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Energy Management in LTE Networks

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ABSTRACT Wireless cellular networks have seen dramatic growth in number of mobile users. As a result, data requirements, and hence the base-station power consumption has increased significantly. It in turn adds to the operational expenditures and also causes global warming. The base station power consumption in long-term evolution (LTE) has, therefore, become a major challenge for vendors to stay green and profitable in competitive cellular industry. It necessitates novel methods to devise energy efficient communication in LTE. Importance of the topic has attracted huge research interests worldwide. Energy saving (ES) approaches proposed in the literature can be broadly classified in categories of energy efficient resource allocation, load balancing, carrier aggregation, and bandwidth expansion. Each of these methods has its own pros and cons leading to a tradeoff between ES and other performance metrics resulting into open research questions. This paper discusses various ES techniques for the LTE systems and critically analyses their usability through a comprehensive comparative study.

INDEX TERMS LTE systems, Energy Efficient Communication, Base Station, Power Consumption.

I. INTRODUCTION

Wireless communication has become one of the basic provisions of the modern world. Since the inception of first radio communication system by Marconi [1], wireless communication systems have seen a massive growth in the last few decades from having a couple of individuals to the majority of the world as their users [2], [3]. The concept of frequency reuse was first introduced in cellular radio communication systems by AT &T [4]. Further developments in radio communication introduced digital cellular systems, which pass through a long chain of evolution known as the Generations (G). We have seen usage of 1G, 2G, 3G and now 4G as the communication standard with each resulting into enhanced performance of cellular systems [5], [6]. Aiming towards the key achievements such as short transmission time, high throughput, low latency and security [7], [8], these systems generally consist of Base Stations (BS) connected to core network. Each BS has designated coverage area, called cell and communicates directly with User Equipment (UE) within its coverage [9], [10], [11]. Whenever UE moves from serving cell to neighbour cell, its transfer of control is initiated through handover process [12], [13]. LTE is a 4G technology, which transmits Digital Broadband Packets over Internet Protocol (IP) while offering peak data rate of 100 – 300 Mbps [14], [15], [16]. This increased data rate in LTE is achieved by employing Orthogonal Frequency Division Multiple Access (OFDMA) based technology which promises low latency, high data rate and packet optimized radio access [17]. This enhanced performance of services compared to previous generations of the cellular networks has helped LTE systems to gain rapid popularity both commercially and academically.

This paper presents a comprehensive study of the existing energy saving techniques for LTE networks. Usability of various methods is critically analyzed through detailed investigation into their strengths and weaknesses. The paper also presents recommendations and highlight open research questions based on the lessons learnt. Following the introduction in section I, rest of the paper is organized as follows. Section II briefly presents architecture of LTE networks, main challenges before highlighting importance of energy saving in the said networks. Section III presents classification of existing ES schemes in LTE networks while Sections IV, V and VI provide detailed description of their

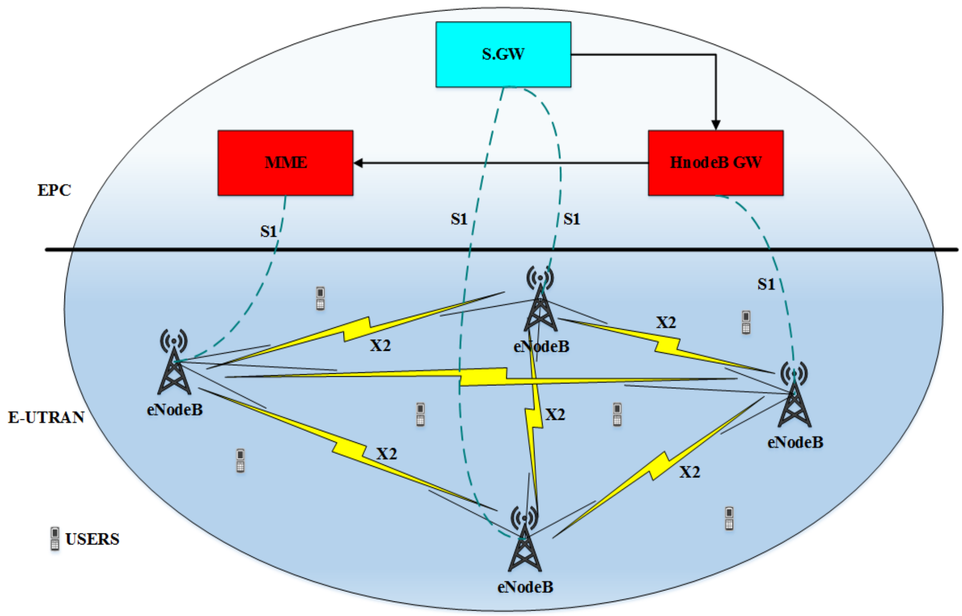

FIGURE 1. Architecture of LTE networks.

TABLE 1. LTE networks components.

Components	Description
Evolved Packet System (EPS)	Provides IP connectivity using E-UTRAN.
Mobility Management Entity (MME)	Responsible for authorization, security, handover, roaming and mobility of Users.
S1 Interface	It connects EPC with BSs (base stations).
Serving Gateway (S.GW)	EPC terminates at this node. It is connected to E-UTRAN through S1 interfaces. Each user is allocated unique S.GW which is responsible for handover, packet routing and forwarding functions.
Packet data network gateway (PDN-GW)	PDN-GW provides UEs with access to packet data network by allocating IP addresses. It is also responsible for secure connection with untrusted devices from non-4G networks.
HnodeB	Femtocells that are employed to improve seamless connectivity in coverage holes.
eNodeB	Also known as BS that serves the UEs.
HnodeB GW	Provides connection to the core network.
X2 Interface	Provides communication between two BSs.

working. Existing energy saving schemes are subsequently critically analysed, discussed and compared for their pros and cons in section VII. Some open research issues and challenges are presented in section VIII. Section IX investigates the learnt lessons before paper is finally concluded in section X.

II. ARCHITECTURE OF LTE NETWORKS

Since the paper is focused on energy management in LTE networks, this section presents a brief overview of the LTE architecture. LTE systems usually provide low latency, high data rate and packet optimized radio access. Compared to 3G, LTE additionally provides international roaming and compatibility with other legacy networks [18], [19]. The 4G systems make use of OFDMA and Single Channel Frequency Division Multiple Access (SC-FDMA) schemes to support flexible bandwidth [20]–[26]. LTE architecture is generally based on Evolved Packet Core (EPC), Universal Terrestrial Radio Access (UTRA), and Universal Terrestrial Radio Access Network (UTRAN), each of which communicates with core network air interfaces and radio access network [27], [28].

Figure 1 illustrates overall architecture of the LTE networks showing both EPC and evolved UTRAN (E-UTRAN) [29], [31] while Table 1 summarizes the core elements of the LTE architecture.

A. COMMUNICATIONS PERSPECTIVE CHALLENGES IN LTE NETWORKS

Though LTE has proven to be a promising technology, it is a complex network and there are some challenges that need to be carefully addressed for optimum functionality.

1) SIGNALLING SYSTEM

In LTE networks, one of the major issues is to avoid or limit signalling overhead and overlapping in control part of the network. Large number of connections between nodes and network fragmentation causes rapid increase in signalling traffic. Any failure in signalling system will drag operators toward increased system latency and outages resulting in to loss of revenues [32], [33]. Increased signalling traffic also leads toward increased energy consumption and definitely needs to be looked in carefully.

2) BACKWARD COMPATIBILITY

LTE is usually compatible with all other relevant major standards. The combination of devices, network interfaces and equipment to support other standards complicates end-to-end functionality testing and interoperability testing (IOT) [34], [35].

3) BS EFFICIENCY

Due to the employment of OFDMA in LTE, signals have high amplitude variability known as Peak-to-Average Power Ratio (PAPR), which reduces transmitter efficiency. Furthermore, the BS provides high data rate at the cost of high dynamic transmission power. Since, high transmission power results in increased energy consumption and thereby increases OPEX; energy management has become major challenge in LTE networks to stay profitable and also to reduce global warming [36].

B. IMPORTANCE OF ES IN LTE NETWORKS

Since increased power consumption (using non-renewable energy sources) directly contributes in climate change, therefore it has become major obstacle for environmental and economic aspects [37], [38]. Vendors highlighted the raising trend of power consumption due to the increased data traffic. Number of users of the mobile networks has 10% annual increase across the world with an increase of 25-50% in each user's data requirements [39]. Therefore, provision of high data rate demanding services with minimum power consumption has become a major challenge for vendors to stay profitable [40], [41]. The Information and Communication Technology (ICT) contributes approximately 10% in worldwide power consumption while it is adding 2% in global warming [42], [43]. Moreover, global warming is growing swiftly due to the additional advance BSs being deployed to fulfill increased users demand thus resulting into 15% to 20% increase per year and this increase almost becomes double every five years [44]. Noteworthy, ICT contribution in Global warming will become 3% by 2020 [45]. Since, BS consumes major part of energy in LTE networks, reducing power consumption at BS could help cutting down OPEX [46]. Vendors choose to deploy automated networks to facilitate energy saving [47]. 3GPP has already introduced Self Organized Networks (SON), which increase the level of automation achieved in operation and maintenance, thereby resulting in a decreased OPEX [48]. Apart from other functionalities, SON also provides opportunities for incorporation of enhanced energy saving (ES) techniques that can help achieve reduced OPEX values. Technologies based on the concept of SON (e.g. LTE), can enjoy a 19% reduced OPEX due to advanced ES techniques [49].

III. CLASSIFICATION OF ENERGY SAVING SCHEMES

The literature presents considerable amount of research work on energy efficiency in LTE systems. Each BS in cellular networks consists of Baseband Units (BBU) with one or more transceivers. Each transceiver contains Radio Frequency (RF) part, Power Amplifier (PA) and Antennas connected through cables [50], [51], [52]. All these components are located very close to each other in a unit called Radio Resource Unit (RRU). PA is the main power hungry element in this unit [53]. Since LTE employs OFDMA [54], [55], [56] and normally PA operates at a level that is 6-12 dB lower than the saturation point, this results into lower adjacent channel interference. Power consumption at BS can be categorized as static and dynamic power consumption [57]. Static power consumption belongs to hardware used in BS and remains nearly constant. Dynamic power (also known as communicational power) on the other hand, depends on traffic load between BS and UEs [58], [59]. The focus of this paper is to investigate, classify and critically analyse existing energy saving techniques to control the dynamic power consumption.

A. STATIC POWER CONSUMPTION

The static power is purely hardware based constant power consumption, which BS needs to cater for necessary operations. The static power consumption can be improved by energy efficient hardware designs and subsequent intelligent deployments. However, in this work our main focus based on dynamic power consumption.

B. DYNAMIC POWER CONSUMPTION

The dynamic power consumption depends on BS's resources utilization and is directly affected by BS transmission operations. Therefore it could be reduced by turning off of BS operations during idle states. Dynamic power management has attracted attention of researchers and could be classified in to three main categories i-e, energy efficient resources allocation, bandwidth expansion and load balancing as shown in Figure 2.

