard to approximate, in the following we provide a sufficient condition that guarantees that the entire content is delivered before its lifetime, i.e., in Z subframes.

Recalling that only one group can be active in a subframe

and using (4), we can write the following identity:

$$B_T w_a(i) \log_2\left(1+\frac{S_a^b(i)}{N_0+\sum_{j\neq b} I_a^j(i)x_{ij}}\right) = \left(\sum_{\alpha=1}^{d_b}\frac{w_\alpha(i)}{t_\alpha(i)}\right)^{-1}.$$

With the above, the condition that a content of size L_c is delivered within Z subframes, as given in the statement of Problem **BS-SCHEDULE**, can be rewritten as follows:

$$\tau\sum_{i=1}^{Z} x_{ib}\left(\sum_{\alpha=1}^{d_b}\frac{w_\alpha(i)}{t_\alpha(i)}\right)^{-1} \geq L_c. \tag{5}$$

from which we derive the following sufficient condition to guarantee that all users under base station b can complete their download in Z subframes:

$$\sum_{\alpha=1}^{d_b}\frac{w_\alpha(i)}{t_\alpha(i)} \leq \frac{\tau\sum_{j=1}^{Z}x_{jb}}{L_c} = \frac{\tau Z_b}{L_c}, \forall i \in \{1,..,Z\}. \tag{6}$$

Let us now consider the worst user as the one with the minimum SINR at any subframe i such that $x_{ib}=1$, resulting in achievable rate equal to $t_{\min}(i)$. From Eq. (6) and $t_{\min}(i)$, we can obtain a stronger sufficient condition to guarantee that all users of base station b complete their download:

$$\sum_{\alpha=1}^{d_b}\frac{w_\alpha(i)}{t_\alpha(i)} \leq \frac{d_b}{t_{\min}(i)} \leq \frac{\tau Z_b}{L_c}, \forall i \in \{1,..,Z\}, b \in N. \tag{7}$$

Therefore, it is sufficient to guarantee that the transmission rate of all stations is above the following threshold for the scheduling to be doable:

$$t_{\min}(i) \geq t_{th} = \frac{d_b L_c}{\tau Z_b}x_{ib}, \tag{8}$$
$$\forall a \in \{1,..,d_b\}, b \in \{1,..,N\}, i \in \{1,..,Z\}.$$

where we recall that $Z_b=\sum_{i=1}^{Z}x_{ib}$ is the number of subframes in which base station b is active.

In conclusion, from (4) and (8), we derive that it is sufficient to schedule a base station when all its scheduled users have at least the following SINR:

$$\text{SINR} \geq 2^{\frac{d_b L_c}{\tau Z_b B_T}} - 1 \doteq \text{TH}. \tag{9}$$

Note that the above equation defines an SINR threshold TH that depends, in addition to some constants, on the number of subframes Z_b in which base station b is allowed to transmit. Next, we derive a lower bound on Z_b for which the inter-BS scheduling guarantees that d_b content injections are doable within the deadline.

D. Lower bound for Z_b

The throughput of a base station b can be bounded by the following expression:

$$\frac{d_b L_c}{\tau\sum_{a=1}^{d_b}\sum_{i=1}^{Z}w_a(i)x_{ib}} = \frac{d_b L_c}{\tau Z_b} \leq R_{\text{MAX}}, \tag{10}$$

where R_{MAX} is the maximum transmission rate permitted in the network (e.g., $R_{\text{MAX}} = 93.24$ Mbps in an FDD LTE network using 20 MHz bandwidth). Therefore, there is a lower

bound for Z_b below which the content injection of d_b contents cannot be guaranteed:

$$Z_b \geq \frac{d_b L_c}{\tau R_{\text{MAX}}}, \quad \forall b \in B. \tag{11}$$

Since we aim to minimize the total transmission time, which is given by $\Theta = \tau\sum_{b\in B}Z_b$, it is reasonable to assume that an ICIC algorithm that approximates the solution of Problem **BS-SCHEDULE** will be able to complete the injection of d_b contents at base station b in a number of subframes that is close to the bound given above, i.e., $Z_b = \frac{d_b L_c}{\tau R_{\text{MAX}}}$. With this approximation, we can express the threshold TH in (9) as a function that does not depend on Z_b.

