Game Theory Framework Applied to Wireless Communication Networks

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Chapter 13

A Game Theoretic Framework for Green HetNets Using D2D Traffic Offload and Renewable Energy Powered Base Stations

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ABSTRACT

This chapter investigates the interplay between cooperative device-to-device (D2D) communications and green communications in LTE heterogeneous networks (HetNets). Two game theoretic concepts are studied and analyzed in order to perform dynamic HetNet base station (BS) on/off switching. The first approach is a coalition-based method whereas the second is based on the Nash bargaining solution. Afterwards, a method for coupling the BS on/off switching approach with D2D collaborative communications is presented and shown to lead to increased energy efficiency. The savings are additionally increased when a portion of the small cell BSs in a HetNet are powered by renewable energy sources. Different utility functions, modeling the game theoretic framework governing the energy consumption balance between the cellular network and the mobile terminals (MTs), are proposed and compared, and their impact on MT quality of service (QoS) is analyzed.

INTRODUCTION

Energy efficiency is representing an increasing concern for cellular network operators. Although the main purpose is to minimize their electricity costs and maintain profitability, reducing negative effects on the environment is also an important objective (Hasan, 2011).

A large portion of the energy dissipated in a cellular system is actually consumed at the base stations (BSs). Hence, putting certain BSs in sleep mode, or switching them off in light traffic conditions,

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is an efficient technique to save energy in wireless networks, e.g., see (Bousia, 2012; Han, 2013). In (Niu, 2010), the cell size is adjusted dynamically depending on the traffic load using a technique called "cell zooming" for the purpose of reducing energy consumption. The power ratio, corresponding to the ratio between the dynamic and the fixed power part of a BS power consumption model, is introduced in (Xiang, 2011). This ratio is used to propose a solution based on traffic load balancing.

Several enhancements incorporated in next generation cellular systems, e.g., LTE-Advanced (LTE-A), consist of reducing effective cell sizes by using combinations of microcells (Lan, 2012), distributed antenna systems (Zhao, 2012), relays (Salem, 2010), and indoor femtocells (Hoydis, 2010). In this chapter, we use the term "small cells" to refer to a combination of these cells. Together with macrocells, they form a heterogenous network (HetNet), with HetNets expected to constitute a paradigm shift in state-of the-art cellular networks (Andrews, 2013). HetNets are one of the possible solutions to address the load increase on state-of-the-art cellular systems, such as LTE-A, due to the exponential increase in multimedia and data traffic. The operation of such HetNets is optimized through the use of advanced interference coordination/mitigation techniques, heterogeneous fractional frequency reuse patterns, and cooperative multipoint transmission/reception techniques. However, network densification brings with it the challenge of increased energy consumption in cellular BSs, which makes BS on/off switching techniques of high importance in HetNets (Bousia, 2012; Han, 2013). Furthermore, renewable energy sources, such as solar panels or wind turbines, could be used to power small cell BSs (SCBSs) whenever possible. This would be difficult to apply with macrocell BSs (MBSs) due to their larger energy consumption. Hence, renewable energy SCBSs (RE-SCBSs) could be used in conjunction with BS switch off techniques.

In addition, device-to-device (D2D) communications have been receiving significant research attention recently, due to their planned incorporation in future releases of LTE-Advanced (LTE-A) in beyond 4G and 5G cellular systems. D2D communications in LTE-A would allow a device to use the cellular spectrum in order to be connected directly to another device. This short range (SR) D2D connectivity allows offloading some traffic from the cellular network. Several previous work focused on using D2D as an underlay network to the traditional LTE/LTE-A cellular communication network (Ma, 2013; Wang & Chu, 2012; Wang, 2013). Other work considers maximizing the spatial reuse while using D2D communications (Lee, 2013). In (Han, 2012), D2D connections are allowed to use the same wireless resources as long range (LR) cellular links in order to maximize the spatial reuse gain. A resource allocation scheme to achieve this objective is proposed. Most of the previously cited references consider D2D in unicast mode. Multicasting in D2D underlay networks is investigated in (Wang & Wang, 2012; Chen, 2013), where the challenge is to group mobile terminals (MTs) into clusters receiving the multicast data through D2D communications. However, efficient cooperative D2D clustering schemes under LTE-A are still an active research topic.

In this chapter, a game theoretic framework based on utility maximization is proposed in order to ensure that green LTE/LTE-A HetNets operate with the least required number of BSs while maintaining a certain degree of quality of service (QoS). The main novelty of this work consists in using the combination of RE-SCBSs and D2D offload in order to achieve green LTE-A HetNets. This is done through a utility maximizing algorithm, along with the selection of utility functions that balance between the energy consumption in the BSs and the MTs to achieve mutual benefit and energy savings.

Starting from the scenario of reaching energy efficiency in green HetNets without D2D, two game theoretic concepts are studied and analyzed in order to perform dynamic BS on/off switching. The first approach is a coalition-based method that assumes a group of BSs in a network form a coalition. The second approach is based on the Nash bargaining solution and considers that BSs play a bargaining game where each BS attempts to maximize its own utility. Then, we extend the approach to a scenario with D2D communications. The objective is to use D2D traffic offload in order to reduce the load on cellular BSs, which allows putting more of them in sleep mode. An efficient approach for grouping MTs into coalitional groups, or cooperative clusters, is described. In each cluster, MTs cooperate via D2D communications to share content of common interest. When coupled with the on/off BS switching approach, the D2D clustering method leads to increased energy efficiency in the network. Furthermore, we investigate the scenario where small cell BSs in a HetNet are powered by renewable energy sources. In fact, due to their small size and limited coverage, certain small cell BSs can be powered by renewable energy sources, e.g., solar panels or wind turbines. In addition, the power consumption of mains powered small cell BSs would be less than that of macrocell BSs. This will favor having more small cells switched on at reduced cost since BSs powered by renewable energy powered do not incur power consumption costs.

After defining game theoretic frameworks for green HetNets and for D2D clustering, different utility functions, modeling the game theoretic framework governing the energy consumption balance between the cellular network and the MTs, are proposed and investigated. This is one of main novel aspects of the chapter, since previous work in the literature investigates separately green HetNets and D2D communications. Since most of the energy consumption in the network occurs at the BSs, and since D2D collaboration for traffic offload could entail and increase in the energy consumption of some MTs, the utility functions should reflect a sort of fairness towards MTs, so that their batteries are not depleted in order to increase the energy savings of cellular BSs. The results show that the joint use of D2D traffic offload and renewable energy small cell BSs leads to significant energy savings in the network while respecting the QoS requirements of the MTs.

SYSTEM MODEL

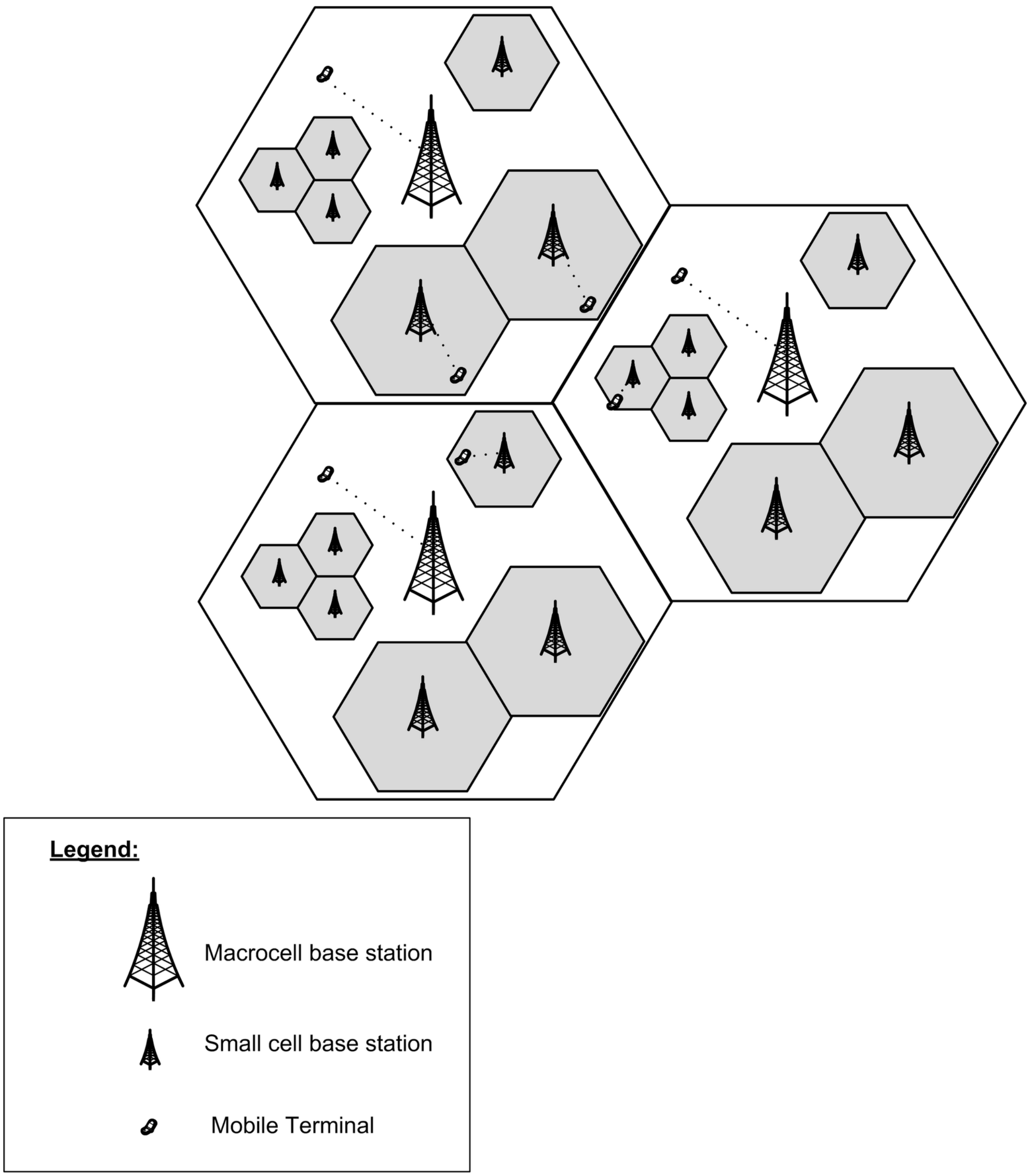
HetNet deployments are considered in this chapter, as shown in Figure 1. The game theoretic techniques are first proposed to a scenario without D2D communications, then extended to the case where D2D can be used to offload traffic and reduce the number of active BSs.

The game theoretic techniques discussed in this chapter will be used in conjunction with several presented utility functions in order to switch-off certain BSs and achieve energy efficiency in the network. The proposed methods can be applied to any combination of macrocells and small cells in the network, independently of the geometric layout of the BSs. Nevertheless, to simplify the simulations, we consider a geographical area of interest with uniform user distribution. The area is covered by a heterogeneous LTE network, consisting of macrocell BSs with a cell radius R_M, and small cell BSs with a smaller cell radius $R_S < R_M$, both placed on a square grid.

In the downlink (DL) direction of LTE, orthogonal frequency division multiple access (OFDMA) is used, whereas single carrier frequency division multiple access (SCFDMA) is used in the uplink (UL) direction (Myung, 2008). The LTE spectrum is subdivided into resource blocks (RB) where each RB consists of 12 adjacent subcarriers. The assignment of a single RB takes place every 1 ms, which is the duration of one transmission time interval (TTI), or the duration of two 0.5 ms slots in LTE (3GPP TS 36.213, 2014).

The data rates depend on the channel gain of each user on each subcarrier. The channel model adopted in this paper includes pathloss, lognormal shadowing, and Rayleigh fading. Intercell interference

Figure 1. HetNet deployment example



is also taken into account in the calculation of the signal to interference plus noise ratio (SINR), and thus affects the data rates achieved and consequently the resource allocation process. The details of the channel model, uplink and downlink SINR, interference, and data rate calculations are presented next.

