Two-level Opportunistic Spectrum Management for Green 5G Radio Access Networks

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***Abstract*—In this paper, we pioneer a novel mechanism that jointly enforces intra-cell and inter-cell resource allocation for future green 5G networks. Our proposal, namely TOMRAN, efficiently coordinates the activity of base stations in small dense cell deployments by means of the ABSF standard tool for inter-cell interference coordination. Additionally, TOMRAN applies intra-cell offloading of the cellular traffic through resource-limited *outband* D2D relay communications, using, e.g., 802.11-based connectivity. We take advantage of this tailwind to show that our approach offers significant performance gain while imposing minor network protocol modifications. Indeed, through an exhaustive simulation campaign, we prove that outband D2D relay communications not only reduce the complexity of interference coordination operations, but also greatly boost the energy efficiency of future green 5G networks.**

I. INTRODUCTION

The densification of wireless networks leads to a serious performance degradation due to the high interference and the low efficiency in the utilization of spectrum and energy in Radio Access Networks (RANs) [4]. These issues are highly intertwined because reducing the impact of either one affects the others. Therefore, support for densification and interference control are key to the design of future 5G networks.[1] So far, the majority of research efforts have taken simplifying assumptions and tackled these issues in isolation. Unfortunately, most of the resulting techniques have conflicting or overlapping objectives, whose compound effects on the energy efficiency have rarely been evaluated.

Several techniques have been proposed to independently cope with interference or low spectral efficiency in RANs, such as beamforming, MIMO or many others, as shown in [3]. Leveraging some preliminary promising results published in [2], in this paper we propose a novel control mechanism for green 5G RANs that *jointly* deals with interference and spectrum efficiency by coordinating intra-cell and inter-cell resource allocation strategies. We call such a control mechanism Two-level Opportunistic Manager for Radio Access Networks (TOMRAN). Specifically, TOMRAN exploits an Inter-Cell Interference Coordination (ICIC) scheme based on the Almost Blank SubFrame (ABSF) paradigm, and a Device-to-Device (D2D) relay strategy for collaborative users. ABSF is a 3GPP standard technique to partially mute some base stations when Inter-Cell Interference (ICI) is above a threshold. Outband D2D communications, instead, avoid unnecessary traffic in the cellular infrastructure and therefore represent the key-enabler to turn green the spectral efficiency of future highly dense networks. TOMRAN allocates intra-cell resources by clustering users in each cell. For each cluster, a *relay node*, opportunistically chosen, conveys the traffic towards other cluster members through outband D2D communication specifications [1]. Furthermore, TOMRAN manages inter-cell resources adopting an ICIC lightweight algorithm which leverages the ABSF technique [14]. However, the ICIC algorithm in TOMRAN is aware that only relay nodes and users that do not belong to clusters can transmit in the cell. This greatly impacts on the user energy consumption while optimizing resource allocation.

Differently from other proposals, TOMRAN takes into account the real capacity attained by each technology (e.g., LTE-A [11] and WiFi Direct [17]) and does not neglect their impact on each other's performance. In fact, offloading traffic through a contention-based system, such as an 802.11-based WLAN, may result in serious congestion that degrades the overall system throughput, dramatically hurting the energy performance. Conversely, TOMRAN is able to estimate the stability region of the 802.11 D2D links and guarantees that the cellular traffic is effectively relayed. Indeed, TOMRAN exploits a new modeling technique recently proposed in [16] to correctly evaluate the 802.11 achievable rates. Making use of such features, TOMRAN dynamically adjusts the amount of the offloaded traffic based on cluster sizes and on the set of *achievable* D2D rates.

The organization of the paper is as follows: in Section II we present TOMRAN. In Section III we discuss advantages offered and complexity issues tackled in TOMRAN. We present in Section IV an extensive simulation campaign to quantify the gains provided by a joint inter-cell and intra-cell resource allocation while in Section V we discuss the state-of-the-art. Finally we conclude the paper in Section VI.

