Performance Evaluation of Energy Efficiency with Sleep Mode in Ultra Dense Networks

Hansong Xu*, Wei Yu*, Amirshahram Hematian*, David Griffith† and Nada Golmie†
* Towson University, Emails: {hxu2,ahemat1}@students.towson.edu, wyu@towson.edu
† National Institute of Standards and Technology, Emails:{david.griffith,nada.golmie}@nist.gov

***Abstract*—The Ultra Dense Network (UDN), as one of key techniques in 5G, is expected to support massive connections and offload the intense volume of data traffic. Nonetheless, the small cell BS density raises the issue of energy efficiency, especially when data transmission is not frequent in a certain time or location. One effective approach to reduce energy consumption is to leverage the BS sleep mode, which disables energy hungry functions and components. In this paper we examine existing energy efficiency schemes, and introduce schemes in the context of UDN. Furthermore, we implement and compare various representative schemes in the UDN scenario via simulation. Through extensive experimentation, we demonstrate the effectiveness and limitations of these schemes, comparing energy consumption and end-to-end delay performance.**

***Keywords*—5G, Ultra Dense Networks, Sleep Mode, Energy Efficiency, Performance Evaluation**

I. Introduction

As one of the main enablers in the 5G technologies, the Ultra Dense Network (UDN) leverages the small cell Base Station (BS), high density deployment, and user-driven deployment. The primary characteristic of UDN, the high density deployment of small cell BSs, is designed to reduce cell size (communication distance) and improve channel quality, spatial reuse, and network capacity [4], [17] and has a great potential to support Internet of Things applications [3], [15]. Research efforts towards the energy efficiency, especially in UDN, is still in its early stages. One effective approach is to leverage the BS sleep mode from the existing network to reduce energy consumption and maintain network performance [1], [10], [16]. The sleep mode of a BS indicates the closure of the energy hungry functions and components (e.g., power amplifier, Radio Frequency (RF) components). In scenarios where data transmission is rare, the BS goes into sleep mode, turning off the transceiver instead of wasting energy on active waiting (idle listening).

In the traditional HetNet, the macro cell BS plays the role of central controller, collecting small cell BS information (location, loads, delay requirements, etc.), and conducts sleep mode scheduling. Comparatively, the centralized sleep mode scheduling becomes difficult in the UDN scenario, due to the large control overhead, user deployed BSs, and latency requirements. Thus, sleep mode scheduling must be conducted in a distributed fashion, and requires additional understanding and investigation to consider control methods and sleep/ON patterns.

In this paper, we investigate and evaluate the distributed sleep mode control schemes. We consider the control methods and sleep/ON patterns of the control schemes. The control methods indicate the ways to control the sleep mode operation. One method is for the small cell BS control to go into sleep mode, such as duty cycle scheduling. The other method is for the UE to control the sleep mode scheduling in an on-demand fashion. The on-demand control scheme turns small cell BS to ON only when the UE demands, thus, minimizing idle listening [5], [6], [11], [14]. One representative technique is to leverage the Low Power Wake-Up Receiver (LP-WUR) [8] on both the sender side and receiver side as an additional radio component. The sender and receiver using LP-WUR to transmit and receive the wake-up beacon (wake-up signal). The LP-WUR wakes up the main transceiver after the wake-up beacon is received.

For the sleep/ON pattern, we consider duty cycle and adaptive duty cycle-based sleep mode scheduling. Each BS goes into sleep mode following a periodic sleep/ON duty cycle. The problem of the duty cycle scheme is the tradeoff between energy efficiency and network latency. On the one hand, the larger duty cycle on the sleep mode improves energy savings. On the other hand, the longer sleep cycle increases network latency. In addition, the duty cycle can be dynamically adjusted based on the traffic condition. We introduce the on-demand UE control sleep mode schemes that leverage LP-WUR in the UDN context, which have been used in existing wireless networks.

We implement several representative energy efficiency schemes, including the duty cycle, adaptive duty cycle, always-on LP-WUR, and duty cycle LP-WUR, which can be categorized into two control methods (i.e., the small cell BS control, and on-demand UE control) in the UDN scenario. We carry out a performance evaluation of those schemes with respect to the energy efficiency and end-to-end delay using the Vienna LTE system level simulator [2], [9][1].