Channel Model

This section presents the channel model adopted in this chapter. The channel gain of user k_l in cell l over subcarrier i on the link with BS j can be expressed as follows (Goldsmith, 2005):

$$H_{k_l,i,j,\mathrm{dB}} = (-\kappa - \upsilon \log_{10} d_{k_l,j}) - \xi_{k_l,j} + 10 \log_{10} F_{k_l,i,j}, \tag{1}$$

where the first factor in (1) captures propagation loss, with κ the pathloss constant, $d_{k_l,j}$ the distance in km from user k_l to BS j, and v the path loss exponent. The second factor in (1), $\xi_{k_l,j}$, captures log-normal shadowing with zero-mean and a standard deviation σ_ξ, whereas the last factor in (1), $F_{k_l,i,j}$, corresponds to Rayleigh fading with a Rayleigh parameter a (usually selected such that $E[a^2]=1$). It should be noted that the above analysis applies to both the UL and DL, depending on whether i is an UL or DL subcarrier, respectively. In the rest of the chapter, whenever there is a need to distinguish between the uplink and downlink directions, the notation $H^{(\mathrm{UL})}_{k_l,i,j}$ and $H^{(\mathrm{DL})}_{k_l,i,j}$ will be used, respectively.

Data Rates in the Downlink

Letting $I^{(\mathrm{DL})}_{\mathrm{sub},k_l}$ be the set of DL subcarriers allocated to user k_l in cell l, $I^{(\mathrm{DL})}_{\mathrm{RB},k_l}$ the set of RBs allocated to user k_l in the DL, $N^{(\mathrm{DL})}_{\mathrm{RB}}$ the total number of DL RBs, $P^{\mathrm{tx}}_{i,l}$ the total power transmitted by the BS l over subcarrier i, .. the maximum transmission power of BS l, N_{BS} the total number of deployed BSs, K_l the total number of subscribers in th ecell covered by BS l and $R^{(\mathrm{DL})}_{k_l}$ the achievable DL rate of k_l. Then, the OFDMA throughput of user k_l is given by:

$$R^{(\mathrm{DL})}_{k_l}\left(P^{(DL)}_{l,\max}, I^{(\mathrm{DL})}_{\mathrm{sub},k_l}\right) = \sum_{i \in I^{(DL)}_{sub,k_l}} B^{(\mathrm{DL})}_{\mathrm{sub}} \cdot \log_2(1 + \Gamma^{(\mathrm{DL})}_{k_l,i,l}), \tag{2}$$

where $\Gamma^{(\mathrm{DL})}_{k_l,i,l}$ is the SINR of user k_l over subcarrier i in cell l, and $B^{(\mathrm{DL})}_{\mathrm{sub}}$ is the subcarrier bandwidth. It is expressed as:

$$B^{(\mathrm{DL})}_{\mathrm{sub}} = \frac{B^{(\mathrm{DL})}}{N^{(\mathrm{DL})}_{\mathrm{sub}}}, \tag{3}$$

with $B^{(\mathrm{DL})}$ the total usable DL bandwidth, and $N^{(\mathrm{DL})}_{\mathrm{sub}}$ the total number of DL subcarriers.In this chapter, we consider equal power transmission over the subcarriers, i.e., for all i, we have:

$$P_{i,l}^{\mathrm{tx}} = \frac{P_{l,\max}^{(DL)}}{N_{\mathrm{sub}}^{(\mathrm{DL})}}. \tag{4}$$

The DL-SINR of user k_l over subcarrier i in cell l, $\Gamma_{k_l,i,l}^{(\mathrm{DL})}$, is given by:

$$\Gamma_{k_l,i,l}^{(\mathrm{DL})} = \frac{P_{i,l}^{\mathrm{tx}} H_{k_l,i,l}^{(\mathrm{DL})}}{I_{i,k_l}^{(\mathrm{DL})} + \sigma_{i,k_l}^2}, \tag{5}$$

where $H_{k_l,i,l}^{(\mathrm{DL})}$ is the channel gain of user k_l over subcarrier i in cell l, σ_{i,k_l}^2 is the noise power over subcarrier i in the receiver of user k_l, and $I_{i,k_l}^{(\mathrm{DL})}$ is the interference on subcarrier i measured at the receiver of user k_l. The expression of the interference is given by:

$$I_{i,k_l}^{(\mathrm{DL})} = \sum_{j=1, j\neq l}^{N_{BS}} \left(\sum_{k_j=1}^{K_j} \alpha_{k_j,i,j}^{(\mathrm{DL})} \right) \cdot P_{i,j}^{\mathrm{tx}} H_{k_l,i,j}^{(\mathrm{DL})}, \tag{6}$$

where $\alpha_{k_j,i,j}^{(\mathrm{DL})} = 1$ if DL subcarrier i is allocated to user k_j in cell j, i.e., $i \in I_{\mathrm{sub},k_j}^{(\mathrm{DL})}$. Otherwise, $\alpha_{k_j,i,j}^{(\mathrm{DL})} = 0$. In each cell, an LTE RB, and hence the subcarriers constituting that RB, can be allocated to a single user at a given Time Transmission Interval (TTI). Hence, in each cell j, we have:

$$\sum_{k_j=1}^{K_j} \alpha_{k_j,i,j}^{(\mathrm{DL})} \leq 1. \tag{7}$$

Data Rates in the Uplink

Let $I_{\mathrm{sub},k_l}^{(\mathrm{UL})}$ be the set of UL subcarriers allocated to user k_l, $I_{\mathrm{RB},k_l}^{(\mathrm{UL})}$ the set of UL RBs allocated to user k_l, $N_{\mathrm{RB}}^{(\mathrm{UL})}$ the total number of RBs in the UL, $P_{k_l}^{(UL)}$ the total transmit power of user k_l, and $R_{k_l}^{(\mathrm{UL})}$ its achievable rate in the UL. Then, the SCFDMA throughput of user k_l is given by:

$$R_{k_l}^{(\mathrm{UL})}\left(P_{k_l}^{(UL)}, I_{\mathrm{sub},k_l}^{(\mathrm{UL})}\right) = \frac{B^{(\mathrm{UL})} \mid I_{\mathrm{sub},k_l}^{(\mathrm{UL})} \mid}{N_{\mathrm{sub}}^{(\mathrm{UL})}} \cdot \log_2\left(1 + \Gamma_{k_l}^{(\mathrm{UL})}\left(P_{k_l}^{(UL)}, I_{\mathrm{sub},k_l}^{(\mathrm{UL})}\right)\right), \tag{8}$$

where $B^{(\mathrm{UL})}$ is the total UL bandwidth, $\mid I_{\mathrm{sub},k_l}^{(\mathrm{UL})} \mid$ is the cardinality of $I_{\mathrm{sub},k_l}^{(\mathrm{UL})}$ and $N_{\mathrm{sub}}^{(\mathrm{UL})}$ is the number of UL subcarriers. Finally, $\Gamma_{k_l}^{(\mathrm{UL})}\left(P_{k_l}^{(UL)}, I_{\mathrm{sub},k_l}^{(\mathrm{UL})}\right)$ is the SINR of user k_l after Minimum Mean Squared Error (MMSE) frequency domain equalization at the receiver (Myung, 2008):

$$\Gamma_{k_l}^{(\mathrm{UL})}\left(P_{k_l}^{(UL)}, I_{\mathrm{sub},k_l}^{(\mathrm{UL})}\right) = \left(\frac{1}{\frac{1}{|\, I_{\mathrm{sub},k_l}^{(\mathrm{UL})} \,|} \sum_{i \in I_{\mathrm{sub},k_l}^{(\mathrm{UL})}} \frac{\Gamma_{k_l,i,l}^{(\mathrm{UL})}}{\Gamma_{k_l,i,l}^{(\mathrm{UL})}+1}} - 1 \right)^{-1}. \tag{9}$$

In (9), $\Gamma_{k_l,i,l}^{(\mathrm{UL})}$ is the UL SINR of user k_l over subcarrier i served by BS l. It is given by:

$$\Gamma_{k_l,i,l}^{(\mathrm{UL})} = \frac{P_{k_l,i,l}^{(\mathrm{UL})} H_{k_l,i,l}^{(\mathrm{UL})}}{I_{i,l}^{(\mathrm{UL})} + \sigma_{i,l}^2}, \tag{10}$$

where $H_{k_l,i,l}^{(\mathrm{UL})}$ is the channel gain between user k_l and BS l over subcarrier i, $\sigma_{i,l}^2$ is the noise power over subcarrier i at BS l, $P_{k_l,i,l}^{(\mathrm{UL})}$ is the power transmitted by user k_l over subcarrier i in cell l, and $I_{i,l}^{(\mathrm{UL})}$ is the UL interference on subcarrier i, measured at BS l. The expression of the interference is given by:

$$I_{i,l}^{(\mathrm{UL})} = \sum_{j=1, j\neq l}^{N_{BS}} \sum_{k_j=1}^{K_j} \alpha_{k_j,i,j}^{(\mathrm{UL})} P_{k_j,i,j}^{(\mathrm{UL})} H_{k_j,i,l}^{(\mathrm{UL})}, \tag{11}$$

where $\alpha_{k_j,i,j}^{(\mathrm{UL})} = 1$ if subcarrier i is allocated to user k_j served by BS j, i.e., $i \in I_{\mathrm{sub},k_j}^{(\mathrm{UL})}$. Otherwise, $\alpha_{k_j,i,j}^{(\mathrm{UL})} = 0$.

The LTE standard imposes the constraint that the RBs allocated to a single user should be consecutive with equal power allocation over the RBs (3GPP TS 36.211, 2014; 3GPP TS 36.213, 2014; Myung, 2008). Hence, we set:

$$P_{k_l,i,l}^{(\mathrm{UL})} = \frac{P_{k_l,\max}^{(UL)}}{|\, I_{\mathrm{sub},k_l}^{(\mathrm{UL})} \,|}. \tag{12}$$

User Admission and QoS Requirements

When a user k joins the network, it is associated with the best serving cell l^*, i.e the cell having the available UL and DL RBs that maximize the user's performance. Assuming one UL RB and one DL RB are allocated for each user, this corresponds to the RBs for which the UL and DL subcarriers, $i^{*(UL)}$ and $i^{*(DL)}$, satisfy (13) and (14), respectively:

$$(i^{*(\mathrm{UL})}, l^*) = \arg\max_{(i,l)} \left(1 - \sum_{k_l=1;k_l\neq k}^{K_l} \alpha_{k_l,i,l}^{(\mathrm{UL})}\right) R_{k,i,l}^{(\mathrm{UL})}, \tag{13}$$

$$i^{*(\mathrm{DL})} = \arg\max_{i}\left(1 - \sum_{k_l=1;k_l\neq k}^{K_l} \alpha_{k_l,i,l^*}^{(\mathrm{DL})}\right) R_{k,i,l^*}^{(\mathrm{DL})}, \tag{14}$$

where $R_{k,i,l}^{(\mathrm{UL})}$ and $R_{k,i,l}^{(\mathrm{DL})}$ represent the UL and DL achievabledata rates, respectively, of user *k* over subcarrier *i* in cell *l*. The first term in the multiplications of (1) and (2) indicates that the search is on the RBs that are not yet allocated to other users, where $\alpha_{k_l,i,l}^{(\mathrm{UL})} = 1$ if UL subcarrier *i* is allocated to user k_l in cell *l*. Otherwise, $\alpha_{k_l,i,l}^{(\mathrm{UL})} = 0$. The same rules apply for DL subcarriers.

A user is considered to be successfully served if the following conditions are satisfied:

$$\left\{\begin{matrix} R_{k_l}^{(\mathrm{UL})} \geq R_{\mathrm{Target},\ k_l}^{(\mathrm{UL})} \\ R_{k_l}^{(\mathrm{DL})} \geq R_{\mathrm{Target},\ k_l}^{(\mathrm{DL})} \end{matrix}\right\}, \tag{15}$$

where $R_{k_l}^{(\mathrm{UL})}$ and $R_{k_l}^{(\mathrm{DL})}$ are the respective UL and DL data rates of user k_l in cell *l*, aggregated over all its allocated UL and DL subcarriers, respectively. $R_{\mathrm{Target},\ k_l}^{(\mathrm{UL})}$ and $R_{\mathrm{Target},\ k_l}^{(\mathrm{DL})}$ are the UL and DL target data rates, respectively, representing the QoS constraints. They can vary depending on the service used by the user. Hence, a user is considered to be in outage if at least one of the conditions in (15) is not met.

PROPOSED GAME THEORETIC TECHNIQUES

This section describes two game theoretic methods proposed in this chapter and implemented first in HetNets without using D2D for energy efficiency. The first approach is a cooperative coalition-based method where a group of BSs in a network are considered to form a coalition. The second approach is based on BS competition where each BS aims to maximize its own utility.