II. THE TOMRAN CONTROL APPLICATION

We assume a multi-cell cellular network with frequency-reuse-1 and M users in the network. We also assume that a Software Defined Network (SDN)-based architecture is deployed in the cellular access network, relying on the existing framework defined in the CROWD FP7 European project.[2] In such architecture, a local controller (CLC) manages a small piece of the network based on fixed policies and adaptive rules. The CLC dynamically takes resource allocation decisions and

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[1] http://5g-ppp.eu

[2] http://www.ict-crowd.eu

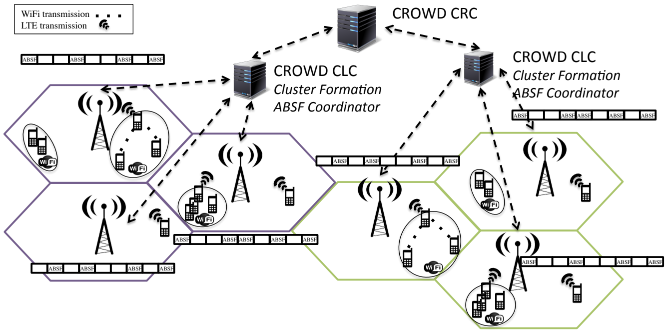


Fig. 1: Network architecture.

promptly issues scheduling policies to base stations under its control. Fig. 1 provides a high level view of this architecture. We envision TOMRAN to be implemented in a control application deployed on top of the CLC in charge of gathering all necessary information for (i) D2D clustering, (ii) D2D intra-cell resource allocation, and (iii) inter-cell interference coordination based on the ABSF technique. Operational details are provided in the following, pointing out how a joint intra-cell and inter-cell resource management can be properly achieved. In this context, we analyze only downlink communications, leaving the analysis of uplink out of the scope of this paper.

D2D clustering and relay. TOMRAN is responsible for the cluster formation process. Each CLC in the system collects the information regarding the channel quality and the location of the users. Based on such information, D2D clusters are formed in the network by means of a *Merge & Split* algorithm [1] targeting the maximization of per-user throughput. In particular, TOMRAN takes into account the distance among cluster members and the achievable throughput gain after clustering them, and assumes that the clustering gain is fairly shared among cluster members. Then, TOMRAN elects the cluster member with the highest cellular channel quality to act as the relay between the eNB and other cluster members. Each cluster member can potentially become a relay once its cellular channel quality becomes the highest in its cluster. Nevertheless, the relay selection decision is renewed only when the channel statistics of the cluster members change considerably. Since TOMRAN is aware of clustering decisions whenever a packet is delivered to a cluster member, the eNB simply transmits the packet to its corresponding relay. However, in order to compensate for the additional energy consumed by relays, TOMRAN separates all users into primary, i.e., relay nodes, and secondary, i.e., all other cluster members. At the eNBs, TOMRAN allows secondary users to be served only when there are no primary users' packets queued. All in all, TOMRAN maximizes the system throughput and improves the energy efficiency since only the most efficient links are enabled as downlink paths from the eNB to the users, without penalizing those users performing as relay nodes.

D2D resource allocation. TOMRAN disposes of several non-overlapping WiFi channels for intra-cell resource allocation for D2D communications (3 channels in the 2.4 GHz bandwidth and several more in the 5 GHz bandwidth, depending on the country). After the cluster formation phase concludes, TOMRAN uniformly assigns the available channels to relay nodes. Hence, relays that are scheduled on the same WiFi channel contend for the same WiFi resources, affecting each other's performance. TOMRAN gathers the statistics of user demands, which are available at the base station side, and the D2D link capacity for each user, which is beforehand reported through cellular CSI indicators. Once all needed pieces of information are available, TOMRAN evaluates the set of achievable rates for each WiFi channel by means of Coupled Processor System (CPS) model [16]. A CPS consists of a set of parallel queues whose instantaneous service rate is univocally determined by the set of active queues. Therefore, CPS modeling perfectly emulates the contention between different relay nodes simultaneously active on the same WiFi channel. More specifically, CPS provides the stability region of the D2D system. Whenever the demands of the relay nodes cannot be served (e.g., user demands lie outside the stability region of D2D), TOMRAN optimally selects a set of rates in a per-user proportional-fair manner, which automatically caps the relay demands. TOMRAN achieves per-user proportional fairness through the following optimization problem:

