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A Survey on LTE/LTE-A Radio Resource Allocation Techniques for Machine-to-Machine Communication for B5G Networks

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ABSTRACT Machine-to-Machine (M2M) communication refers to autonomous communication among devices that aims for a massive number of connected devices. M2M communication can support ubiquitous communication and full mechanical automation, and it will change everything from industry to ourselves. Recent developments in communication technology make Long Term Evolution (LTE)/Long Term Evolution-Advance (LTE-A) a promising technology for supporting M2M communication. LTE can support the diverse characteristic of M2M communication due to its IP connectivity, coverage area, and scalability. Therefore, the LTE schedulers should satisfy the need for M2M communication. Motivated by these facts, in this paper, we present a survey on the classification of LTE / LTE-A scheduling methodologies from the perspective of M2M communication. We classify the schedulers based on their objectives, such as energy efficiency, spectrum efficiency, group-based, and Quality-of-Service (QoS) support for Machine Type Communication Devices (MTCs). We also highlight the scope of future research direction for the scheduling work.

INDEX TERMS M2M communication, LTE/LTE-A, scheduling, uplink, QoS, cluster, energy efficiency, spectrum efficiency.

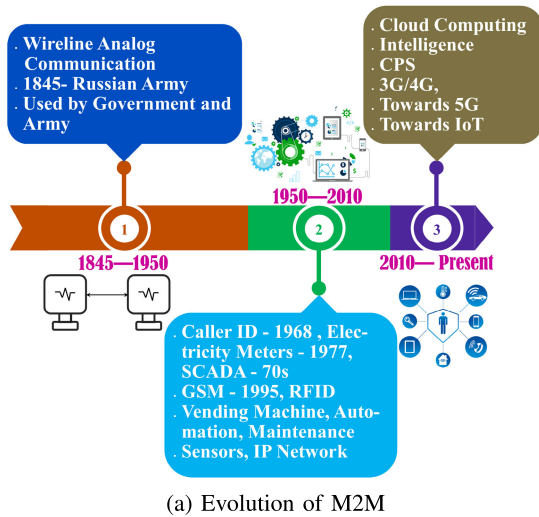
I. INTRODUCTION

The growing adaptation of advanced communication technology like 4G and 5G and advancement in device connectivity encourage the research community to take advantage of the LTE network for M2M communication [1]. Security and privacy issues, device capacity enhancement, and high-end application development are some factors that direct the attention towards M2M communication [2], [3]. The term M2M communication is not new. It started in the year 1845 with the invention of the Russian Military's information exchange system. This was an elemental wired system for data transfer. It was followed by a duplex radio communication network for data transmission in the 1900s. Wired communication has been used to exchange information

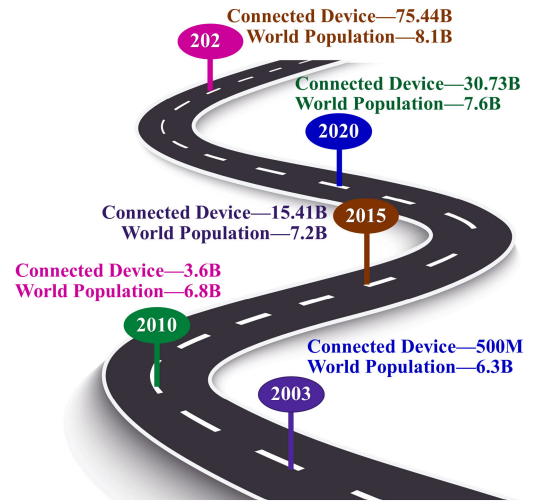
among devices in the early 20th century. Later in the 20th century, M2M communication became more sophisticated with the advancement in computer networking and the rise of cellular communication. M2M communication expanded to applications like industrial automation, telemetry, Supervisory Control and Data Acquisition (SCADA), and many more. Although in the early years of its use, most of the M2M communication had been implemented through the wire-line channel. However, after the invention of Global System for Mobile communications (GSM), the 2nd Generation cellular network technology in 1995, became mature and grounds in countless applications [4]–[6].