BS Coalition Approach

BSs in a certain geographical area are assumed to cooperate together by forming a coalition. Hence, the objective would be to maximize the benefits of the coalition as a whole, not of individual BSs. Considering there are N_{BS} BSs in the coalition, each having its own payoff function or utility, such that the utility of BS *l* is denoted by U_l, then the objective is to maximize the total utility of the coalition as follows:

$$\max_{\alpha_{k_l,i,l}^{(DL)},\alpha_{k_l,i,l}^{(UL)},P_l^{(DL)},P_{k_l}^{(UL)}} \left(\sum_{l=1}^{N_{BS}} U_l\right) \tag{16}$$

Subject to:

$$P_{k_l}^{(UL)} \leq P_{k_l,\max}^{(UL)}; \forall k_l = 1,\cdots,K_l; \forall l = 1,\cdots,N_{BS} \tag{17}$$

$$P_l^{(DL)} \leq P_{l,\max}^{(DL)}; \forall l = 1, \cdots, N_{BS} \tag{18}$$

$$\sum_{k_l=1}^{K_l} \alpha_{k_l,i,l}^{(UL)} \leq 1; \forall i = 1, \cdots, N_{sub}^{(UL)}; \forall l = 1, \cdots, N_{BS} \tag{19}$$

$$\sum_{k_l=1}^{K_l} \alpha_{k_l,i,l}^{(DL)} \leq 1; \forall i = 1, \cdots, N_{sub}^{(DL)}; \forall l = 1, \cdots, N_{BS} \tag{20}$$

$$\sum_{l=1}^{N_{BS}} \frac{N_{out,l}}{N_{served,l} + N_{out,l}} \leq P_{out,th} \tag{21}$$

The constraints in (17) and (18) indicate that the transmit power cannot exceed the maximum power for the UL and DL, respectively. The constraints in (19) and (20) correspond to the exclusivity of subcarrier allocations in each cell for the UL and DL, respectively, since in each cell, a subcarrier can be allocated at most to a unique user at a given scheduling instant. Finally, the constraint in (21) is related to enforcing QoS, where $N_{out,l}$ corresponds to the number of users in outage in cell *l*, i.e., the users associated with cell *l* as their best serving cell according to (13) and (14), but that were not able to satisfy their QoS requirements in (15). $N_{served,l}$ indicates the number of users served successfully in cell *l*. Hence, this constraint indicates that the total outage rate in the network should not exceed a tolerated outage threshold $P_{out,th}$.

To perform this sum-utility maximization, Algorithm 1 is implemented. In this algorithm, we introduce two indicator variables: I_j^{ON} j indicates if a BS *j* is on or off, by setting its value to 1 or 0, respectively, whereas I_j^{attempt} is a tracking parameter that indicates whether an attempt has been made to switch BS *j* off in the current iteration or not. It is set to 1 if the attempt was made and to 0 otherwise. The loop at Lines 1-4 is an initialization phase. In the Loop at Lines 5-23, the algorithm finds the BS having the weakest individual utility, then checks if the reassignment of its users to other BSs and putting it in sleep mode leads to an enhancement for the coalition's utility. If an enhancement is reached, the BS is switched off. Otherwise it is kept on. Then, the algorithm moves to the next BS, and so on. The iterations are repeated until no improvement can be made in the sum-utility, even if an attempt is made on all the BSs that remained "on" (which in this case will lead to $\prod_{j=1; I_j^{ON}=1}^{N_{BS}} I_j^{\mathrm{attempt}} = 1$ and allows exiting the loop at Line 5).

In this approach, the BS acts in the benefit of the coalition by allowing its utility to be set to zero if this leads to an increase in the utility of the coalition. This can be implemented in the case of centralized control in the coalition, or in the case of a single operator that would hardwire the intelligence of Algorithm 1 in all its BSs.

Algorithm 1: Uitlity Maximization Algorithm

for all BS j **do**
$I_j^{\mathrm{ON}} = 1$
$I_j^{\mathrm{attempt}} = 1$
end for
while $\prod_{j=1;I_j^{ON}=1}^{N_{BS}} I_j^{\mathrm{attempt}} = 0$ do
Find: $j^* = \underset{I_j^{ON}=1, I_j^{\mathrm{attempt}}=0}{\arg\min} U_j$
for all k_{j*} served by BS $j*$ **do**
Implement (13) and (14) after excluding $j*$ from the BS search in (13); i.e. the search is done over BSs $l \neq j*$
end for
for all $j \neq j*$ such that $I_j^{\mathrm{ON}} = 1$ **do**
Compute $U_j^{(\mathrm{new})}$ obtained after moving the users k_{j*} as described above
Set $U_{j^*}^{(\mathrm{new})} = 0$
end for
if $\sum_{j=1}^{N_{BS}} U_j^{(\mathrm{new})} > \sum_{j=1}^{N_{BS}} U_j$ then
for all j such that $I_j^{\mathrm{ON}} = 1$ **do**
Set $U_j = U_j^{(\mathrm{new})}$ and $I_j^{\mathrm{attempt}} = 0$
end for
Set $I_{j^*}^{\mathrm{ON}} = 0$
else
No changes are made (keep the old utility values)
Set $I_{j^*}^{\mathrm{attempt}} = 1$
end if
end while

BS Competition Approach

In this section, we consider that BSs are competing selfishly to maximize their individual utilities. However, we consider that they negotiate the allocation of resources and users by communicating with each other. This corresponds in game theory to a bargaining game, where each player attempts to maximize its payoff (or utility) by bargaining with other players to share the resources in a way they cannot jointly improve on. The solution in game theory to this bargaining game consists of maximizing the Nash product, and it is known as the Nash bargaining solution (NBS) (Carmichael, 2005). Hence, this translates into:

$$\max_{\alpha_{k_l,i,l}^{(DL)}, \alpha_{k_l,i,l}^{(UL)}, P_l^{(DL)}, P_{k_l}^{(UL)}} \left(\prod_{l=1}^{N_{BS}} U_l \right), \tag{22}$$

subject to the constraints (17)-(21). Since the logarithm is a continuous strictly increasing function, (22) is equivalent to:

$$\max\left(\prod_{l=1}^{N_{BS}} U_l\right) \Leftrightarrow \max \ln\left(\prod_{l=1}^{N_{BS}} U_l\right) = \max \sum_{l=1}^{N_{BS}} \ln\left(U_l\right). \tag{23}$$

Interestingly, the algorithmic implementation of (22) can be handled by Algorithm 1, by using, in that algorithm, $U_l^{(\mathrm{NBS})} = \ln\left(U_l\right)$ as the BS utility instead of U_l. Thus, to model a bargaining game in a practical network, bargaining "negotiations" do not need to take place between BSs, and the implementation of Algorithm 1 with $U_l^{(\mathrm{NBS})} = \ln\left(U_l\right)$ is sufficient to lead to the NBS, i.e., to the equilibrium solution of the bargaining problem. Hence, with this approach, the BS knows it is achieving its best possible utility, given the utilities of the other BSs and the conditions of the network. Thus, the NBS solution can be hardwired in the BSs, even if multiple operators are involved (in this case, pricing and billing issues due to potentially moving subscribers of one operator to the BS of another by Algorithm 1 should be taken into account, e.g., by being included in a suitable utility).

UTILITY CALCULATIONS

This section presents utility metrics that can be used with the proposed game theoretic methods of the previous section. The two utilities presented focus either on traffic load and QoS, or on the QoS versus the consumed power in the network.

Utility Based on Load and QoS Performance

In this section, we define a utility that depends on the traffic load and QoS performance of each BS. It is selected as follows:

$$U_l = N_{\mathrm{served},l} \cdot \exp\left(P_{\mathrm{out,th}} - \frac{N_{\mathrm{out},l}}{N_{\mathrm{served},l} + N_{\mathrm{out},l}}\right). \tag{24}$$

The utility in (24) increases with the number of served users and decreases with the number of users in outage. When the outage rate exceeds the tolerated threshold $P_{\mathrm{out,th}}$, the exponential term in (24) becomes negative and the utility decreases quickly towards zero. If no users are served by a certain BS, then $U_l = 0$ and the BS will be switched off by Algorithm 1.

In the NBS case, we have: $U_l^{(\mathrm{NBS})} = \ln\left(U_l\right)$. However, to avoid having ln(0) in computer implementations, the utility needs to be redefined for boundary conditions. Thus, when a BS is "on", we set the utility to:

$$U_l^{(\mathrm{NBS})} = \begin{Bmatrix} \ln\left(N_{\mathrm{served},l}\right) + \left(P_{\mathrm{out,th}} - \dfrac{N_{\mathrm{out},l}}{N_{\mathrm{served},l} + N_{\mathrm{out},l}}\right); N_{\mathrm{served},l} > 0 \\ -1 + \left(P_{\mathrm{out,th}} - \min\left(N_{\mathrm{out},l}, 1\right)\right); N_{\mathrm{served},l} = 0 \end{Bmatrix}. \tag{25}$$

When a BS is switched-off, we set U_l=0 and $U_l^{(\mathrm{NBS})} = 0$. In the NBS case with $N_{\mathrm{serverd},l}$=0, the utility in (25) will have a negative value. This will favor the switching-off of the corresponding BS by Algorithm 1, since this will lead to an increase in its utility (which will become zero).

Utility Based on Load and Power Consumption

The utility defined in (24) does not explicitly depend on the consumed power at the BS. In this section, we define a utility that reflects the number of served users versus the power consumption in the network. The selected utility is given by:

$$U_l = \frac{N_{\mathrm{served},l}}{P_{C,l}}, \tag{26}$$

where $P_{C,l}$ is the total power consumed by BS l (not to be confused with the transmit power at the antenna, which is included as a fraction of this power term). In general, utilities aiming at maximizing the sum rate while being concerned with energy efficiency can be defined in terms of bps/Hz/Watt. However, in this chapter, the interest is in maximizing the number of served users satisfying the constraints in (15), while minimizing the power consumption in the network.

In the NBS case, we have: $U_l^{(\mathrm{NBS})} = \ln\left(U_l\right)$. Thus, when a BS is "on", we obtain:

$$U_l^{(\mathrm{NBS})} = \begin{Bmatrix} \ln\left(N_{\mathrm{served},l}\right) - \ln\left(P_{C,l}\right); N_{\mathrm{served},l} > 0 \\ -1 - \ln\left(P_{C,l}\right); N_{\mathrm{served},l} = 0 \end{Bmatrix}. \tag{27}$$

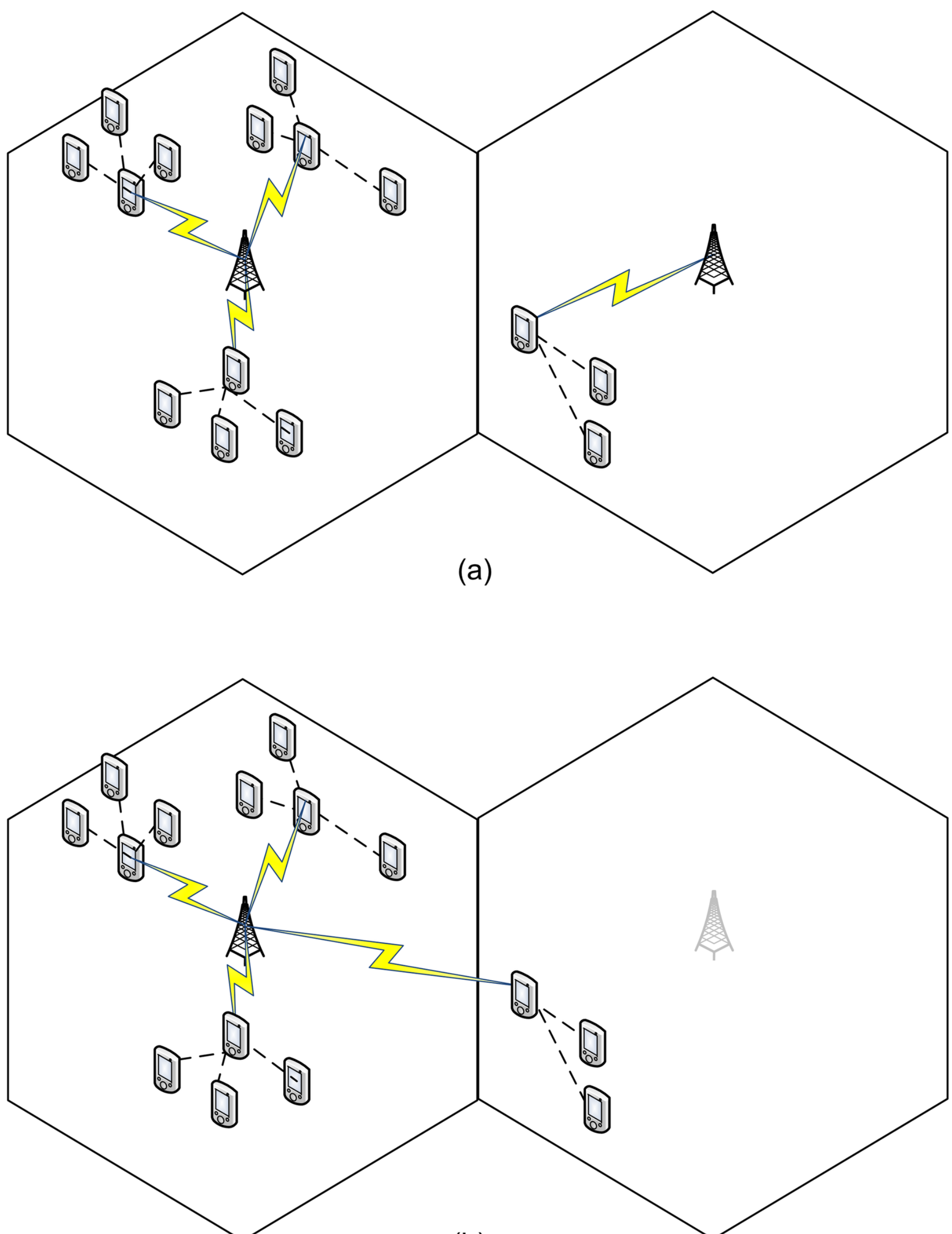
When a BS is switched-off, we have U_l=0 and $U_l^{(\mathrm{NBS})} = 0$.