The above provides a sufficient condition to guarantee that d_b contents are delivered within their lifetime; in particular, we have found a threshold TH for the SINR of users to be scheduled. In Section IV, we leverage this result for the design of our ICIC algorithm.

E. Maximum number of contents

Before describing our heuristic for Problem **BS-SCHEDULE** in Section IV, we compute the maximum number of contents that can be handled by a base station. This result will be useful in Section V, when it comes to evaluate the performance of ICIC schemes. To achieve our goal, we assume that all the base stations have, at least on average, the same number of contents to inject in interval T_c.

If all base stations have the same number of contents to inject, we can derive an upper bound for Z_b. The total number of subframes used by all base stations cannot exceed $\sum_{b\in B}Z_b = NZ_b$. If Z is the total number of subframes in which the content is valid, we have that $NZ_b \leq Z$ and thus, we can derive an upper bound for Z_b as follows:

$$Z_b \leq \frac{Z}{N}, \quad \forall b \in B. \tag{12}$$

From (11) and (12), we obtain the following range for Z_b:

$$\frac{d_b L_c}{\tau R_{\text{MAX}}} \leq Z_b \leq \frac{Z}{N}, \quad \forall b \in B. \tag{13}$$

From the analysis above, we can then compute the maximum number of injectable contents that can be handled by a base station while guaranteeing that all contents are served within the deadline $T_c = \tau Z$. In particular, from (13), it is clear that the Z_b range is not empty under the following condition, which gives an upper bound for d_b:

$$d_b \leq d_b^* = \frac{\tau Z R_{\text{MAX}}}{L_c N}. \tag{14}$$

IV. Base Station Blanking Algorithm

In this section, we propose BSB (Base Stations Blanking), an algorithm to approximate the optimal solution of Problem **BS-SCHEDULE** formulated in Section III. BSB relies on the sufficient condition given by (9). Following this condition, BSB aims to find an optimal ABSF pattern, i.e., an allocation of base stations to subframes, in which base station can partially interfere with each other, while guaranteeing a minimum SINR to any mobile device that might be scheduled. Note that

our algorithm is meant to allocate ABSF patterns, and does not impose any user scheduling policy.

A schematic view of BSB is reported here. BSB runs in a LTE-A network, and requires the presence of a central controller, namely the Base Stations Coordinator (BSC), which could be run on the Mobility Management Entity (MME) [13]. Our algorithm requires cooperation between the BSC and base stations, which can be implemented over the standard $X2$ interface [5]. The main role of BSC is to collect SINR statistics from the base stations, run BSB, and announce ABSF patterns to the base stations, as detailed in what follows:

BSB Algorithm

The BSC collects user statistics, puts all active base stations in a candidate set, and checks whether the resulting SINR for each user is above the SINR threshold TH.

If at least one user does not reach the SINR threshold:

- compute the most interfering base station b^*
- remove b^* from the candidate set,
- check the SINR of all users of the remaining base stations.

Repeat the check and remove base stations from the candidate set until all remaining users meet the SINR constraint. The resulting set of base stations is scheduled in the first subframe and inserted in a *priority*-1 list. In general, at each subframe, scheduled base stations are added to the *priority*-k list, where k is the number of subframes in which a base station has been scheduled so far. All other base stations go to a *priority*-0 list.

For each successive subframe, populate the candidate set with the *priority*-0 list and repeat the operation described for the first subframe until the SINR constraint is met.

Then, for $k = 1, 2, \ldots$, in increasing order:

- add to the candidate set all base stations in the *priority*-k list,
- remove base stations which cause SINR below TH only if they belong to the *priority*-k list.

The algorithm stops when the priority list is empty.

The BSC issues the resulting ABSF pattern to each base station via the $X2$ interface.

In the above description, the interference caused by a base station is computed as the aggregate sum of interferences caused towards all users of all other bees station in the candidate set. The threshold TH is computed based on d_b and the lowest possible value for Z_b, given by (11). The scheduling pattern computed with BSB can range between 1 and N subframes. However, since the standard specifies that ABSF patterns should be issued every 40 subframes, the BSB pattern is repeated in order to cover a multiple of 40 subframes. The obtained sequence of scheduling patterns represents the ABSF pattern according to [5].

