Energy Efficiency Improvements in HetNets by Exploiting Device-to-Device Communications

Yusuf A. Sambo, Muhammad Z. Shakir, Khalid A. Qaraqe, Erchin Serpedin, Muhammad A. Imran, and Beena Ahmed

***Abstract*—The growth in mobile communications has resulted in a significant increase in energy consumption and carbon emissions, which could have serious economic and environmental implications. Consequently, energy consumption has become a key criterion for the design of future mobile communication systems. Device-to-device (D2D) communication has been shown to improve the spectral efficiency and also reduce the power consumption of mobile communication networks. In this paper, we propose a two-tier deployment of D2D communication within a network to reduce the overall power consumption of the network and compared it with full small-cell deployment throughout the network. In this context, we computed the backhaul power consumption of each link in the networks and derived the backhaul energy efficiency expression of the networks. Simulation results show that our proposed network deployment outperforms the network with full small-cell deployment in terms of backhaul power consumption, backhaul energy-efficiency, total power consumption of the tier 2 users and downlink power consumption, thus providing a greener alternative to small-cell deployment.**

***Index Terms*—D2D communication; small-cells; backhaul; power consumption; and energy efficiency.**

I. Introduction

The quest for higher data rates has led to the development of heterogeneous networks (HetNets), where low power small base stations (SBSs) such as femtocell, pico cells and relays, are deployed within a macrocell to improve the spectral efficiency (SE) of cellular networks and address network coverage issues. SBS deployments ensure better transmission quality due to the short distance between the small-cell users and the SBSs, thus, improving the network SE [1, 2]. Moreover, femtocell deployment has been shown to be more energy-efficient due to the short transmitter-receiver distance [3, 4]. The authors in [5] proposed a heterogeneous deployment of femtocells around the cell-edge of a macrocell to improve the area spectral efficiency (ASE) of the network. However, mobile communications is projected to contribute over half of the carbon footprint of the telecommunications industry by 2020 [6]. This implies massive deployment of small-cells in the network could result in a significant increase in the power consumption of the network resulting in higher operational expenditure (OPEX) and CO_2 emissions. Hence, there is need for other techniques of improving capacity and reducing the power consumption of mobile communication networks.

Another promising way of increasing the achievable rate in cellular communications is direct communication between closely located users, termed device-to-device (D2D) communication [7, 8]. Mobile devices involved in D2D communication form a direct link with each other without the need of routing data via the cellular access network, resulting in lower transmit power and end-to-end delay, as well as freeing network resources. The lower transmit powers bring about reduced interference levels in the system and battery power savings, while the improved rate is as a result of the low path-loss between any pair of devices involved in the D2D communication. D2D communication also exhibits the gains of offloading traffic from the core network, usage of both uplink and downlink resources and extending the coverage area of cellular networks. Due to the nature of D2D communication, there is no need for any backhaul because mobile devices engaged in D2D communication form a direct link between them without the need for routing the traffic via the access network. However, the D2D communication devices would still need some form of signaling, especially during D2D communication setup [9].

In this context, we propose in this paper, a two-tier network deployment where D2D communication is introduced within a macrocell to improve the SE of the network, such that a percentage of the mobile users engage in D2D communication while the remaining are connected to the macrocell BS. D2D communication signaling could either be through the macrocell or Wi-Fi. This deployment setting is compared with that of a uniform small-cell deployment throughout the macrocell in terms of backhaul power consumption, backhaul energy efficiency of the network and the uplink power consumption of the tier 2 network. Simulation results show that D2D communication has much lower total power consumption and achieves higher backhaul energy efficiency.

The rest of this paper is organized as follows. Section II describes the system model. In Section III, we calculate the backhaul power consumption of the networks and the backhaul energy-efficiency. Section IV presents the performance analysis of the network and discussions. Finally, Section V concludes the paper.

II. System Model

In this section, we describe the network architecture, spectrum partitioning and channel allocation and power control of the proposed network model.