The dynamic (a.k.a. communicational) power consumption can be reduced by appropriate activation and deactivation of BS's transceivers also known as Discontinuous Transmission (DTX) during off peak time periods. Discontinuous

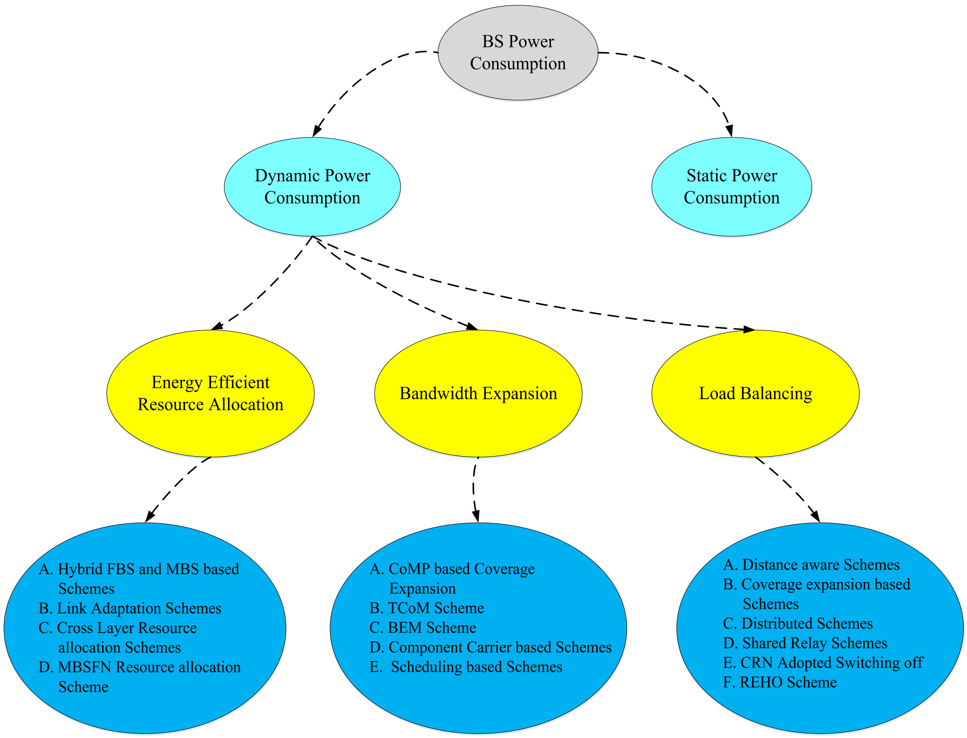

FIGURE 2. **Classification of Energy Saving Schemes.**

Transmission (DTX) based schemes allocate Multicast and Broadcast Single Frequency Network (MBSFN) sub-frames through traffic load consideration [60], [61]. The power aware algorithm analyzes the traffic that cells need to serve, then calculates the amount of resources required and distributes them among the sub frames (SFs) to minimize the power consumption. In lightly loaded conditions, there is a possibility of some frames being not utilized, which could help to achieve improved energy conservation by configuration and turning off of idle frames. Importantly micro cell DTX significantly reduces power consumption during low traffic rate; however it does not work during high traffic loads because there are no empty sub frames left. Results indicate that average power consumption per cell without DTX is 170W [60], while micro DTX enabled cell reduces this Figure by 60%. Next to this, the work presented in [62], [63], [64] avail the concept of energy efficient resource allocation and significantly reduce overall BS power consumption.

Aggregation of resource blocks through carrier aggregation algorithms can also help achieve better energy saving [65], [66]. This helps in reduced overheads thereby increasing energy conservation. On the same line, energy-efficient carrier aggregation algorithms group together the component carriers (CC) to achieve greater energy saving [67]. Distance-aware schemes, which involve switching off of the BS having greater distance from UEs, can also help to obtain better ES [68], [69], [70]. These schemes reduce energy consumption by appropriate activation/deactivation of the BS, based on information of varying distance and load. Another dynamic traffic-aware approach is introduced in [71], which uses time varying traffic information for energy conservation. Each BS divides its cell in different number of sectors, then switch off appropriate sector (with low traffic) providing power saving opportunities. Centralized and distributed schemes which engage UE migration also help achieve better energy saving [72], [73]. Centralized schemes select highest loaded BS through analysing traffic information and determine if it could accommodate more UEs. Considering Selected BS, if available bandwidth is greater than the capacity required to serve neighbour cell, UEs with lowest load traffic will then be shifted towards heavily loaded BS resulting into switching off of lightly loaded BS for reduced energy consumption. Compared to centralised, distributed schemes in contrast, select pair of BSs and then determine the ES state of each BS. Initially, schemes activate energy saving on particular BS, which examines neighbour cells list, and select one BS with lowest load forming a pair. The BS preferred to keep powered ON is the one that could accommodate more UEs. On the same lines, work presented in [74], [75], employ distributed scheduling and energy efficient power control approaches for reduced power consumption. Another work in [76] shares relay between different operators thus resulting into energy saving. In [77] authors introduced an energy-efficient link adaptation scheme that combines the traditional link adaptation with power control, thereby resulting into improved energy efficiency at the BS. This scheme uses BS's transmitted power as a new feedback parameter and predicts an optimal set of parameters in order to maximize the BS's energy efficiency and satisfy the Block Error Rate (BLER) constraint for the channel state. Another interesting scheme is presented in [78], [79] which suggests an energy-efficient resource allocation scheme that operates in multi-cells OFDMA-based LTE networks. In the same context, [80], [81] introduce energy efficient resource allocation for reduced power consumption in LTE networks. This method combines dynamic resource block allocation with energy-efficient power allocation and reduces overall BS power consumption. Bandwidth expansion scheme with load balancing is introduced in [82], [83] which employs the idea of moving UEs from overlapping area of lightly loaded cell to the heavily loaded cell. The Time Compression Mode (TCoM) is presented in [84], which saves power by reducing control signals overhead's transmission. Resource blocks (RBs) are compressed together in TCoM, either in time or frequency domain by usage of higher order modulation. ES is achieved through reduction in overhead signalling by appropriately turning off of the unused RBs [84]. On the same lines, optimized resource allocation could also lead towards reduced energy consumption as discussed in [85]. Energy efficient BSs deployment too has helped for improved energy conservation [86]. Energy saving approaches for D2D communication in LTE networks resulting in to reduced power consumption are presented in [87], [88], and [89]. The most recent research work has established the idea of integrating Cognitive Radio Networks (CRNs) [90] with LTE infrastructure for improved energy saving. This predominantly lies in the fact of isolating users in two categories (i.e. Pus and SUs). During awake periods, BS transmits PUs data over licensed spectrum while in contrast SUs data is sent over unlicensed spectrum. BSs are switched in to sleep mode right after completion of data packets transmission thus resulting into opportunities for improved power conservation. Energy saving can also be achieved through suitable cells coverage expansion and turning off of idle BSs [91]. Importantly, mentioned scheme initially splits cells in two main categories, i.e. cooperative cells and dormant cells. Where, cooperative cells serve associated users while dormant cells are turned off during low traffic time periods for energy saving. Next to this, intelligent resource allocation and power control [92], [93] can help reduce dynamic power consumption thus resulting into improved energy efficiency. Noteworthy, energy efficient schemes while deployed at every BS allocates lower transmit power to suitable resources in line with the associated Signal to Noise plus interference (SINR) ratio. Among others, D2D communication based scheme presented in [94] uses energy efficient heterogeneous routing for enhanced energy conservation.

Significant amount of research work has been carried out to develop different ES Schemes, which help to reduce dynamic power consumption. However, increasing trends of OPEX and global warming indicate that there is always need to do more research work to achieve enhanced ES systems for future wireless systems. Based on discussion above, broad classification of the energy saving schemes is presented in Figure. 2 while detailed insight into individual schemes are provided in the following sections.

IV. ENERGY EFFICIENT RESOURCE ALLOCATION

In order to transport UE data across wireless medium, wireless cellular systems employee various control channels which segregate dissimilar types of data and transport them across radio access network in orderly routine. LTE consist of physical channels, transport channels and logical channels. Further, physical channels consist of Physical Broadcast Channel (PBCH), Master Information Block (MIB) and Physical Downlink Control Channel (PDCCH). Intelligent switching on and off of these control channels can result in increased energy saving. Some Energy Efficient Schemes in energy efficient resource allocation category are explained below.

A. HYBRID FBS AND MBS BASED SCHEMES

The use of Femto base stations (FBS) has proven to be promising technology to cover those areas where macro base stations (MBS) are limited. In the same context, work presented in [92] introduces power control based resource blocks allocation scheme in LTE network with MBS and FBS, which employ the concept of Almost Blank Sub frame (ABS) and Reduced Power Blocks (RBs) to allocate reduced transmission power to resource blocks thereby resulting in to reduced downlink power consumption. Said scheme is recommended for two tier heterogeneous networks with MBS and few FBSs as shown in Figure 3. The main idea lies in the fact that varying transmit power levels can be assigned to different resources thus resulting into reduced BS power consumption. The level of transmit power is measured through SINR, thus if users SINR is higher than predefined threshold then they are allocated with lower transmit power, while higher power is assign to users with lower SINR. Since SINR values changes rapidly, accordingly estimation of transmit power also changes continuously. Next to this Breathing technique is introduced for resource blocks allocation which divided users in two classes, i.e. (Inhale and Exhale). Users are arranged in ascending order in Inhale class in relation to the required transmit power and are mapped with resource blocks in sequence. On the other hand, Exhale class involves sorting of users in descending order of their transmission power value, [92].

B. LINK ADAPTATION SCHEMES

LTE provides high data rate through the effective resources utilization in available bandwidth. The Channel Quality Indicator (CQI), Precoding Matrix Indicator (PMI) and Rank Indicator (RI) parameters play key role in efficient use of resources. PMI determines which precoding matrix should be used for downlink transmission while RI presents the number of layers that should be used for downlink transmission. CQI is reported from UEs to the BS that contains information about the supported Modulation and Coding Schemes (MCS).

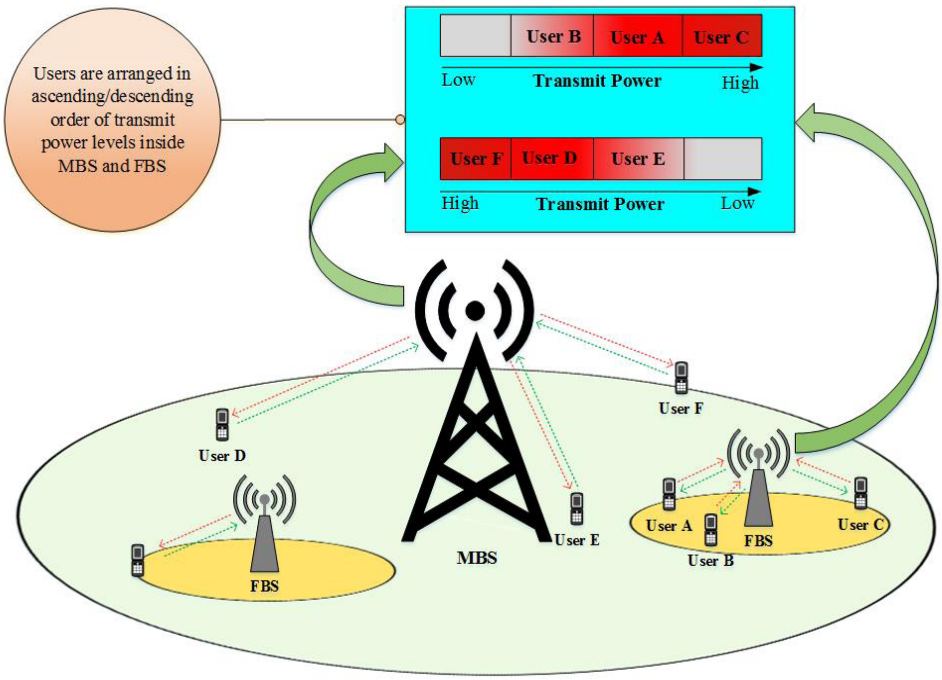

FIGURE 3. Hybrid FBS and MBS based ES scheme.

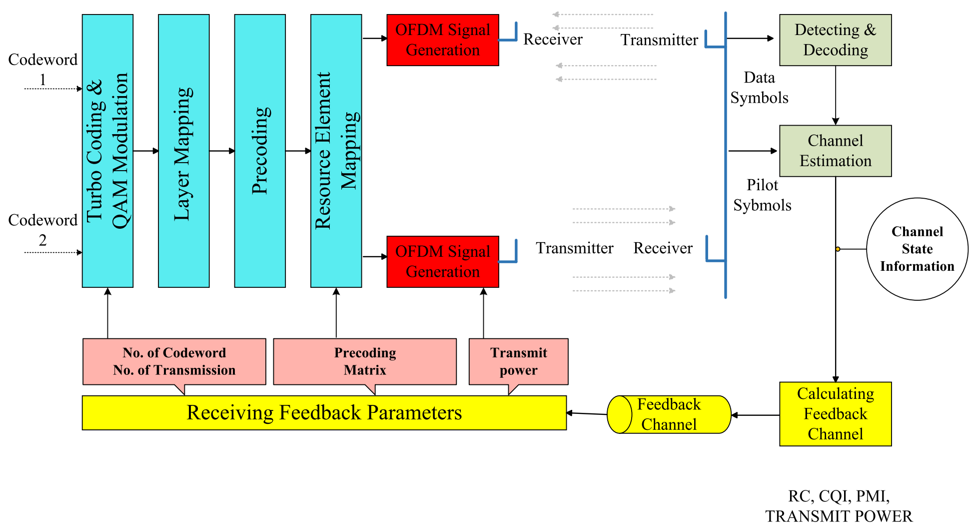

FIGURE 4. Link Adaptation Scheme - LTE based downlink transmission.