$$\begin{array}{lll} \underset{\rho\geq\mathbf{0}}{\text{maximize}} & \sum_{i=1}^{H} w_i \log\rho_i, & \\ \text{subject to} & \{\rho_1,...,\rho_i,...,\rho_H\}\subseteq R; & \\ & \rho_i\leq\lambda_i, & \forall i\in\mathcal{H}, \end{array} \tag{1}$$

where ρ_i and λ_i are the maximum throughput that relay node i is allowed to retransmit to its relay members and the initial total demand of those relay members, R is the set of achievable rates for all relay nodes scheduled in the same WiFi channel, as determined by the CPS model, $H = |\mathcal{H}|$ is the number of relay nodes transmitting in that channel, and w_i is the number of cluster members under relay node i.

Inter-cell ABSF control. After achieving the maximum traffic each relay node could transmit to its relay members, TOMRAN manages the coordination of base stations to enforce an ICIC strategy. Specifically, TOMRAN uses (i) cellular channel information for relays and non-clustered nodes (if any), which are the only active cellular users, and (ii) the real downlink demand of each cluster, computed through Problem (1). Based on the collected information, TOMRAN instructs each of the eNBs to transmit on a periodic pattern of subframes (ABSF pattern). The ICIC algorithm we adopt in TOMRAN is BSB, a fast centralized approach [14]. In practice, with BSB, every "decision period" (typically 200 frames), TOMRAN collects user and channel information and issues an ABSF pattern to each eNB through the CLC. Such pattern is optimized to guarantee a minimum SINR level to any downlink transmission in the cellular network while using as little as possible the cellular airtime to serve the offered traffic demand. We refer the reader to [14] for more details on BSB.

In summary, from cluster formation to relay capacity estimation and rate allocation, passing through D2D resource allocation and interference coordination, TOMRAN permits to control and optimize cellular network operation at both inter-cell and intra-cell levels, achieving high energy saving.

III. KEY PERFORMANCE ADVANTAGES

TOMRAN combines D2D clustering and ICIC techniques, which might pursue partially overlapping or even conflicting objectives. However, as shown in what follows, TOMRAN manages to orchestrate the two aforementioned techniques with scalable complexity, achieving efficient resource utilization and guaranteeing stability.

First, the D2D clustering reduces the number of cellular users scheduled by the eNB (only one user per cluster, e.g., the relay node). The selected relay node is the user experiencing the best channel quality in the cluster. When relay nodes are placed close to the base stations, the useful signal strength perceived is much higher than the interference due to the fact that signal attenuation grows quadratically or more with the distance. In this cases, the additional complexity introduced with BSB for enforcing ICIC might only marginally improve the overall network performance. Thus, both ICIC and relay node selection aim at using channels with limited interference. However, the computational effort may dramatically increase: for BSB, the complexity is dominated by the number of users in the most crowded cell [14], which, in turn, increases with the coverage area of the cell itself [1]. Conversely, when the coverage decreases, the distance of the relay nodes from the base station decreases and thus, the number of users in a cell is reduced. Thus, the complexity of BSB used by TOMRAN scales and becomes small when ICIC is scarcely needed.

Second, the complexity of BSB may become significant when the number of relay nodes in each cell is small while the number of interfering cells explodes. In this case, ICIC and relay selection work in a quite orthogonal way, leaving to the ICIC scheme the ability of improving consistently the scheduling of relay nodes potentially suffering from higher interference. As a result, the complexity of the ICIC technique used in TOMRAN scales automatically to pursue the optimal achievable gains.

Third, to reduce interference, BSB (as any ICIC scheme) limits the number of transmission opportunities of the base stations. This objective conflicts with the goal of scheduling relays as often as possible, to take advantage of their high channel qualities. In turn, the quantity of traffic that relay nodes can handle is mostly limited by the capacity of the D2D system. Therefore, rather than using independent optimizations of relay nodes activity and cellular scheduling, TOMRAN jointly solves the two problems and identifies whether the system bottleneck lies in the cellular capacity or in the D2D achievable rates. Specifically, to evaluate whether the traffic received by relay nodes can be retransmitted using D2D, TOMRAN uses a conservative estimation of the rates achievable over WiFi D2D links [16], and instructs the base station scheduler to never exceed such rates using the proportional fair optimization expressed by Problem (1). Therefore, TOMRAN ensures an efficient and fair utilization of the resources at the base stations, and frees the highest quantity of resources, which allows to serve more users, consuming much less energy than legacy systems. However, it is possible that some relay node could also achieve rates higher than the ones assigned by TOMRAN, which are sufficient but not necessary for the stability. Nevertheless, such conditions always guarantee that the backlogs of relay nodes never explode in a cellular network controlled by TOMRAN.

