LAA-Based LTE and ZigBee Coexistence for Unlicensed-Band Smart Grid Communications

Imtiaz Parvez, Nasidul Islam, Nadisanka Rupasinghe, Arif I. Sarwat, and İsmail Güvenç
Department of Electrical and Computer Engineering, Florida International University, Miami, FL 33174
Email: {iparv001, nisla004, rrupa001, asarwat, iguvenc}@fiu.edu

***Abstract*—The advent of smart grid introduces abundant number of smart meters which require bidirectional reliable communication. The deployment of advanced metering infrastructure (AMI) in smart grid networks will be auspicious if the existing infrastructure of LTE networks can be utilized. On the other hand, use of LTE infrastructure and spectrum by AMIs will further load the already congested broadband wireless networks. Recently, use of the unlicensed spectrum by the LTE technology is seen as a promising approach to offload the existing traffic from the licensed spectrum. In our study, we investigate the coexistence of LTE and ZigBee networks at the unlicensed frequency band of 2.4 GHz. We consider a time division duplexing (TDD)-LTE system accompanied by ZigBee network with FTP traffic model for system level simulations. The simulation results demonstrate that the simultaneous operation of LTE and ZigBee on the 2.4 GHz band reduces ZigBee's performance, but still meets the data communication requirements for AMI as prescribed by Department of Energy (DoE).**

***Index Terms*—AMI, smart grid communication, cognitive radio, dynamic spectrum access, Internet of Things(IoT), licensed assisted access (LAA), LTE-U, smart meter, ZigBee.**

I. Introduction

The Long Term Evolution (LTE) technology has been the dominant technology in the past several years for broadband wireless communications. The evolution of LTE requires the coexistence of human-to-human (H2H) and Machine-to-machine (M2M) communication which need to accommodate abundant number of devices [1]. Along with LTE, M2M communication may utilize diverse communication technologies such as WiFi, ZigBee and Bluetooth. Furthermore, to meet the demand of exponentially expanding data rate in LTE, frequency spectrum is a critical issue. One approach to solve this problem is to operate LTE in unlicensed frequency band along with licensed band. Indeed, 3GPP standardization group has been recently studying licensed assisted access (LAA) of LTE in the unlicensed spectrum [2].

Advanced metering infrastructure (AMI) of smart grid is the notable example of M2M communication. In AMI, thousands of meters communicate to back office of utility service provider through a mesh or hierarchical or hybrid connected network [3], [4]. ZigBee is the prominent candidate for such AMI-based meter-to-meter communication, because of supporting a large number of nodes, self organizing features, and capability of working on mesh network utilizing public frequency band (868 MHz, 915 MHz, 2.4 GHz). First of all, LTE has existing infrastructure, and the access points(APs) of ZigBee can utilize LTE while smart meters are using ZigBee to communicate with the APs. Secondly the LTE and ZigBee may operate on unlicensed band, so there is a strong need to study the coexistence performance of LTE and ZigBee networks when they operate in the same spectrum [5], [6].

This research was supported in part by the U.S. National Science Foundation under the grant ACI-1541108 and Presidential fellowship under Florida International University.

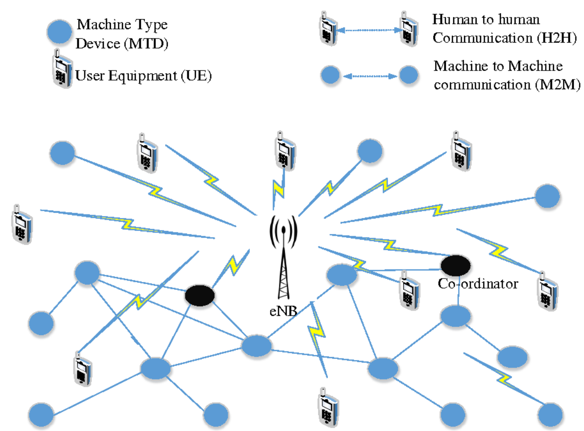


Fig. 1: Wireless communication encompassing H2H and M2M communication in same spectrum.

Coexistence between different communication standards have been studied before in the literatures. In [7], [8], coexistence among IEEE 802.15.4, WiFi and Bluetooth has been investigated. Interference suppression technique for coexistence has been presented in [9], [10]. In [11], simultaneous operation of ultra-wideband (UWB) and WiMAX on same frequency band has been proposed using spectrum sensing by detect-and-avoid mechanisms. In [12], coexistence among UWB, WiFi and ZigBee have been studied. In [13]–[15], coexistence of LTE and WiFi using different mechanism such as listen before talk (LBT), silent gap and common database have been proposed. However, for smart grid applications, coexistence of ZigBee and LTE on the same frequency spectrum calls for investigation.