The remainder of the paper is as follow: In Section II, we introduce several energy efficiency schemes, with regards to the control methods and sleep/ON pattern, which will be evaluated

[1]Certain commercial equipment, instruments, or materials are identified in this chapter in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

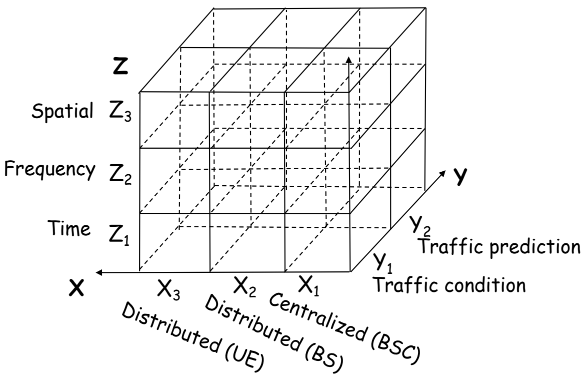


Fig. 1: The Sleep Mode Control Scheme Space

Sleep Mode Representatives	Description	Application Scenario
Duty cycled	Each BS follows a specific duty cycle of sleep/ON scheduling, UE can only connect to a small cell BS in ON state, UE needs handover to the best possible awake BS nearby the current BS goes to sleep	Considering the tradeoff between energy efficiency and delay, the user traffic is predictable and follows a certain pattern
Adaptive Duty Cycled	The duty cycle of the sleep interval is dynamically adjusted based on the traffic condition or prediction (i.e., the traffic volume and traffic frequency), When in heavy traffic conditions, small cell BS may increase the ON percentage, and vice versa	The user traffic varies greatly during operation and has unpredictable data volume
On-demand LP-WUR (Always-on)	The LP-WUR is in always-on mode, i.e., idle listening, The LP-WUR wakes up the main transceiver for data transmission when a wake-up package has been successfully received. After the data transmission is complete, the small cell BS goes into sleep mode	High requirement on delay performance, Serve frequent data traffic
On-demand LP-WUR (Duty Cycled)	The LP-WUR is in duty cycled sleep/ON scheduling, During the ON state of the LP-WUR, the LP-WUR wakes up main transceiver for the data transmission when a wake-up signal comes in.	Serve rare data traffic, Consider the tradeoff of minor delay and energy efficiency

TABLE I: Representatives of the Sleep Mode Schemes

in UDN. In Section III, we evaluate the conducted simulation experiments to evaluate the effectiveness investigated schemes. We conclude the paper in Section IV.

II. Investigated Schemes

In this section, we present the four representative energy efficiency schemes (i.e., duty cycle, adaptive duty cycle, always-on LP-WUR and duty cycle LP-WUR) in detail, based on Table I. The duty cycle and adaptive duty cycle are categorized into the small cell BS control schemes. The always-on LP-WUR and duty cycle LP-WUR are categorized as on-demand UE control schemes. Notice that two setting parameters, i.e., the sleep cycle and wait-to-sleep time 'T', are introduced for the small cell BS control schemes and on-demand UE control schemes, separately. In the following, we introduce these control schemes in detail.

A. Small Cell BS Control Scheme

Figure 2 illustrates timing diagrams of several sleep/ON duty cycles. The state of the small cell BS transitions between sleep mode and ON mode in a cycle. In the ON mode, the small cell BS processes the data, receiving and transmitting. In sleep mode, the small cell BS goes into an energy saving state (i.e., no data transmission). When a packet comes during the sleep mode cycle, the delay starts to accumulate until the next ON mode.