EXTENSION TO THE CASE WITH D2D COMMUNICATIONS

In this part of the chapter, we extend the proposed method to the case where D2D communications are implemented for the purpose of energy efficiency. In this case, the concern is not only for saving energy in the cellular networks, but also in reducing the energy consumed from the MTs' batteries. The presented method is presented in a general framework first then customized to a multicasting scenario as a special case. In this scenario, content of common interest is to be delivered from the BS to requesting MTs distributed throughout the cell area of the BS. MTs communicate with the BS using LTE, or with neighboring MTs using D2D communications. MTs form cooperating clusters for the purpose of energy minimization during cooperative content distribution. Within each cooperating cluster, the content is delivered on the LR to a single MT, the cluster head (CH), which in turn sends the data to the other MTs in that cluster using SR collaboration. Figure 2 shows the scenario considered.

At a given fading realization, each MT receives the data content from a single source, which could be either the BS or another MT. We assume that MTs form coalitions where the energy consumption in

Figure 2. D2D collaboration used to enhance BS switch off



the coalition is lower than the sum of the individual energy consumptions of the coalition members. In a coalition cluster C_k, n_k is the cluster head communicating on the LR with the BS on behalf of all the cluster members. After forming the clusters as shown in Figure 2(a), the BS switch off techniques can be implemented by considering only the CHs that are still connected to the BSs on the LR. This allows enhancing the switch off process and increasing energy savings since a reduced number of MTs (CHs only) have to be offloaded from a given BS in order to put it in sleep mode, as it is shown in Figure 2(b).

Rate and Interference Calculations

In this section, we adapt the notation to the scenario where D2D communications are involved in the green operation of the network. We use the term 'node' to refer to either an MT or a BS. The N_{BS} BSs are numbered from node n_1 to node $n_{N_{BS}}$. Having K MTs in the system ($K = \sum_{j=1}^{N_{BS}} K_j$), they are numbered from node $n_{N_{BS}+1}$ to node $n_{N_{BS}+K}$. We denote by C_k the coalition of nodes forming a single cooperative cluster with n_k as CH communicating on the LR with a BS on behalf of all the cluster members. We generalize the notation of Section "System Model" by using the notation X_{kij} to denote the value of a quantity X between nodes n_k and n_j over subcarrier i (X could be, for example, the data rate R, the channel gain H, the transmit power P, etc.) .

With this generalized notation, the interference expression can be made more general in order to take D2D communications into account. In fact, the transmission from node n_k to node n_l over subcarrier i is subjected to the following interference, measured at n_l:

$$I_{k,i,l} = \sum_{\substack{m=1,\\ m\neq k}}^{N_{BS}+K} \sum_{\substack{j=1,\\ j\neq l}}^{N_{BS}+K} \alpha_{m,i,j} P_{m,i,j} H_{m,i,l}. \tag{28}$$

However, in the scenario of this chapter, a link is broken with the BS in order to use D2D communications instead. Thus, interference between SR D2D communications and the LR communications with the BS in a single cell can be avoided by allocating the freed subcarriers from the LR MT-BS link to be used for the SR D2D communications instead. Furthermore, selecting UL subcarriers for D2D allows reducing the interference from D2D transmissions to cell edge users in neighboring cells. Instead, interference from D2D will be received at the BSs of other cells, which are relatively at a larger distance. Coupled with reduced transmission power on the SR due to the short distances, this interference will be significantly reduced.

Energy Calculations

In this section, we discuss the energy consumption of MTs in order to take it into account in the green operation of the network, in addition to the energy consumption of BSs. The time needed to transmit a content of size S_T bits on a link between nodes n_k and n_j having an achievable rate R_{kj} bps is given by S_T/P_{kj}. Denoting the power drained from the battery of node n_j to receive the data from node n_k by $P_{Rx,kj}$, then the energy consumed by n_j to receive the data from n_k is given by $S_T \bullet P_{Rx,kj}/R_{kj}$. Similarly, denoting by $P_{Tx,k}$

the power drained by the battery of n_k to transmit the data via multicasting, then the energy consumed by n_k to transmit the content to n_j is given by $S_T \bullet P_{Tx,k}/R_{kj}$. It should be noted that $P_{Tx,k}$ can be expressed as:

$$P_{\mathrm{Tx},k} = P_{\mathrm{Tx}_{\mathrm{ref}},k} + P_{t,k}, \tag{29}$$

where $P_{\mathrm{Tx}_{\mathrm{ref}},k}$ corresponds to the power consumed by the circuitry of node n_k during transmission on the communication interface, and $P_{t,k}$ corresponds to the power transmitted over the air interface by n_k.

We present the formulation first in a general case where different data are transmitted to the different users and where both UL and DL directions are taken into account. Denoting by E_{C_k} the energy consumed by the MTs that are members of cluster C_k with node n_k as cluster head, and assuming, without loss of generality, that we are considering cell l with n_l as BS in this section, then the energy consumed in C_k is given by: $E_{C_k} = E_{C_k}^{(UL)} + E_{C_k}^{(DL)}$.

The cluster energy consumption for UL transmission is given by:

$$E_{C_k}^{(UL)} = \sum_{j \neq k; n_j \in C_k} S_{jk} \cdot \left(\frac{P_{\mathrm{Tx,j}k}}{R_{jk}} + \frac{P_{\mathrm{Rx,j}k}}{R_{jk}} + \frac{P_{\mathrm{Tx},kl}}{R_{kl}} \right), \tag{30}$$

where the first term corresponds to the energy consumed by the nodes to transmit their data to node n_k on the SR via D2D communications, the second term corresponds to the energy consumed by node n_k for reception on the SR, and the last term corresponds to the energy consumed by node n_k for transmission to the BS on the LR cellular link. S_{jk} denotes the number of bits transmitted from n_j to BS l through CH n_k. The summation is used to indicate that n_k aggregates the data of the MTs within its coalition cluster before transmitting it to the BS.

Similarly, the cluster energy consumption for DL transmission is expressed as:

$$E_{C_k}^{(DL)} = \sum_{j \neq k; n_j \in C_k} S_{kj} \cdot \left(\frac{P_{\mathrm{Rx},lk}}{R_{lk}} + \frac{P_{\mathrm{Tx},kj}}{R_{kj}} + \frac{P_{\mathrm{Rx},kj}}{R_{kj}} \right). \tag{31}$$

In (31), S_{kj} denotes the number of bits transmitted to n_j through CH n_k. The first term corresponds to the energy consumed by node n_k to receive the data destined to the various nodes in C_k from BS l on the LR link, the second term corresponds to the energy consumed by node n_k for transmission on the SR via D2D communications, and the last term corresponds to the energy consumed by the nodes in C_k to receive their data from node n_k on the SR via D2D communications.

In the results of this chapter, we consider the DL scenario (31). Without loss of generality, we assume that all MTs are interested in downloading files of similar size S_{kj}=S_T (set to S_T=1Mbits in the simulations). In (Yaacoub, 2013), the scenario where users are interested in the same content was considered. In this case, the equation (31) can be customized to a scenario where multicasting is used in the DL. Hence, the energy consumed in C_k with multicasting is given by:

$$E_{C_k} = \frac{S_T \cdot P_{\mathrm{Rx},lk}}{R_{lk}} + \frac{S_T \cdot P_{\mathrm{Tx},k}}{\min\limits_{i \neq k; n_i \in C_k} R_{ki}} + \sum_{j \neq k; n_j \in C_k} \frac{S_T \cdot P_{\mathrm{Rx},kj}}{\min\limits_{i \neq k; n_i \in C_k} R_{ki}}, \tag{32}$$

where the first term corresponds to the energy consumed by node n_k to receive the data from the BS on the LR cellular link, the second term corresponds to the energy consumed by node n_k to transmit the data to the other nodes in its cluster on the SR via D2D communications, and the last term corresponds to the energy consumed by the nodes to receive their data from node n_k on the SR. To avoid multiple transmissions among nodes of the same cluster, MT n_k transmits using multicasting. Therefore, the second term does not involve any summation over the MTs, conversely to the third term. In addition, with SR multicasting, $R_{kj} = \min_{i \neq k; n_i \in C_i} R_{ki}$, since transmission should take place at the minimum achievable rate in the cluster in order to guarantee that all MTs in the cluster receive the desired information. When all MTs have similar characteristics in terms of power consumption, then we have: $P_{Rx,lk}=P_{Rx,LR} \forall k,j$ for the power drained from the batteries of the MTs during reception on the LR from the BS, $P_{Rx,kj}=P_{Rx,SR} \forall k,j$ for the power drained from the batteries of the MTs during reception on the SR from the CHs, and $P_{Tx,k}=P_{Tx,SR} \forall k$ for the power drained from the batteries of the CHs during multicasting on the SR to the other MTs. In this case, (32) can be simplified as follows:

$$E_{C_k} = S_T \cdot \left(\frac{P_{\mathrm{Rx,LR}}}{R_{lk}} + \frac{P_{\mathrm{Tx,SR}} + (|C_k| - 1) P_{\mathrm{Rx,SR}}}{\min\limits_{i \neq k; n_i \in C_k} R_{ki}} \right), \tag{33}$$

where |•| denotes set cardinality.

It should be noted that the work in (Yaacoub, 2013) did not consider neither HetNets nor RE-SCBSs as in this chapter. In addition, it did not compare various utility functions derived based on a game theoretical frawmework. Although the results presented in this chapter are focused on the DL transmission, from the BS to the MTs, the proposed approach can be applied to the joint UL/DL scenario, by simply replacing, in the remaining sections, the energy expression of (31) by $E_{C_k} = E_{C_k}^{(UL)} + E_{C_k}^{(DL)}$, that is, the sum of energies in (30) and (31). It should be noted that, because different data are being transmitted on each SR link via unicasting in (30) and (31), the actual rates R_{kj} are used instead of the minimum SR rate in the cluster as in the multicasting case of (32) and (33). With the scenarios of (30) and (31), a CH needs to aggregate the data of all the MTs in its cluster before transmitting the data to/from the BS. Although this leads to additional energy consumption, it was still shown to lead to significant gains in (Yaacoub, 2012), where UL clustering was considered in wireless sensor networks, but within a single macrocell (i.e., without considering green networking in a multiple cell scenario).

Algorithms to Implement the Proposed Approach

This section describes the proposed method based on joint D2D offload and green networking through BS switch off. First, D2D clustering is performed according to Algorithm 2. Then, Algorithm 1 is implemented after D2D clustering is performed with Algorithm 2. Algorithm 3 summarizes the procedure, which is based on Algorithms 1 and 2.

Algorithm 2 describes the D2D cluster formation approach. After finding the best candidate clusters at Lines 3 and 4, they are merged together if the merger leads to a cluster with better energy efficiency (Lines 5-8). Otherwise no changes are made. The process is repeated (Loop at Lines 2-10) until no additional improvement is reached. The step at Line 1 of Algorithm 3 leads to offloading traffic from the cellular network via D2D communications, while the step at Line 2 leads to switching redundant BSs off using Algorithm 1, which is facilitated by having to consider only the links between the CHs and the BSs instead of the links between all MTs and the BSs.