TABLE I: System simulation parameters

Parameter	Value
Scenario	Circular area
Cellular downlink bandwidth	20 MHz
Number of Base Stations	7
Number of WiFi Channels	11
Number of users (N)	350
Base Station transmit power	27 dBm
Thermal noise power	-174 dBm/Hz
Relay node selection time (T)	every 2 s
Slow fading, Pathloss model	9 dB, UMa [9]
WiFi relay node transmit power	20 dBm
WiFi bandwidth	20 MHz

IV. PERFORMANCE EVALUATION

Numerical simulations have been carried out to assess the system performance. All simulations are based on a 5G cellular scenario, where mobile users are provided with a standard LTE-A interface. Users are entitled to form D2D clusters through a second interface, e.g., WiFi-Direct interface, in order to relay the cellular traffic. We benchmark our TOMRAN mechanism against legacy LTE-A. Moreover, we show how either the ICIC or D2D clustering approach in isolation would impact energy efficiency and spectral efficiency. We label as "BSB" those results in which only ICIC is adopted, and as "D2D" those results in which only D2D clustering is involved.

A. Simulation details

We consider a scenario that consists of a seven-cell network with 350 users uniformly distributed over a circular area with a variable radius. Users attach to the eNB with the strongest signal and neither move nor leave the network during the simulation. As a result, D2D clusters do not change after cluster formation, while relay nodes can change based on instantaneous cellular channel qualities, which change due to fading. Outband D2D communications use 802.11n compliant WiFi-Direct in the 5 GHz bandwidth. When clustering is in place, the CLC issues ABSF patterns considering only the relay nodes as input for the eNB scheduler. Each eNB schedules relay nodes using a Round Robin equal time scheduling policy. As previously mentioned, the traffic of relay nodes is prioritized and it is served before the traffic of cluster members. The total amount of cluster members traffic that is queued is finite and it is shaped by a leaky bucket controller, whose long term rate is given by the optimal solution of Problem (1). The simulation details, based on the values suggested by the ITU-R guidelines for IMT-Advanced networks [9], are summarized in Table I. In what follows, we evaluate the system performance in terms of power consumed and of average throughput achieved by the base stations, assuming that all users offer the same demand.

B. Simulation results

Fig. 2 shows the normalized average distance between the relay node and its serving base station as the radius of

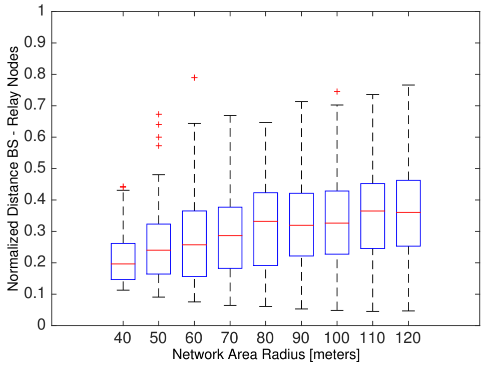
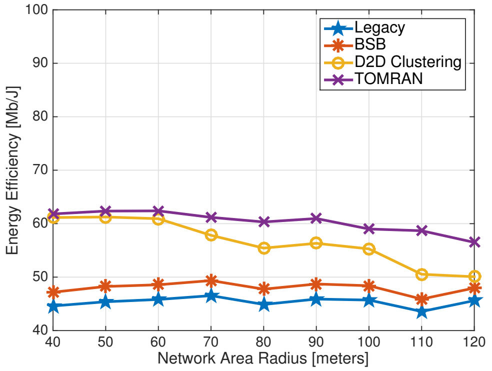