A. Network Architecture

Consider a network with $U = \mu\pi(R_m^2 - R_0^2)$ users distributed between R_0 and R_m, where R_m is the macrocell radius, R_0 is minimum distance between a mobile user and the macrocell BS and μ is the user distribution per m^2 throughout the network. We consider the mobile users to be mutually independent and uniformly distributed throughout the macrocell. Hence, the probability density function (PDF) of a macrocell mobile user with polar coordinate (r, θ)

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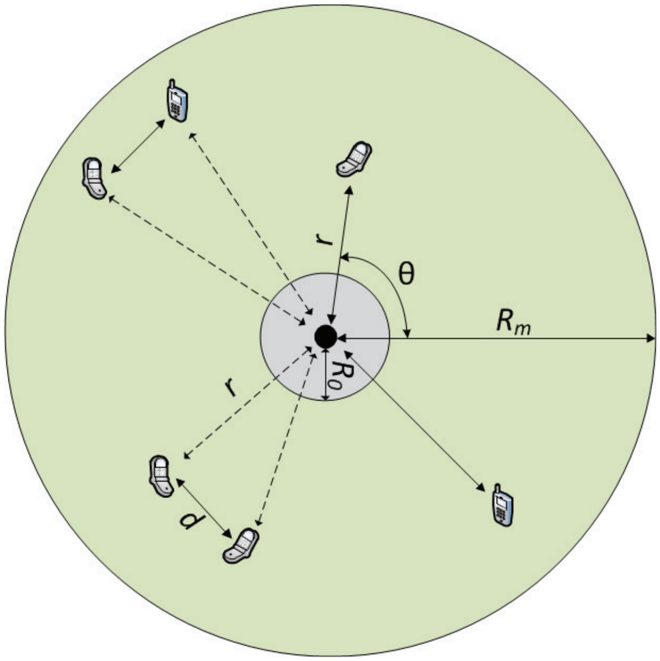

Figure 1. Network diagram showing a network consisting of a macrocell, and D2D communication links. The solid lines represent data traffic path while the dashed lines represent signaling.

relative to its serving BS is:

$$p(r) = \frac{2(r-R_0)}{(R_m-R_0)^2}, P(\theta) = \frac{1}{2\pi}, \tag{1}$$

where $R_0 \leq r \leq R_m$ and $0 \leq \theta \leq 2\pi$.

Moreover, $M = \mu_m U$ randomly distributed users within the macrocell are connected to the macrocell BS. Here, μ_m is a parameter that gives the percentage of the users that are connected to the macrocell BS and it is assumed to be 20% in this paper. The remaining $D = U - M$ users are assumed to engage in D2D communication such that the distance between any two communicating D2D communication users is d [m], as shown in Fig. 1. The D2D communication users exchange signaling information with the macrocell BS or Wi-Fi access points within the network.

Now consider a scenario where instead of having D2D communication users in the network, we have small-cells (femtocells) uniformly distributed across the whole macrocell. Similar to the network with D2D communication, M randomly distributed users within the macrocell are connected to the macrocell BS, while the remaining users are served by the small-cells. The number of small-cells in both deployment scenarios can be calculated as:

$$N = \left\lceil \frac{U-M}{Z} \right\rceil, \tag{2}$$

where $Z = \mu\pi R_s^2$ denotes the number of users in each small-cell, such that R_s represents the radius of a small-cell. Here, $\lceil x \rceil$ is the smallest integer not less than x. Likewise, the PDF of a small-cell user with polar coordinate $(\tilde{r}, \tilde{\theta})$ from its serving SBS is given by:

$$p(\tilde{r}) = \frac{2\tilde{r}}{R_s^2}, P(\tilde{\theta}) = \frac{1}{2\pi}, \tag{3}$$

where $0 \leq \tilde{r} \leq R_s$, $0 \leq \tilde{\theta} \leq 2\pi$.

B. Spectrum Partitioning and Interference Coordination

We assume a dedicated carrier deployment in the network, where the macrocell users, small-cell users and D2D communication users operate on separate bandwidths based on the number of users they contain. Let the total available spectrum be w_t, it implies that

$$w_t = w_m + w_d, \tag{4}$$

for the network with D2D communication and

$$w_t = w_m + w_s, \tag{5}$$

for the network with full small-cell deployment, where $w_m = w_t(M/U)$ [Hz] is the dedicated spectrum of the macrocell, $w_d = w_t(D/U)$ [Hz] is the dedicated spectrum of the D2D communication users and $w_s = w_t(ZN/U)$ [Hz] is the total dedicated spectrum of the small-cells. The number of channels in both the macrocell and the small-cells are assumed to be equal to the number of users they contain and each channel is allocated to a single user [3].

Hence, interference received at the macrocell BS is from mobile users in each of the neighboring co-channel macrocells that are transmitting on the same channel. Similarly, in the uplink of the small-cells, interference is assumed to be from a co-channel user in each of the neighboring small-cells. While interference in each D2D communication link is assumed to be from the closest D2D communication user that is not part of that communication link. This assumption was made because mobile devices engaged D2D communication usually transmit with very low power which brings about reduced interference.

