On the Efficient Utilization of Radio Resources in Extremely Dense Wireless Networks

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Abstract—**The emergence of popular wireless technologies such as LTE and WiFi, and exponential growth in usage of these technologies led to extremely dense wireless networks. There are many proposals for coping with such densification. In particular, we evaluate the compound effect of inter-cell interference schemes and spectrum efficient intra-cell relay techniques, which have been individually proposed recently as separate solutions. We provide a jointly coordinated intra-cell and inter-cell resource allocation mechanism which opportunistically exploits network density as resource. We show that intra-cell opportunistic relay, based on WiFi communications, reduces the complexity of inter-cell interference coordination (ICIC) and boosts the efficiency of ICIC in LTE. The superiority of the proposed solution to the legacy cellular network operation is proven via simulations.**

I. Introduction

Wireless networks are densifying rapidly due to high emergence of wireless technologies in consumer devices (e.g., mobiles, laptops, and house appliances), rapid growth of data-driven applications in the market (e.g., online games and social networks), and high adoption of these applications by users [1]. While this densification indicates the popularity of wireless technologies, it also introduces pressing issues such as interference, and spectral and energy efficiency. These issues also exist in the legacy wireless networks but they are mostly circumvented by weakening their impact on the system performance. Interestingly, all the aforementioned issues are related to the use of wireless spectrum and require an efficient approach to the utilization of radio resources. This goal can be achieved by using suitable mechanisms for interference mitigation/control and efficient use of the spectrum. In this article we give a concrete example of such integration, with particular focus on interference mitigation and opportunistic channel utilization.

The existing solutions for the aforementioned issues are abundant. The interference issue is usually addressed by using interference mitigation techniques such as coordinated beamforming, power allocation, and cooperative multipoint (CoMP). For instance, fast distributed beamforming in multi-cell environments has been proposed in [2], in which scheduling is performed in two steps: (i) each base station chooses the proper beamforming pattern in order to minimize the intercell interference; and (ii) a particular set of users is scheduled in each cell. Additionally, valid heuristics have been designed to properly allocate the resource blocks when adjacent cells interfere with each other [3], [4]. These approaches avoid the interference of the two most interfering base stations by allocating the cell-edge users (where the interference is proved to be significant) on different resource blocks. Graph theory is another tool for modeling network interference in CoMP mechanisms. The authors of [5] propose a graph coloring technique for interference coordination which is based on two interference graphs. The first graph (*outer graph*) uses global per-user interference information and the second graph (*inner graph*) takes advantage of local information obtained from the base station, and global constraints derived from the global graph. Recently, 3GPP has standardized a new technique, called ABSF (Almost Blank Sub-Frame[1]) that assigns resources in such a way that a subframe may be blanked for some base stations in order to prevent their activity in high interference scenarios. Some of the inter-cell interference coordination mechanisms leverage the ABSF in order to improve the spectral efficiency of the network by reducing the global interference [6].

Although interference mitigation implicitly improves the spectral efficiency, some researchers explicitly aim to improve spectral efficiency of dense networks by exploiting new resource allocation methods that leverage the high user density. For example, the authors of [7], [8] propose to integrate opportunistic scheduling and a popular branch of cooperative communications, namely, Device-to-Device (D2D) communication, to enhance the spectral efficiency of the networks by leveraging dynamic clusters of users. Interestingly, this approach also improves the energy efficiency in dense networks by increasing transmission rate and reducing the power spent for keeping the wireless interface in active mode.

Many of the above mentioned solutions require small modifications in the operations or infrastructure of the network. However, the rigidness of the current infrastructure does not allow these modifications without going through the lengthy standardization process. Software Defined Networking (SDN) is proposed to turn the current rigid network structure into a flexible network. Although SDN paves the way towards implementing a variety of enhancing techniques for dense network, one should carefully choose

[1] 3GPP, "Evolved Universal Terrestrial Radio Access Network (E-UTRAN); X2 application protocol (X2AP), 3rd ed" 3GPP, technical Specification Group Radio Access Network, Tech. Rep.