For each subframe, the algorithm starts by selecting the full set of base stations that have not been scheduled in previously allotted subframes. The rationale behind this choice is twofold: (i) the aggregate interference caused by a base station grows with the size of the candidate set, and thus the importance of the interference generated by a base station is more properly quantified by the full candidate set; (ii) existing ICIC algorithms suggest to mitigate interference by preventing the transmission of a few base stations, beginning with the most interfering one [6], [14], [7].

Once a base station receives its ABSF pattern, it can schedule its users accordingly.

The complexity of BSB is dominated by the number of base station, as stated in the following theorem.

Theorem 4. *The complexity of BSB is* $O(U \cdot N^3)$, *where* $U = \max_{b \in B}\{U_b\}$, *and* $N = |B|$.

Sketch of Proof: The BSB algorithm runs in at most N rounds, corresponding to N allocated subframes: in the worst case, exactly one base station is allocated in exactly one subframe. At subframe $q = 1, 2, ..., N$, there are at most q priority lists. In the worst case, the *priority*-0 list contains $N - q + 1$ base stations and each other priority list contains 1 base station. Evaluating the SINR for all users of base stations in *priority*-0 requires checking all reconfigurations with $N - q + 1$, $N - q$, ..., 1 base stations in the candidate set. Checking the possibility to add to the resulting scheduled set any base station in the other priority lists is at most involving $N - q + 2$ base stations for considering *priority*-1 list, $N - q + 3$ for *priority*-2 and so on until N base stations for the last priority list. Overall, the cost per subframe is $O(U \cdot N^2)$. Therefore, in the worst case, in which N subframes are needed, the complexity is $O(U \cdot N^3)$. $\square$

V. PERFORMANCE EVALUATION

Here we study the impact of BSB on the performance of D2D-assisted content update distribution. We benchmark the performance achieved with BSB against the one achieved under different frequency reuse schemes (in particular frequency reuse 1, 3, and 5), and against a state-of-the-art dynamic resource allocation scheme proposed for ICIC in LTE-like networks [14]. We refer to the latter as ECE. Differently from BSB, ECE assigns resource blocks rather than subframes, thus implementing a scheme for *soft fractional frequency reuse* [15]. For all tested resource allocation mechanisms, we adopt the opportunistic user scheduling scheme presented in [2]. Summarizing, we compare five inter-BS resource allocation mechanisms, as reported in Table I.

As concerns the system parameters used in our performance evaluation, we use FDD LTE frame specifications, with 20 MHz bandwidth distributed over 100 frequency chunks, resulting in 100 resource blocks per time slot, i.e., 200 resource

TABLE I: Resource allocation mechanisms

BSB	ABSF patterns are computed according to BSB
FR1	No interference coordination is enforced
FR3	Base stations are allocated different frequencies, according to a frequency reuse 3 scheme, and each base station uses 1/3 of the band available
FR5	Base stations are allocated different frequencies, according to a frequency reuse 5 scheme, and each base station uses 1/5 of the band available
ECE	LTE resource blocks are allocated to base stations according to [14].

blocks per LTE subframe [16]. Transmission power is fixed to 40 W, antenna gain and path loss are computed according to [17], and the spectral noise density is $3.98 \cdot 10^{-21}$ W/Hz for all nodes [18]. Modulations and coding schemes are selected according to the SINR thresholds reported in [16]. while the ratio between transmitted power and noise, for each pair of transmitting base station and user in the network (be it signal or interference), is computed as for Rayleigh fading, with average given by transmission power and path loss.

D2D communications occur *outband* (i.e., on a channel not interfering with any of the base stations), and mobile devices exchange data when their distance is 30 m or less. Content updates occur synchronously every $T_c = 100$ s. Each content update consists in a file of 8 Mbits, and each mobile device is interested in at most one content. Background traffic is also generated in some of our experiments, and consists in random file requests, uniformly distributed over time, with file size equal to 8 Mbits. Background file requests are dealt with and scheduled as content updates for single-user groups.