C. Power Control

Transmission with maximum power often results in a higher level of co-channel interference at the neighboring co-channel BSs. This leads to poor received signal to interference plus noise ratio (SINR) of the desired mobile user at the reference BS. Hence, power control is needed to achieve a uniform SINR of mobile users at the reference BS in the uplink, such that each mobile user is allowed to transmit with just enough power to neutralize the effect of the path-loss between the mobile user and its serving BS. However, at long distances, the mobile user would have to transmit at full power to overcome the effect of path-loss. Accordingly, mobile users closer to the BS would transmit with lower power because of the lower path-loss. Consequently, power control reduces the interference received from the mobile users in neighboring cells and allows for concurrent mobile user transmissions throughout the network [10, 11].

In D2D communication, power control is needed to regulate the transmit power levels of the devices because the path-loss is usually low and transmission with full power would lead to a high interference regime and power wastage, thus defeating the purpose of D2D communication.

All users in the network are assumed to transmit with an adaptive power while maintaining a certain received signal threshold. The adaptive transmit power is based on the two-slope path-loss model [12] and is given as:

$$P^{tx} \text{ [W]} = \min\Big(P_{\text{u}}, P_0\big(10^{PL(r)/10}\big)\Big), \tag{6}$$

where

$$PL(r) \text{ [dB]} = 10\log_{10} r^{\alpha} + 10\log_{10}(1+r/g)^{\beta} - 10\log_{10}\Gamma \tag{7}$$

is the path-loss of a mobile user, P_{u} [W] is the maximum transmit power of a mobile device, P_0 [W] is the received signal power threshold, α is the basic path-loss exponent, β denotes the additional path-loss exponent and Γ stands for the path-loss dependent constant. The parameter $g = \frac{4H_{bs}H_u}{\lambda_c}$ [m] is the break point of the path-loss curve, H_{bs} [m] represents the BS antenna height, H_u [m] denotes the mobile user antenna height and λ_c [m] stands for the wavelength of the carrier frequency. For D2D communication, $H_{bs} = H_u$ because the height of the mobile users are assumed to be equal, the path-loss exponents are the same with those of the small-cells and $r = d$ in (6) and (7).

III. Backhaul Energy Analysis

In this section, we analyse the backhaul energy consumption of the networks in terms of backhaul power consumption and backhaul energy efficiency.

A. Backhaul Power Consumption

The backhaul power consumption, which is the power needed to carry user traffic to the core network, depends on the type of deployment and the small-cell technology used. D2D communication has no backhaul power requirement because D2D communication user traffic is not routed to the core network, as the mobile users engage in direct communication without the need for any intermediary nodes. As a result of this, the total backhaul power requirement of the network with D2D communication is simply the backhaul power requirement of the macrocell BS, which is expressed as [13]:

$$P_{bh}^{macro} = \left\lceil \frac{1}{\max_{dl}} \right\rceil P_s + P_{dl} + I_{ul} P_{ul} \tag{8}$$

where $\max_{dl}$ represents the maximum number of downlink interfaces at the macrocell BS aggregation switch and it is used to compute the number of aggregation switches needed, P_{dl} denotes the power consumed by a downlink interface at the macrocell aggregation switch which is used to receive the backhaul traffic. Moreover, I_{ul} and P_{ul} represent the total number of uplink interfaces and the power consumption of one uplink interface, respectively. The number of uplink interfaces can be obtained from [13] as:

$$I_{ul} = \left\lceil \frac{C_{agg}}{T_{max}} \right\rceil, \tag{9}$$

where C_{agg} is the aggregate traffic at the macrocell BS switch(es) and T_{max} is the maximum transmission rate of an uplink switch. The term P_s denotes the power consumption of the aggregation switch, and it is expressed as:

$$P_s = \Phi P_{max} + (1 - \Phi) \frac{C_{agg}}{C_{switch}^{max}} P_{max} \tag{10}$$

where P_{max} is the maximum power consumption of the switch, C_{switch}^{max} represents the maximum traffic that the switch can carry, and Φ stands for the weighting factor [13].