Algorithm 2: D2D Cluster Formation Algorithm

1: At the start of the proposed method, all the nodes n_k are directly connected to the BS via LR LTE links; i.e., each cluster consists of a single node such that $C_k = \{n_k\}$ and $|C_k| = 1$. This is equivalent to the scenario without D2D collaboration. All clusters are in the search space $S = \{k;\ C_k \neq \emptyset\}$.
2: **while** $S \neq \emptyset$ **do**
3: Find the cluster having the highest energy consumption per node: $k = \arg\max_{m \in S} E_{C_m} / |C_m|$.
4: Find the cluster C_j that leads to the lowest energy consumption when merged with cluster C_k: $j = \arg\min_{m \neq k} E_{C_m \cup C_k}$.
5: **if** $E_{C_j \cup C_k} \leq E_{C_j} + E_{C_k}$ then
6: Set $C'_j = C_j \cup C_k$
7: Set $C_j = C'_j$ and $C_k = \emptyset$
8: **end if**
9: Remove k from the search space: $S = S \setminus \{k\}$.
10: **end while**

Algorithm 3: Joint Green/D2D Algorithm

1: Form D2D clusters by implementing Algorithm 2.
2: Implement the green communications method of Algorithm 1.

Utility Calculation for Green Networking with D2D

As the purpose in green networks is energy efficiency, the simplest way to set the utility value is to consider minimizing the energy consumption in the network. However, considering only BS energy is unfair towards MTs when D2D offload is used. In fact, CHs consume additional energy to relay data to other MTs instead of just receiving their own. Thus, MT energy consumption should be taken into account in addition to BS energy consumption. But it should be noted that MT battery and transmit power are much smaller than those of BSs. Therefore, taking the sum of consumed energies at the BSs and MTs will not make a significant difference for the MTs, since the sum will be dominated by the BS energy consumption.

Hence, there is a need for a balanced utility function that takes into account the role of all components in the network: the cellular BSs handling LR communications and the collaborating MTs communicating via D2D. Consequently, the proposed utility functions used in this chapter are defined according to the form:

$$U_l = f\left(\frac{N_{\text{served},l}}{E_{C,l}}, \frac{N_{\text{served},C_{k_l}}}{E_{C_{k_l}}}\right), \tag{34}$$

where U_l is the utility of cell l, $E_{C,l}$ is the energy consumed by BS n_l during the transmission of the data in cell l, $E_{C_{k_l}}$ is the energy consumed by cluster C_{k_l} in cell l, $N_{served,l}$ is the number of MTs served directly by BS n_l on the LR (including CHs), and $N_{\text{served},C_{k_l}}$ is the number of MTs served by D2D communications on the SR in cluster C_{k_l}. The function $f(x,y)$ is selected such that it is increasing with x and y. Thus, the first term in (34), $N_{\text{served},l} / E_{C,l}$, corresponds to the network of BSs, and the second term, $N_{\text{served},C_{k_l}} / E_{C_{k_l}}$, corresponds to the D2D clusters. By considering the ratio of the number of served users to the energy consumed, the components for the network and for the MTs in the utility become within the same order of magnitude, conversely to taking the sum of energies for example. Furthermore, for RE-SCBSs, the energy is obtained at no cost. For such BSs, we set $E_{C,l}$=1 (to avoid division by zero), which makes it much less than the energy consumed by mains powered BSs (MP-BSs). This will favor the offload of MTs to RE-SCBSs and switch off MP-BSs, since this would lead to a significant increase in the first term of (34). In addition, since the D2D energy consumption on the SR consumes significantly less energy than the BS energy, an increase in D2D offload will lead to a significant increase of the second term of (34). Hence, the combined use of RE-SCBSs and D2D offload will increase (34), thus favoring the switch off of significant numbers of MP-BSs. In this chapter, we consider the transmission of a file of size S_T bits to all MTs. Denoting by $T_{max,l}$ the time needed to transmit the content by BS n_l to all the MTs served by the BS (which depends on their achievable data rates), then we have:

$$E_{C,l} = P_{C,l} \cdot T_{\max,l}, \tag{35}$$

with $P_{C,l}$ denoting the total power consumed to operate BS n_l (including circuitry power, transmit power, processing power, etc.).

Based on (34), we define three cell utilities in this section. The network utility to be maximized is taken as the sum of individual cell utilities.

Utility 1

The first cell utility is defined as follows:

$$U_{l,1} = \frac{N_{\text{served},l}}{E_{C,l}} + \frac{N_{\text{served},C_{k_l}}}{E_{C_{k_l}}}. \tag{36}$$

The corresponding network utility is thus defined as:

$$U_1 = \sum_{l=1}^{N_{BS}} U_{l,1} = \sum_{l=1}^{N_{BS}} \left(\frac{N_{\text{served},l}}{E_{C,l}} + \frac{N_{\text{served},C_{k_l}}}{E_{C_{k_l}}} \right). \tag{37}$$

This utility corresponds to a cooperative coalitional utility between all BSs and MT clusters. The BSs and MT clusters are treated similarly in this utility, and the objective is to minimize the energy consumption of both BSs and MTs jointly by considering the overall sum of utilities. This utility extends (26) by assuming a coalition between all network entities, whether BSs or MTs, for the sake of energy minimization while satisfying QoS. Hence, (37) also extends (16) to green networking in a D2D scenario.

Utility 2

The second cell utility is defined as follows:

$$U_{l,2} = \frac{N_{\text{served},l}}{E_{C,l}} \cdot \frac{N_{\text{served},C_{k_l}}}{E_{C_{k_l}}}. \tag{38}$$

The corresponding network utility is thus defined as:

$$U_2 = \sum_{l=1}^{N_{BS}} U_{l,2} = \sum_{l=1}^{N_{BS}} \left(\frac{N_{\text{served},l}}{E_{C,l}} \cdot \frac{N_{\text{served},C_{k_l}}}{E_{C_{k_l}}} \right). \tag{39}$$

Utility 2 represents a hybrid scenario involving both coalition and competition: In each cell, a Nash Bargaining Game is played between the BS and MTs served by CHs in its coverage area, since the utility of the cell is the product of the BS utility and the utility of the MT cluster(s) in that cell, as it is expressed in (38). Then, the network utility in (39) considers the sum of cell utilities, i.e., the cells in the network are assumed to cooperate by forming a coalition. Consequently, with this network utility, the purpose is to maximize the sum of cell utilities; i.e., the Nash Bargaining Game is played separately in each cell, but not across cells. This latter situation corresponds to Utility 3, defined next.

Utility 3

The third cell utility is defined as follows:

$$U_{l,3} = \ln\left(\frac{N_{\text{served},l}}{E_{C,l}}\right) + \ln\left(\frac{N_{\text{served},C_{k_l}}}{E_{C_{k_l}}}\right). \tag{40}$$

The corresponding network utility is defined as:

$$U_3 = \sum_{l=1}^{N_{BS}} U_{l,3} = \sum_{l=1}^{N_{BS}} \left(\ln\left(\frac{N_{\text{served},l}}{E_{C,l}}\right) + \ln\left(\frac{N_{\text{served},C_{k_l}}}{E_{C_{k_l}}}\right)\right). \tag{41}$$

Maximizing U_3 is equivalent to:

$$\max U_3 \Leftrightarrow \max \prod_{l=1}^{N_{BS}} \left(\frac{N_{\text{served},l}}{E_{C,l}} \cdot \frac{N_{\text{served},C_{k_l}}}{E_{C_{k_l}}}\right). \tag{42}$$

The utility in (40) extends (26) by assuming a competition between all network entities, whether BSs or MTs, for the sake of energy minimization while satisfying QoS. Hence, (41) and (42) also extend (22) and (23) to green networking in a D2D scenario. Using this utility is equivalent to playing a Nash Bargaining Game between all the BSs and MTs. In this case, each BS acts selfishly to minimize its energy consumption, whereas each cluster of MTs forms a coalition aiming at reducing its energy consumption. This utility represents the NBS to this bargaining problem in a game theoretical framework.

SIMULATION RESULTS AND DISCUSSION

This section presents the Matlab simulation results. In the simulations, a uniform user distribution is considered over a coverage area of size 5×5 km^2. BSs are placed on a rectangular grid uniformly in the area. The cell radii are set to $R_M = 0.5$ km and $R_S = 0.1$ km for macrocells and small cells, respectively. The transmit power is set to $P_{l,\max}^{(DL)} = 10$ W for macrocell BSs, $P_{l,\max}^{(DL)} = 1$ W for small cell BSs, and $P_{k_l,\max}^{(UL)} = 0.125$ W for mobile devices. The power consumption is set to $P_{C,l} = 500$ W for macrocell BSs and $P_{C,l} = 100$ W for small cell BSs. We consider an LTE bandwidth of 10 MHz for each of the UL and DL directions, subdivided into 50 RBs. LTE parameters are obtained from (3GPP TS 36.211, 2014; 3GPP TS 36.213, 2014), and channel parameters are obtained from (3GPP TR 25.814, 2006). The complete list of parameters is shown in Table 1.

Green Networking Results without D2D

This section describes the proposed method based on green networking through BS switch off without resorting to D2D communications. Different services are analyzed depending on their UL and DL target data rates. They are presented in Table 2. Service 1 could correspond to a symmetric voice service,

Table 1. Simulation parameters

Parameter	Value	Parameter	Value
κ	-128.1 dB	v	3.76
σ_ξ (dB)	8 dB	Rayleigh parameter a	$E[a^2]=1$
Macrocell Radius R_M	0.5 km	Small cell Radius R_S	0.1 km
B	10 MHz	B_{sub}	15 kHz
N_{RB}	50	$P_{\mathrm{Rx,LR}}$	1.8 Joules/s
$P_{\mathrm{Tx,SR}}$	1.425 Joules/s	$P_{\mathrm{Rx,SR}}$	0.925 Joules/s
S_T	1 Mbits	Area size	5×5 km^2
Max. macro BS transmit power	10 W	Max. small BS transmit power	1 W
Power Consumption of MBSs	500 W	Power Consumption of MP-SCBSs	100 W
Max. MT transmit power	0.125 W	Percentage of RE-SCBSs	50% (η=0.5)

Table 2. Studied scenarios

Scenario	$R^{(\mathrm{UL})}_{\mathrm{Target},\,k_l}$ (kbps)	$R^{(\mathrm{DL})}_{\mathrm{Target},\,k_l}$ (kbps)
Service 1	64	64
Service 2	56	256
Service 3	384	384
Service 4	384	1000

Services 2 and 4 are asymmetric services with different rates (e.g., comparable to fixed ADSL services), and Scenario 3 can represent a symmetric service with rates sufficient for video conferencing. It should be noted that significantly higher data rates can be reached compared to these services when the whole LTE bandwidth of 20 MHz (100 RBs) is allocated to a single user in the absence of interference. But these services are more realistic in the case of one RB allocated per user in a loaded network with high interference levels.The outage threshold is set to $P_{\mathrm{out,th}}=0.05$.

The simulation results are shown in Figures 3 to 10. Figures 3 and 4 show the number of macrocell BSs that are active for the utilities (24) and (26), respectively, whereas Figures 5 and 6 show the number of SCBSs that are active for the utilities (24) and (26), respectively. In addition, Figures 7 and 8 show the network power consumption while using the utilities (24) and (26), respectively.

It can be seen that the coalitional approach outperforms the NBS approach since it leads to a lower number of active BSs (as shown in Figures 3 to 6), which leads to a lower power consumption in the network, as shown in Figures 7 and 8, for both utilities (24) and (26).