For LTE and ZigBee to coexist in the same spectrum, the main challenge is that LTE uses dynamic scheduling for user equipments (UEs) whereas ZigBee utilizes collision sensed multiple access/ collision avoidance (CSMA/CA) mechanism for accessing network. In case of simultaneous CSMA/CA and LTE operation, several techniques are proposed such as carrier sensing and co-existence gap in transmission frame [2], [16].

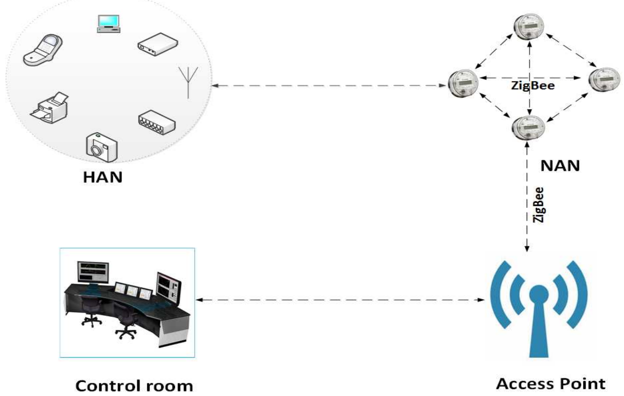


Fig. 2: AMI communication architecture encompassing Home Area Network (HAN), Neighbor Area Network (NAN), data concentrator, and control center.

In LBT mechanism of LTE operation, Request-to-Send (RTS) and Clear-to-Send (CTS) messages are exchanged prior to LTE transmission [2]. In blank subframe allocation technique [16], LTE will refrain from transmission in certain subframes. Both the techniques have been proposed for coexistence of LTE and WiFi where LTE and WiFi transmission power are greater than 20 dBm. On the other hand, ZigBee transmission power is between -3 dBm to 10 dBm. Therefore, ZigBee will have less interference effect on LTE while LTE will cause significant interference on ZigBee.

In this paper, we investigate coexistence of LTE and ZigBee in the unlicensed 2.4 GHz ISM band for AMI communication and usual H2H communication. We consider time division duplexing (TDD)-LTE and ZigBee for simulation on multi layer network layout. In the 10 ms subframe of LTE transmission, ZigBee will transmit during the guard band (blank subframe) time. We evaluate the performance under different LTE traffic arrival rates defined by 3GPP through the FTP traffic model [17] as well as different combination of down link (DL)/ uplink (UL) subframes. The simulation results yield insights about interference effect on each other in the PHY/MAC operating regimes and will help to develop effective coexistence mechanism between LTE and ZigBee.

The rest of this paper is organized as follows. Section II describes the overview of AMI. In Section III, key aspects of LTE and ZigBee technologies has been discussed. In Section IV and Section V, deployment scenario and simulation results are illustrated, respectively. Finally, a brief conclusion and future work is presented in Section VI.

II. Architecture of AMI

Smart grid is the evolution from one-directional power system to modern bi-directional power system which employs innovative communication and distribution to deliver electricity to consumer with enhanced monitoring, control and efficiency [18]. A proclaimed feature of the smart grid is the usage of bidirectional communication for interacting among its entities.

In the arena of smart grid, AMI is the distribution level building block consists of a network of smart meters. AMI is responsible for collecting and sending consumption data from smart meter periodically using wireless communication. It consists of various components which have diverse applications. An example of AMI communication scenario that encompasses communication among home appliances and the control center is shown in Fig. 2, which consists of a home area network (HAN), smart meters, neighborhood area network (NAN), and control center.

The network by which home appliances (such as stove, microwave, dishwasher etc) are connected to a meter is termed as the HAN. The most common communication standard used for HAN is Bluetooth and WiFi. The energy consumed by home appliances is encapsulated as a consumption unit which is measured, stored and sent by smart meter.

Smart meter is a solid state device responsible for measuring, storing and sending energy consumption data to the back office of the energy service provider. A smart meter sends data every 10 - 30 minutes based on energy service provider's choice. The meter is connected to a network named as the NAN. The popular communication standard for NAN is ZigBee and WiFi. In our study, we use ZigBee for investigation.

The meters are connected among themselves through a mesh connected network. The network may be wired (PLC) or wireless such as LTE, WiFi, ZigBee. The head end of the NAN is the data concentrator or gateway which is connected to a back office by a dedicated wired or wireless connection (optic fiber, cellular network, etc.).

The control center receives consumption data and prepares bills for the consumers. The fine grained data can be used to forecast and optimize the electrical power generation and distribution. Controlling and monitoring is also performed from remote locations depending on the usage and load requirement.