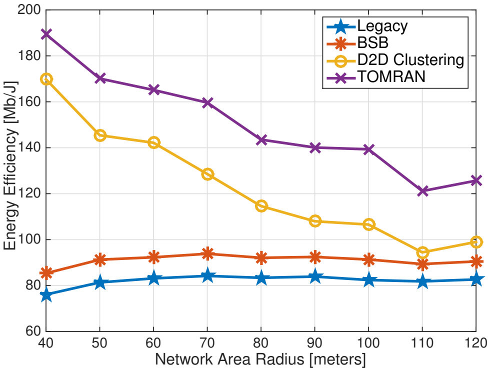
Fig. 2: Distribution of distances among relay nodes and corresponding BS normalized over inter-site distance (5th, 25th, 75th, and 95th percentiles are plotted together with the median, while red crosses represent outliers).

the simulated area varies. Interestingly, the results exhibit an increasing behavior, which leads to a higher probability to find a relay node on the cell-edge when the network area radius is larger. This is also confirmed by 75th percentiles reported in the figure, which grow while increasing the network area radius. Thus, the larger the network area radius, the lower the probability to select a relay node with a good cellular channel quality. Even in presence of clustering techniques, this results in a cellular performance degradation, as several cellular users (e.g., relay nodes) suffer from intense interference. Therefore, an efficient ICIC solution is needed to fully boost the system performance by limiting cellular interference effects on relay nodes, as done with TOMRAN.

The network radius plays an important role in the cluster formation process which directly impacts on the energy performance of the network. In Fig. 3(a), we show the energy efficiency of different schemes varying the network radius with a fixed user demand of 0.5 Mbps, while in Fig. 3(b), we increase the user traffic demand to 2.5 Mbps. In these experiments, we assume that the base station hardware is always in full operational state. Therefore, we make the conservative assumption that ABSF patterns do not alter the base stations power consumption. With this assumption, the power consumption at the base station side is fixed to 2.8 W and energy efficiency changes due to the aggregate traffic transmitted [7]. Spatial densification of base stations and users (e.g., network area radius equal to 40 meters) seriously impairs the legacy cellular network performance. In such conditions, energy efficiency always improves even if using only ICIC mechanisms or D2D clustering of users. Specifically, energy efficiency improves by 37.5% when user demands are 0.5 Mbps and by 120% when user demands are 2.5 Mbps. TOMRAN, that jointly exploits the advantages of both techniques, improves energy efficiency even further. Interestingly, it brings additional gain when the cellular interference becomes challenging (e.g., when relay nodes are on the cell edge). This result confirms our intuitions presented in Section III, showing the ability of TOMRAN to trade off energy efficiency for computational complexity. Again, if compared with a simple clustering technique, TOMRAN shows an increasing relative gain in energy efficiency. Indeed, when the per-user demand is 2.5 Mbps, the gain passes from 15% to 30% when the considered area radius goes from 40 to 120 meters. This validates our intuitions, proving that a compound effect study of applying two independent enhancement approaches leads to a huge gain in term of energy efficiency, even though WiFi resource sharing limitation is considered.



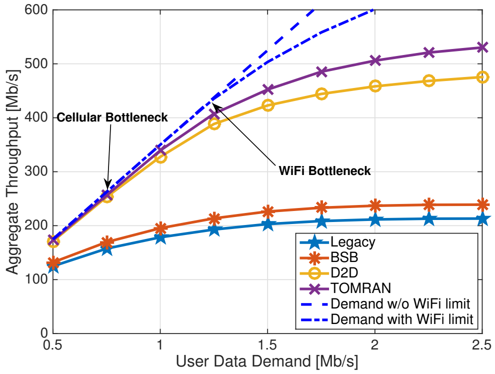
(a) User traffic demand equal to 0.5 Mbps.



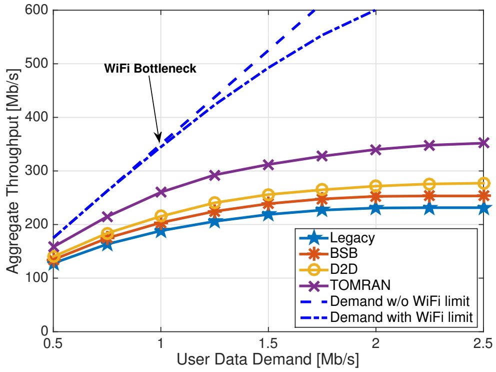
(b) User traffic demand equal to 2.5 Mbps.