CQI plays major role in selection of MCS at downlink in BS. CQI value ranges from 0 to 15. Higher value of CQI indicates use of higher modulation scheme while BS can use higher coding rate for increased energy efficiency [77]. An energy efficient (EE) link adaptation scheme, which combines traditional link adaptation with power control resulting into improved energy efficiency at BS is presented in [77]. This scheme uses BS transmitted power as a new feedback parameter and predicts optimal parameters that maximize the BS energy efficiency and satisfy the Block Error Rate (BLER) constraint which is used for demodulation tests in multipath conditions during radio link monitoring. This scheme can be best described with the help of LTE based downlink transmission model shown in Figure 4. UE estimates channel gain between BS and itself to calculate the parameters RI, PMI, CQI and transmit power. These parameters are then feedback to BS through feedback channel as shown in Figure.4. The BS uses feedback received from UEs as input parameter to adjust its transmission power; where RI helps to determine the code word, CQI helps to select MCS scheme for each transmission, and PMI is used by BS to select the precoding matrix.

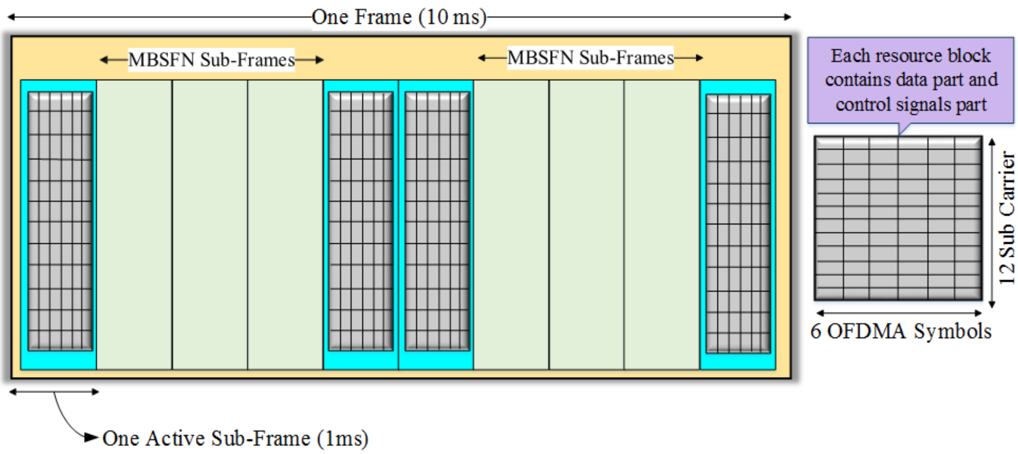

FIGURE 5. MBSFN based Frame architecture.

C. CROSS LAYER RESOURCE ALLOCATION SCHEMES

A cross layer based energy efficient resource allocation scheme for multi-cells OFDMA based LTE networks is presented in [78]. This technique encompasses physical and medium access control (MAC) layers combining dynamic resource block allocation at MAC layer with energy efficient power allocation at physical layer thus resulting in reduced overall power consumption by the BS. Dynamic resource block allocation is based on feedback (energy efficiency indicator) that is used to adjust scheduling process. This method also promotes the user's fairness through allocating equal resources to all users either with good and bad quality channels.

D. MBSFN RESOURCE ALLOCATION SCHEME

The MBFN predicts future traffic load that needs to be served in the next frame, this predicted load is used to calculate the required RBs while turning off the unused resources. The future load prediction is made using previously served load information exchanged between BSs through X2 interface (standard interface used for BS communication in LTE). An interesting MBSFN based ES saving scheme in [61] configures MBSFN sub-frames that helps to provide and setup transmitter switching-off periods. Additionally, this method estimates the resources required to serve the predictive load for effective resource allocation resulting into enhanced power saving by turning off the idle resources. Based on LTE specifications, six out of ten sub-frames can be configured as MBSFN (Figure 5). Importantly MBSFN sub-frames carry less Reference Signals (RS) compared to the standard sub-frame. Therefore, in case no data is available, MBSFN sub-frames can be turned off resulting into reduced energy consumption.

V. BANDWIDTH EXPANSION SCHEMES

The energy efficient LTE networks can also be realized through bandwidth expansion. Several proposed techniques employing bandwidth expansion for improved energy efficiency are presented below.

A. CoMP BASED COVERAGE EXPANSION

Work in [91] uses Coordinated Multiple Point (CoMP) for improved energy saving. CoMP expands cell coverage thus resulting into better expansion compared to antenna adjustments and transmission power measurements (section VI below). Proposed work employs link budget and SINR as input parameters and then divides networks in clusters on the basis of equivalent cell principle with distributed method (Figure 6). Cells in this scheme are divided in two main categories, i.e. cooperative and dormant cells, which is decided by Joint Processing (JP) cooperative cell selection model. During off peak traffic time periods, cooperative cells expand their coverage to serve dormant cells which are turned off for energy saving purposes.

B. TIME COMPRESSION (TCoM) SCHEME

The 10 ms frame in OFDMA consists of 10 subframes. Each subframe includes two slots of 0.5 ms each and each time slot consists of 12 subcarriers and 7 symbols as shown in Figure 7. Subcarriers of each symbol can be allocated to multiple users thereby making efficient use of radio resources. TCoM tries to reduce the power consumption caused by the usage of higher order modulation schemes in OFDMA through decrease in control channel overhead [84]. RBs in TCoM are compressed together and energy saving is achieved through reduced overhead signalling by appropriately turning off unused RBs during idle state. The time and frequency implementations of TCoM do not differ in performance because of the fact that changes in either length or bandwidth of a transmission have the same impact on the transmitter's energy. A compression factor to represent the number of RBs to be pooled together is introduced in [84]. It also uses Shannon's capacity to derive required Signal-to-Noise Ratio (SINR). TCoM is found to be around 26% more energy efficient compared to LTE benchmark standard.

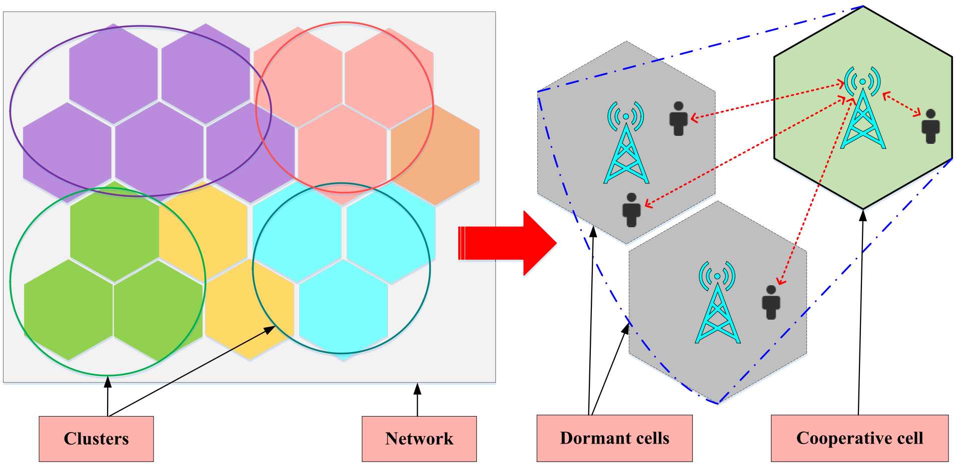

FIGURE 6. CoMP based Coverage Expansion.

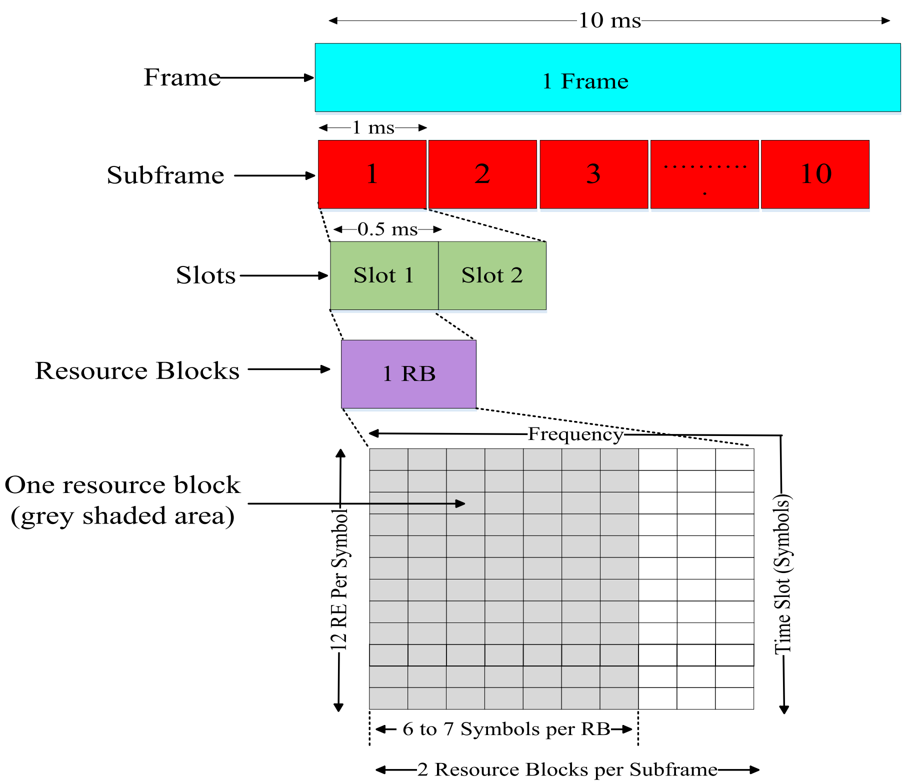

FIGURE 7. OFDMA frame architecture.

C. BANDWIDTH EXPANSION MODE (BEM) SCHEME

Another Bandwidth Expansion Scheme (BEM) is described in [82]. This method is based on the concept that when the network is lightly loaded (larger number of RBs is free), in this scenario bandwidth allocation can be increased to reduce power consumption at BS. In LTE systems, minimum resource allocation is one RB for each user and allocation is done by schedulers. Expanded RB allocation (allocating more than 1 RBs per user) reduces the Modulation and Coding Scheme (MCS) and Signal-to-Noise Interference (SINR) per frequency channel for each user, which in turn provides more energy efficient transmission. Work in [82] specially is recommended for low loaded networks, because extra RBs that are idle during off peak traffic helps in bandwidth expansion. BEM addresses two important factors; Energy Efficiency (EE) and Mobility Load Balancing (MLB) in networks. This work proposes an effective EE resource allocation optimization model by employing

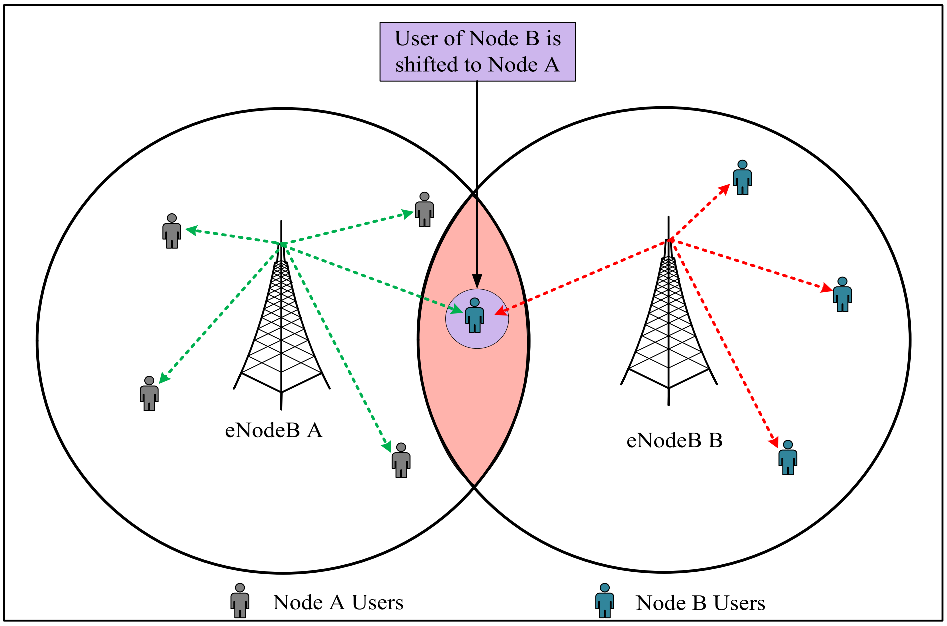

FIGURE 8. Resource Allocation through Load Balancing.

a low complexity method called Energy Efficient Virtual Bandwidth Expansion Mode (EE-VBEM). The concept of Virtual Load Balancing (VLB) that distributes some of the traffic (users) from highly loaded cells to the lightly loaded cells is used as shown in Figure 8. The EE-VBEM consists of two major parts: 1) EE Resource Allocation Optimization Model; 2) Low Complexity Method to achieve 1. Firstly, all base stations exchange load information of neighbouring cells through X2 Interface. Based on this information; each BS determines if there is a need of load balancing. In case load balancing is required, VLB automatically start shifting users from overlapping area to lightly loaded BS. BEM then calculates the required RBs for each UE using minimum required data rate and user channel quality. Once RB calculation is done, the BEM prioritize the users according to the SINR value. Higher SINR indicates higher BEM priority for the user and vice versa. After priority assignment, RBs are allocated to the UEs. BEM saves energy by allocating extra resources at the expense of reduced overall capacity of the BSs [82].