Figures 9 and 10 show the number of users in outage for the utilities (24) and (26), respectively. These figures show that both game theoretic techniques (coalition and NBS), when used with either of the utilities (24) or (26), satisfy the QoS requirements by leading to an outage rate below $P_{\mathrm{out,th}}$. However,

Figure 3. Number of macrocell BSs that are "on" using the utility (24)

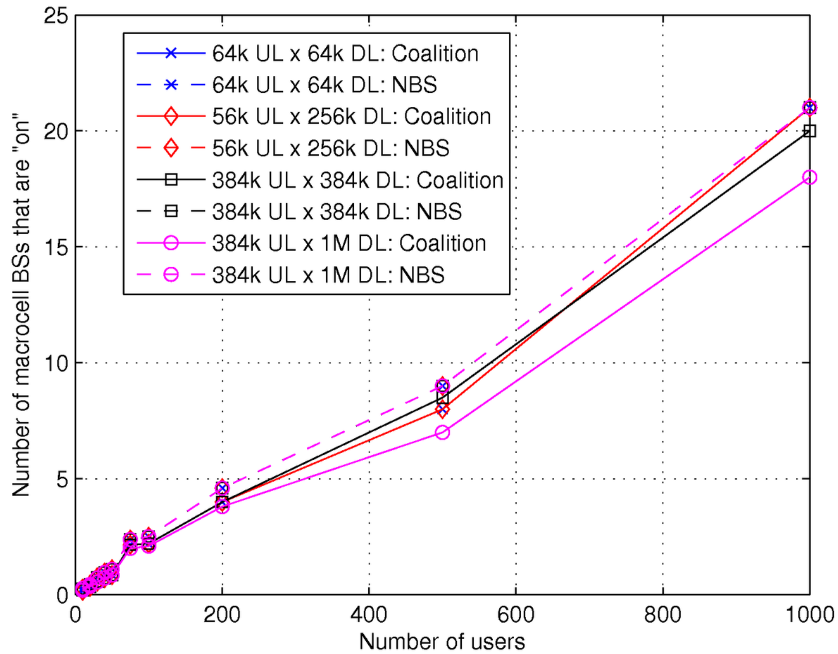


Figure 4. Number of macrocell BSs that are "on" using the utility (26)

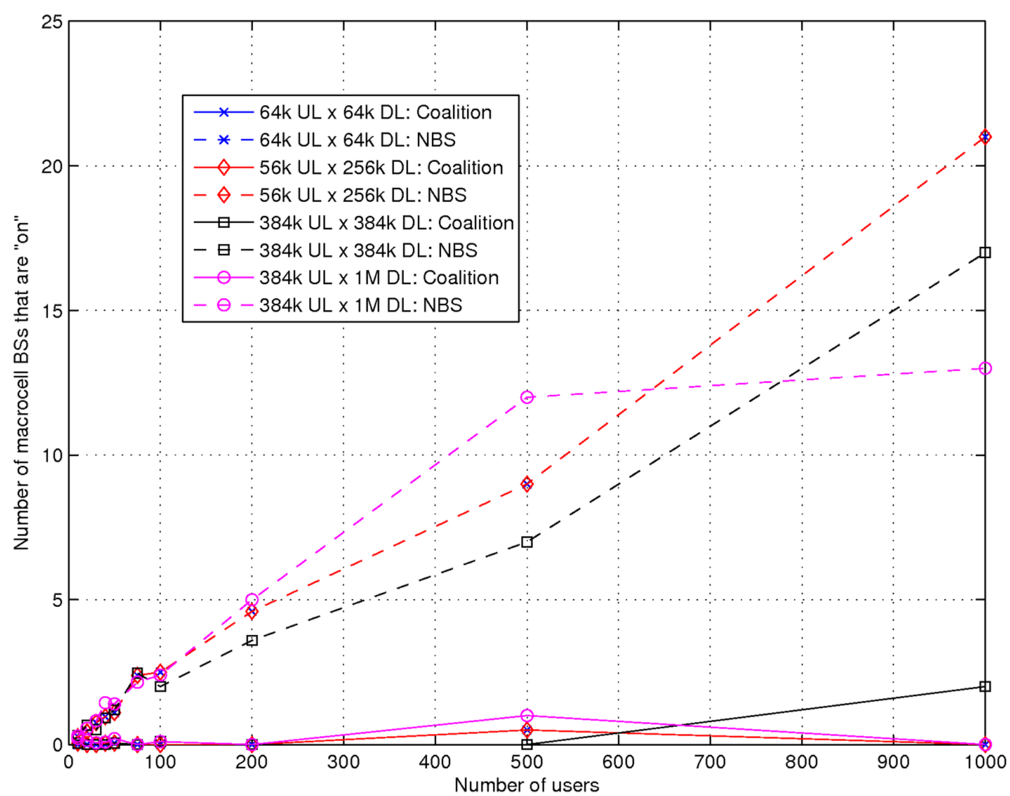
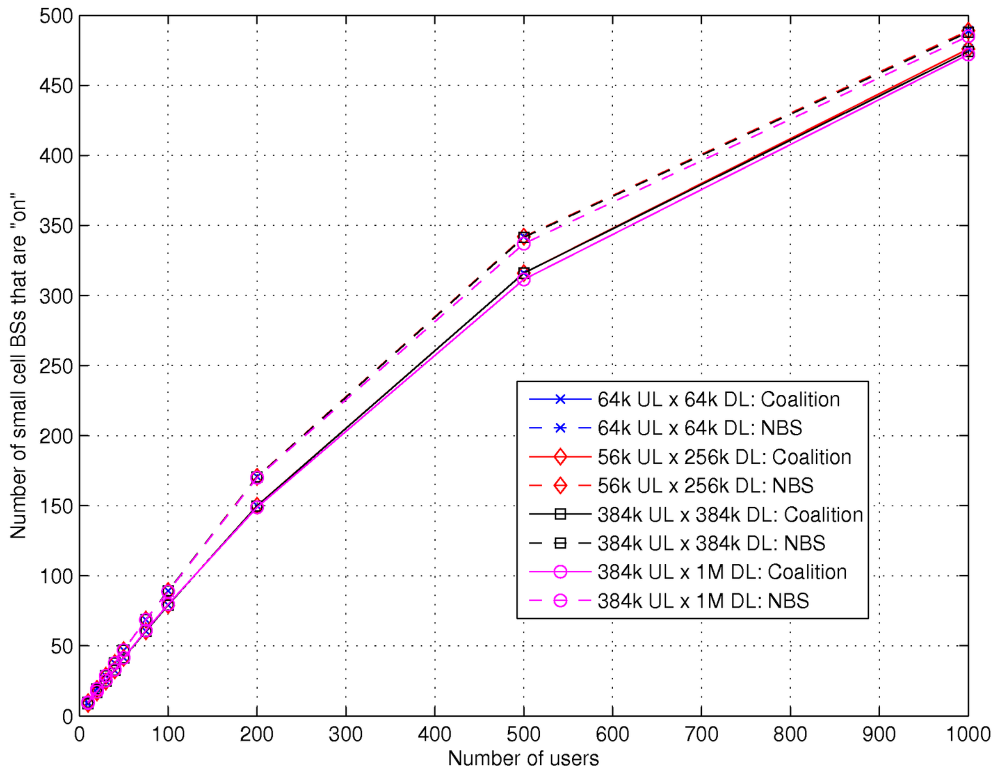


Figure 5. Number of small cell BSs that are "on" using the utility (24)



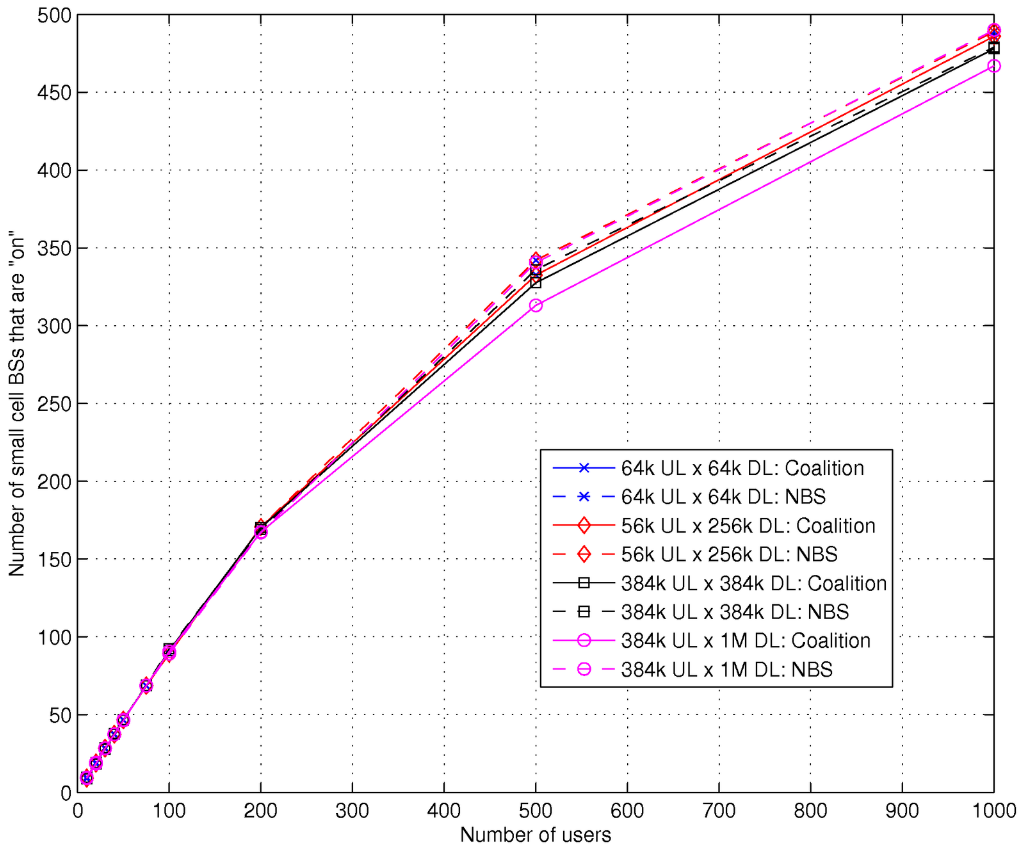
it should be noted that the utility in (26) leads to a slightly worse outage performance, since it is not explicitly dependent on $N_{out,l}$, conversely to the utility in (24), which is highly dependent on the increase of the number of users in outage.

On the other hand, the utility in (26) is more sensitive to the power consumption. This is clearly seen in Figures 3 to 8, where, although the number of active small cell BSs is comparable between the two utilities (see Figures 5 and 6), the number of active macrocell BSs is obviously less with the utility in (26), as it is shown by comparing Figures 3 and 4. This is particularly true with the coalitional game theoretic approach, where power consuming macrocell BSs are replaced by lower power small cell BSs, to an extent that the number of active macrocell BSs is zero most of the time. This is due to the "altruistic" behavior of BSs in the coalitional model, where the players act in the interest of the coalition as a whole.

In the NBS case, where each player "bargains" to increase its own utility, the overall performance becomes worse than the coalition scenario. This translates into a higher number of active macro and small cell BSs, and a higher power consumption, although large gains are achieved compared to the "traditional" scenario where no BSs are switched-off: in such a scenario, the network power consumption in the simulated model is around 75 kW, even when the number of users is reduced.

In the following section, we analyze the performance in the scenario where D2D communications are used in the network to enhance the energy efficiency for both BSs and MTs.

Figure 6. Number of small cell BSs that are "on" using the utility (26)



Green Networking Results with D2D

This section describes the proposed method based on joint D2D offload and green networking through BS switch off. First, D2D clustering is performed according to Algorithm 2 in order to reduce the number of LR links connected to BSs. Then, Algorithm 1 is implemented, considering that only CHs need to be handed over to neighboring BSs in order to put their serving BS into sleep mode.