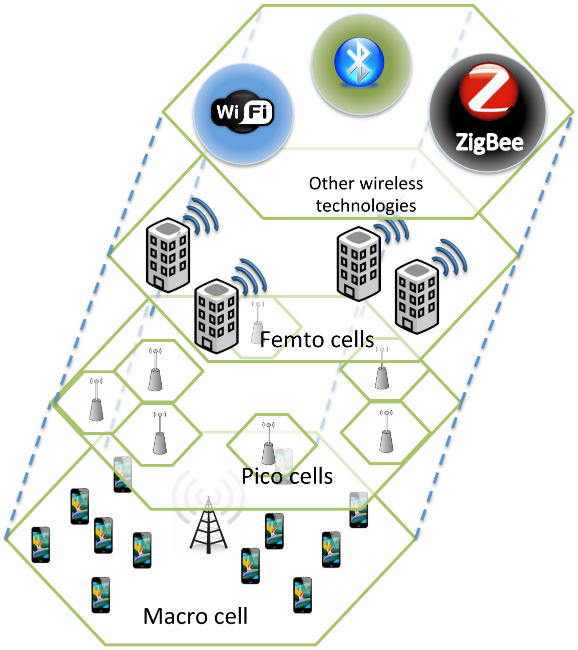

Fig. 1. Today's wireless networks include multiple overlapping technologies.

these techniques as some of them might act on common network features and parameters. In general, a thorough solution for dense wireless network provides the means for (i) controlling intercell interference caused by dense base station implementations; (ii) improving spectral and energy efficiency inside the cell; and (iii) creating a flexible architecture that accommodates (i) and (ii) while allowing interoperability among different platforms (e.g., LTE and WiFi).

In our work, we select ABSF, D2D-enabled opportunistic scheduling, clustering, and SDN techniques, which satisfy all the requirements of a comprehensive network solution. To improve efficiency of the resource utilization in dense wireless networks, we present the solution developed in the frame of the CROWD project,[2] which targets frequency reuse 1 to maximize the use of licensed spectrum in the network. We show how the combination of intra-cell resource optimization (achieved via D2D and clustering techniques), and inter-cell interference control (achieved via ABSF) is feasible and suitable for dense scenarios.

II. Network Densification: Issues and Solutions

Dense wireless networks inherit the same issues of the legacy cellular system. It is the magnification of these issues that demands for solutions specific for dense networks. In what follows, an overview of the issues and feasible solution for dense network is provided.

A. Issues

1) Interference: The cellular technology manufacturers counterbalanced the intensive demand with implementation of micro cells and femto cells to increase the frequency reuse and hence spectral efficiency, as shown in Fig.1. However, this approach also exposes the system to more interference. In general, cellular communication is exposed to two major sources of interference, namely, intracell interference and intercell interference (ICI). The former is not a significant issue in today's cellular networks due to the use of Orthogonal Frequency Division Multiple Access (OFDMA) technology and base station controlled scheduling. On the other hand, ICI is a more relevant issue due to the emergence of small cells and the higher frequency reuse factor. Conventional cellular networks rely on the physical distance among cells and sectoring techniques to handle ICI. This approach cannot be used in dense deployments.

2) Spectral efficiency: Due to high channel variation of wireless networks, the instantaneous channel quality of users varies significantly in a cell. Therefore, users experiencing low channel qualities can severely degrade spectrum efficiency. To counteract the impact of low channel quality users and to leverage the statistic fluctuations of channel qualities, opportunistic schedulers have been proposed and implemented, e.g., the Proportional Fair Scheduler or Max Rate [9]. A generic opportunistic scheduler always prioritizes the communication to the users with high channel quality and delays its communication to users with poor channel quality until their channel improves. Nevertheless, the scheduler waiting time should not result in transmission of expired data. Therefore, an opportunistic scheduler requires accurate information regarding the QoS constraints of the traffic and channel quality of the users. In a dense network, getting accurate feedbacks and processing them for a large number of users imposes high overhead in terms of data transmission and computational complexity. These problems are commonly tackled using selective feedbacks and machine learning techniques (to estimate the channel qualities). The latter reduces the transmission overhead but increases computational complexity.