D. COMPONENT CARRIER BASED SCHEMES

Carrier Aggregation is well known technology used in LTE networks for the effective use of bandwidth. Each aggregated carrier is known as Component Carrier (CC) which can have bandwidth ranging from 1.4, 3, 5, 10, 15 or 20 MHz, while maximum of 5 carriers can be aggregated at a time. Carrier aggregation can be achieved through three methods as shown in Figure 9. The simplest method is known as Intra-Band Contiguous; which uses contiguous carrier aggregation at the same frequency band. Second method is known as Non-Contiguous Intra Band Carrier Aggregation in which CC operates at same frequency band but have gaps as shown in Figure 9. Third method is Non-Contiguous Inter Band Carrier Aggregation in which carriers operate at different frequency bands. To achieve an energy efficient communication in the LTE networks, more CCs can be jointly utilized in a BS for enhanced ES opportunities.

In [65], authors recommended OFDMA based multiple CC technique for energy efficient transmission that uses two CCs for data transmission. The main idea is to transmit only necessary CCs thus providing opportunities for appropriate deactivation of idle CCs to reduce the power consumption. The ES scheme in [65] works in downlink in BS and support both real and non-real time traffic simultaneously as shown in Figure.10. The ES scheme consists of 2 CCs operating at same frequency band and can be jointly utilized in BS for data transmission. The two CCs are called Primary Component Carrier (PCC) and Secondary Component Carrier (SCC), respectively. Normal data transmission uses PCC while SCC is only used during high traffic conditions. During transmission, user's data packets are transmitted to the session level where they are classified as Real Time (RT) or Non-Real-Time (NRT) by the classifier and forwarded to RT and NRT Queues, respectively (Figure 10). The data packets then wait in transmission queue to be served by the proposed ES scheme, which consists of two algorithms. First algorithm allocates radio resources, while second algorithm is used for the appropriate activation/deactivation of the SCC. The first algorithm further contains two sub-algorithms called Bandwidth Allocation Algorithm (BAA) and Resource Block Allocation Algorithm (RBAA), respectively. All these algorithms are executed at the beginning of every sub frame and jointly provide ES opportunities at BS.

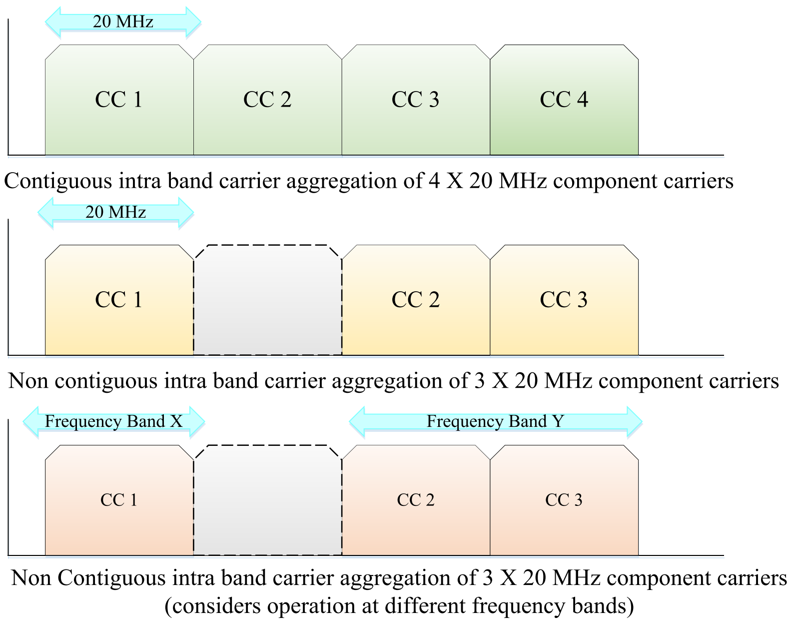

FIGURE 9. Carrier Aggregation.

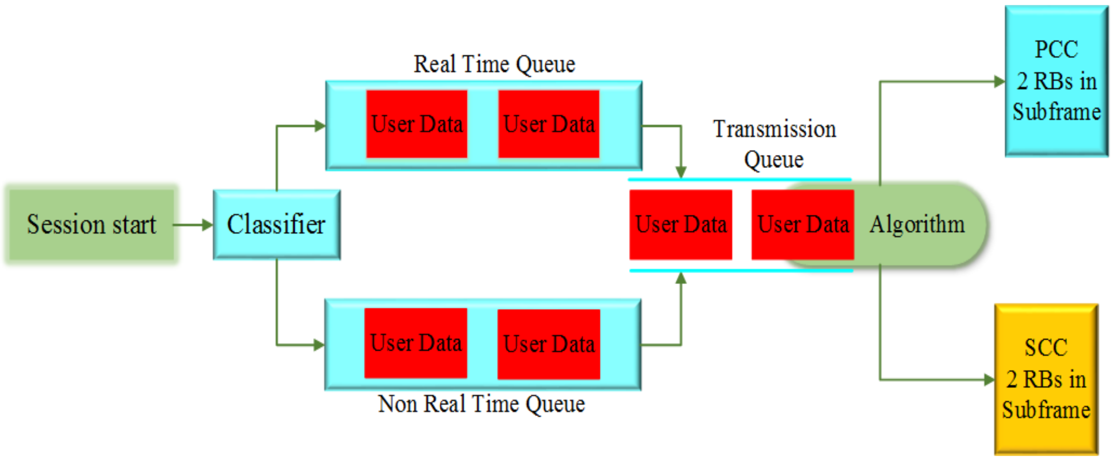

FIGURE 10. OFDMA based Component Carrier ES Scheme.

E. SCHEDULING BASED SCHEMES

Videv et al. have presented an energy efficient scheduling scheme in [95]. The method is based on bandwidth expansion through allocation of extra resources to the UEs and uses lower order modulation schemes for ES. This scheme reduces power consumption by 44% while maintaining throughput and QoS constraints. It uses energy-aware scoring scheduler, which considers best channel conditions and allocates additional resources to the UEs. The scheduler allocates resources by following the integer factor defined for bandwidth expansion. This method is effective only for networks where traffic is low and more free resources are available to be allocated to the UEs. This scheme provides ES at the cost of overall system capacity and therefore, not effective in practical real time environment.

VI. LOAD BALANCING SCHEMES

Research has shown that traffic load varies significantly at the BSs and a lot of energy is wasted during low load operation. Load Balancing is a part of Radio Resource Management (RRM). The term *'Load Balancing'* presents any method that could be used to transfer load from highly loaded cells to lightly loaded neighbour cells for the efficient use of radio resources. The user's distribution and traffic flow is irregular in cells, which can cause an unbalanced load condition in the network. In wireless cellular networks with unequal traffic load distribution, some of the users at the edges of cells can be transferred from highly loaded cells to the lightly loaded cells thereby providing opportunities for efficient resources utilization. When UEs detect that neighbour cells can provide better signal quality than its current

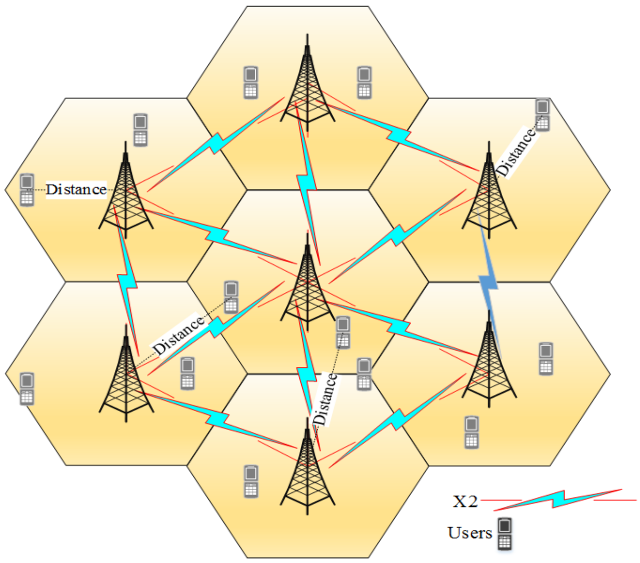

FIGURE 11. Distance aware based BSs communication.

serving BS, they are handed over to that neighbour cell. During load balancing, if the cell is desirable or already in ES mode and it is selected as a candidate for load balancing from a nearby heavily loaded cell, then there exist two options. To prioritize the load balance without considering the ES, and secondly focus is made only to prioritize the ES. In the second case, UEs are not allowed to be handed over to the cells, which are desirable, or already in ES mode and the heavy loaded cell has to find another neighbour cell for load balancing. In this case, edge users may not be served efficiently but power saving could be improved.

A. DISTANCE AWARE SCHEMES

Work in [68] has introduced distance aware schemes that involve switching off of BS having greater distance from UEs. This work reduces energy consumption by appropriate activation/deactivation of BS through information of varying distance and load. Each BS in 7 cells base cluster calculates its average distance from associated UEs and adjacent cells UEs as shown in Figure 11. Since the larger average distance between BS and UEs leads to the higher power consumption, appropriate BS (with larger average distance) is selected for switching OFF. If the bandwidth requirements to serve associated UEs are less than the total available capacity supported by adjacent cells, then the selected BS is switched off and traffic is allocated to the neighbour cells resulting in a reduced power consumption. Moreover, the BSs in sleep mode can be activated if network becomes busy due to high volume of traffic. ES scheme aims to turn off as much BSs as possible without any degradation of QoS. This scheme divides the day in two zones, a night zone (7PM to 7AM) and a day zone (8AM to 6PM). Turning off the BS is performed during night zone to achieve ES during 12 hours of low traffic load conditions. The BS is switched ON during the day zone when traffic load increases and network becomes busy. In high traffic load conditions, a number of BSs should remain switched ON in order to serve the UEs appropriately without affecting the QoS. ES scheme proposed in [68] significantly reduces power consumption by deactivating BSs while neighbour cells can send activation instruction back to the BS in sleep mode through X2 interface.

B. COVERAGE EXPANSION BASED SCHEMES

A centralized ES algorithm is proposed in [72] that provides ES by turning off the lightly loaded BSs. This scheme is based on the idea of shifting the traffic towards highest loaded BS using load and coverage information of the network and switch off lightly loaded BS.

The main idea lies in the fact that all UEs of lightly loaded BS are served by neighbour busiest BS, thus permits lightly loaded BS to turn OFF for energy saving. Initially neighbour BS sectorize its coverage, then extends coverage of appropriate sector through transmission power adjustment and reconfiguration of antenna as shown in Figure 12. The extended sector coverage helps BS to serve UEs of lightly loaded BS being turned off. Proposed algorithm while deployed at every BS, sectorize and extend its coverage for energy saving purposes. It uses two algorithms; first one monitors network for load information while second operates on individual BS and manage its sectorization and transmission expansion process. Initially, on the basis of load information, centralized algorithm selects busiest BS and analyze its resources availability. If selected BS has enough resources to serve neighbour BS's users, then one of its sector transmission coverage is expanded to serve UEs of the neighbour cell being switched off for energy saving as shown in Figure 12 [72].