We assume that the traffic from the small-cells (femtocells) is routed straight to the core network via the Internet, without going through the aggregation node at the macrocell BS. Hence, the access network of the small-cells is assumed to be a passive optical network (PON). A single fiber cable from the core network which serves a group of small-cells is fed into an optical line terminal (OLT) which may be located at the local exchange. A passive curb at the local exchange splits the fiber cable from the OLT into several fibers, each connected to an optical network unit (ONU). Each ONU then serves a single small-cell. The OLTs are connected to edge routers which serve as the small-cell gateways for transmission to the core network. The power consumption of the small-cell backhaul can be expressed as follows:

$$P_{bh}^{sc} = \left\lceil \frac{N}{K} \right\rceil \left[\frac{P_{router}}{40} + P_{OLT} \right] + N \times P_{ONU} \tag{11}$$

where $K = 4$ Gbps$/C_s$ denotes the number of ONUs that connect to one OLT such that C_s represents the total traffic of the small-cells, P_{OLT} denotes the power consumption of the OLT, P_{ONU} stands for the power consumption of the ONU [14] and P_{router} represents the power consumption of the edge router and it can support up to 40 OLTs [15].

B. Backhaul Energy Efficiency

The backhaul energy efficiency (BEE) which shows the energy utilization of the backhaul technology used has become a key performance indicator for future mobile communication systems. It is given as the maximum amount of bits that can be transmitted per Joule of energy consumed by the backhaul network, measured in bit/Joule [16]. The BEE is important especially when choosing the type of backhaul technology to use during network planning to bring down the operational expenditure (OPEX) of the network. The BEE is expressed as:

$$BEE = \frac{C}{P^{net}}, \tag{12}$$

where C is the achievable throughput of the network and P^{net} represents the resultant backhaul power consumption of the network, which is the sum of the power consumption of the backhaul network and the downlink power consumption and it is given as:

$$P^{net} = P_{bh}^{macro} + P^{macro} + P^{D2D}, \tag{13}$$

for the network with D2D communication, where P^{D2D} represents the total transmit power of the D2D communication users. The total power consumption of the full small-cell network is expressed as:

$$P^{net} = P_{bh}^{macro} + P_{bh}^{sc} + P^{macro} + NP^{sbs}, \tag{14}$$

where

$$P^{macro} = \Delta_m P_{mbs} + P_{mbs,0}, \tag{15}$$

and

$$P^{sbs} = \Delta_s P_{sbs} + P_{sbs,0} \tag{16}$$

denote the power consumption of the macrocell BS and the power consumption of each small-cell BS, respectively. The parameters Δ_m and Δ_s represent the slope of the load dependent power consumption of the macrocell BS and a small-cell BS, respectively, while P_{mbs} and P_{sbs} denote the transmit power of the macrocell BS and a small-cell BSs, respectively. Furthermore, $P_{mbs,0}$ and $P_{sbs,0}$ denote the overhead power consumption of the macrocell BS and a small-cell BS, respectively [17].

IV. Performance Results and Discussions

In this section, we compare the performances of the proposed network with D2D communication against the network with full small-cell deployment in terms of the backhaul power consumption and the BEE. The simulation parameters are summarized in Table I.

In Fig. 2, we first compare the backhaul power consumption of the proposed network with D2D communication against network with full small-cell deployment by assuming the throughput as constant and varying the macrocell radius from $R_m = 300$ m to $R_m = 800$ m. Fig. 2 indicates that the network with D2D communication has significantly lower

Table I
BACKHAUL POWER CONSUMPTION SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
P_{max} [W]	300	P_{dl} [W]	1
P_{router} [kW]	4	P_{OLT} [W]	100
P_{ONU} [W]	4.69	P_{ul} [W]	2
T_{max} [Gbps]	10	max_{dl}	24
C_{switch}^{max} [Gbps]	24	Φ	0.9
P_{mbs} [W]	20	P_{sbs} [W]	0.05
$P_{mbs,0}$ [W]	354.44	$P_{sbs,0}$ [W]	4.8
P_{u} [W]	0.8	P_0 [μW]	0.8
R_s [m]	25	R_0 [m]	10
Δ_m	21.4	Δ_s	7.5
$\alpha_m = \beta_m$	2.1	$\alpha_s = \beta_s$	1.8
H_{bs} (macro) [m]	25	H_{bs} (SBS) [m]	5
H_u [m]	2	Γ	1
μ [user/m^2]	0.003	λ_c [m]	0.125