Since ZigBee is currently used in many utility companies for NAN communication, we will study its coexistence performance in the rest of the paper.

III. Overview of LTE and ZigBee

In this section, in order to better explain the ZigBee and LTE coexistence mechanism in the rest of the paper, key aspects of both technologies are briefly summarized.

A. *Overview of LTE Systems*

LTE is a standard for high speed wireless communication to meet the rapid increase of mobile data usage in the future. The standard is developed by the 3rd Generation Partnership Project (3GPP) and is an upgrade from 3G standards for significantly reducing data transfer latency and increasing capacity of data transfer. The PHY layer of LTE includes the DL and UL features. The requirements of this layer are high peak transmission rates, spectral efficiency and multiple channel bandwidths. Therefore, in order to meet these requirements, Orthogonal Frequency Division Multiplex (OFDM) technology is used due to its robustness against fading and interference. To further improve the performance of this standard, multiple antenna techniques are used, which are responsible for increasing channel capacity and increasing the robustness of transmitted signals. The MAC layer, on the other hand, provides an interface between logical channels and physical channels. It is responsible for transport format

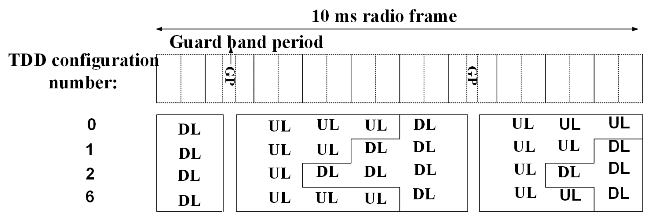


Fig. 3: 10 ms radio frame of LTE [19].

of the frames, in addition to scheduling techniques and error correction using HARQ.

The LTE DL transmission consists of user-plane and control plane data in the protocol stack multiplexed with physical layer signaling to support the data transmission, facilitated by the Orthogonal Frequency Division Multiple Access (OFDMA). The transmission resource is structured in 3 dimensions- time, frequency, and space. In time domain, the largest radio frame is 10 ms, subdivided into ten 1 ms subframes as illustrated in Fig. 3 . Each subframe is further split into two 0.5 ms slots, which is termed as a resource block (RB).

On the other hand, UL utilizes Discrete Fourier transform-Spread OFDM (DFT-S-OFDM). Before transmitting, the signal is frequency-shifted by half a sub carrier frequency in order to overcome the distortion caused by the d.c. subcarrier being concentrated in a single RB.

For LAA of LTE in unlicensed band, two approaches were proposed. In the early deployment stage of LAA in USA, Korea, China and India, adaptive duty cycle- carrier sensed adaptive transmission (CSAT) [20] was considered whereas in Europe listen before talk (LBT) [21] was used. For fair sharing of spectrum, recently 3GPP Rel. 13 LAA proposes active LTE transmission time 1-10 ms based on load which is similar to CSAT [22].

B. Overview of ZigBee Systems

ZigBee is a low-cost, low-power, short-range, low-data rate and energy-efficient wireless technology, and it suits good to be used for applications that involve wireless M2M communications. It gained ratification from IEEE 802.15.4 in 2003. It consists of 16 channels in the 2.4 GHz ISM band worldwide, 10 channels in the 915 MHz band in North America, and one channel in the 868 MHz band in Europe (see Table I). Its operational range is 30-90 m and it can simultaneously support up to 64000 nodes. In the protocol stack, MAC and PHY layers are defined by IEEE 802.15.4 whereas the upper network layers are defined by ZigBee.

The routing protocol was tailored to be uphold with both ZigBee alliance and IEEE 802.15.4. ZigBee renders the software command of application layers to new command and then conveys those to the MAC layer. IEEE 802.15.4 supports both peer to peer and star networks. A typical example of ZigBee superframe structure has been illustrated in Fig. 4 where $aBaseSuperframeDuration$= 5.36 ms and duty cycle is between $10\% - 100\%$. The superframe is divided into inactive portion and active portion, and the latter is further subdivided into contention access period and contention free period. By specifying a duty cycle, we can decide the active transmission time (as for example, at 18% duty cycle, the transmission duration is 1 ms).

IEEE 802.15.4 works at three different frequency bands. The first band is 868 MHz which supports a data rate of 20 Kbps and uses the BPSK modulation technique. The second band is 915 MHz and supports a maximum data rate of 40 Kbps modulated by BPSK. The global 2.4 GHz band supports 250 Kbps data rate and is modulated by offset quadrature phase-shift keying (OQPSK).