Figure 11 shows the BS energy consumption results in the simulated area. The scenarios without green communications, where all BSs are active, correspond to a power consumption of 75 kW when all BSs are MP-BSs, and of 43.75 kW when RE-SCBSs are used with $\eta = 0.5$, regardless of the number of users. They are not plotted for clarity purposes. Figures 12 and 13 show the number of active MBSs and SCBSs, respectively. The results of Figure 11 show that implementing Algorithm 1 ("Green Hetnet") leads to significant energy savings. Furthermore, the use of RE-SCBSs (denoted "Green Hetnet + renewable energy small cells (RESC)" in the figures) leads to large gains compared to the scenario where only MP-BSs are used, especially when the number of users increases, i.e., when the load in the network becomes high. Moreover, D2D traffic offloading, i.e., the implementation of Algorithm 3, consisting of the sequential implementation of Algorithms 2 and 1 (case "Green Hetnet + D2D" without RE-SCBSs and "Green Hetnet + RESC + D2D" when RE-SCBSs are available), leads to additional energy savings. The largest savings are obtained when D2D traffic offloading is combined with green BS switch-off

Figure 7. Network power consumption with the utility (24)

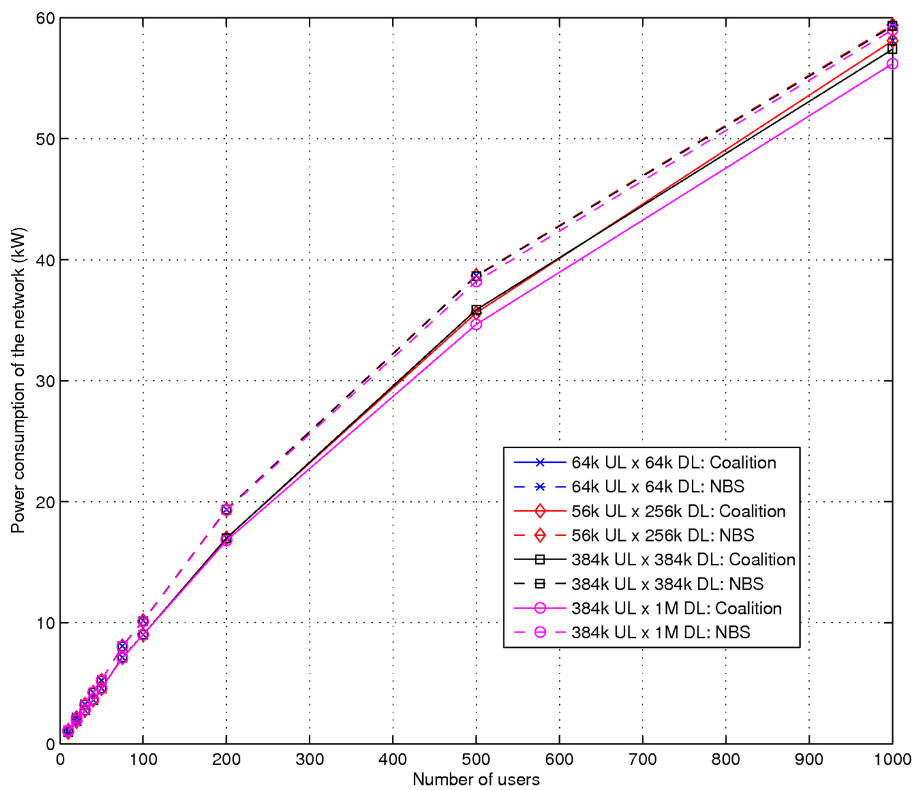


Figure 8. Network power consumption with the utility (26)

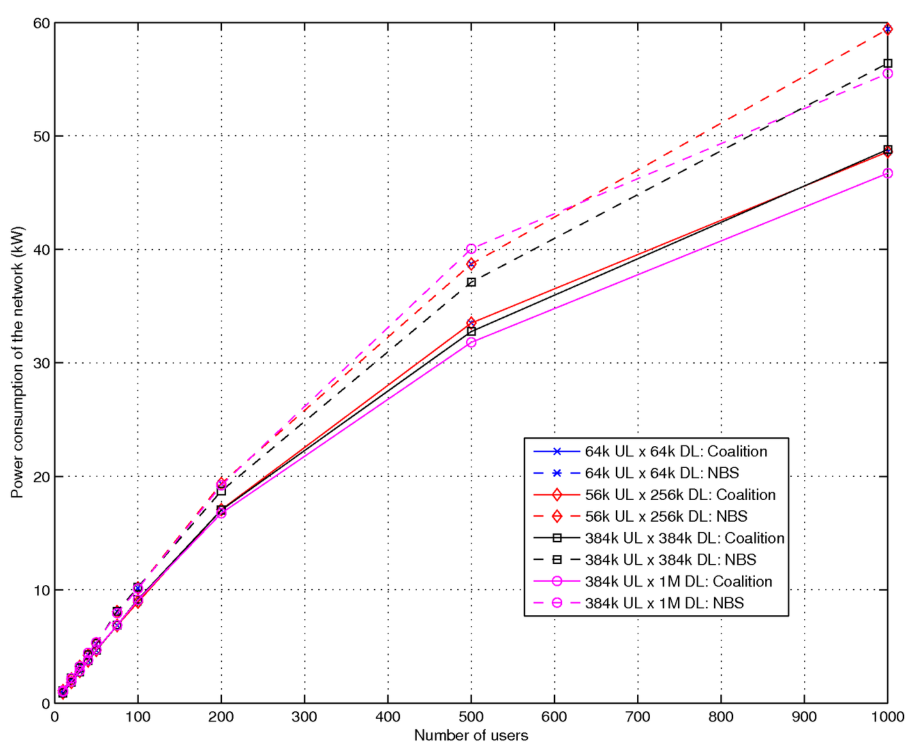


Figure 9. Percentage of users in outage with the utility (24)

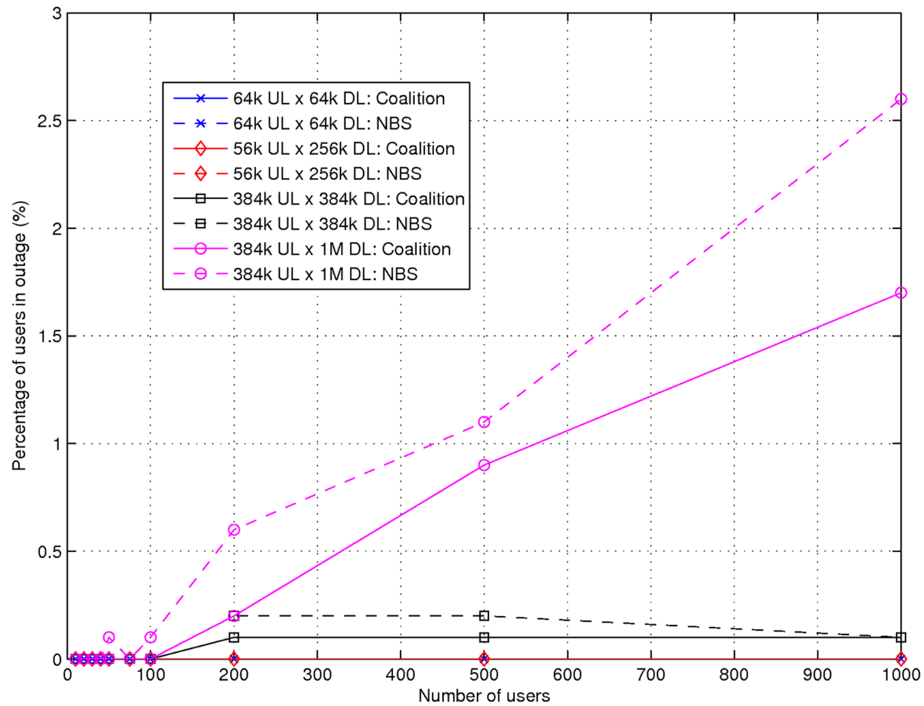


Figure 10. Percentage of users in outage with the utility (26)

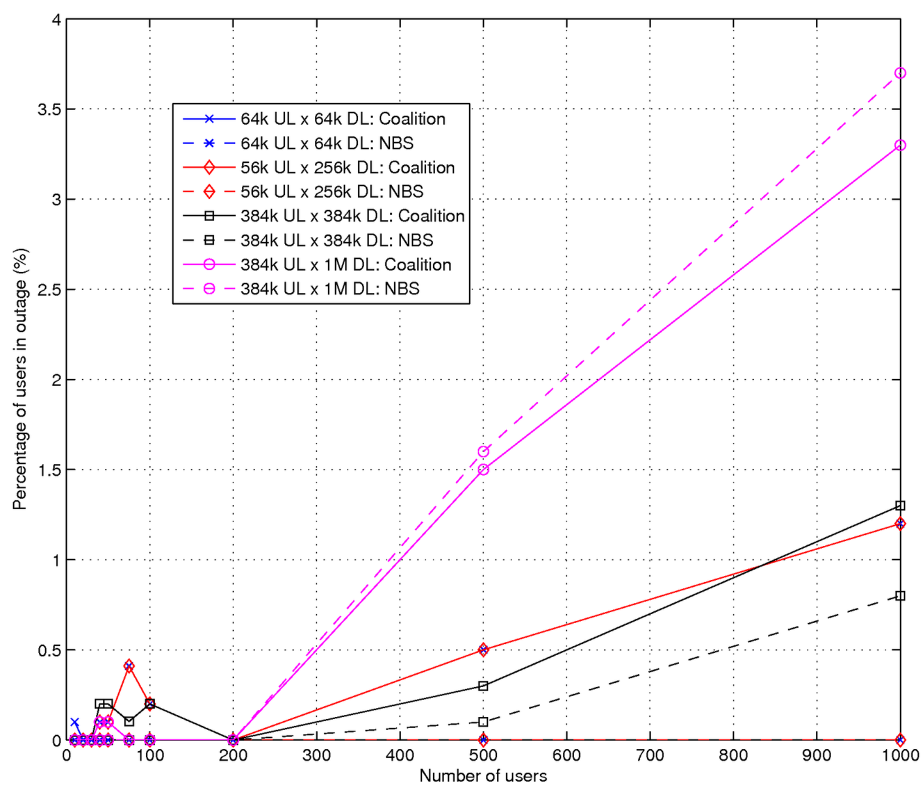


Figure 11. BS power consumption

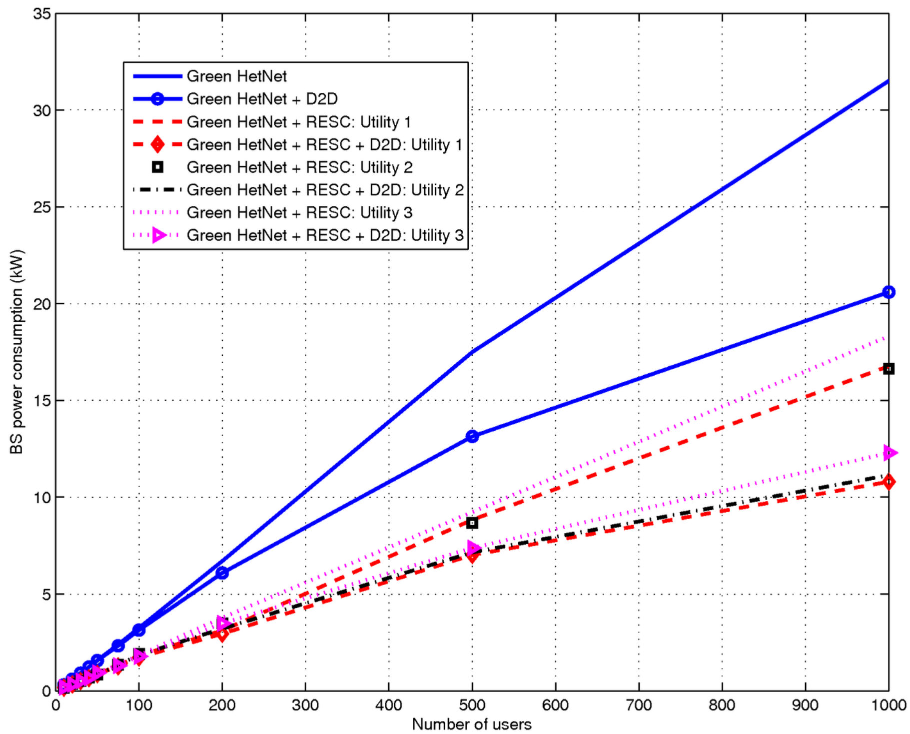


Figure 12. Number of macrocell BSs (MBSs) that are "on"