As concerns the mobility of users, we account for a Random Waypoint mobility model over a regular grid [19]. Initially each mobile user is assigned a uniform location in the area. The mobile user chooses a random uniformly distributed destination, i.e., a waypoint P_u, and a speed V_n, uniformly distributed in range $[1, 2]$ m/s, independently of past and present speed values. Then, the mobile user travels toward the newly chosen destination at constant speed V_n. Upon arrival to destination P_u, the mobile user randomly chooses another destination and speed. Note that, at the considered low speed, the resulting contact time is long (several seconds). Therefore, we assume that complete file transfers are possible during the contact time.

All experiments refers to a dense LTE deployment, with 5 to 7 overlapping cells, and several hundreds of mobile users. Each experiment includes 50 content updates for each content, with period 100 s (i.e., the experiment simulates 5 000 s), and is repeated 20 times. Average and 95% confidence intervals are reported in the figures. When using BSB, a specific ABSF pattern is issued every 40 subframes, which is the value specified by the standard [5].

A. Base station transmission time

For the first set of results, we simulate the network depicted in Fig. 1, with 5 base stations and 750 mobile devices. Therefore, in the described results, scheme FR1 represents the case with no ICIC, while FR5 guarantees no interference.

Fig. 2 shows the per-base station average transmission time, expressed in terms of used subframes, when the simultaneous update of 20 contents is periodically distributed in the network. No background traffic was injected during the experiment. For the case of ECE, in which resource blocks are allotted rather than subframes, we count the total number of used resource blocks, and normalize that number with respect to the number of resource blocks per subframe. BSB clearly outperforms all other schemes and uses a number of subframes very close to the lower edge of the interval predicted in (13). Moreover, BSB outperforms FR3 and ECE by a factor ~ 3, and up to ~ 5 for
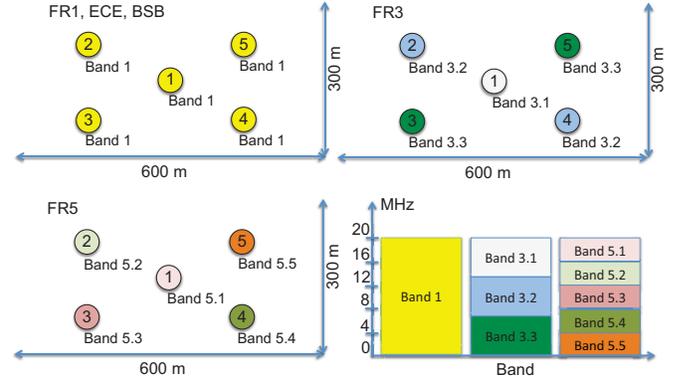
Fig. 1: Network scenario with 5 base stations placed at regularly spaced positions, and 750 users (not shown in the figure) randomly dropped into an area of 600 m × 300 m. For each tested scheme, the figure reports the baseband bandwidth used by the each base station.
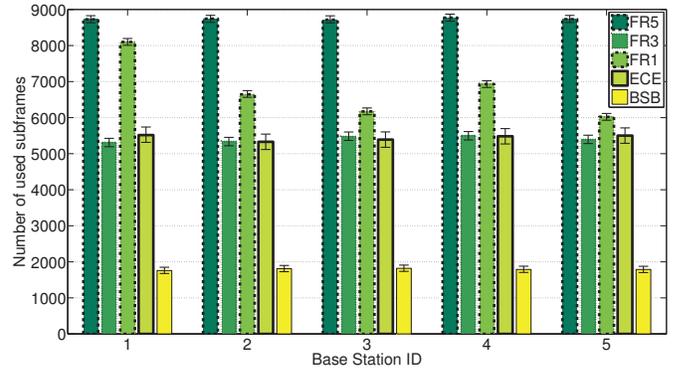
Fig. 2: Content update transmission time with 5 base stations, 750 users, and no background traffic.
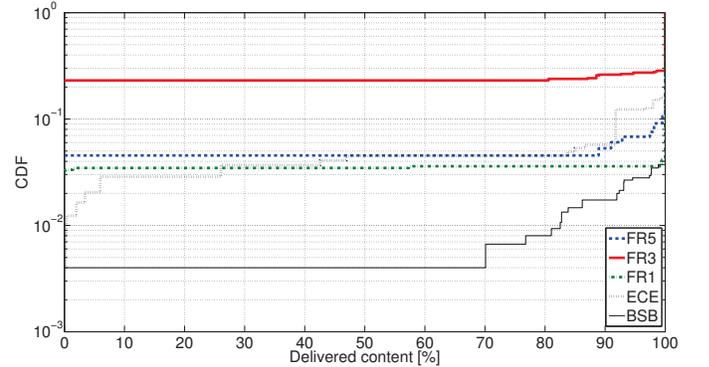
Fig. 3: Content update success probability with 5 base stations, 750 users, and no background traffic.