TABLE I: IEEE 802.15.4 frequency nomenclature.

Band	Number of Channels	Channel Number	Channel Center Frequency	Channel Spacing
868 MHz	1	$k = 0$	868.3 MHz	0
915 MHz	10	$k = 1, 2, 3 \ldots 10$	906+2($k-$1) MHz	2 MHz
2.5 GHz	16	$k = 11, 12 \ldots 26$	2405 + 5(k − 1) MHz	5 MHz

The MAC and PHY layers are based on the CSMA/CA algorithm along with slotted binary exponential backoff (to reduce collision during simultaneous data transfers by multiple channels). It supports two kinds of channel access modalities- beacon enabled slotted CSMA/CA and simple un-slotted CSMA/CA without beacon. ZigBee utilizes CSMA/CA [23] mechanism to access the network. When a packet comes to the queue of a node, the MAC layer starts two variables- the number of backoff ($\mathrm{N_B}$) tries and the exponential backoff (BE) with a minimum value of 3. The MAC layer initiates a random value within the range [0, 2^{BE} - 1] and sets the delay accordingly. When the value of BE is found 0, the channel is sensed by MAC. If the channel is idle, packet is transmitted. Otherwise, the system will increase the value of BE and NB by 1. If the value of $\mathrm{N_B}$ is less than the maximum number of Backoff ($\mathrm{N_{Bmax}}$), the system will repeat the transmission process for the packet. If otherwise, the transmission will be discarded.

In the 10 RBs of 10 ms LTE subframe, ZigBee will transmit only during the 2 guard band period (blank RBs). On the other hand, during the remaining 8 RBs, ZigBee will cease transmission due to CSMA/CA mechanism.

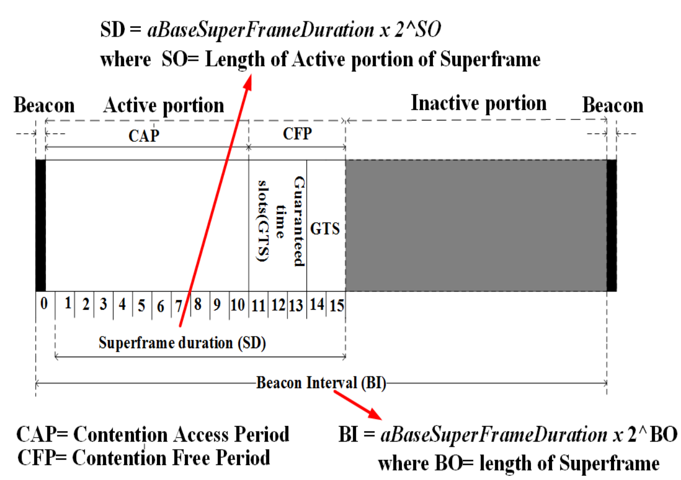
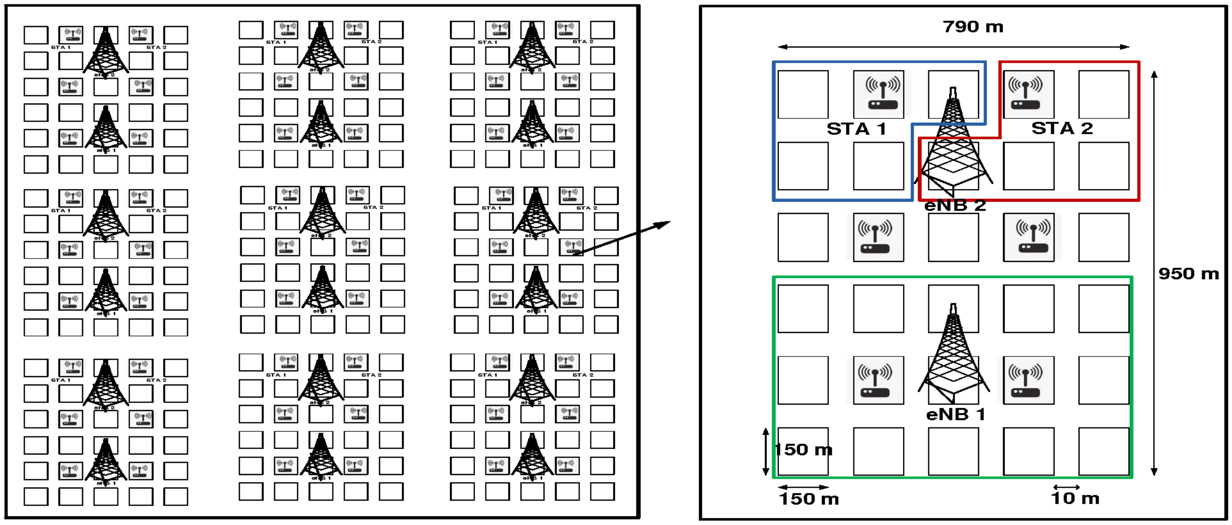


Fig. 4: A typical example of superframe of ZigBee.