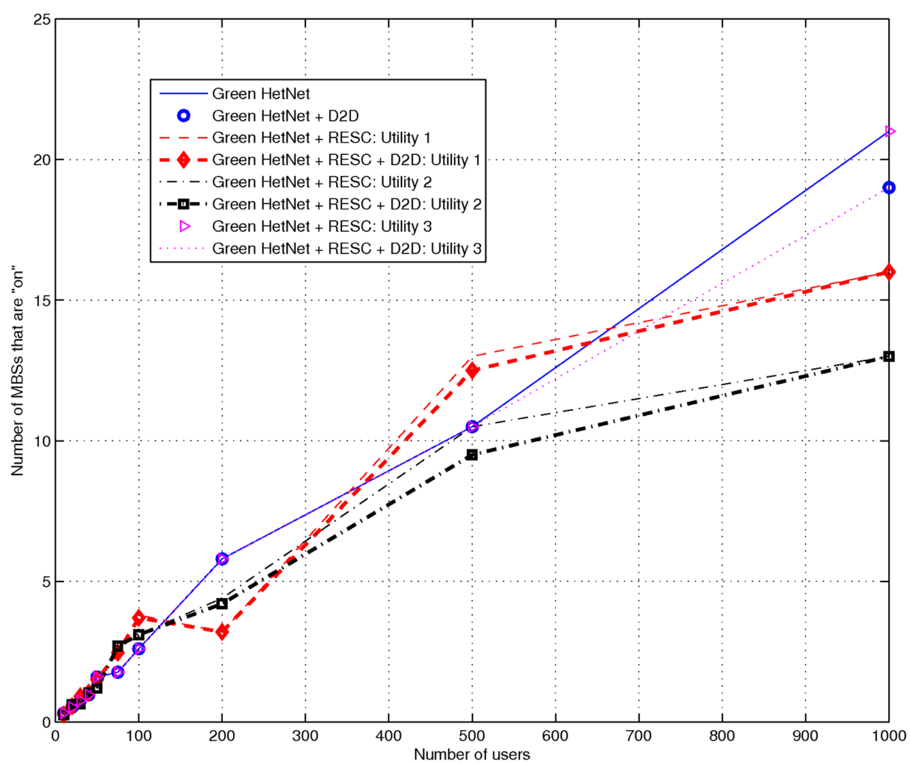
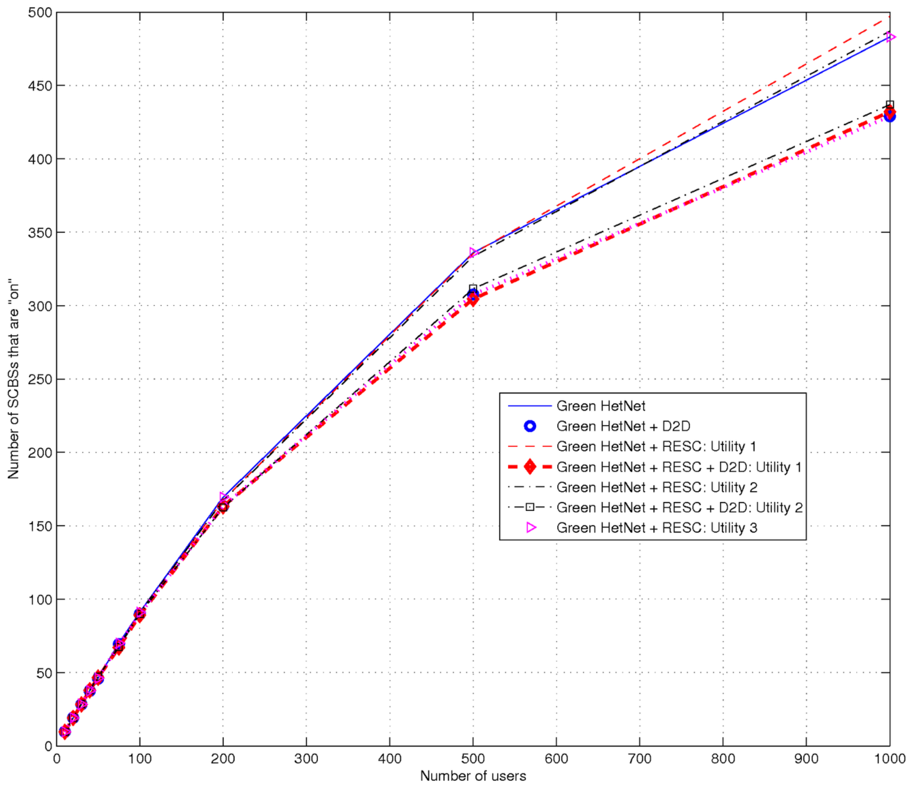


Figure 13. Number of small cell BSs that are "on"



techniques in the presence of RE-SCBSs. Indeed, with 1000 users, the power consumption with the scenario "Green Hetnet + RESC + D2D" is around 10 kW, with savings of more than 85% compared to the traditional scenario where all BSs are on without D2D offload (having a consumption of 75 kW).

The MT power consumption is shown in Figure 14. It can be seen that the use of D2D communications according to Algorithm 2 leads to energy savings. Figure 15 shows the minimum data rates in the network, i.e., the data rates of the MT that is the last to finish receiving the content. It can be seen that when D2D clustering is implemented, the data rates increase in the network. In fact, CHs that are selected according to Algorithm 2 have relatively high LR data rates, in order to minimize (31). Due to the short distances during D2D communications, higher data rates can be achieved compared to the case where the MTs receive the content directly from the BS. Hence, the energy savings obtained by implementing the proposed approach do not cause any QoS degradation, but rather an increase in the data rate of the MTs.

Comparing the performance of the three utilities in Figures 11 to 15, it can be seen that Utility 1 leads to the lowest BS energy consumption (Figure 11), whereas the three utilities have comparable performance in terms of MT energy consumption (Figure 14). Hence, performing a single coalition between BSs and MTs leads to the best results. This validates the conclusion reached in the previous section: cooperation leads to gains for all involved players within the proposed game theoretical framework. It should be noted that from Figures 12 and 13, it can be seen that the number of active macro and small cell BSs with Utility 1 is not always less than the scenarios with Utilities 2 and 3. However, the implementation of Algorithms 1 and 3 leads to a judicious selection of active BSs by letting more RE-SCBSs be active

Figure 14. MT power consumption in the network

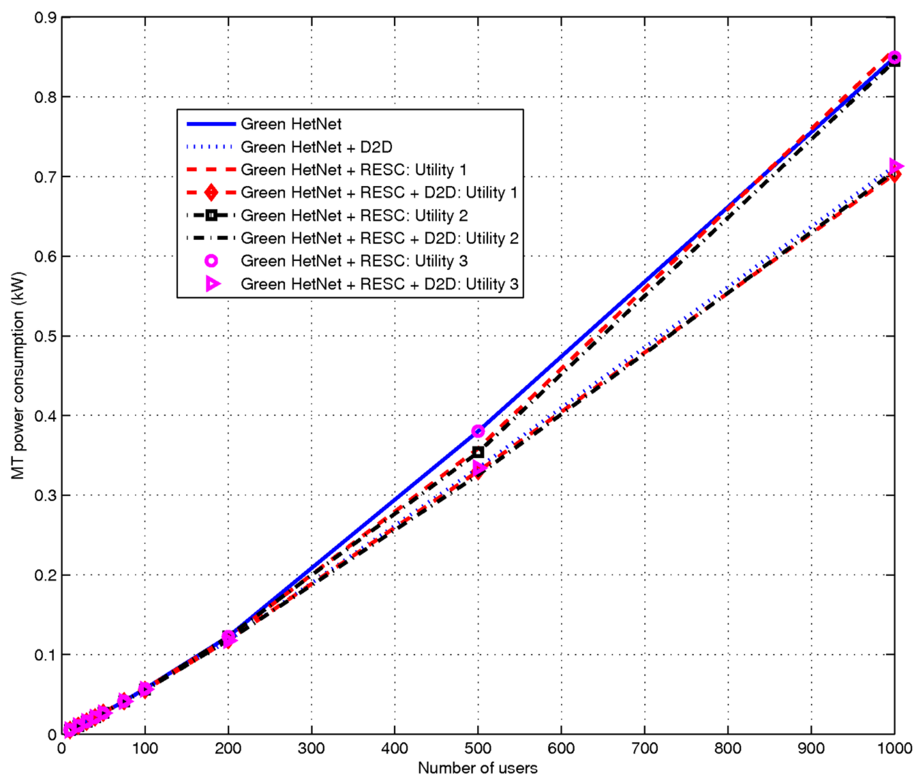
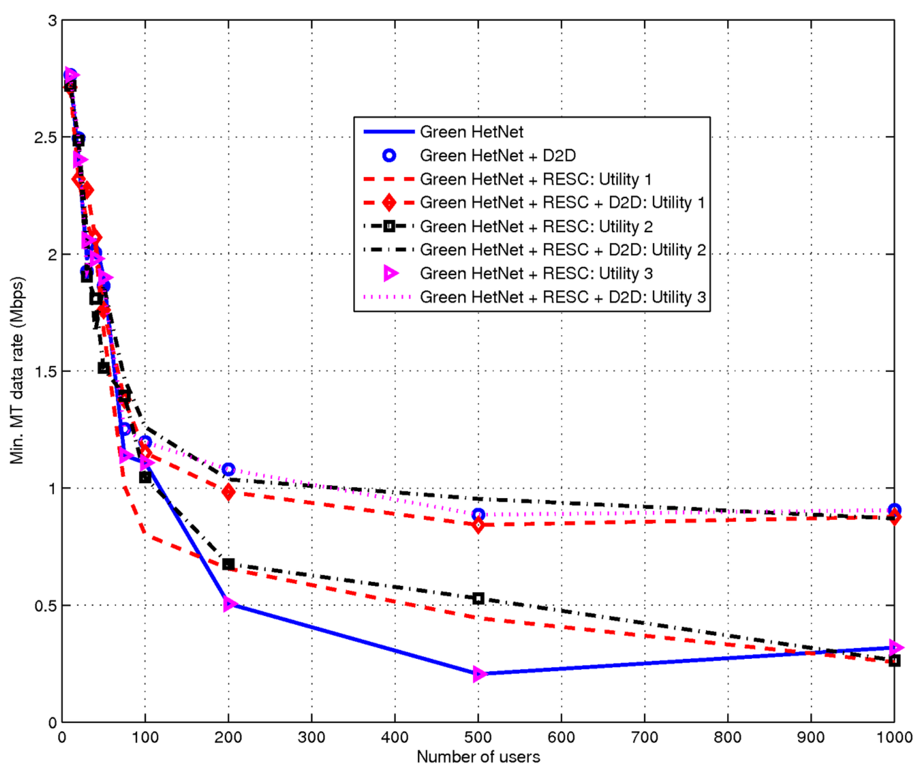


Figure 15. Minimum data rate achieved by MTs in the network



and reducing the number of MP-BSs. This is due to the "altruistic" behavior of Utility 1, which allows RE-SCBSs to be active for the benefit of the network, which optimizes performance. The "selfishness" in the NBS solution to the competition between cells in Utilities 2 and 3 reduces the gains, since RE-SCBSs in this case attempt to maximize their own cell utility, regardless of the fact that their energy costs are much less than for MP-BSs.

CONCLUSION

A game theoretical framework was proposed for ensuring green energy efficient communications in heterogeneous LTE cellular networks. Two game theoretic concepts were studied within this framework: a coalition-based approach and a competition approach based on the Nash bargaining solution. Within each approach, the tradeoffs between QoS and energy consumption were investigated, depending on the utility selected. In fact, the game theoretic techniques were implemented with utilities focusing either on traffic load and QoS, or on the QoS versus the consumed power in the network. The game theoretical framework was then extended to a scenario with device-to-device communications, where energy aware coordination between mobile devices and the cellular network infrastructure was investigated. The purpose is to reach a green cellular network through the joint use of device-to-device communications and small cell base stations powered by renewable energy. The benefits of traffic offloading and energy savings were captured by balanced utility functions that take into account the role of all components in the network: the cellular BSs handling long range communications and the collaborating devices communicating via device-to-device communications. The results showed significant energy savings in the network, in addition to savings for the mobile devices, without compromising their QoS, especially when cooperative utilities involving coalitions between the various network entities (base stations and mobile terminals) were adopted.

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KEY TERMS AND DEFINITIONS

Device-to-Device Communications: Technique whereby mobile terminals can communicate directly with each other whenever they are in proximity without relying on base stations for routing their traffic.

Green Communications: Approach to achieve energy efficiency in the network by reducing the redundant power consumption whenever possible.

Heterogeneous Networks: Networks consisting of a combination of macrocells and small cells.

LTE: Long Term Evolution. It is the state of the art cellular system being deployed for commercial cellular communications.

LTE-A: Long Term Evolution - Advanced.

OFDMA: Orthogonal Frequency Division Multiple Access. It is the accessing scheme used for LTE downlink. It consists of subdividing the bandwidth into a large number of subcarriers, each having a small bandwidth where the fading can generally be considered flat.

Quality of Service (QoS): Measure to assess the network performance.

Radio Resource Management: Algorithms and techniques to allocate the wireless resources and set certain parameters of the wireless system depending on the channel characteristics and interference levels, with the objective of optimizing the network performance.

SCFDMA: Single Carrier FDMA. It is the accessing scheme used for LTE uplink. It is a modified form of OFDMA that allows the subcarriers to be transmitted sequentially rather than in parallel. Its main advantage is a reduction in the signal peak to average power ratio (PAPR), which allows cheaper power amplifiers to be used in LTE handsets (UEs).