C. DISTRIBUTED SCHEMES

In [71], a distributed self-organized sectorization of BSs is presented for energy efficient communication. Based on the varying load information, each BS reconfigures itself in real time thus utilizes minimum number of sectors for energy saving while promising adequate QoS. Since each BS dynamically reconfigures itself and no correspondence is required with neighbour BSs, this scheme is inherently distributed and self-organized. Each BS is implemented with traffic aware algorithm for continuous reconfiguration of sectors depending on time varying load. Objective of traffic aware algorithm is to regulate sectorisation and minimize the number of sectors in each BS, while maintaining necessary signal power required for each UE and QoS constraints. Noteworthy during low traffic durations, less number of sectors are sufficient to serve BS users thus unused sectors are turned off to achieve ES as shown in Figure 11. Said scheme estimates the required number of RBs for each UE and uses both time-inhomogeneous and time-homogeneous traffic models for performance analysis. It also employs interference-managing arrangements to handle inter-cell interference and significantly reduces overall system dynamic power consumption by turning off the unused sectors in each BS (Figure 11). However, one of the major disadvantages of this technique

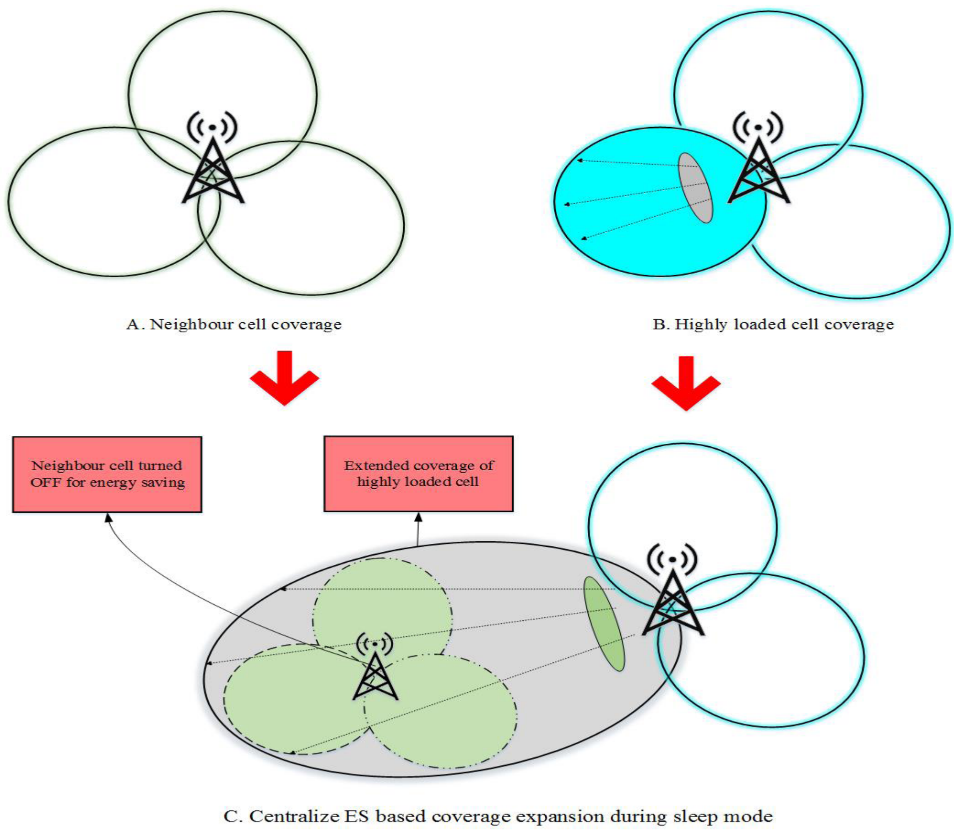

FIGURE 12. BS Coverage Expansion for Energy Saving.

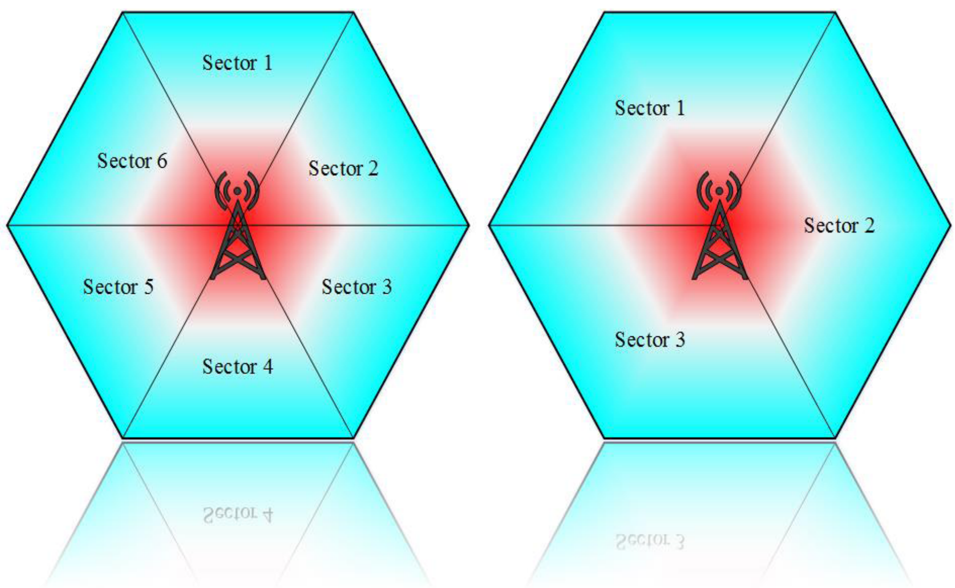

FIGURE 13. Distributed Schemes - Sectorization in Base Stations.

is that a sector can be turned off only if it does not serve even a single UE in low traffic durations.

D. SHARED RELAY BASED SCHEMES

Authors have proposed shared relay based load balancing ES scheme for the LTE networks in [76]. The operators or service providers share their network resources to accommodate additional users and support their demand of increased voice and data services through load balancing. This scheme however, needs reasonable investment in the network infrastructure and is based on two assumptions. First assumption states that two different network operators jointly provide

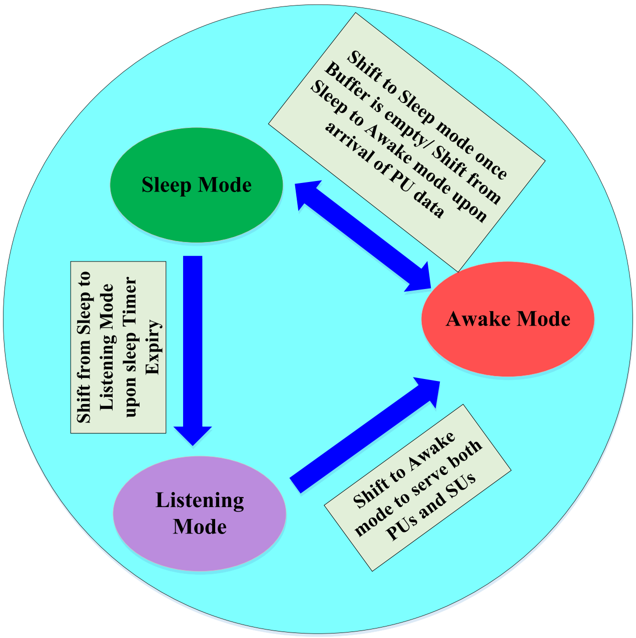

FIGURE 14. State diagram for CRN based energy saving.

coverage to the service area through service level agreement, which allows UEs to communicate with operators through load balancing algorithm. Second assumption says that a centralized SON algorithm is used for optimization of communication between UEs for ES. It lays foundation for a relay based shared network based on two LTE networks belonging to two different operators having their own BSs. UEs of both operators can freely communicate with any BS regardless of their operator. BSs of both operators are connected through backhaul link, which is monitored and controlled by a remote entity called Radio Access Network (RAN). Having information of load and channel conditions, SON algorithm calculates Reference Signal Received Power (RSRP) of both BSs for each user. Once RSRP has been calculated, the UE is then allocated to the BS having better RSRP for it. However, if RSRP of both BSs is same then UEs prefer to communicate with their own operator BS because both operators prefer to utilize their own resources first. This scheme reduces power consumption from 15 to 20% with the help of SON based load balancing.

E. CRN ADOPTED SWITCHING OFF OF BS

The work presented in [90] incorporates Cognitive radio networks with LTE and turns off BSs for energy saving purposes. Proposed algorithm employs three modes of operation, namely sleep, awake and listening modes respectively (Figure 14). During awake mode, PUs data is transmitted using pre-emptive priority while SUs data is sent using unused remaining spectrum. Once all packets have been transmitted and buffer becomes empty, the BS is turned in to sleep mode for energy saving purposes. Importantly arrival of PUs data can shift BS from sleep mode straight back to awake mode. Otherwise BS remains in Sleep mode to conserve energy and shifts to listening mode upon expiry of sleep mode timer. The BS listens to data traffic in listening mode before it repeats the whole cycle.

F. REDUCED EARLY HANDOVER (REHO) SCHEME

Taking into account challenges and open research issues, we have proposed reduced early handover (REHO) energy scheme in [96]. REHO merges bandwidth expansion with resource blocks switching off for enhanced energy saving purposes. REHO scheme while deployed at every BS relocate users from overlapping areas of seven neighbour cells to the one center cell through load balancing thus enabling neighbour cells to turn off freed resource blocks for energy saving. REHO employs the concept of time compression thus combines two RBs to form one incremental RB and allocate to single user resulting into reduced control channels overhead transmission, further it initiates early handover using reduced value of hysteresis.

REHO achieves energy saving through fine-tuning of hysteresis, offset and is explained with help of Figure 15. BSs transmit cell specific Reference Signals to all users within its coverage area, which are used by users to measure reference signals receive power (RSRP). When RSRP of target cell becomes better then serving cell, then user trigger A3 event and send measurement report (best candidate BS information) to serving cell to initiate handover [97]. The hysteresis and offset are used to push user closer to the target cell thus ensuring minimal radio link failure. REHO uses minimum reduced value of hysteresis thus resulting in to early handover initiation as compared to standard handover for energy saving while maintaining radio link failure at acceptable levels. Systems level simulations are performed to demonstrate the behavior of REHO. The chosen network scenario consists of 7 overlapping cells with 50 users randomly distributed in each cell. Figure 16 compares REHO with standard LTE handover for dynamic power consumption. Clearly REHO outperforms standard handover in terms of dynamic power consumption where the reduction in power consumption in REHO is achieved by early turning off of RBs.

VII. DISCUSSION AND CRITICAL ANALYSIS

Table 2 critically compares existing ES schemes in terms of their pros and cons followed by detailed discussion and analysis. Table 2 shows that distance aware scheme [68] operates during 12 hours and save energy up to 30% as compared to always on network during night zone. Since traffic load is high in daytime, distance aware schemes fail to turn off BSs during day time and are only effective in night zone when traffic load is low. Dynamic distance aware approach achieves energy saving up to 70% in comparison to always on network and operates every hour in contrast to distance aware scheme [69]. Since each BS is required to exchange load information every hour with other neighbor cells, it results in an increased overhead in the network.

Discontinuous Transmission (DTX) is one of the most interesting ES schemes. Main advantage of DTX is that it

TABLE 2. Critical analysis of existing ES Schemes.

ES Schemes	Advantages	Disadvantages
Distance Aware [68]	• Power saving up to 30% as compared to always ON network.	• Runs during limited time period (8:00 PM – 8:00 AM). • No power saving during peak traffic time period.
Dynamic Distance aware [69]	• Power saving up to 70% as compared to always ON network. • Low blocking probability. • Runs every hour.	• Exchange of information overhead between cells every hour. • Low power saving during 7PM to 11PM.
Micro DTX scheme [60]	• Power saving up to 61% as compared to cell without any DTX • No need to power off whole base-station • Uses MBSFN sub-frames for power saving. • It creates empty transmission intervals during which PA can be deactivated.	• Longer sleep mode increase the delays; 10 to 20 seconds in going back to active mode. • Increased number of MBSFN sub-frames decreases the capacity and bandwidth. • In LTE rel-8, information could change at system broadcast channel only once in every six minutes.
Enhanced DTX scheme [60]	• Power saving up to 89% as compared to cell without any DTX. • Only synchronization and other secondary signals transmitted.	• Increased number of MBSFN sub-frames decreases the capacity and bandwidth • In LTE rel-8, information could change at system broadcast channel only once every six minutes.
Energy efficient bandwidth expansion scheme [96]	• Save Power up to 44% • Effective for lightly loaded network.	• Reduce the actual capacity or bandwidth. • As traffic load increases, bandwidth decreases.
Centralized Algorithm [73]	• Uses load information scope from entire network. • More effective with lower number of users.	• Lower transition cost with low bandwidth requirements • Higher worst case complexity due to binary heaps.
TCoM [85]	• Provide ES up to 26% as compared to always ON System. • Deactivation of RBs is very effective ES Technique.	• Not effective energy saving at the cell edges. • Suffer from capacity limitation.
EE Link Adaptation Scheme [78]	• More effective for the UEs closer to the BS.	• Limited reduction. • Increased feedback overhead.
BEM [83]	• Significantly Reduced Power Consumption at BS in Low Load Cells. • Distribute Users only from Overlapping area between two Cells thus reduces Overhead. • Allows the use of Lower Order Modulation Schemes, which consume less Power.	• Not suitable for Highly Loaded cells. • ES in trade off with more bandwidth used. • Distribute Users to those cells that are already desirable for Energy saving mode, thus reduce the Power Saving Opportunities in overall Network.
Component Carrier Based EE Scheme [65]	• Support both Real and non-Real time Traffic simultaneously. • Reduce Power Consumption by 50% as compared to always ON CCs Network.	• Only considers two Component Carriers. • Session Blocking increases the delay in high traffic period.
Energy Efficient BS deployment [87]	• Provide Static hardware base energy saving.	• Scheme does not provide further energy saving opportunities, once BSs have deployed.
Power Aware allocation of MBSFN sub-frames [61]	• Uses two power saving concepts. • Deactivates unused sub-frames. • Allocate RBs as much as required depending on load.	• Increased delays. • Only few sub-frames can be switched off because control signals require capacity in few sub-frames.