the case of FR5. Note that, for a fair comparison to BSB and ECE, frequency reuse schemes simulated in the experiment allocate only $1/n$, $n \in \{1, 3, 5\}$ of the available bandwidth to each base station. With the data reported in the figure, it is clear that BSB improves the results of FRn, $n \in \{3, 5\}$, by a factor $\sim n$. Therefore, we could extrapolate that modifying FR3 and FR5 schemes using n times the bandwidth used by BSB would achieve similar results as BSB. Indeed, we have

validated such an intuitive result by running an experiment in which all base stations always use the entire 20 MHz bandwidth. Results, not reported here for lack of space, show negligible performance differences (below 1%) between the schemes. However, we remark that BSB would require $1/n$ of the frequencies needed by frequency reuse schemes.

B. Success probability

For the same set of experiments commented in Section V-A, Fig. 3 reports the cumulative distribution function (CDF) of the portion of delivered content updates, under the tested schemes. For this performance metric, we count the number of content updates that were correctly and entirely delivered to the subscribers, and normalize to the number of subscribers. BSB emerges as the scheme that guarantees the highest content delivery probabilities, resulting in an average 97.24% of delivered contents. Noticeably, FR1, FR3, FR5 and ECE perform *much worst* than BSB. This result points out that both static frequency planning schemes and classic resource allocation schemes are not able to cope with the interference generated in dense environments. Moreover, FR3 achieves by far the worst results. Therefore, comparing FR1 (all base stations use the same wide bandwidth) and FR3 (at most two base stations share the same bandwidth, which is $1/3$ of the one used under FR1), we argue that the interference generated by few neighbors in a dense scenario is much less important than the available bandwidth. As a consequence, spectral efficiency over wide frequency bands is key to boost network performances, while bandwidth fragmentation due to frequency planning is undesirable.

C. Impact of background traffic

To show the efficacy of BSB in more generic traffic scenarios, in addition to periodic content updates, we next simulate background file requests uniformly distributed over time at different request rates. Note that (14) expresses the maximum number of contents that can be distributed with guaranteed maximum transmission time. That expression can be also interpreted as the maximum cell load that can be handled by a base station while guaranteeing that content updates will be delivered within the deadline (with each content unit used for d_b^* corresponding to an offered load $L_c/(\tau Z)$). Therefore, we expect that BSB is able to handle a background traffic equivalent to, at most, $(d_b^* - d_b) \cdot L_c/(\tau Z)$ bps. With 8-Mbit background files, $d_b = 20$, $L_c = 8$ Mbits, $\tau Z = 100$ s, and 5 base stations, the maximum background traffic is 2.125 requests per second.

In Fig. 4, we show the impact of background traffic on the probability to complete the content update distribution, for various background loads. Similarly to the case in which no background traffic is injected, BSB outperforms other schemes. Interestingly, BSB is more robust to background traffic than other schemes, as shown by the fact that content delivery probability under BSB is barely affected by the background traffic. The performance of BSB starts degrading only when the offered background exceeds 3 file requests per second, which is well above 2.125 requests per second, i.e.,
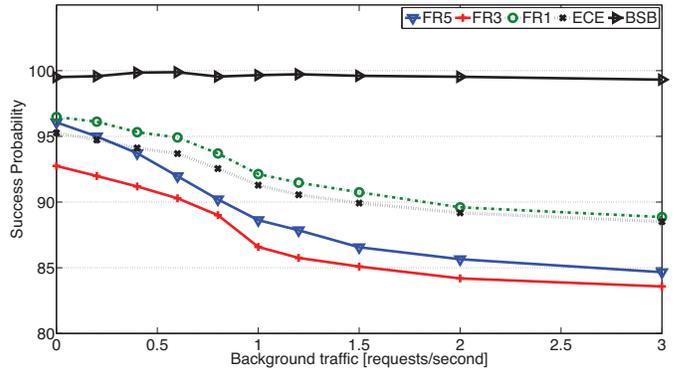
Fig. 4: Content update success probability with 5 base stations, 750 users, and background traffic.