In Figure 2, (A) and (B) show examples of a short sleep cycle and a long sleep cycle. The longer sleep cycle (A)

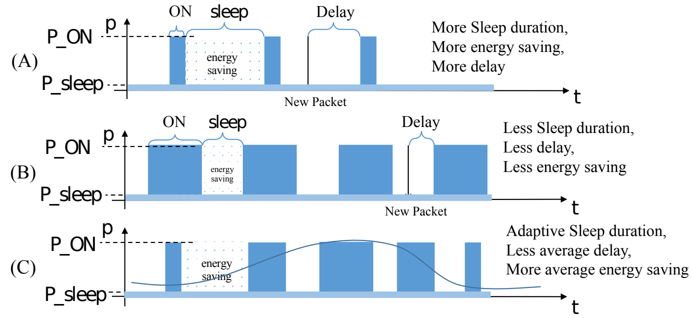


Fig. 2: Timing Diagram on Duty Cycle

reduces energy consumption, and increases delay on average. In contrast, the shorter sleep cycle shown in (B) leads to reduced delay, but additional energy consumption. In Figure 2, (C) shows an adaptive sleep cycle, in which the sleep cycle is changing corresponding to the traffic variation. With high traffic adaptation, the sleep cycle decreases when facing high traffic volume (less sleep), and increases when traffic volume decrease (more sleep). Thus, the adaptive duty cycle performs better with respect to energy efficiency, while reducing delay, compared to duty cycle.

1) Duty Cycle: The sleep cycle in the duty cycle-based sleep mode scheduling scheme can vary in a range, say 10 % to 90 %. For example, the 60 % sleep cycle indicates that the small cell BS is in sleep mode for 60 % of the duty cycle, and ON for the remaining 40 %. Each BS automatically switches between sleep and ON states following the pre-defined duty cycle. Every UE has multiple BSs nearby. The UE will receive the nearby BSs' channel information and their duty cycle information (time remaining to sleep). The UE compares and selects a BS to connect or handover based on the shortest distance, best channel quality or the longest remaining ON time. Duty cycle scheduling is simple to implement, and effective for improving energy efficiency.

2) Adaptive Duty Cycle: The adaptive duty cycle incorporates the adaptability of the sleep cycle to the data traffic. The better the sleep cycle adapts to the data traffic, the better the delay performance and energy efficiency will be achieved. In principle, reducing the sleep cycle in the heavy traffic conditions improves the traffic offload and reduces average delay. Increasing sleep cycle in light traffic case can maintain the service quality and obtain larger energy savings. For example, the sleep cycle during the day should generally be smaller than at night time. Here, the sleep cycle can be adjusted based on the traffic volume (e.g., increasing or decreasing the sleep cycle by 10 % when traffic volume increases or decreases by a certain level).

B. On-demand UE Control

Figure 3 shows timing diagrams of on-demand sleep mode scheduling with LP-WUR. The P_{sleep} and P_{ON} indicate the power level of sleep and ON states of the main transceiver. LP-WUR is implemented either as always-on or duty cycle. The WUR (Always-on) indicates the process that the LP-WUR

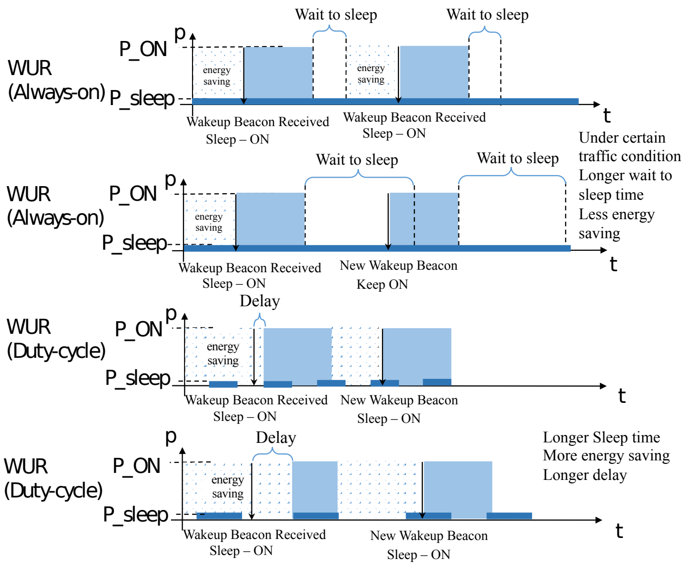


Fig. 3: Timing Diagram on the LP-WUR

is always in the ON state to wait for the wake-up beacon. The WUR (duty cycle) shows that the LP-WUR follows the ON/OFF cycle (i.e., periodically transitions between ON and OFF states). When the wake-up beacon comes and the LP-WUR is ON, the LP-WUR processes the beacon and signals (wakes up) the main transceiver. Then, the main transceiver transits from the sleep to ON state and performs the data transmission. When the wake-up beacon comes and the LP-WUR is OFF, the LP-WUR will not process the beacon until it is in ON state. The intention of wait-to-sleep time is to discover the timing for sending the main transceiver to sleep.