3) Energy efficiency: Cisco predicts that there will be over 10 billion mobile devices by 2018 which makes the carbon footprint of wireless communication significant[3]. Notwithstanding the recent effort to improve the energy efficiency of the wireless networks, the current infrastructure is not designed to be energy efficient. A popular method to reduce the power consumption of the wireless networks is to put mobile devices and base stations to sleep whenever they are idle. Although the sleep functionality reduces the power consumption, it increases the delay in the network. This delay is proportional to the sleep period and the delay to switch from sleep to active mode.

4) Inflexible infrastructure: The current cellular infrastructure is highly technology dependent and inflexible to change. Any change in the standard operations of the network should go through the tedious standardization

[2]www.ict-crowd.eu

[3]Cisco Visual Networking, "Global mobile data traffic forecast update, 2013-2018," White Paper, February, 2014.

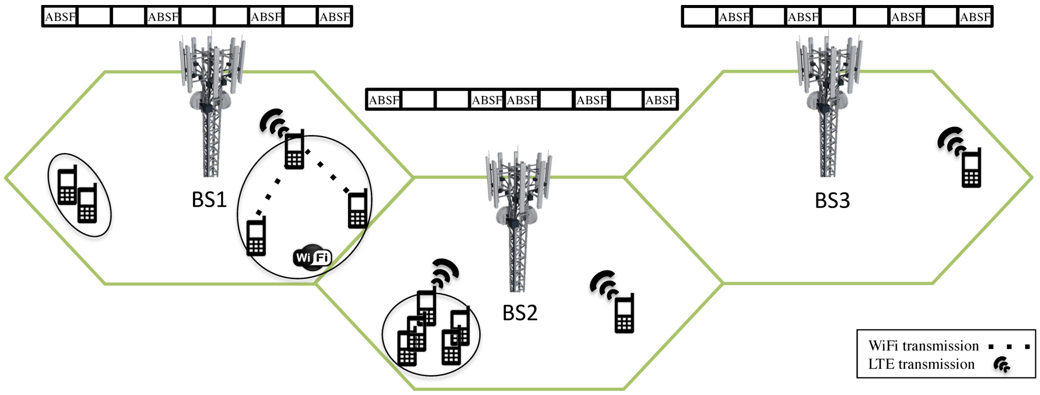

Fig. 2. An example of a cellular network using D2D clustering and ABSF techniques.

process in order to be finally implemented by the equipment manufacturers. As a result the solutions are implemented in the network with at least a few years delay. In fact, this is one of the reasons why the cellular technology could not catch up with the exponential network densification rate in wireless networks.

B. Feasible solutions

1) Smart interference mitigation: As mentioned earlier, current ICI avoidance/control methods are not effective in today's dense wireless networks anymore. It has been shown that although dense network deployments suffer more from ICI, the ICI power is not uniform over all radio frequencies. Therefore, ICI in dense networks is better managed if there exists a central controller with a bird-eye view of the occupied radio frequencies and ICI measurements. To this aim, researchers propose Intercell Interference Coordination (ICIC) techniques to take advantage of non-uniform ICI power distribution over the cell's radio spectrum. A very promising tool used to cope with the ICI problem is called ABSF. Specifically, ABSF allows the base stations to blank a set of subframes which results in drastic ICI reduction. Note that the blank subframes can only be used for control signals which is why those subframes are called *almost-blank*).

2) New communication paradigms: With the advent of cooperative communications, in particular D2D communications in cellular networks [10], researchers start to probe the potentialities of this new paradigm [10]. In D2D communications, cellular users are allowed to communicate with each other without traversing the base station. The studies show that D2D communication can potentially boost energy efficiency, throughput, delay, and fairness performances in cellular networks. To obtain even higher performance gain, some studies propose to integrate D2D communications and opportunistic scheduling in order to increase the spectral efficiency of the network [7]. As mentioned before, opportunistic schedulers gain from the channel opportunistic scheduling of users with high channel quality and deferring the communication with those in low channel quality. It should be noted that this opportunistic gain is harnessed by QoS requirement of the applications because the scheduler should schedule the user upon expiry of the QoS constraint even if the user has a poor channel quality. These D2D opportunistic schemes exploit the users with high channel quality to relay mobile traffic for those with lower channel quality. Therefore, the base station can transmit with higher modulation coding scheme (MCS) which increases the spectral efficiency of the system.