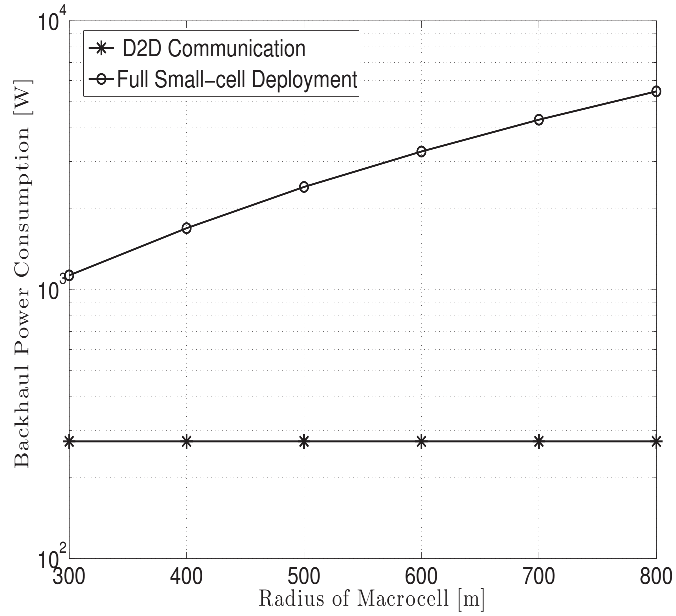

Figure 2. Backhaul power consumption comparison of the network with D2D communication against full small-cell deployment.

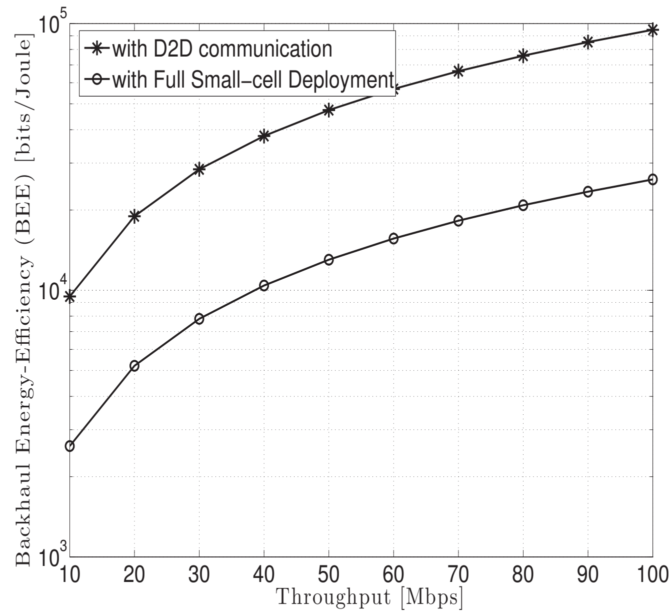

Figure 3. Backhaul energy-efficiency comparison of D2D communication against full small-cell deployment for fixed macrocell radius of $R_m = 500$ m.

backhaul power consumption compared to the network with full small-cell deployment. This is because D2D communication users have no need for any backhaul network to convey their traffic to the core network and only the macrocell users have their traffic carried by the backhaul network from the macrocell BS to the core network. On the other hand, the backhaul power requirement of the network with full small-cell deployment increases as the radius of the macrocell increases. This is as a result of the increase in the population of small-cells in the network as the macrocell radius increases and each small-cell has its own backhaul power requirement. It is evident that the network with full small-cell deployment has about 4 to 20 times higher backhaul power consumption than that of the network with D2D communication, depending on the radius of the macrocell.

In Fig. 3 we show the BEE comparison of the network with D2D communication and full small-cell deployment. The radius and the throughput of the macrocell were fixed at $R_m = 500$ m and $C_{agg} = 5$ Mbps, while the total throughput of the network was varied from 10 Mbps to 100 Mbps. It can be seen that the BEE of both networks increases as the throughput of the network increases. This is because the BEE is a function of through put and the total power consumption of the backhaul network. The BEE of the network with D2D communication is at least 260% higher than that of the network with full small-cell deployment. The higher BEE of the D2D communication is due to the lack of backhaul power consumption for the D2D communication users and only the macrocell users' traffic is backhauled to the core network. However, the backhaul power consumption of each small-cell in the network with full small-cell deployment has to be considered in calculating the BEE which results in a lower BEE of the network.

Fig. 4 depicts the total transmit power comparison of the tier 2 D2D communication users and small-cell users against the macrocell radius. It evident that the D2D communication users have a lower transmit power compared to the small-cell user. The lower transmit power is due to the shorter transmitter-receiver link in D2D communication relative to the small-cell access distance and the mobile users transmit with just enough power to overcome the effect of path loss using power control. The D2D communication users achieve up to 250% transmit power reduction at a macrocell radius of 600 m, compared to the small-cell users. However, the sum transmit powers of both schemes increases, which is due to increase in the number of users as a result of the increase in the macrocell radius.