1) Always-on LP-WUR: The main concept of on-demand UE controlling is that the UE requires service, waking up the transceiver function of a nearby BS. An additional radio (LP-WUR) is equipped on each BS to perform the transmitting and receiving of wake-up beacon. The LP-WUR continually listens for wake-up beacons when the LP-WUR is in always-on mode. Energy consumption in the always-on LP-WUR scheme is computed by both the LP-WUR and the sleep mode of the main transceiver. The delay performance of always-on LP-WUR is minimum, and limited by only the hardware components, since the UE decides the transmission time.

2) Duty Cycle LP-WUR: To further reduce the energy consumption in the rare traffic scenario, the duty cycle LP-WUR operates the LP-WUR in an ON/OFF cycle. Duty cycle LP-WUR sets the LP-WUR in the OFF state periodically compared with the always-on LP-WUR. Here, we consider the OFF cycle as the controlling parameter of the duty cycle LP-WUR, setting the OFF cycle from 10 % (minimum OFF time) to 90 % (maximum OFF time). Recall the above illustrated sleep cycle setting of the duty cycle sleep mode scheme.

III. Performance Evaluation

In this section, we conduct extensive performance evaluations to assess the effectiveness and limitations of the duty cycle and on-demand control schemes. We outline the construction of the UDN simulation environment using the Vienna LTE simulator [9], and the implementation of the key control schemes in the UDN scenario. Then, we elaborate upon our experiments evaluating the energy efficiency and end-to-end delay, varying the setting parameters: sleep cycle, and wait-to-sleep time.

Parameter	Setting
UE Number	100
BS Number	100
BS-BS distance	50 m
Deployment area	500 m^2
Data rate	$\geq$ 0.1 Gbit/s [13]
Data size	1 byte to 1.25×10^8 bytes
Simulation time	500 s as a unit

TABLE II: Simulation Specification

Operation Mode	Energy Consumption (%)	wake-up Time (s)
ON	100 % = 5 W	N/A
Sleep	15 % = 0.75 W	10
LP-WUR	10 μW = 10^{-5} W [7]	< 1 s

TABLE III: Small Cell Operation Specifications [12]

A. Evaluation Methodology

1) UDN Simulation Environment: We first introduce the evaluation parameters and operational specifications to describe the construction of the UDN environment. The implementation parameters on the setup of the UDN environment are shown in Table II. The implementation on the UDN environment considers several parameters, including small cell BS to UE ratio, small cell BS distance, small cell BS density, UE distribution, and data packets. The small cell BS to UE density ratio is approximately 1 in the ideal case of the UDN, based on the analysis from [4]. Here, 100 BSs and 100 UEs are deployed in a 500 m^2 space. The small cell BSs are distributed in a 10×10 square fashion, where the BS to BS distance is 50 m. The small cell BS density is 100 per 500 m^2. UEs are randomly distributed throughout the square space. The specifications of the operational parameters (e.g., energy consumption and end-to-end delay) for small cell BSs are shown in Table III. The energy consumption is measured in watts, and the end-to-end delay is measured in seconds.

2) Experimental Implementation: The experiment tasks were designed to compare the energy efficiency and network delay performance of the key sleep mode schemes: duty cycle, duty cycle (adaptive), always-on LP-WUR, and duty cycle LP-WUR. For the Duty Cycle scheme, on the BS side, we construct the small cell BS sleep mode and ON mode. The details on the energy cost and end-to-end delay follow the operational specifications from Table III. All BSs perform the sleep/ON following its duty cycle, and the starting time is randomized. For every BS, we set the sleep cycle to vary from 10 % to 90 % by 10 %. On the UE side, the UE associates with the nearest BS. The UE can conduct transmission only when the associated BS is ON, and otherwise must wait.