3) Flexible infrastructure: The above solutions and many other techniques for improving network performance in dense scenarios demand changes which are not foreseen by product manufacturers or by the standard. However, flexible architectures have been proposed, e.g., in international research programs like CROWD, and manufacturers are now endowing their devices with rich control interfaces. In this framework, SDN is an attractive paradigm that would allow network administrators to modify the behavior of the data plane by acting on the control plane. Although SDN was first proposed for wired networks [11], it is being considered as a viable solution to create a flexible wireless infrastructure.

III. Opportunistic Channel Utilization in Interference-Controlled Cells

We propose an SDN-controlled architecture for cellular networks with dense deployments of cells using a frequency reuse 1 scheme. we assume mobile users have off-the-shelf dual radio devices (e.g., LTE and WiFi). To counteract the occurrence of interference and inefficient utilization of the licensed (and expensive) cellular spectrum, we propose to coordinate the activity of neighboring cells and to promote cooperation among users. The first component of our architecture is a mechanism that keeps inter-cell interference under control. We adopt ABSF for ICIC and use a smart and conservative approach to dynamically control and assign ABSF patterns to interfering base stations. The second component is a clustering technique that leverages D2D communications within a cell to enable fully opportunistic channel access without incurring fairness penalties.

A. ICI mitigation using ABSF

ABSF mitigates the inter-cell interference by assigning resources such that some base stations almost-blank their subframes, thus preventing their activity when the interference gets significant, see Fig. 2. Several solutions have been already proposed in the literature to leverage the ABSF mechanism. In our proposal, , a central authority is in charge of acquiring the user channel conditions and then computing an optimal base station scheduling pattern, hereafter called ABSF pattern, for the available subframes [12]. The algorithm exploits the ABSF technique to minimize the time required by the base stations to achieve high spectral efficiency when performing packet transmissions. The BSB algorithm provides a valid ABSF pattern by guaranteeing a minimum SINR for any user that might be scheduled in the system. Basically, the BSB algorithm tries to accommodate as much base stations as possible in the same scheduling interval, checking whether the minimum SINR constraint is fulfilled. In the case of a constraint violation, the algorithm sequentially removes the most interfering base stations, following the general guidelines provided for bin-packing heuristic methods. In addition, we slightly modified standard bin-packing procedures in order to accommodate base stations more than once within the ABSF pattern. However, the BSB algorithm is a conservative algorithm, which does not rely on the knowledge of base stations scheduling decisions but just guarantees a decent user SINR, properly calculated a-priori.

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B. D2D clustering

D2D communication can occur over the cellular spectrum (i.e., inband) or Industrial, Science and Medical (ISM) band (i.e., outband). Each approach has its cons and pros [10]. For instance, interference management is a major challenge in inband D2D communications because both cellular and D2D users share the same resources. While this type of interference is not an issue in outband D2D, the unregulated nature of ISM band makes QoS guarantee a challenging task.

In CROWD, we have proposed a scheme, namely DRONEE (Dual-Radio Opportunistic Networking for Energy Efficiency), which leverages both D2D communications and opportunistic scheduling [7]. In DRONEE, neighboring mobile users can form a cluster using WiFi Direct (i.e., outband D2D), see Fig. 2. In every cluster, only the cluster member with the highest channel quality (i.e., cluster head) will communicate with the base station (opportunistic scheduling). The cluster header is responsible to relay the traffic of the other members to the base station. Using this scheme, the base station has a better chance to avoid communicating with users with poor channel quality unless the whole cluster is suffering from deep fading and high interference. Moreover, the users with poor channel quality can enjoy higher transmission rates by relaying through the cluster head. Simulation results show that the D2D clustering scheme can achieve significant throughput, energy efficiency and fairness gain in comparison to conventional cellular networks. For more details on D2D-enabled opportunistic clustering schemes, please refer to [7].