TABLE 2. *Continued.*Critical analysis of existing ES Schemes.

ES Schemes	Advantages	Disadvantages
Coverage Based Scheme [72]	• Significantly reduce power consumption. • Recommended for lightly loaded network. • Only one partition of BS could be expended rather than full BS coverage area.	• Execution of multiple algorithms increases processing computation. • Challenging for BS to use one sector to provide coverage to full area of neighbour BS. • Load information overhead.
Sector Based Scheme [71]	• SON based ES scheme. • Distributed in nature; each BS provide ES without communicating with other BSs. • Divide coverage in different number of sector depending on load.	• Additional processing computation for sectorization of coverage of BS. • Even existence of users in each sector reduces energy saving opportunities for BS. • Challenging for BS to manage varying sectors in their coverage.
Relay Based Scheme [77]	• Significantly reduce power consumption from 15 to 20%. • UEs can freely access recourses of two different operators. • Does not require load information exchange through X2 interface.	• Difficult for two operators to work together • Allocation of resources to the UEs of other operator may cause capacity limitation for their own associated UEs.
CRN Based Schemes [91]	• Turn off only unused resources during idle time frames.	• Secondary users wait until sleep mode has completed thus resulting in to delay.
REHO Scheme [97]	• Early handover helps resources to become free earlier and turned off for energy saving.	• Increased radio link failure due to early handover.

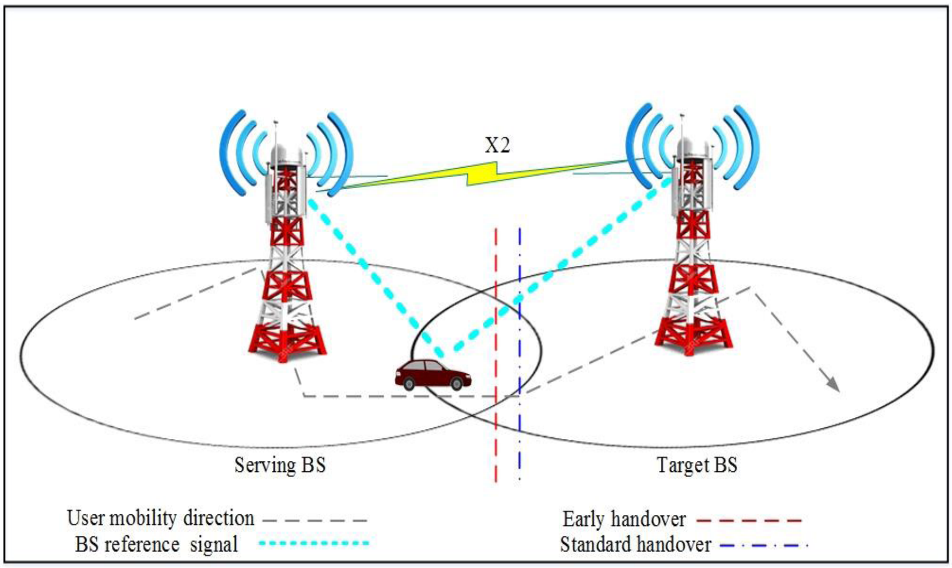

FIGURE 15. REHO Energy Saving Scheme.

targets operational ES where there is no need of turning off whole BS and only unused RBs are switched off [60], [61]. On the other hand, main disadvantage of DTX is the long sleep mode of unused RBs that increases delay time required by RBs to go back to active mode. Distributed schemes also contribute in ES in LTE networks by effectively migrating UEs to the neighbour cells [72], [73]. In these types of schemes, BSs keep exchanging load information with each other resulting in an increased traffic information overhead. Bandwidth expansion is also used to achieve 44% of ES in lightly loaded networks. However, allocation of extra RBs results into reduced available capacity of the BS and thus not

TABLE 3. QoS factors involved in ES schemes.

ES Scheme	QoS Issues				
	Lightly loaded	Heavily loaded	Reduced capacity	Increased delay	Increased Overhead
Distance Aware [68]	✓	X	X	X	✓
Dynamic Distance aware [69]	✓	X	X	X	✓
Micro DTX scheme [60]	✓	✓	X	✓	X
Bandwidth expansion [83]	✓	X	✓	X	X
Centralized Algorithm [73]	✓	X	X	X	✓
TCoM [85]	✓	✓	X	X	X
EE Link Adaptation [78]	✓	✓	✓	X	✓
Component Carrier [65]	✓	✓	✓	X	X
EE BS deployment [87]	✓	✓	X	X	X
Power Aware MBSFN [61]	✓	✓	✓	✓	X
Coverage Based Scheme [72]	✓	X	X	✓	✓
Sector Based Scheme [71]	✓	X	X	✓	X
Relay Based Scheme [77]	✓	✓	X	✓	✓
CRN Based Scheme [91]	✓	X	X	✓	X
REHO Scheme [97]	✓	✓	✓	X	X

very effective during peak hours time period [95]. A combination of load balancing with bandwidth expansion is also used to reduce power consumption in the network [82]. However, this scheme could migrate UEs to those cells that are already desirable for ES mode thus reducing ES opportunities in overall network. The centralized schemes also provide ES but suffer from high traffic load similar to the distributed scheme. The TCoM scheme provides 26% ES by cutting down control channels signalling [84]. Its main idea is similar to the bandwidth expansion, however, it reduces control channel overhead by transmitting two RBs jointly to a single user. TCoM suffers from the drawback of being not effective at cell edges and also requires a reduced overall system capacity. The energy efficient link adaption scheme is only effective for the UEs located closer to the BS and saves 9.4% of energy while increasing the feedback overhead in the network [77]. Carrier aggregation approach is also used for ES reducing power consumption by 50% as compared to always on network [65]. One of the disadvantages of this scheme is session blocking which may increase the delay during high traffic time period.

Coverage expansion is also used as a means to realize ES in the LTE networks [72]. It is however very complicated for the BS to make partitions to expand their transmission power and provide coverage to full neighbour BS using one

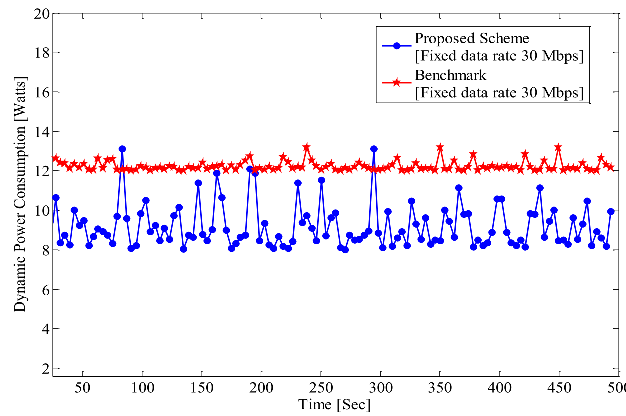

FIGURE 16. REHO Dynamic Power consumption.

partition. On the other hand, execution of two algorithms to implement this scheme also increases overall computation overhead. Division of the BS in different sectors and turning off unused or free sectors is also employed to attain ES [71]. This scheme however only works for a completely free sector and existence of even a single user would not allow the BS to turn off that sector. A shared relay ES scheme based on the idea of sharing resources of two different operators is proposed in [76].

TABLE 4. Open research issues.

ES Scheme	Open Research Areas
Distance Aware [68]	ES can be extended for 24 hours including daytime.
Dynamic Distance aware [69]	Load information overhead could be reduced for enhanced system performance, whereas ES could be extended to include daytime period.
Micro DTX scheme [60]	Delay could be reduced or controlled for better performance.
Enhanced DTX scheme [60]	Capacity limitation could be explored as an open research issue.
Centralized Algorithm [73]	Complex system due to binary heaps could be explored for better performing ES scheme.
TCoM [85]	ES could be further improved at cell edges for enhanced system performance.
EE Link Adaptation Scheme [78]	Feedback overhead could be considered as an open research issue.
BEM [83]	Further enhancement can be done offering ES during peak load hours.
Component Carrier Based EE Scheme [65]	More component carriers can be considered in future research work.
Energy Efficient BS deployment [87]	ES could be extended towards dynamic part of an enhanced system.
Power Aware allocation of MBSFN sub-frames [61]	Capacity limitations can be studied as an open research issue.

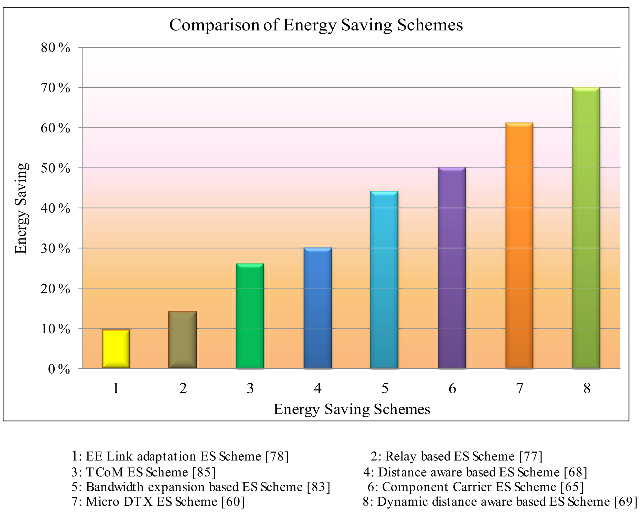

FIGURE 17. Percentage of energy saved in each ES scheme.

However, it is very difficult for two different operators to work and integrate their operations under a shared environment.

Table 3 summarizes the performance of the discussed ES schemes in relation to other QoS issues. Figure 17 presents ES percentage achieved by different ES schemes discussed above. It can be observed that dynamic distance aware scheme is the most energy efficient technique among other ES schemes.

VIII. OPEN RESEARCH ISSUES

Comparative study of various existing ES schemes has shown that most of these schemes are only effective for lightly loaded networks and energy is not saved during highly loaded network conditions. DTX based schemes affected from delay that occur for RBs to come back in active mode [60]. Further research work is needed to reduce these delays. Reduced delay could have significant effect on overall performance of the system. The distance aware and bandwidth expansion based schemes fail to reduce power consumption during peak traffic hours. Therefore, these schemes could be further explored to provide enhanced energy saving during highly loaded traffic [68], [69]. Bandwidth expansion schemes could work more effectively in balanced network. Therefore, load balancing could be further exploited with bandwidth expansion [82], [95]. On the other hand, centralized and distributed schemes exchange load information between the entire BS that increases load information overhead in network and reduces system efficiency [72], [73]. Means should be devised to reduce the load information overhead. Similarly, link adaptation based ES scheme also suffers from overhead produced by energy consumption feedback sent to the BS [77]. Feedback overhead reduction could be exploited for an improved ES in the LTE networks. Energy efficient BS deployment provision could be integrated with any other dynamic energy saving based schemes for enhanced energy efficient systems [86]. MBSFN based ES scheme suffers from control signals which basically reduce the opportunities of turning off the unused RBs [61]. Energy saving through control signals could be further explored for enhanced MBSFN based energy saving. In other words, few aspects of both the TCoM and MBSFN schemes can be taken into account to develop a hybrid ES scheme which may provide better energy efficient system as compared to the systems using TCoM and MBSFN schemes on individual basis [61], [86]. Table 4 presents open research areas for energy saving in LTE networks.

IX. LESSONS LEARNT

Though various schemes have been discussed which help to achieve energy saving thereby improving energy efficiency, however significant lessons have been learnt. DTX provides significant ES however it does not consider any delay related issues which may occur due to the longer sleep mode from 10ms to 20ms cycle. Similarly, distance aware switching off of BSs are effective for lightly loaded networks, however these schemes are not at all suitable for heavily loaded networks. Since during peak load hours, it is not possible to turn off BS therefore these schemes fail to save energy. Bandwidth expansion schemes allocate extra RBs to the UEs which reduces overall available capacity of the system. Accordingly, BEM does not provide energy saving opportunities during peak hour traffic. Further exploring literature review, TCoM considered constant SINR and provides energy saving through reduced control channels overhead, yet RBs still consume power during idle mode and TCoM loses energy saving opportunities. Importantly centralized schemes have also proven to be effective for lightly loaded networks only; these schemes fail to provide energy saving in highly loaded networks. Link adaptation schemes reduce power consumption only by 9.4%, while it considerably increases overhead of feedback sent back to BS for energy saving purpose. The carrier aggregation based ES scheme combines two carrier components whereas it suffers from session blocking resulting in to increased delay during high traffic periods. Most of existing energy saving proposals mostly work in lightly loaded networks while do not provide adequate and considerable energy saving during peak hours. Indeed there exists plenty of room and need for additional research work which could be carried out to provide energy saving during peak traffic time periods too. Mentioned drawbacks and learnt lessons can indeed be carefully employed and guide future researchers to conduct and develop novel robust energy efficient schemes in the light of mentioned open research issues (Table 4).