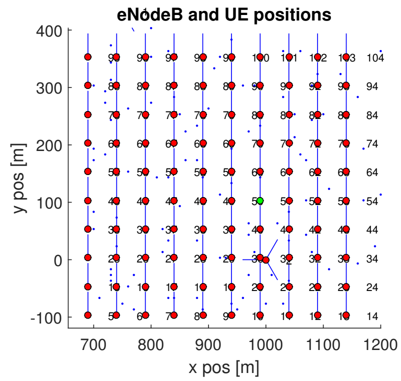


Fig. 4: A Deployment Example of UDN

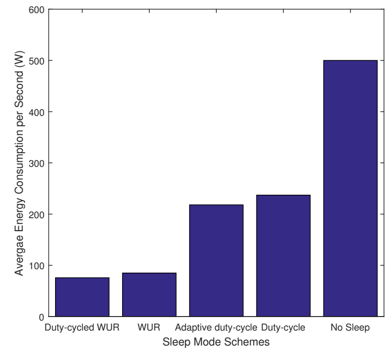


Fig. 5: Energy Efficiency Performance

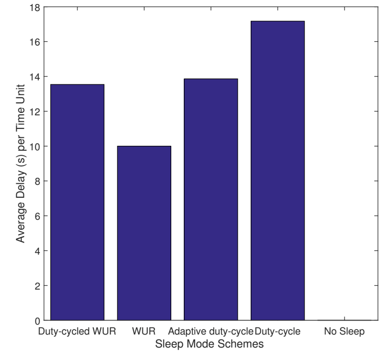
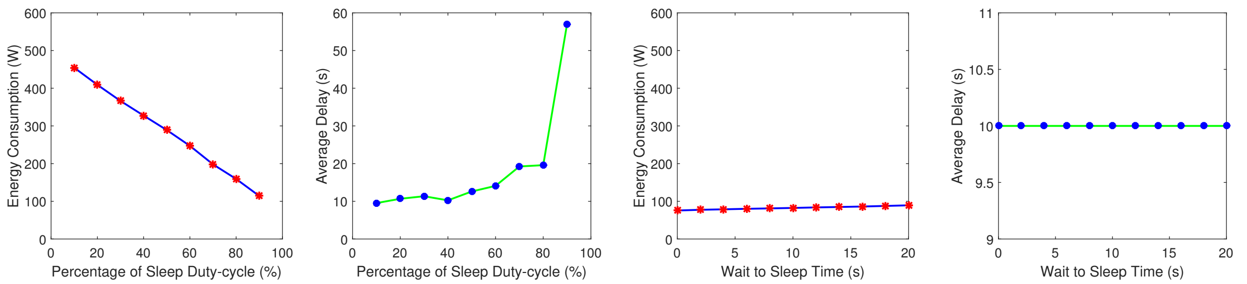


Fig. 6: Delay Performance



(a) Energy Efficiency on Sleep Cycle (b) Delay Performance on Sleep Cycle (c) Energy Efficiency on Wait-to-sleep Time (d) Delay Performance on Wait-to-sleep Time

Fig. 7: Performance with Simulation Parameters

For the Adaptive Duty Cycle scheme, the sleep cycle is dynamically changing based on the traffic duration in steps of 10 %. The traffic duration is defined as how long one transmission lasts. The longer time one transmission lasts, the higher traffic successiveness of the current data transmission is. The sleep cycle will increase by 10 % when the traffic successiveness (transmission time) increases, and vice versa.

The always-on LP-WUR is constructed in such a way that the small cell BS is acknowledged for the data transmission. The BS and UE both have LP-WUR functions (i.e., they can transmit and receive the wake-up beacon solely). The LP-WUR is always-on, and waiting for the wake-up beacon. When the wake-up beacon is received, the main transceiver transitions from sleep mode to ON mode. Similarly, the duty cycle LP-WUR is implemented by leveraging the duty cycle pattern. The LP-WUR is in ON/OFF scheduling. The wake-up beacon can only be received in the ON state of LP-WUR. If the wake-up beacon comes while in the OFF state, the delay starts accumulating until the ON state.

In the duty cycle schemes, the energy efficiency of the experiments considers the energy consumed both in sleep mode and ON mode. In the LP-WUR schemes, the additional energy consumed from LP-WUR is also involved in the energy efficiency calculation. The delay performance is measured from the data transmission start time until the data packet been completely delivered. The delay performance computes the average delay of all data packets delivered during the simulation.