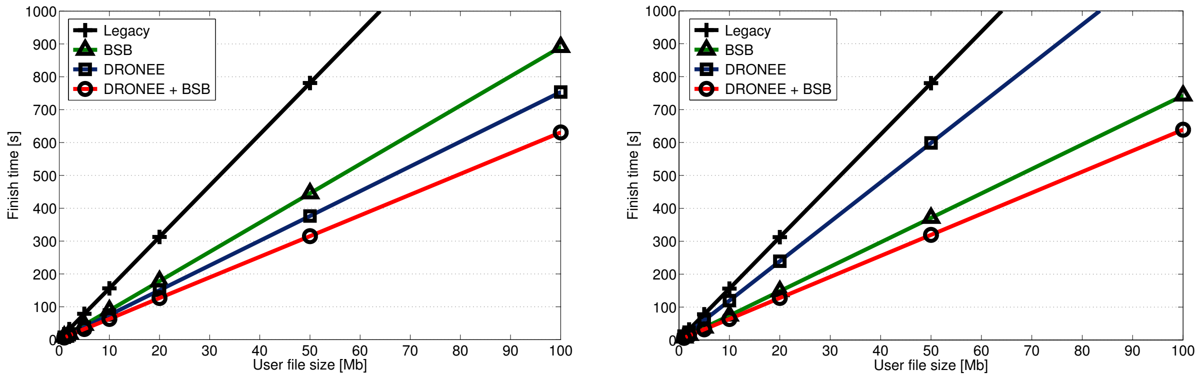
C. Interoperation of ABSF control and D2D-enabled Opportunistic clustering techniques

The control of ABSF patterns is key to orchestrate the activity of multiple cells, while the D2D-based opportunistic channel access is key to use the radio spectrum efficiently. The combination of the two mechanisms is beneficial for the performance of the networks, as we will show in Section IV. Moreover, it is important to note that the two mechanisms help each other to achieve their goals, therefore creating a positive feedback effect. On one hand, the reason why D2D clusters with opportunistic scheduling benefits from the presence of inter-cell interference relies on the reduction of uncontrolled interference entering a cell from the outside. Therefore, intra-cell channels are affected by less unpredictable interference and are more stables, which means that opportunistic changes of cluster heads will occur less often. On the other hand, the computation of ABSF patterns via the BSB algorithm is simplified in presence of clusters in the cells, since the algorithm will only need to consider clusters instead of users. As a consequence, the complexity of the BSB reduces with a cubic function of the average cluster size. Moreover, the fact that few clusters (which with high probability have a cluster head experiencing a good channel) are scheduled instead of many regular users (many of which with poor channels) reduces the number of cases in which BSB assigns very conservative ABSF patterns. Those conservative patterns are typically due to the presence of poor users, although the probability that the base station will schedule those users is not known to the controller.

D. SDN

ABSF and D2D clustering schemes both require a wireless infrastructure with high interoperability among heterogeneous networks. This can be easily achieved using the SDN architecture proposed in CROWD project. In fact, the proposed SDN-based architecture offers a flexible network with the capability to accommodate other wireless technologies. Therefore, CROWD SDN solution not only allows integration of ABSF and D2D clustering into existing cellular architecture, but also it paves the way for future enhancing proposals that may require unforeseen infrastructural modification.

Our solutions are validated through simulation and benchmarked against legacy network operation schemes in the next section. We assume that the practical modifications required for the implementation of our solutions are supported by the CROWD SDN architecture. Note that SDN is not a necessity but a suitable tool which offers flexible and upgradable solutions. In addition, SDN allows to coordinate intra-cell and inter-cell resource optimization mechanisms, e.g., by creating per-cluster statistic (based on user statistics) to be passed to the BSB algorithm.



(a) Inter-site distance equal to 300 m.