At the beginning of the 21st century, cellular communication technology got advanced and proposed new communication technologies named 3G and 4G LTE, which started to provide high-speed and secure data transmissions with a lower cost per bit [7], [8]. With the advancement

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(a) Evolution of M2M



(b) Growth in number of connected devices

FIGURE 1. Chronological evolution of M2M communication and growth in connected devices.

in cellular technology, the Internet, and single-chip systems witnessed a great surge in the growth of M2M communication towards the Internet-of-Things (IoT) [9]–[11]. Both the number of connected devices and the market grew bigger. Research advisory firms, Statista and CISCO, have predicted that the number of connected devices will grow to 75.44 billion by 2025, which was 15.41 billion in 2015. Market advisory firm Mordor Intelligence forecasts that the M2M market will rise to US\$ 26.52 billion by 2025, which was US\$ 19.18 billion in 2019 [11]–[13]. After 2010, M2M communication started adding information processing on its own, i.e., Cloud Computing, which helps to store large data and provide complex processing facilities for the M2M communication system [14]. It is anticipated as a new Cyber-Physical System (CPS) area with the integration of intelligence to M2M communication [9]. In the present time, the research community is actively working on integrating M2M communication with LTE-A / 5th Generation-New Radio (5G-NR) Network to support the diverse requirement, including traffic, the number of devices, etc. Fig. 1 shows the evolution of M2M communication system.

M2M communication is a paradigm in which the devices can communicate autonomously without the intervention of humans or with minimal intervention of humans. For example, switching on a light bulb by a human is a kind of Human-to-Machine (H2M) communication, whereas the detection of the human by a motion sensor and switching on the lights automatically is a Machine-to-Machine communication [15]–[17]. The rapid development of a variety of smart machines, i.e., communication devices, home appliances, vehicles, industrial equipment’s, security systems, and many applications like the infotainment system, entertainment services, surveillance, etc. make M2M communication a dominant system for ease of living and work for the humans [18], [19]. So it’s likely to adopt the new

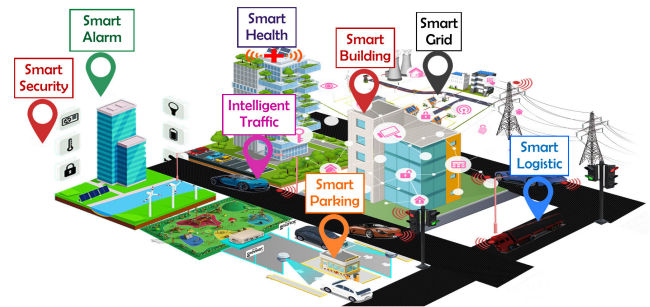


FIGURE 2. M2M communication in smart city environment.

communication technologies, services, and standardization of the M2M communication system for better performance, security, stability, and scalability of the system [20]. Fig. 2 shows M2M communication in smart city environment [21].

The M2M communication is different from the traditional H2H communication in terms of the packet size, traffic pattern, limited capacity of the device, delay roundness larger application domain [22]–[24]. M2M devices are usually tasked to gather information from their surroundings and forward it to a server/computer for further processing. Thus, most of their communication is towards the uplink, which enforces the contiguity of radio resources for an individual device. Some devices deployed for critical information sensing may be delay-bound, such as intruder detection or disaster alarming. To preserve specific QoS for such devices or to send data before it becomes obsolete, the data should be transmitted within the specified delay budget [25], [26]. H2H communication differs against the following specific requirements of M2M communication [27].

- Massive number of connected devices generate a massive amount of data.
- Periodic or event-driven packet generation.
- Small packet size but the frequent generation of packets.

- Wide range of delay and throughput requirements.
- Vast variety of applications promulgate for a more extensive range of service requirements.

In this study, we focus on the LTE/LTE-A scheduling approaches proposed by various endeavors and present a detailed literature survey of the proposed scheduling schemes from the perspective of M2M communication. All the work related to scheduling schemes is broadly classified into four categories, namely Efficiency Focused, Group Based, QoS Focused, and Hybrid or Multi-Objective. Classification of scheduling schemes as shown in Fig. 9.

The rest of the paper is organized as follows. Section II presents an overview of the M2M communication system. Section III explains about LTE Network and scheduling process. Section IV provides a detailed survey of existing LTE scheduling schemes. Section V highlights the future research direction for resource scheduling and Section VII finally conclude the paper.

II. BACKGROUND

In this section, we provide brief backgrounds on M2M communication, system architecture, and applications of M2M. We also brief the enabling technologies for the M2M area network and M2M standardization efforts given by worldwide standardization bodies.