B. *Experimental Results*

Figure 4 shows an example of deployment in UDN with the Vienna LTE simulator [9]. The red and green circles indicate the location of small cell BSs. The BSs are located as a 10×10 square. The red indicates the ON mode of a BS. The green indicates sleep mode. The random distributed UEs are shown as the blue dots.

Figure 5 and Figure 6 show the comparison on the energy efficiency performance and delay performance for various key sleep mode schemes and a scheme with no sleep mode enabled, respectively. Figure 5 shows the average energy consumption of the 100 small cell BSs with various control schemes per second during a unit simulation time (500 s). The energy consumption reduces at least 47.4 % with sleep mode enabled (leftmost four bar graphs), compared to sleep mode disabled case (rightmost bar graph), which consumes 500 W energy per second. The energy consumption reduction validates the effectiveness on the energy efficiency of BS sleep mode.

Among the leftmost four bar graphs, the always-on LP-WUR and duty cycle LP-WUR consume 65 % less energy than the duty cycle and adaptive duty cycle, on average. The energy consumption reduction indicates that the on-demand control schemes are able to minimize the idle listening duration.

Thus, the on-demand control schemes are able to decrease unnecessary energy waste compared to the duty cycle schemes. In addition, the duty cycle LP-WUR consumes slightly less energy than the always-on LP-WUR, at 75.78 W compared to 84.82 W, respectively. This is because the periodical ON/OFF pattern of the LP-WUR provides more opportunities for small cell BS to remain asleep.

The energy consumption of duty cycle is around 236.96 W per second, on average. This depends highly on the sleep cycle variation (i.e., the longer the sleep cycle, the more energy saved). The adaptive duty cycle consumes less energy, at 218.06 W, compared to the duty cycle. The reduction in energy consumption comes from its adaptability to users (traffic volume) and less unnecessary idle listening time.

Figure 6 demonstrates the average end-to-end delay for the data transmission on 100 UEs during a unit simulation time. We assume that when all small cell BSs are in ON mode constantly, the delay mainly comes from the transmission time in the micro second level (e.g., $10\,\mu$s), including propagation and processing (rightmost bar graph). For the leftmost four bar graphs, the LP-WUR has the minimum possible delay at 10 s, which is only the wake-up process time due to hardware constraints. The increased delay for the duty cycle LP-WUR is mainly from the waiting time from the OFF state of LP-WUR. In general, the duty cycle LP-WUR and always-on LP-WUR have better delay performance compared to the adaptive duty cycle and duty cycle. This is because the duty cycle consumes periodical sleep time and wake-up time, compared to the LP-WUR, which consumes only wake-up time.

We thus conclude that the always-on LP-WUR schemes provide the maximum energy efficiency and minimal delay in combination. The duty cycle LP-WUR does not outperform the always-on LP-WUR due to the minor energy efficiency with greater delay as the penalty. The duty cycle schemes facing the tradeoff issue of the energy efficiency and delay performance. Thus, they cannot obtain optimal performance on both energy efficiency and delay performance. Meanwhile, the energy consumption of the adaptive duty cycle is significantly less than the duty cycle due to high traffic adaptability. Nonetheless, the tradeoff is the increased network delay.

Figure 7 (a)-(d) show the performance on the control parameters (i.e., sleep cycle and wait-to-sleep time). Figure 7(a) and (b) show the tradeoff in the duty cycle schemes. The energy efficiency decreases when the sleep cycle increases, especially in the phase where most time (90 % sleep cycle) small cell BSs are in sleep mode. The reason for the extreme delay is the overstocked traffic and the very low availability of small cell BSs. Figure 7(c) and (d) demonstrate the relationship of the wait-to-sleep time to energy efficiency and delay performance in the on-demand schemes. The longer wait-to-sleep time increases minor energy consumption, as shown in Figure 7(c). Figure 7(d) indicates that the longer wait-to-sleep time does not improve the delay performance. This is because of the memoryless property of the exponential distribution of UE traffic.

IV. Final Remark

In this paper, we addressed the energy efficiency issue in UDN. In particular, we introduced and compared several energy efficiency schemes (i.e., small cell BS control and on-demand UE control) in UDN scenarios. Via performance evaluation, we demonstrated the advantages and limitations of BS sleep mode and the effectiveness of the on-demand control schemes. The future work include simulating the LP-WUR on testbed, and applying the LP-WUR in real world deployment.