(a) (b)

Fig. 5: Deployment scenario of eNBs and STA in a conventional Manhattan grid in simulation environment. (a) A Manhattan grid consists of 30×9 blocks. (b) Distribution of eNBs and STA in a 30 blocks.

IV. Deployment scenario for LTE-ZigBee Coexistence

To evaluate the coexistence performance of LAA based LTE and ZigBee networks, a suburban building block topology (Manhattan grid) [24] has been considered as shown in Fig. 5. In the topology, there are 30×9 blocks in which each block contains 5×5 buildings. Groups of 5 blocks are each served by an STA (ZigBee access point) whereas each 15 block building is served by an evolved NodeB (eNB). In each building, there are M UEs (LTE subscriber) and a smart meter (ZigBee device) which are uniformly distributed. Each UE/ZigBee device communicates with corresponding eNB or STA. Since a smart meter sends its data to the corresponding STA by hop-to-hop communication, and the STA may also send the data to control center by LTE, its location has been considered to be near an eNB. In each case of 10 ms LTE sub frame transmission, two blank slots (Guard band,0.5 ms each) has been kept for ZigBee/WiFi transmission and the corresponding ZigBee duty cycle is 18% (i.e. 1 ms). Since LTE and ZigBee are transmitting simultaneously on the same 2.4 GHz spectrum, high power LTE and low power ZigBee transmission cause interference on each other from other cells. To assess the performance, Shannon capacity of both technologies are simulated under interference from each other. For this, PHY layer has been abstracted at the granularity level of a transmission frame of ZigBee and LTE.

The number of received bits (N_{B}) at a ZigBee/LTE node (i) over a frame duration is given by

$$N_{\mathrm{B}}(i) = B \log_2 \big(1 + SINR(i)\big) T, \tag{1}$$

where B is the bandwidth, $SINR$ is the signal to interference plus noise ratio and T is the single symbol duration.

Capacity of the ZigBee/LTE node is given by

$$C = \frac{\sum_{i=1}^{N} N_{\mathrm{B}}(i)}{NT}, \tag{2}$$

	10 ms									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Conf#1	**U**	**G**	**U**	**U**	**U**	**U**	**U**	**U**	**G**	**U**
Conf#2	**D**	**G**	**D**	**D**	**D**	**D**	**D**	**D**	**G**	**D**

Fig. 6: LTE TDD subframe structure for two different configurations.

where N is the number of ZigBee/LTE symbols transmitted in one second.

Two configurations of LTE (as shown in Fig. 6) have been employed to obtain an insight into the effect of interference on ZigBee performance owing to the fact that both DL and UL uses different transmission power. The UL fractional power control in LTE is given by the following equation

$$P_{\mathrm{UL}} = P_0 + \alpha P_{\mathrm{L}} + 10 \log_{10} R, \tag{3}$$

where P_0 is the base power level, P_{L} is the path loss from BS to UE, α is the path loss compensation factor, and R is the number of RBs allocated for UL transmission of the specific LTE UE.

Since in case of ZigBee, the packet size from smart meter is fixed, a non-Poisson full buffer model has been used. On the hand, for LTE, a non full buffer traffic model has been considered as given in 3GPP FTP traffic model-2 [17]. For traffic arrival rate λ_{L} in the LTE transmission, the distribution function of delay between two packets (d) is given by

$$f(d) = \lambda_{\mathrm{L}} e^{\lambda_{\mathrm{L}} d}. \tag{4}$$

For path loss and shadowing parameters, urban micro (UMi) model has been considered in our simulation.

TABLE II: LTE MAC/PHY parameters.

Parameter	Value
Transmission Scheme	OFDM
Central Frequency	2405 MHz
Bandwidth	5 MHz
DL Tx Power	20 dBm
UL Tx Power	PL Based TPC
Frame Duration	10 ms
Scheduling	Round Robin
P0	-106 dBm
TTI	1 ms
Pathloss model	Urban micro (UMi)
Traffic Model	FTP Traffic Model-2 [17]

TABLE III: ZigBee MAC/PHY Parameters.