(b) Inter-site distance equal to 30 m.

Fig. 3. Finish time in a network with 10 base stations, 500 users, and maximum cluster size for DRONEE equal to 10 users.

IV. Evaluation

Let us compare the performance of BSB and DRONEE, and their compound impact on the performance of dense cellular networks. We compare the performance achieved with our proposed schemes to the ones achieved in conventional cellular networks without ICIC. We evaluate our solution for an LTE network with 20 MHz bandwidth. Users in this network are randomly distributed over the coverage area of the cells according to a uniform distribution. Each user is trying to download a 1 Mb file and each simulation terminates when all users have completed their download (we call this the *finish time*). Users are allowed to form clusters and use D2D within 50 m radius. The cluster formation is done using the *merge and split* algorithm [13] and each simulation is repeated 20 times.

Fig. 3(a) and 3(b) show the finish time achieved under the adoption of different schemes in a network with 500 users and 10 base stations regularly distributed over the simulated area with an inter-site distance of 300 m. For D2D-based clustering, base stations adopt a weighted round robin policy, assign resources to cluster heads with weights proportional to the cluster sizes. In both figures, we can see that BSB and DRONEE (with clusters of at most 10 users) significantly reduce the finish time in comparison to conventional cellular networks. This improvement is due to efficient ICI management of BSB and high spectral efficiency of DRONEE. In Fig. 3(b), we reduced the inter-site distance by a factor of 10 which results in increased ICI. As expected, here BSB shows better performance because it is designed to deal with high ICI. Interestingly, the combination of BSB and DRONEE demonstrates even higher gain. This happens because these two schemes aim to solve two different issues in dense network so they are complementary. However, the gain stemming from the coupled control of BSB and DRONEE is not equivalent to the sum of the gain from BSB and DRONEE clustering because both techniques rely on wireless channel diversity to improve the performance. Therefore, the diversity gain of clustering after applying ICIC via ABSF patterns with BSB is lower because channel quality of users increases due to lower interference (i.e., the opportunistic scheduling gain is lower).

Fig. 4 illustrates the impact of user density on the finish time where the maximum cluster size is 5. The finish time of all schemes follows an increasing trend with increasing number of users, due to increased traffic load and interference. However, the network densification is better handled by jointly coordinating BSB and DRONEE because they are designed to reduce inter-cell and intra-cell inefficiencies. Moreover, DRONEE facilitates the interference control operated by BSB and BSB facilitates the management of clusters in DRONEE, although this aspect cannot be shown in the figure. Clustering schemes like DRONEE take advantage of the user density to form more clusters, which results in better opportunistic gain and lower interference. The BSB algorithm, orchestrate interference and allows base stations to allocate more traffic in less subframes. The results shown in the figure also confirm that the compound impact of inter- and intra-cell resource allocations through BSB and DRONEE reduces the finish time drastically (60% less, w.r.t. legacy network operation).

The impact of cluster size on the finish time is shown in Fig. 5. Performance improves as the maximum allowable cluster size increases because the opportunistic clustering gain increases with the cluster size [7]. In the figure, we show the average finish time of all the users (solid lines) and the finish time of the users in clusters with exact size of n users, where n is the value reported in the horizontal axis of the figure (dotted lines). The latter shows a stable decreasing trend while the former has higher variation because smaller clusters and single unclustered users can take much longer to finish their download. The figure also shows that the clustering gain saturates for clusters bigger than 15. This is due to the fact that the room for improving the aggregated channel quality of the cluster becomes marginal in big clusters.

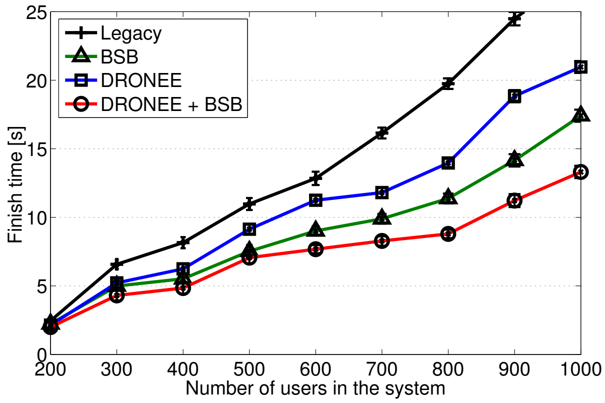


Fig. 4. The impact of user density on finish time with 10 base stations and inter-site distance equal to 300 m (results for DRONEE and DRONEE+BSB are achieved with clusters of max 5 users).