References

[1] P. Ghosh, S. S. Das, S. Naravaram, and P. Chandhar. Energy saving in ofdma cellular systems using base-station sleep mode: 3gpp-lte a case study. In *Proc. of IEEE National Conference on Communications (NCC)*, 2012.

[2] A. Hematian, W. Yu, C. Lu, D. Griffith, and N. Golmie. Towards clustering-based device-to-device communications for supporting applications. *SIGAPP Appl. Comput. Rev.*, 17(1):35–48, May 2017.

[3] J. Lin, W. Yu, N. Zhang, X. Yang, H. Zhang, and W. Zhao. A survey on internet of things: Architecture, enabling technologies, security and privacy, and applications. *IEEE Internet of Things Journal*, PP(99), 2017.

[4] D. López-Pérez, M. Ding, H. Claussen, and A. H. Jafari. Towards 1 gbps/ue in cellular systems: Understanding ultra-dense small cell deployments. *IEEE Communications Surveys & Tutorials*, 17, 2015.

[5] N. S. Mazloum and O. Edfors. Performance analysis and energy optimization of wake-up receiver schemes for wireless low-power applications. *IEEE Transactions on Wireless Communications*, 13, 2014.

[6] J. Oller, E. Garcia, E. Lopez, I. Demirkol, J. Casademont, J. Paradells, U. Gamm, and L. Reindl. Ieee 802.11- enabled wake-up radio system: Design and performance evaluation. *Electronics Letters*, 50, 2014.

[7] M. Park. Ieee p802.11 - wake-up radio (wur) study group. http://www.ieee802.org/11/Reports/wur_update.htm.

[8] M. Prinn, L. Moore, M. Hayes, and B. O'Flynn. Comparing low power listening techniques with wake-up receiver technology. In *Proc. of SMART*, 2014.

[9] M. Rupp, S. Schwarz, and M. Taranetz. *The Vienna LTE-Advanced Simulators: Up and Downlink, Link and System Level Simulation*. Signals and Communication Technology. Springer Singapore, 1 edition, 2016.

[10] L. Suárez, L. Nuaymi, and J.-M. Bonnin. Energy-efficient bs switching-off and cell topology management for macro/femto environments. *Computer Networks*, 78, 2015.

[11] S. Tang, H. Yomo, Y. Kondo, and S. Obana. Wake-up receiver for radio-on-demand wireless lans. *EURASIP Journal on Wireless Communications and Networking*, 2012.

[12] W. Vereecken, I. Haratcherev, M. Deruyck, W. Joseph, M. Pickavet, L. Martens, and P. Demeester. The effect of variable wake up time on the utilization of sleep modes in femtocell mobile access networks. In *Proc. of 9th Annual Conference on Wireless On-demand Network Systems and Services (WONS)*, 2012.

[13] D. Wu, J. Gu, X. Gu, S. Nie, M. Zhao, and L. Zhang. User average data rate analysis in future dense small cells. In *Proc. of IEEE 16th International Conference on Communication Technology (ICCT)*, 2015.

[14] H. Yomo, Y. Kondo, N. Miyamoto, S. Tang, M. Iwai, and T. Ito. Receiver design for realizing on-demand wifi wake-up using wlan signals. In *Proc. of IEEE Global Communications Conference (GLOBECOM)*, 2012.

[15] W. Yu, D. Griffith, L. Ge, S. Bhattarai, and N. Golmie. An integrated detection system against false data injection attacks in the smart grid. *Security and Communication Networks*, 8(2):91–109, 2015.

[16] W. Yu, H. Xu, A. Hematian, D. Griffith, and N. Golmie. Towards energy efficiency in ultra dense networks. In *Proc. of IEEE 35th International Performance Computing and Communications Conference (IPCCC)*, 2016.

[17] W. Yu, H. Xu, H. Zhang, D. Griffith, and N. Golmie. Ultra-dense networks: Survey of state of the art and future directions. In *Proc. of IEEE 25th International Conference on Computer Communication and Networks (ICCCN)*, 2016.