In Fig. 5, we show the downlink power consumption comparison of the network with D2D communication and the network with full small-cell deployment against the macrocell radius. It can be observed that the full small-cell network has a much higher downlink power consumption and it increases as the macrocell radius increases. This is as a

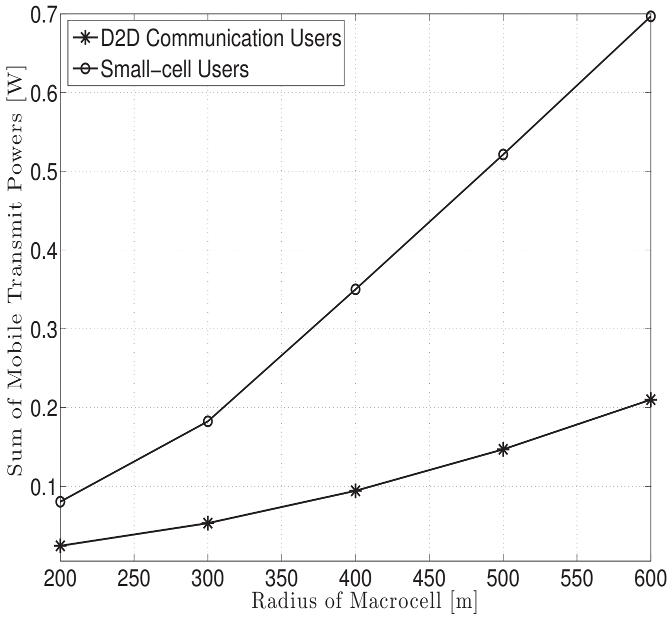

Figure 4. Tier 2 uplink sum transmit power comparison of D2D communication against full small-cell deployment.

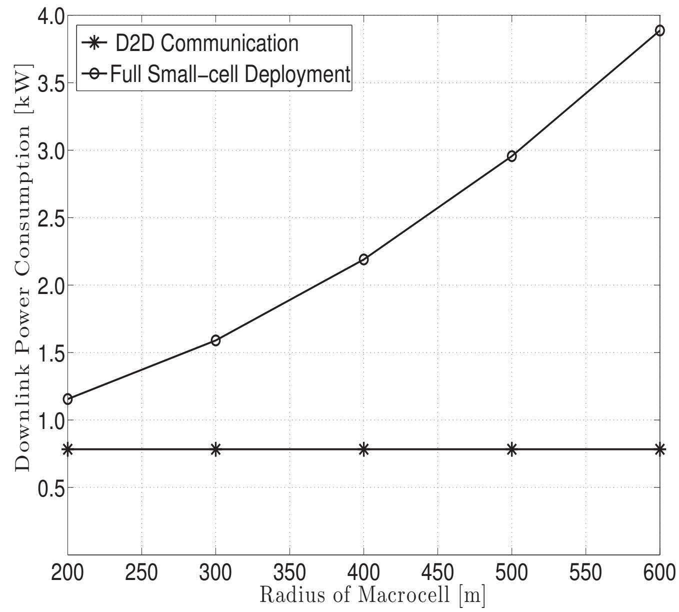

Figure 5. Downlink power consumption comparison of D2D communication against full small-cell deployment.

result of the increase in the population of the small-cells in the network as the radius of the macrocell increases. Although the downlink power consumption of the network with D2D communication appears to be constant, there is a marginal increase in the downlink power consumption due to increased user population as the macrocell radius increases. It is evident that the network with D2D communication achieves a downlink power consumption reduction of up to 400% at a macrocell radius of 600 m. Even though the transmit power of the D2D communication users is very low, transmissions over long periods of time (as is the case with mobile multi-player gaming) may have significant effect on the battery life of the D2D communication terminals.

V. Conclusion

In this paper, we have proposed and analyzed the energy consumption gains of incorporating D2D communication in mobile communication networks. The proposed deployment was compared with full small-cell deployment in terms of the backhaul power consumption, backhaul energy efficiency and the total transmit power of the tier 2 networks. Simulation results show that the proposed deployment outperforms the full small-cell deployment by reducing the backhaul power consumption of the network which increases the backhaul energy efficiency of the network. Moreover, the smaller transmitter-receiver distance in D2D communications reduces the total uplink transmit power of the tier 2 mobile users.

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