X. CONCLUSION

Due to increased Global warming and worldwide climate change, energy consumption has become major hurdle. The ICT contributes approximately 2% in global warming, while major part is attributed to telecommunication in ICT. In cellular networks, energy consumption is effected from growing mobiles users and their data requirements. Moreover, further deployment of additional and enhanced BSs to fulfill ever growing users requirements also adds in ICT contribution. Therefore, increasing trend of energy consumption has become major challenge for vendors thus affecting both economical and environmental aspects. The rapid increase in energy consumption not only increases OPEX but also effects climate change. Research work has proven that BSs in LTE networks consume a lot of dynamic power during idle state, which could be saved by appropriate energy saving schemes. The reduced power consumption enhances the LTE system performance through cutting down the OPEX and carbon emission thus also helping the vendors to have high profile in green communication. This paper has provided detailed discussion of existing energy saving schemes developed for LTE networks. Critical analysis of the schemes has been presented before open research issues are discussed. Finally, authors novel REHO energy saving scheme is also briefly described which takes into account challenges and builds itself upon research issues. The paper is a comprehensive account of the existing ES schemes for LTE networks and can help researchers to understand current state of art, open research issues to come up with innovative solutions resulting in optimized system performance.

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REFERENCES

[1] M. A. Garrett, "Radio astronomy transformed: Aperture arrays—Past, present and future," in *Proc. AFRICON*, 2013, pp. 1–5.
[2] Q. Fan, H. Lu, P. Hong, and Z. Zhu, "Throughput-power tradeoff association for user equipments in wlan/cellular integrated networks," *IEEE Trans. Veh. Technol.*, to be published, doi: 10.1109/TVT.2016.2594874.
[3] Y. W. Blankenship, "Achieving high capacity with small cells in LTE-A," in *Proc. 50th Annu. Allerton Conf. Commun., Control, Comput. (Allerton)*, Monticello, IL, USA, Oct. 2012, pp. 1680–1687.
[4] M. Agiwal, A. Roy, and N. Saxena, "Next generation 5G wireless networks: A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 3, pp. 1617–1655, 3rd Quart., 2016.
[5] A. Damnjanovic *et al.*, "A survey on 3GPP heterogeneous networks," *IEEE Wireless Commun.*, vol. 18, no. 3, pp. 10–21, Jun. 2011.
[6] F. Adachi, "Wireless evolution and challenges for 5G wireless networks," in *Proc. 2nd Nat. Found. Sci. Technol. Develop. Conf. Inf. Comput. Sci. (NICS)*, 2015, pp. 21–22.
[7] N. Chandran and M. C. Valenti, "Three generations of cellular wireless systems," *IEEE Potentials*, vol. 20, no. 1, pp. 32–35, Feb. 2001.
[8] B. Esmailpour, S. Salehi, and N. Safavi, "Quality of service differentiation measurements in 4G networks," in *Proc. Wireless Telecommun. Symp. (WTS)*, Phoenix, AZ, USA, 2013, pp. 1–5.
[9] Y. Tian, A. Nix, and M. Beach, "4G femtocell LTE base station with diversity and adaptive antenna techniques," in *Proc. 10th Int. Conf. Wireless Commun., Netw. Mobile Comput. (WiCOM)*, 2014, pp. 216–221.
[10] *Evolved Universal Terrestrial Radio Access (E-UTRA): Base Station (BS) Radio Transmission and Reception*, document TS 36.104 V11.9.0, 3GPP, 2015.
[11] M. Nasimi, F. Hashim, and C. K. Ng, "Characterizing energy efficiency for heterogeneous cellular networks," in *Proc. IEEE Student Conf. Res. Develop. (SCOReD)*, 2012, pp. 198–202.
[12] I. Shayea, M. Ismail, and R. Nordin, "Advanced handover techniques in LTE- advanced system," in *Proc. Int. Conf. Comput. Commun. Eng. (ICCCE)*, 2012, pp. 74–79.
[13] U. Dampage and C. B. Wavegedara, "A low-latency and energy efficient forward handover scheme for LTE-femtocell networks," in *Proc. IEEE 8th Int. Conf. Ind. Inf. Syst.*, 2013, pp. 53–58.

[14] P. Skocir, D. Katusic, I. Novotni, I. Bojic, and G. Jezic, "Data rate fluctuations from user perspective in 4G mobile networks," in *Proc. 22nd Int. Conf. Softw., Telecommun. Comput. Netw. (SoftCOM)*, 2014, pp. 180–185.
[15] S. Abeta, "Toward LTE commercial launch and future plan for LTE enhancements (LTE-Advanced)," in *Proc. IEEE Int. Conf. Commun. Syst. (ICCS)*, Singapor, Nov. 2010, pp. 146–150.
[16] M. F. L. Abdullah and A. Z. Yonis, "Performance of LTE release 8 and release 10 in wireless communications," in *Proc. Cyber Secur., Cyber Warfare Digit. Forensic (CyberSec)*, 2012, pp. 236–241.
[17] A. Navita, "Performance analysis of OFDMA, MIMO and SC-FDMA technology in 4G LTE networks," in *Proc. 6th Int. Conf.-Cloud Syst. Big Data Eng.*, 2016, pp. 554–558.
[18] N. Takaharu, "LTE and LTE-advanced: Radio technology aspects for mobile communications," in *Proc. General Assembly Sci. Symp.*, 2011, pp. 1–4.
[19] H. Lee, S. Vahid, and K. Moessner, "A survey of radio resource management for spectrum aggregation in LTE-advanced," *IEEE Commun. Surv. Tuts.*, vol. 16, no. 2, pp. 745–760, 2nd Quart., 2014.
[20] N. Becker, A. Rizk, and M. Fidler, "A measurement study on the application-level performance of LTE," in *Proc. Netw. Conf.*, 2014, pp. 1–9.
[21] S. B. Manir, M. M. Rahman, and T. Ahmed, "Comparison between FDD and TDD frame structure in SC-FDMA," in *Proc. Int. Conf. Inf., Electron. Vis. (ICIEV)*, 2012, pp. 795–799.
[22] L. Wan, M. Zhou, and R. Wen, "Evolving LTE with flexible duplex," in *Proc. IEEE Globecom Workshops (GCWkshps)*, 2013, pp. 49–54.
[23] R. Ratasuk, A. Ghosh, W. Xiao, R. Love, R. Nory, and B. Classon, "TDD design for UMTS long-term evolution," in *Proc. IEEE 19th Int. Symp. Pers., Indoor Mobile Radio Commun.*, 2008, pp. 1–5.
[24] R. Zheng, X. Zhang, X. Li, Q. Pan, Y. Fang, and D. Yang, "Performance evaluation on the coexistence scenario of two 3GPP LTE systems," in *Proc. IEEE 70th Veh. Technol. Conf. Fall (VTC-Fall)*, Anchorage, AK, USA, Aug. 2009, pp. 1–6.
[25] S. S. Prasad, C. K. Shukla, and R. F. Chisab, "Performance analysis of OFDMA in LTE," in *Proc. 3rd Int. Conf. Comput. Commun. Netw. Technol. (ICCCNT)*, 2012, pp. 1–7.
[26] L. A. M. R. de Temino, G. Berardinelli, S. Frattasi, K. Pajukoski, and P. Mogensen, "Single-user MIMO for LTE-A Uplink: Performance evaluation of OFDMA vs. SC-FDMA," in *Proc. IEEE Radio Wireless Symp.*, San Diego, CA, USA, Jan. 2009, pp. 304–307.
[27] *Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Networks (E UTRAN): Overall description*, document TS 36.300V10.4.0, 3GPP, 2016.
[28] *Technical Specification Group Radio Access Network; Further advancements for E-UTRA—LTE-Advanced feasibility Studies in RAN WG4*, document TR 36.815V9.0.0, 3GPP, 2015.
[29] *General Packet Radio Service (GPRS) Enhancements for Evolved Universal Terrestrial Radio Access Network (E-UTRAN) Access, 3rd Generation Partnership Project*, document TR 36.815V9.0.0, 3GPP, Jun. 2011.
[30] S. B. H. Said *et al.*, "New control plane in 3GPP LTE/EPC architecture for on-demand connectivity service," in *Proc. Cloud Netw. (CloudNet)*, San Francisco, CA, USA, 2013, pp. 205–209.
[31] A. Cox, *An Introduction to LTE: LTE, LTE-Advanced, SAE and 4G Mobile Communications*. Hoboken, NJ, USA: Wiley, 2012, pp. 21–28.
[32] K. P. Makhecha and K. H. Wandra, "4G wireless networks: Opportunities and challenges," in *Proc. Annu. IEEE India Conf.*, Mar. 2009, pp. 1–4.
[33] A. Pande, V. Ahuja, R. Sivaraj, E. Baik, and P. Mohapatra, "Video delivery challenges and opportunities in 4G networks," *IEEE Multimedia Mag.*, vol. 20, no. 3, pp. 88–94, Sep. 2013.
[34] M. Iwamura, K. Etemad, M. H. Fong, R. Nory, and R. Love, "Carrier aggregation framework in 3GPP LTE-advanced [WiMAX/LTE Update]," *IEEE Commun. Mag.*, vol. 48, no. 8, pp. 60–67, Aug. 2010.
[35] Y. Yuan, S. Wu, J. Yang, F. Bi, S. Xia, and G. Li, "Relay backhaul subframe allocation in LTE-Advanced for TDD," in *Proc. 5th Int. ICST Conf. Commun. Netw. China (CHINACOM)*, 2010, pp. 1–5.
[36] S. Ahmadi, *LTE-Advanced: A Practical Systems Approach to Understanding 3GPP LTE Release 10 and 11 Radio Access Technologies*. Waltham, MA, USA: Elsevier2014, pp. 61–65.
[37] G. Cili, H. Yanikomeroglu, and F. R. Yu, "Cell switch off technique combined with coordinated multi-point (CoMP) transmission for energy efficiency in beyond-LTE cellular networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Ottawa, ON, Canada, Jun. 2012, pp. 5931–5935.
[38] M. Pickavet *et al.*, "Worldwide energy needs for ICT: The rise of power-aware networking," in *Proc. 2nd Int. Symp. Adv. Netw. Telecommun. Syst.*, 2008, pp. 1–3.
[39] Y. L. Chung, "Energy-saving transmission for green macrocell-small cell systems: A system-level perspective," *IEEE Syst. J.*, to be published, doi: 10.1109/JSYST.2015.2475377.
[40] E. Oh, B. Krishnamachari, X. Liu, and Z. Niu, "Toward dynamic energy-efficient operation of cellular network infrastructure," *IEEE Commun. Mag.*, vol. 49, no. 6, pp. 56–61, Jun. 2011.
[41] R. Maihaniemi, "ICT getting green," in *Proc. 4th Int. Conf. Telecommun. Energy Special Conf. (TELESCON)*, Vienna, Austria, 2009, pp. 1–6.
[42] H. O. Scheck, "ICT & wireless networks and their impact on global warming," in *Proc. Eur. Wireless Conf. (EW)*, 2010, pp. 911–915.
[43] Y. Chen *et al.*, "Fundamental trade-offs on green wireless networks," *IEEE Commun. Mag.*, vol. 49, no. 6, pp. 30–37, Jun. 2011.
[44] G. Fettweis and E. Zimmermann, "ICT energy consumption-Trends and challenges," in *Proc. 11th Int. Symp. WPMC*, Sep. 2008, pp. 2–4.
[45] M. Griffiths. (Dec. 2008). ICT and CO_2 emissions. Parliamentary Office Sci. Technol., London, U.K. [Online]. Available: http://www.parliament.uk/documents/post/postpn319.pdf
[46] T. M. Knoll, "A combined CAPEX and OPEX cost model for LTE networks," in *Proc. 16th Int. Telecommun. Netw. Strategy Planning Symp. (Netw.)*, Sep. 2014, pp. 1–6.
[47] J. Moysen and L. Giupponi, "Self coordination among SON functions in LTE heterogeneous networks," in *Proc. IEEE 81st Veh. Technol. Conf. (VTC Spring)*, May 2015, pp. 1–6.
[48] T. M. Knoll, "Life-cycle cost modelling for NFV/SDN based mobile networks," in *Proc. Telecommun., Media Internet Techno-Econ. (CTTE)*, 2015, pp. 1–8.
[49] N. Zhang and H. Hämmäinen, "Cost efficiency of SDN in LTE-based mobile networks: Case Finland," in *Proc. Int. Conf. Workshops Netw. Syst. (NetSys)*, 2015, pp. 1–5.
[50] S. M. Azzam and T. Elshabrawy, "Re-dimensioning number of active eNodeBs for green LTE networks using genetic algorithms," in *Proc. 21th Eur. Wireless Conf., Eur. Wireless*, May 2015, pp. 1–6.
[51] O. Arnold, F. Richter, G. Fettweis, and O. Blume, "Power consumption modeling of different base station types in heterogeneous cellular networks," in *Proc. Future Netw. Mobile Summit*, 2010, pp. 1–8.
[52] K. Hiltunen, "Utilizing eNodeB sleep mode to improve the energy-efficiency of dense LTE networks," in *Proc. IEEE 24th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, London, U.K., Sep. 2013, pp. 3249–3253.
[53] T. Chen, H. Zhang, Z. Zhao, and X. Chen, "Towards green wireless access networks," in *Proc. 5th Int. ICST Conf. Commun. Netw. China (CHINACOM)*, 2010, pp. 1–6.
[54] S. Srikanth, P. A. Murugesa Pandian, and X. Fernando, "Orthogonal frequency division multiple access in WiMAX and LTE: A comparison," *IEEE Commun. Mag.*, vol. 50, no. 9, pp. 153–161, Sep. 2012.
[55] S. Janaaththanan, C. Kasparis, and B. G. Evans, "Comparison of SC-FDMA and HSUPA in the return-link of evolved S-UMTS architecture," in *Proc. Int. Workshop Satellite Space Commun. (IWSSC)*, 2007, pp. 56–60.
[56] M. Salem, A. Adinoyi, H. Yanikomeroglu, and Y. D. Kim, "Radio resource management in OFDMA-based cellular networks enhanced with fixed and nomadic relays," in *Proc. IEEE Wireless Commun. Netw. Conf.*, Apr. 2010, pp. 1–6.
[57] M. M. Matalgah, B. Paudel, and O. M. Hammouri, "Cross-layer resource allocation approach in OFDMA systems with multi-class QoS services and users queue status," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2013, pp. 1385–1390.
[58] M. Deruyck, E. Tanghe, W. Joseph, and L. Martens, "Modelling the energy efficiency of microcell base stations," in *Proc. 1st Int. Conf. Smart Grids, Green Commun. IT Energy-Aware Technol.*, 2012, pp. 1–6.
[59] W. Tomaselli, D. Sabella, V. Palestini, and V. Bernasconi, "Energy efficiency performances of selective switch OFF algorithm in LTE mobile networks," in *Proc. IEEE 24th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, London, U.K., Sep. 2013, pp. 3254–3258.
[60] P. Frenger, P. Moberg, J. Malmodin, Y. Jading, and I. Godor, "Reducing energy consumption in LTE with cell DTX," in *Proc. IEEE 73rd Veh. Technol. Conf. (VTC Spring)*, May 2011, pp. 1–5.
[61] A. Migliorini, G. Stea, M. Caretti, and D. Sabella, "Power-aware allocation of MBSFN subframes using discontinuous cell transmission in LTE systems," in *Proc. IEEE 78th Veh. Technol. Conf. (VTC Fall)*, Las Vegas, NV, USA, Sep. 2013, pp. 1–5.