TABLE II: Scenario with 7 base stations, 1000 users and 30 contents to disseminate

ICIC scheme	Transmitting Time [subframes in T_c]	Throughput [Mb/s]	Delivery Success Probability
FR5	14047	16.90	89.98%
FR3	6024	39.84	87.14%
FR1	11814	20.02	95.50%
ECE	6241	37.87	92.27%
BSB	2912	82.41	97.37%

the maximum value that guarantees the doability of content transmission within the deadline, according to (14). In contrast, frequency reuse schemes and ECE are seriously impaired by the background traffic as soon as the offered load reaches as low as 1 background file request per second.

D. Impact of network size

Table II illustrates a performance comparison in case of 7 base stations and 1 000 content subscribers, with 30 contents to be simultaneously distributed every 100 s. No background traffic was considered in this experiment. The table shows that the average base station activity time is minimal under BSB operations, and other schemes needs much higher utilizations. Being the overall load the same for all cases, the throughput sustained while transmitting is much higher for BSB than for any other scheme. Noticeably, BSB is only 10% below the maximum achievable LTE rate (the rate corresponding to perfect channel quality at any time). Moreover, BSB outperforms all other schemes also in terms of delivered contents. Most importantly, BSB achieves a 97.27% success probability, which means that D2D content dissemination is almost perfect when combined with BSB.

VI. RELATED WORK

Our proposal can be classified as semi-distributed [15], since it relies on a central entity that coordinates scheduling resources (ABSF patterns), while each base station remains responsible for scheduling its users. In this section, we comment on other semi-centralized ICIC schemes that have been proposed in the literature.

The authors of [14], [20] design a heuristic to allocate resource blocks when adjacent cells interfere with each other. Their approach allows the reuse of resource blocks in cell centers, while users at the cell edge, which suffer higher

interference, cannot be allocated specific resource blocks, as figured out by the proposed heuristic. However, differently from our proposal, that work only considers avoiding the interference of the two most interfering base stations. As a results, we have shown in Section V that their approach is not suitable for dense networks.

Similarly, the proposal in [21] assigns resource blocks via a central entity. However, [21] allocates resources not only to base stations but also to users, based on backlog and channel conditions, and hence results in intractable complexity, in contrast to our approach which has a much lower complexity.

The author of [7] uses graph theory to model network interference. That work proposes a graph coloring technique to cope with interference coordination, based on two interference graphs: one *outer* graph using global per-user interference information, and an *inner* graph using local information, available at the base station, and global constraints derived from the global graph. To reduce the complexity of the proposal, [7] uses genetic algorithms to seek a suboptimal resource block allocation. However, differently from BSB, that approach does not allow to use a generic user scheduler, since users are allocated according to the *inner* graph coloring problem.

In our previous work on ICIC [6], we have investigated on the optimization of ABSF pattern allocations in a fully saturated network. However, that work does not account for content deadlines, and therefore the choice of the SINR threshold to be used in a real network was not investigated. Moreover, the resource allocation protocol proposed in [6] is far from being throughput maximal, since it is designed for achieving fairness among base stations, and so it does not guarantee the delivery of contents within a given deadline.

None of the above works tackle the impact of interference in dense scenarios, in presence of offloading traffic strategies.

VII. CONCLUSIONS

In this paper, we formulated a base station scheduling problem to minimize the time required to inject contents in a D2D-assisted cellular offloading system. We proved that the problem is NP-complete and NP-hard to approximate, and proposed BSB, an ICIC algorithm that approximates the solution of the formulated problem. BSB algorithm is meant to allocate ABSF patterns to base stations, and does not impose any user scheduling policy. Therefore, BSB can be used in combination with any user scheduling scheme implemented at the base station.

For a dense multicellular environment, we showed that interference coordination is key to successfully operate content distribution schemes based on D2D communications. We also showed that current diffused practices based on frequency reuse schemes and/or on the most interfering base station set are not accurate for dense deployments. Indeed, our proposed algorithm substantially outperforms classical intercell interference approaches proposed in the literature.

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