Fig. 3: Energy efficiency for 7 base stations evaluated for different network area radius [7].

The overall energy efficiency greatly benefits from applying TOMRAN, since base stations may exhibit much more throughput while consuming the same amount of energy, compared with the conventional cellular system. In particular, here we evaluate the system performance in terms of aggregate throughput. Fig. 4(a) illustrates the achieved throughput for the different schemes tested in a network with radius of 40 meters. The fixed per-user demand ranges from 0.5 Mbps to 2.5 Mbps. Notably, we observe a significant improvement with TOMRAN, in which both D2D clustering and ICIC work simultaneously. Indeed, TOMRAN boosts the network capacity by achieving up to 250% gain compared to the legacy scheme. In addition, TOMRAN exhibits up to the 200% and 15% gain in comparison to BSB and D2D schemes, respectively. Fig. 4(b) shows the throughput results when the network radius is increased to 120 meters. An interesting difference with the previous case emerges here due to the behavior of D2D clustering when applied either in isolation or jointly with ICIC. The overall gain of TOMRAN and D2D is considerably reduced here, and is comparable to the gain achieved by using the ICIC algorithm in isolation (BSB). This



(a) Network area radius equal to 40 meters.



(b) Network area radius equal to 120 meters.

Fig. 4: Aggregate throughput of 7 base stations for different user traffic demands, when 350 users are placed.

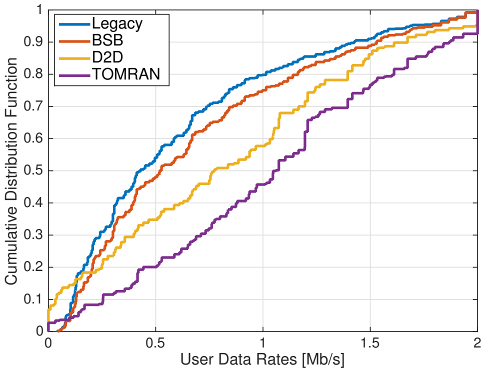


Fig. 5: Cumulative distribution function of cluster members' data rates for different schemes in a network with a radius of 70 meters and 2 Mbps as user data demand.

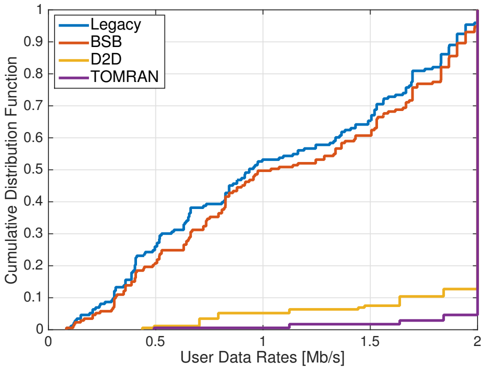


Fig. 6: Cumulative distribution function of relay users' data rates for different schemes in a network with a radius of 70 meters and 2 Mbps as user data demand.

is clearly explained by the user positions and average distances from serving base stations, as shown in Fig. 2: several relay nodes are placed at the edge of different cells, experiencing bad SINR values. However, even in this case, TOMRAN outperforms all other schemes by 59%, 40%, and 25% with respect to legacy, BSB, and D2D, respectively. Due to the sparseness of relay nodes in the scenario, D2D-based solutions are indeed not sufficient to cope with spectrum efficiency issues. Thus, simultaneously applying an ICIC mechanism with D2D clustering allows reducing the cellular interference sensed by relay nodes at the edge of the cells and improving the overall throughput. In addition, in both the cases addressed in Fig. 4, while the legacy cellular network is not able to satisfy all user traffic demands, TOMRAN is robust to user traffic increasing. Moreover the figures show the demand offered with and without considering the limitation of the WiFi shared media. Note that there are two "special" operational points. The first represents the "WiFi Bottleneck", and shows the minimum per-user demand for which the traffic of at least one cluster member is larger than the D2D outband capacity. The second represents the "Cellular Bottleneck", and shows the minimum per-user demand at which the TOMRAN capacity does not match the available WiFi capacity. It is important to note that TOMRAN performs similarly to D2D clustering only when all user traffic is served (below the "Cellular Bottleneck"). Moreover, the gain stemming from the coupled control of ICIC and D2D clustering in TOMRAN is not equivalent to the sum of the gains provided by BSB and D2D. In fact, both ICIC and D2D clustering techniques used in isolation rely on wireless channel diversity to improve the performance. However, the diversity gain of D2D after applying ICIC via ABSF patterns is lower because channel quality of users increases due to lower interference (i.e., the opportunistic D2D scheduling gain is lower).