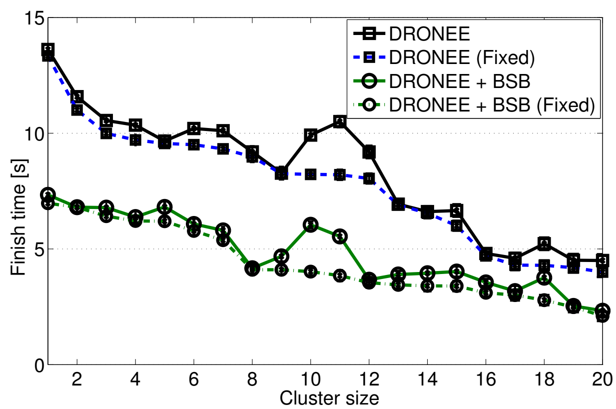


Fig. 5. The impact of cluster size on finish time with 10 base stations and inter-site distance equal to 300 m (curves labeled with (Fixed) correspond to the statistics obtained with clusters of exactly n users, where n is the value reported in the horizontal axis).

V. DISCUSSION

The evaluation results confirm the great performance gain of ABSF and D2D clustering schemes, in particular for BSB and DRONEE and their combination. The gain is evident with respect to legacy-operated networks, and exemplifies the capability of the proposed schemes to leverage network densification as a resource. CROWD approach is advantageous because it proposes SDN to combine DRONEE and BSB, and easily embed them into today's cellular network architecture. Moreover, it has been shown that D2D clustering can be readily integrated into the LTE-A infrastructure with minimal modifications [14]. Therefore, with the current capabilities of WiFi Direct and LTE-A, D2D clustering is not a far-fetched concept anymore. Moreover, ABSF is already available in LTE-A and our proposed algorithm can be readily implemented in the current system.

The merits of our CROWD solution are not limited to throughput increment. For instance, D2D clustering enhances energy efficiency by allowing mobiles to switch to a low power consumption technology (i.e., WiFi) and to reduce the overall transmission time because only the users with the highest channel quality communicate with the base station. Cluster formation also paves the way towards improving user fairness in the system. Once a cluster is formed, a virtual pool of cellular resources can be created which is equivalent to the aggregate of the individual resources of each cluster member. Base stations can exploit these virtual pools to use cluster heads to provide more data to the users with lower channel quality and avoid the starvation issue well known for opportunistic schedulers. Our evaluation results indicate that bigger cluster sizes result in higher gain. However, the relation between cluster size and gain is not linear and most of the gain is achieved when the cluster size is between 5 to 10, which happens to be small enough to avoid overwhelming signaling and contention overhead in WiFi D2D operation.

VI. CONCLUSIONS

In this article we have shown that the interference arising in dense wireless networks can be counteracted by controlling inter-cell interference while using intra-cell resources opportunistically. Specifically, we have shown the compound beneficial impact of BSB (a mechanism proposed for inter-cell resource allocation) and DRONEE (a mechanisms proposed for channel opportunistic use of cellular resources). Our results showed that ICIC can be implemented via smart allocation of ABSF patterns for interfering base stations, and, most importantly, the impact of ICIC can be magnified by adopting channel opportunistic scheduling within the cells. Indeed, D2D communications and clustering techniques not only improve the spectral efficiency within the cell, but also reduce the complexity of ICIC algorithms such as BSB. The proposed joint orchestration of BSB and DRONEE represents a powerful and feasible solution for extremely dense wireless networks, and can be suitably implemented by means of SDN controllers.

VII. ACKNOWLEDGEMENTS

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