A. M2M COMMUNICATION SYSTEM ARCHITECTURE

The M2M communication system consists of three domains: MTCs Domain, M2M Area Network Domain, and Application Domain. MTCs domain consists of devices, i.e., Sensors, actuators, metering devices, Machine Type Communication Gateways (MTCG), etc. and M2M area network [28], [29]. M2M area network provides the low range connectivity among the MTCs and MTCG using communication technologies like SamrtBLE, ZigBee, WiFi, Ultra Wide-Band (UWB), Programmable Logic Controller (PLC), etc. M2M devices can access the LTE network in three ways: direct, indirect, and hybrid, as shown in Fig. 3. In direct

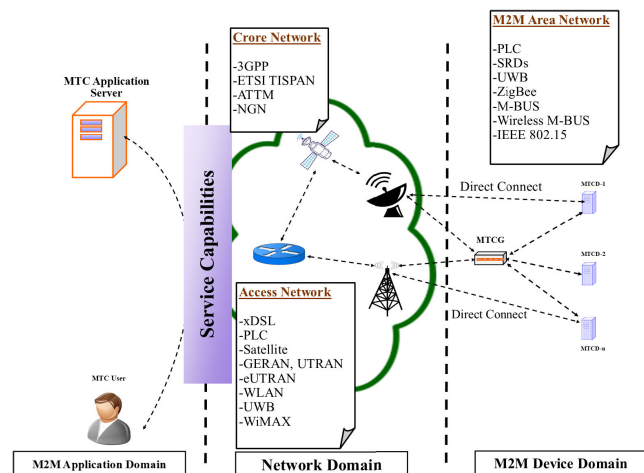


FIGURE 3. M2M communication system architecture [33].

communication, the MTCs itself can communicate with the evolved NodeB (eNB). In indirect connection, Machine Type Communication (MTC) gateway or cluster head/coordinator is responsible for transmission between eNB and UE while the rest of the devices in the cluster communicate with that MTC gateway or cluster head/coordinator [30]–[32].

In hybrid communication, the device can communicate with the eNB directly as well as through a gateway. The network domain provides the communication services between the MTCG and the application server (Indirect Connect) or between the MTCs and the application server (Direct Connect) by using any type of wired or wireless WLAN network technology. The application domain provides a facility for users to access the information gathered by the MTCs. It provides access between the user and the application server through the service capability layer. Thus, the M2M communication system enables end-to-end connectivity between the MTCs and the application server. Fig. 3 shows the M2M communication system architecture as specified by the European Telecommunications Standards Institute (ETSI) [33]–[35].

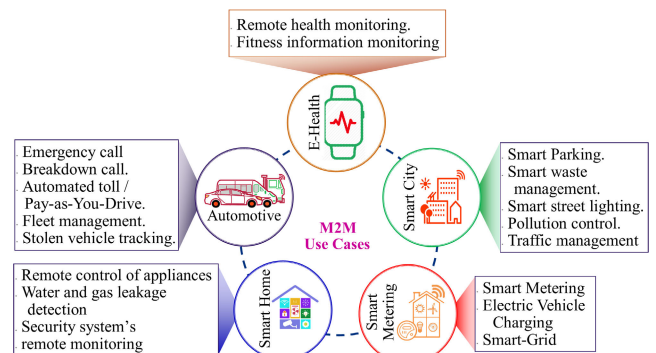


FIGURE 4. M2M applications and use case.

B. M2M APPLICATION AND USE CASE

M2M systems are continually developing and covering more application areas. The automotive sector gaining more attention, leading to the emergence of server applications [5], [36], [37]. The applications found in the literature are categorized into five groups according to the area of application, namely automotive, smart home, smart city, e-Health, and smart metering, as shown in Fig. 4.

1) AUTOMOTIVE

This category of M2M application encompasses all the applications related to vehicles or intelligent transportation systems [38]. For the implementation, each vehicle has some communication modules such as GPS and single-chip systems, enabling communication with remote servers [39]. Some of the main applications in this domain are as follows [36], [40], [41].

- Emergency call
- Breakdown call

- Automated toll / Pay-as-You-Drive [42]
- Fleet management
- Stolen vehicle tracking

2) E-HEALTH

This type of application is useful in monitoring a person's health remotely [43]. Usually, a person wears sensors like a smartwatch, which monitors a person's health, such as blood pressure monitoring, heart rate monitoring, etc.; due to limited resources and processing power, these sensors send the gathered data to the MTCG, usually a smartphone [44]. The MTCG collects the data and sends it to the remote server of the e-Health service via eNB, where health care professionals analyze the data and act accordingly. These applications work like Body Sensor Network except the communication is bidirectional [45]–[47]. Applications that fall in this category are as follows.