Parameter	Value
Transmission Scheme	O-OFDM
Central Frequency	2405 MHz
Bandwidth	5 MHz
DL/UL Tx Power	10 dBm
AC	Best Effort
MAC Protocol	EDCA
Slot Time	5.36 ms
CCA-CS Threshold	-82 dBm
CCA-ED Threshold	-62 dBm
macMaxFrame Retries	3
macMaxCSMA Backoffs	4
macMin BE	5
macMax BE	3
Unit Backoff Period	3e-10 seconds
Frame Length	808 bits
CW size	8
Noise Figure	6 [19]
Traffic Model	FTP Traffic Model - 2 [17]

V. Simulation Results

We used TDD-LTE system with FTP traffic model for simulation in Matlab environment. In case of each building, $M = 1.24$ UEs on the average have been uniformly randomly dropped into the building. Therefore, each block has 31 LTE subscribers. For LTE configuration 1, we used all subframes as UL and in configuration 2, we used all subframes as DL in a 10 ms radio frame duration. In all case, during guard band period (G) of LTE transmission, ZigBee will transmit. The parameters used for the simulation are illustrated in Table II and Table III.

From Fig. 7, we found that without ZigBee, the aggregate capacity of LTE DL is 48 Mbps, and with ZigBee, its capacity reduces to 32 Mbps and 28 Mbps on traffic arrival rate $\lambda_{\mathrm{L}} = 1.8$ and $\lambda_{\mathrm{L}} = 2.5$, respectively. On the other hand, with the LTE transmission, ZigBee capacity reduces from 220 Kbps to 40 Kbps at $\lambda_{\mathrm{L}} = 1.8$ and 20 Kbps at $\lambda_{\mathrm{L}} = 2.5$, as shown in Fig. 8.

For all LTE UL transmission in a 10 ms radio frame, the Shannon capacity of ZigBee is increased significantly compared to all DL LTE transmission in a 10 ms radio frame, which is reflected in Fig. 9. The reason behind this is that the UE uses less power for UL transmission which creates less interference in bit reception at ZigBee node. Contrary to ZigBee, for all LTE DL transmission in a 10 ms radio frame, aggregated capacity of LTE DL is more than all LTE UL transmission while ZigBee transmission is also taking place simultaneously. This is illustrated in Fig. 10.

In Fig. 11, it is shown that ZigBee has limited interference effect on LTE SINR distribution. For interference caused by ZigBee, the median SINR of LTE is downgraded by 5 dB. On the other hand, LTE DL interference has degraded the ZigBee SINR by over 20 dB, which is illustrated in SINR CDFs Fig. 12. This significant SINR downfall causes momentous capacity reduction in ZigBee.

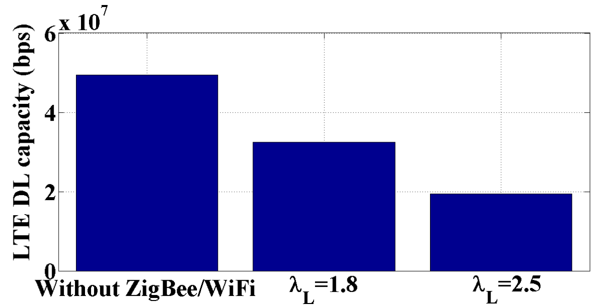


Fig. 7: LTE DL capacity without ZigBee, and with ZigBee transmission at different traffic rates.

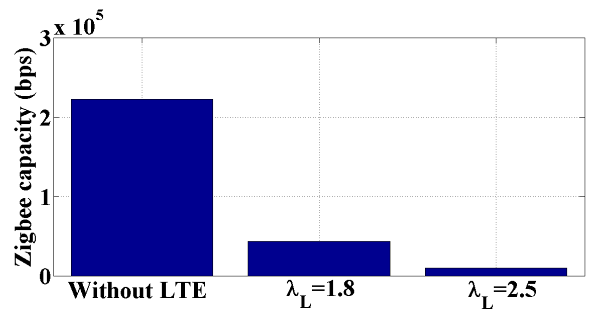


Fig. 8: ZigBee capacity without LTE, and with LTE DL transmission at different traffic rates.

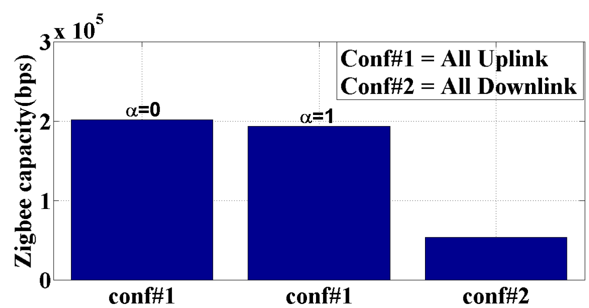


Fig. 9: ZigBee capacity with all LTE DL or all LTE UL traffic in a 10 ms radio frame at different α, and at $\lambda_{\mathrm{L}} = 1.5$.