We show in Fig. 5 the cumulative distribution function of the average data rates achieved by cluster members, excluding relay nodes. Even if relay node traffic is prioritized, it is easy to note that cluster members do not starve. On the contrary, they receive a higher throughput than what they would achieve with any other mechanism. Finally, in Fig. 6 we summarize data rates associated to relay users. D2D substantially improves the relay nodes' condition with respect to legacy cellular networks and with respect to BSB. When TOMRAN is operated, cluster relay nodes' capacity is fully maximized, and high data rates compensate the additional energy required for relaying traffic.

V. RELATED WORK

Since TOMRAN is the first proposal for joint inter-cell interference coordination and intra-cellular traffic offloading mechanism guaranteeing high level of energy efficiency, here we limit our overview of the related work to D2D clustering and ICIC techniques.

D2D clustering. The works in [6], [15], [18] focus on D2D clustering in cellular networks. The authors of [6], [15] show via simulations that D2D cluster increases the network performance by up to 66% in comparison to legacy cellular systems. Zhou *et al.* [18] propose an optimal resource utilization for multicast relaying with D2D clusters. They provide a closed-form expression for the probability distribution function of the optimal number of relays in a cluster, and an intra-cluster retransmission scheme. They also show via numerical simulations that their proposed scheme achieves up to 40% gain in resource utilization efficiency.

ABSF. The authors of [8] provide a clear overview about different ICIC proposals, classifying them as (i) semi-distributed, where a central entity coordinates scheduling resources, through ABSF patterns, while each base station is in charge of scheduling its users, and (ii) distributed, where each base station makes locally decisions on its own ABSF patterns. In the former class of ICIC proposals, [13] presents BASICS, an efficient algorithm which leverages the ABSF technique to optimally increase the network throughput by serving best effort traffic and guaranteeing an acceptable level of fairness between users, while keeping low energy consumptions. Moreover, in [14], ABSF is tuned to guarantee inelastic traffic demand for delay-guaranteed networks. For what concerns the class of distributed ICIC mechanisms, [12] presents a lightweight fully distributed solution, where each base station makes its own scheduling decisions based on a game theory approach.

Unlike the majority of the prior works [1], [2], we do not ignore the fact that WiFi can be a bottleneck for relaying cellular data. Although the achievable rate with WiFi is higher than with cellular technologies of the same generation, WiFi transmissions mainly suffer from poor coordination of transmitters, exhibiting high performance degradation. Indeed, the work in [5], [10], [16] aim to study the impact of resource sharing in WiFi and quantify the set of achievable rates in unsaturated conditions.

Our work differentiates from the related work because it takes into account the impact of different communication technologies on each other's performance, and dynamically adjusts offloaded traffic based on two factors: cluster size and set of achievable D2D rates, thus shedding light on how the energy consumption is emphatically affected.

VI. CONCLUSION

Densification phenomena with spectrum resource shortage lead to a dramatic system performance degradation, which challenges the cellular access network and requires sophisticated and advanced network tools to cope with strict requirements of green 5G future networks. In this framework, we have proposed TOMRAN, a control mechanism that combines inter-cell interference coordination with intra-cellular D2D-based traffic offloading to enhance the system energy efficiency. We have shown how TOMRAN leverages the knowledge of the stability region of the system to promptly abate the neighbouring cellular interference with scalable complexity, and to boost energy efficiency through D2D clustering communications. We have proven that TOMRAN achieves outstanding results with respect to ICIC and D2D solutions taken in isolation, bringing substantial gain even when outband D2D resource sharing limitations represent the communication bottleneck. Thus, we envision TOMRAN as one of the most promising solutions for the future green 5G networks. Indeed, TOMRAN would permit to benefit from orchestrating two enhanced network control mechanisms while exhibiting very low complexity.

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