- Remote health monitoring
- Fitness information monitoring

3) SMART METERING

M2M applications that fall in this category are responsible for the efficient use of water, electricity, and gas through smart metering devices. These meters are an essential part of the smart grid [48], [49]. The applications in this category are as follows [50], [51].

- Smart Metering
- Electric Vehicle Charging
- Smart-Grid

4) SMART CITY

This category of M2M application belongs to the applications that are developed and deployed to make easy and smooth access to service to the citizen and save energy and cost [52], [53]. Sensors are deployed across the city, and they will send data to the gateway, and then it is forwarded to the MTC server [46], [47], [54] for further analysis. Some of the significant applications are as follows.

- Smart vehicle parking
- Smart city-waste management
- Smart street lights
- Pollution control
- Smart traffic management

5) SMART HOME

These applications are developed to provide comfortable living to home users with remote detection and execution of particular tasks such as Smart Wi-Fi Plug [55], [56]. Some of the significant M2M applications for the smart home are as follows [46], [47], [57].

- Remote control of appliances
- Water and gas leakage detection
- Security system's remote monitoring

The applications mentioned above are not the only applications of M2M. The application domain of M2M is far more significant and vast than specified in this section.

C. WIRELESS TECHNOLOGY LANDSCAPE FOR M2M AREA NETWORK

The realization of a stable M2M system requires reliable and robust communication among MTCs. For that, it is desirable to integrate the cellular network infrastructure to the M2M system [3], [58]. The cellular network provides reliable and stable transmission with comprehensive coverage and also supports the mobility of devices. As most of the devices in M2M are stationary and periodically send small data packets using only cellular networks for communication among MTCs is not efficient because the cellular system is primarily developed for H2H communication with the support of mobility of devices and large data packets transmission [9], [59]–[61]. Besides the cellular network, there are various other wireless technologies available for M2M communication such as WAN, PAN, Bluetooth, Low-Power WiFi, ZigBee, UWB. UWB provides a high data rate for indoor communication such as surveillance systems [62]. However, most of the MTCs are battery-operated, so it is beneficial to use low power technologies for M2M communication like Bluetooth 4.0, ZigBee (IEEE 802.14q), WAN (IEEE 802.11ah). Low-Power Wide Area Network (LP-WAN) provides not only small power communication but also a wide distribution of MTCs in a large area [9], [33], [63].

D. M2M COMMUNICATION STANDARDIZATION EFFORTS

Various research exercises on M2M were carried out by various endeavors and establishments across the globe. In the past, many telecommunication operators proposed commercial solutions for M2M communication in different parts of the world. These solutions were application-specific and were introduced as vertical M2M architecture or tools for a particular M2M application [64], [65]. For the scalable development of M2M communication, standardization bodies felt the requirement for generic horizontal M2M architecture as a common platform for M2M application development. In Aug 2010, ETSI published the first listing of general provisions for M2M service, followed by the functional requirements for M2M communication [59], [66]. A cooperative effort of seven standardization institutes of the world created a unique partnership for the standardization of M2M in 2012 called oneM2M. In the 3rd Generation Partnership Project (3GPP) release 8 and 9, the first standard was included to support M2M communication. More specific methods have been proposed in 3GPP release 12 for M2M communication such as privacy, power control, group management, and service maintenance [9], [67], [68].

E. WHY IS M2M SCHEDULING IN LTE IMPORTANT?

LTE is a cellular communication standard that offers high bandwidth, mobility as well as flexibility to accommodate for varying requirements of UEs. M2M communication typically consists of low bandwidth, bursts of data with a different set of QoS requirements from their H2H counterparts. M2M communication is predominantly uplink-based and