VI. Conclusion

In this paper, we study the coexistence of ZigBee and LTE on multi-layer network. From simulation results, we found that ZigBee capacity is more affected by simultaneous operation of LTE, than LTE capacity being affected by ZigBee transmission. However, by changing the configuration of LTE transmission (DL/UL) and UL power control parameter, we can improve the performance of ZigBee significantly. Since both the ZigBee and WiFi uses CSMA/CA for accessing same channel, SINR of LTE is affected by any of the two.

According to US Department of Energy (DOE), the recommended data rate for AMI is 10-100 Kbps/node. Therefore

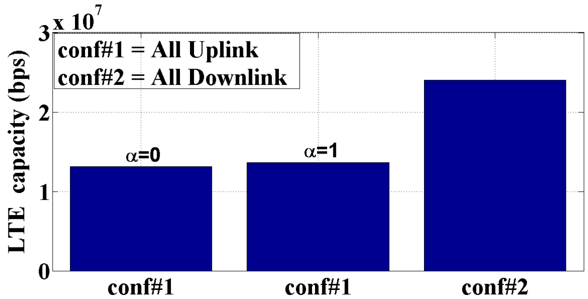


Fig. 10: LTE capacity with all LTE DL or all LTE UL traffic in a 10 ms radio frame at different α, and at λ_L = 1.5.

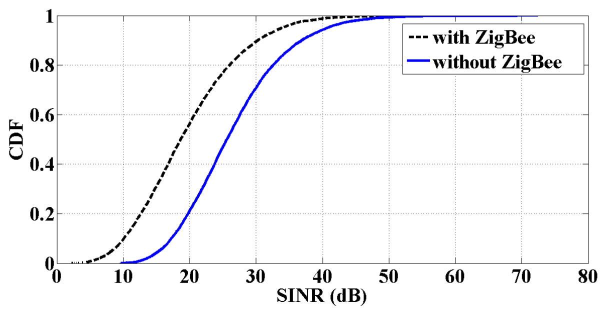


Fig. 11: SINR distribution of LTE without ZigBee transmission, and with DL ZigBee transmission.

the coexistence of LTE and ZigBee on unlicensed 2.4 GHz band fulfills the requirement for smart meter communication. At the same time, LTE can get more free spectrum for its operation. Furthermore, the STAs of ZigBee cells can utilize the LTE for faster data transfer to the back office of utility service provider while meter to meter communication utilizing self organizing low power ZigBee network. This will allow the utility service provider company to save significant amount of revenue spending on smart meter communication. Considering all these issues, our preliminary studies show that joint operation of LTE and ZigBee on the unlicensed 2.4 GHz might be potential communication solution for smart grid while maintaining QoS. Our future work includes investigation of interaction between other wireless transmission in the 2.4 GHz band such as WiFi, Bluetooth, and microwave ovens. We will also investigate the feasibility of using LTE for smart grid communications in the 5 GHz band, in coexistence with WiFi technology using the same band.

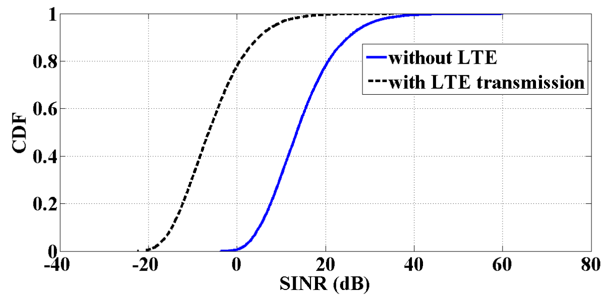


Fig. 12: SINR distribution of ZigBee without LTE transmission, and with LTE DL transmission.

References

[1] R. Ratasuk, M. Uusitalo, N. Mangalvedhe, A. Sorri, S. Iraji, C. Wijting, and A. Ghosh, "License-exempt LTE deployment in heterogeneous network," in *Proc. Int. Symp. Wireless Comm. Sys. (ISWCS)*, Aug. 2012, pp. 246–250.

[2] 3GPP, "Study on Licensed-Assisted Access using LTE," 3GPP Study Item - RP-141397, Tech. Rep., Sep. 2014.

[3] B. Lichtensteiger, B. Bjelajac, C. Muller, and C. Wietfeld, "RF Mesh Systems for Smart Metering: System Architecture and Performance," in *Proc. IEEE Int. Conf. on Smart Grid Comm (SmartGridComm)*, Oct. 2010, pp. 379–384.