[62] S. Herrería-Alonso, M. Rodríguez-Pérez, M. Fernández-Veiga, and C. López-García, "Adaptive DRX scheme to improve energy efficiency in LTE networks with bounded delay," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 12, pp. 2963–2973, Dec. 2015.
[63] K. Davaslioglu, C. C. Coskun, and E. Ayanoglu, "Energy-efficient resource allocation for fractional frequency reuse in heterogeneous networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 10, pp. 5484–5497, Oct. 2015.
[64] X. Xiao, X. Tao, and J. Lu, "Energy-efficient resource allocation in LTE-based MIMO-OFDMA systems with user rate constraints," *IEEE Trans. Veh. Technol.*, vol. 64, no. 1, pp. 185–197, Jan. 2015.
[65] A. T. Tung, Y. L. Chung, and Z. Tsai, "An efficient power-saving downlink transmission scheme in OFDM-based multiple component carrier systems," in *Proc. 14th Int. Conf. Adv. Commun. Technol. (ICACT)*, 2012, pp. 116–120.
[66] K. Sundaresan and S. Rangarajan, "Energy efficient carrier aggregation algorithms for next generation cellular networks," in *Proc. 21st IEEE Int. Conf. Netw. Protocols (ICNP)*, 2013, pp. 1–10.
[67] F. Liu, K. Zheng, W. Xiang, and H. Zhao, "Design and performance analysis of an energy-efficient uplink carrier aggregation scheme," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 2, pp. 197–207, Feb. 2014.
[68] A. Bousia, A. Antonopoulos, L. Alonso, and C. Verikoukis, "'Green' distance-aware base station sleeping algorithm LTE-Advanced," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Ottawa, ON, Canada, Jun. 2012, pp. 1347–1351.
[69] A. Bousia, E. Kartsakli, L. Alonso, and C. Verikoukis, "Dynamic energy efficient distance-aware base station switch on/off scheme for LTE-advanced," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Jun. 2012, pp. 1532–1537.
[70] L. Li, Y. Zhang, B. Fan, and H. Tian, "Mobility-aware load balancing scheme in hybrid VLC-LTE networks," *IEEE Commun. Lett.*, vol. 20, no. 11, pp. 2276–2279, Nov. 2016.
[71] M. F. Hossain, K. S. Munasinghe, and A. Jamalipour, "Toward self-organizing sectorization of LTE eNBs for energy efficient network operation under QoS constraints," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*0, Apr. 2013, pp. 1279–1284.
[72] K. Samdanis, D. Kutscher, and M. Brunner, "Self-organized energy efficient cellular networks," in *Proc. IEEE 21st Int. Symp. Pers. Indoor Mobile Radio Commun. (PIMRC)*, Sep. 2010, pp. 1665–1670.
[73] K. Samdanis, T. Taleb, D. Kutscher, and M. Brunner, "Self organized network management functions for energy efficient cellular urban infrastructures," in *Proc. Mob. Netw. Appl.*, vol. 17. 2012, pp. 119–131.
[74] S. A. Ahmad and D. Datla, "Distributed power allocations in heterogeneous networks with dual connectivity using backhaul state information," *IEEE Trans. Wireless Commun.*, vol. 14, no. 8, pp. 4574–4581, Aug. 2015.
[75] H. H. Nguyen and W. J. Hwang, "Distributed scheduling and discrete power control for energy efficiency in multi-cell networks," *IEEE Commun. Lett.*, vol. 19, no. 12, pp. 2198–2201, Dec. 2015.
[76] V. Monteiro, T. Ramrekha, D. Yang, J. Rodriguez, S. Mumtaz, and C. Politis, "An energy efficient proposal in shared relay-based LTE network," in *Proc. 10th Int. Symp. Wireless Commun. Syst. (ISWCS)*, 2013, pp. 1–5.
[77] A. Li, S. Jin, F. Zheng, X. Gao, and X. Wang, "Energy efficient link adaptation for downlink transmission of LTE/LTE-A systems," in *Proc. IEEE 78th Veh. Technol. Conf. (VTC Fall)*, Las Vegas, NV, USA, Jun. 2013, pp. 1–5.
[78] D. D. Ling, Z. Lu, W. Zheng, X. Wen, and Y. Ju, "Energy efficient cross-layer resource allocation scheme based on potential games in LTE-A," in *Proc. 15th Int. Symp. Wireless Pers. Multimedia Commun. (WPMC)*, Dec. 2012, pp. 623–627.
[79] Z. Zhou, M. Dong, K. Ota, G. Wang, and L. T. Yang, "Energy-efficient resource allocation for d2d communications underlaying cloud-RAN-based LTE—A networks," *IEEE Internet Things J.*, vol. 3, no. 3, pp. 428–438, Jun. 2016.
[80] S. Rostami, K. Arshad, and P. Rapajic, "Energy-efficient resource allocation for LTE—A networks," *IEEE Commun. Lett.*, vol. 20, no. 7, pp. 1429–1432, Jul. 2016.
[81] F. Z. Kaddour, E. Vivier, L. Mroueh, M. Pischella, and P. Martins, "Green opportunistic and efficient resource block allocation algorithm for LTE uplink networks," *IEEE Trans. Veh. Technol.*, vol. 64, no. 10, pp. 4537–4550, Oct. 2015.
[82] Y. Li, W. Liu, B. Cao, and M. Li, "Green resource allocation in LTE system for unbalanced low load networks," in *Proc. IEEE 23rd Int. Symp. Pers., Indoor Mobile Radio Commun. (PIMRC)*, Dec. 2012, pp. 1009–1014.
[83] S. Almowuena, M. M. Rahman, C. H. Hsu, A. A. Hassan, and M. Hefeeda, "Energy-aware and bandwidth-efficient hybrid video streaming over mobile networks," *IEEE Trans. Multimedia*, vol. 18, no. 1, pp. 102–115, Jan. 2016.
[84] S. Videv, H. Haas, J. S. Thompson, and P. M. Grant, "Energy efficient resource allocation in wireless systems with control channel overhead," in *Proc. IEEE Wireless Commun. Netw. Conf. Workshops (WCNCW)*, Jun. 2012, pp. 64–68.
[85] A. Han and S. Armour, "Energy efficient radio resource management strategies for green radio," *IET Commun.*, vol. 5, no. 18, pp. 2629–2639, Dec. 2011.
[86] C. Coskun and E. Ayanoglu, "Energy-efficient base station deployment in heterogeneous networks," *IEEE Wireless Commun. Lett.*, vol. 3, no. 6, pp. 593–596, Dec. 2014.
[87] P. Van, B. P. Rimal, S. Andreev, T. Tirronen, and M. Maier, "Machine-to-machine communications over FiWi enhanced LTE networks: A power-saving framework and end-to-end performance," *J. Lightw. Technol.*, vol. 34, no. 4, pp. 1062–1071, Feb. 15, 2016.
[88] S. Mumtaz, K. M. Saidul Huq, J. Rodriguez, and V. Frascolla, "Energy-efficient interference management in LTE-D2D communication," *IET Signal Process.*, vol. 10, no. 3, pp. 197–202, Jun. 2016.
[89] J. Liu, N. Kato, J. Ma, and N. Kadowaki, "Device-to-device communication in LTE-advanced networks: A survey," *IEEE Commun. Surv. Tuts.*, vol. 17, no. 4, pp. 1923–1940, 4th Quart., 2015.
[90] S. Jin, X. Ma, and W. Yue, "Energy-saving strategy for green cognitive radio networks with an LTE-advanced structure," *J. Commun. Netw.*, vol. 18, no. 4, pp. 610–618, Aug. 2016.
[91] F. Zheng, W. Li, L. Meng, P. Yu, and L. Peng, "Distributed energy saving mechanism based on CoMP in LTE-A system," *China Commun.*, vol. 13, no. 7, pp. 39–47, Jul. 2016.
[92] V. J. Kotagi, R. Thakur, S. Mishra, and C. S. R. Murthy, "Breathe to save energy: Assigning downlink transmit power and resource blocks to LTE enabled IoT networks," *IEEE Commun. Lett.*, vol. 20, no. 8, pp. 1607–1610, Aug. 2016.
[93] L. You, L. Lei, and D. Yuan, "Optimizing power and user association for energy saving in load-coupled cooperative LTE," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2016, pp. 1–6.
[94] G. Kalogridis and O. Georgiou, "CreD2D: A credit-driven self-evolving D2D towards LTE HetNet energy saving," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC)*, May 2016, pp. 742–748.
[95] S. Videv and H. Haas, "Energy-efficient scheduling and bandwidth-energy efficiency trade-off with low load," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2011, pp. 1–5.
[96] K. Kanwal and G. A. Safdar, "Reduced early handover for energy saving in LTE networks," *IEEE Commun. Lett.*, vol. 20, no. 1, pp. 153–156, Jan. 2016.
[97] G. A. Safdar, M. Ur-Rehman, M. Muhammad, M. A. Imran, and R. Tafazolli, "Interference mitigation in D2D communication underlaying LTE-a network," *IEEE Access*, vol. 4, pp. 7967–7987, 2016.

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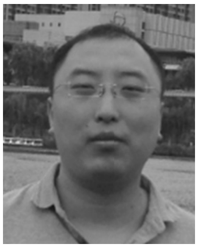

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