[4] I. Parvez, A. Islam, and F. Kaleem, "A key management-based two-level encryption method for AMI," in *Proc. IEEE Power and Energy Socitey General Meeting (PES GM)*, Jul. 2014, pp. 1–5.

[5] J. Markkula and J. Haapola, "Impact of smart grid traffic peak loads on shared LTE network performance," in *Proc. IEEE Int. Conf. Comm. (ICC)*, Jun. 2013, pp. 4046–4051.

[6] J. Brown and J. Khan, "Performance analysis of an LTE TDD based smart grid communications network for uplink biased traffic," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2012, pp. 1502–1507.

[7] S. Zacharias, T. Newe, S. O'Keeffe, and E. Lewis, "Coexistence measurements and analysis of IEEE 802.15.4 with WiFi and bluetooth for vehicle networks," in *Proc. Int. Conf. on ITS Telecom. (ITST)*, Nov. 2012, pp. 785–790.

[8] W. Yuan, X. Wang, and J.-P. Linnartz, "A Coexistence Model of IEEE 802.15.4 and IEEE 802.11b/g," in *Proc. 14th IEEE Symp. on Commun. and Vehic. Tech.*, Nov. 2007, pp. 1–5.

[9] M. Sahin, I. Guvenc, and H. Arslan, "Iterative Interference Cancellation for Co-Channel Multicarrier and Narrowband Systems," in *Proc. IEEE Wireless Commun. and Networking Conf. (WCNC)*, Apr. 2010, pp. 1–6.

[10] M. B. Celebi, I. Guvenc, H. Arslan, and K. A. Qaraqe, "Interference suppression for the LTE uplink," *Proc. Physical Comm.*, vol. 9, no. 0, pp. 23–44, 2013.

[11] A. Rahim, S. Zeisberg, and A. Finger, "Coexistence Study between UWB and WiMax at 3.5 GHz Band," in *Proc. IEEE Int. Conf. Ultra-Wideband (ICUWB)*, Sep. 2007, pp. 915–920.

[12] J. Choliz, A. Hernandez-Solana, A. Sierra, and P. Cluzeaud, "Coexistence of MB-OFDM UWB with Impulse Radio UWB and other radio systems," in *Proc. IEEE Int. Conf. Ultra-Wideband (ICUWB)*, Sept. 2011, pp. 410–414.

[13] 3GPP, "3GPP Workshop on LTE in Unlicensed Spectrum," Tech. Rep., Jun. 2014.

[14] N. Rupasinghe and I. Guvenc, "Reinforcement learning for licensed-assisted access of LTE in the unlicensed spectrum," in *Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, 2015, pp. 1279–1284.

[15] ——, "Licensed-Assisted Access for WiFi-LTE Co-existence in the Unlicensed Spectrum," in *Proc. IEEE Emerging Tech. 5G Wireless Cellular Networks Workshop (co-located with IEEE GLOBECOM)*, Dec. 2014, Atlanta, GA.

[16] E. Almeida, A. Cavalcante, R. Paiva, F. Chaves, F. Abinader, R. Vieira, S. Choudhury, E. Tuomaala, and K. Doppler, "Enabling LTE/WiFi coexistence by LTE blank subframe allocation," in *Proc. IEEE Int. Conf. Comm. (ICC)*, June 2013, pp. 5083–5088.

[17] 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA); Further advancements for E-UTRA physical layer aspects (Release 9)," 3GPP Technical Report, Tech. Rep., Mar. 2010.

[18] I. Parvez, A. Sundararajan, and A. I. Sarwat, "Frequency band for han and nan communication in smart grid," in *IEEE Symposium Series on Computational Intelligence (SSCI)*.

[19] S. Sesia, I. Toufik, and M. Baker (Editors), *LTE, The UMTS Long Term Evolution: From Theory to Practice*. Wiley, 2nd Edition, 2011.

[20] Qualcomm, "Extending the benefits of LTE to unlicensed spectrum," 3GPP RAN1 standard contribution - RWS-140008, Sophia Antipolis, France, Jun. 2014.

[21] N. DOCOMO, "Views on LAA for Unlicensed Spectrum - Scenarios and Initial Evaluation Results," 3GPP RAN1 standard contribution - RWS-140026, Sophia Antipolis, France, Jun. 2014.

[22] 3GPP, "LTE in unlicensed spectrum," 3GPP Technical Report, Tech. Rep., Jun. 2014.

[23] IEEE Standard 802.15.4, IEEE, Jun. 2003.

[24] J. Markkula and J. Haapola, "LTE and hybrid sensor-LTE network performances in smart grid demand response scenarios," in *Proc. IEEE Int. Conf. Smart Grid Commun.*, Oct. 2013, pp. 187–192.