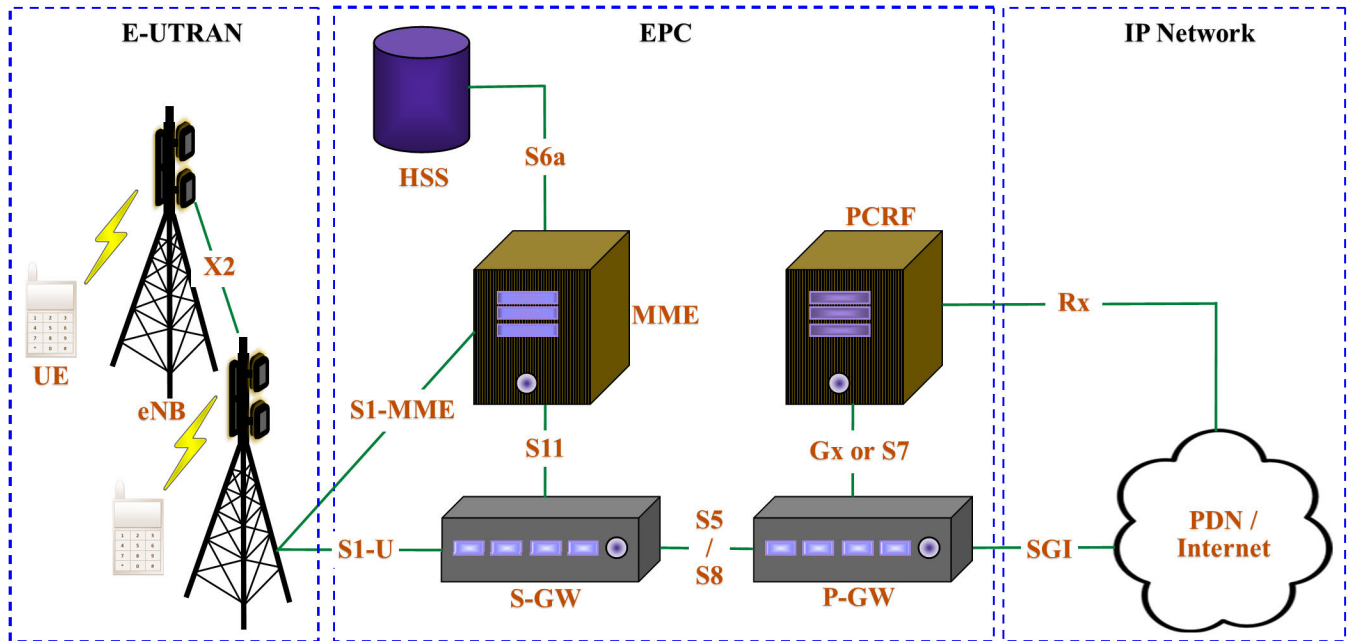


FIGURE 5. LTE communication network architecture.

contends with the uplink H2H traffic. There is a variety of mission-critical applications of M2M communication that need to be prioritized over H2H, and this contention is an issue that the uplink scheduler has to manage [69], [70].

As the M2M communication system has a massive number of devices with varying QoS requirements, therefore designing scheduling schemes that support machine type communication over the LTE network is a challenging task [71]. A massive number of MTC devices are infrequently sending varying sizes of data packets; the LTE bandwidth offers a limited number of physical resources and is optimized for H2H communication [72], [73]. Therefore, it is required to design a solution for M2M communication, which gives optimum utilization of the available physical resources while satisfying unique QoS requirements of M2M communication. The following constraints should take into consideration to design scheduling schemes for M2M communication [74]; (i) Scaling of Scheduling, as the M2M communication system has a massive number of connected MTCs, (ii) Standardization and backward compatibility of the scheme, (iii) Capacity limitation (Power and Processing) of MTCs, and (iv) QoS requirements of MTCs [75], [76].

III. LTE COMMUNICATION

LTE is a cellular communication standard for mobile devices. It provides an efficient high-speed transmission up to 50 Mbps data-rate in uplink direction and 100 Mbps data-rate in downlink direction at a reduced cost per bit. The LTE communication is based on Orthogonal Frequency Division Multiplexing (OFDM) technology and uses Orthogonal Frequency Division Multiple Access (OFDMA) modulation scheme for downlink

transmission and Single Carrier - Frequency Division Multiple Access (SC-FDMA) modulation scheme for uplink transmission. Moreover LTE provides better resource sharing and lower interference than the previous generations of cellular communication [74], [77].

A. LTE NETWORK ARCHITECTURE

The LTE network architecture consists of evolved Node Base (eNodeB or eNB), UEs, and core-network, called System Architecture Evolution (SAE), as described in Fig. 5. The SAE primarily consists of the following components: the Mobility Management Entity (MME), the Serving-Gateway (S-GW), the Packet Data Network Gateway (PDN-GW/P-GW), and the Home Subscriber Server (HSS). The SAE core, known as Evolved Packet Core (EPC), provides multiple services like authentication, mobility management, setting up of bearers, and control of QoS parameters [78], [79]. The eNodeB is responsible for connecting the UEs to this core network. UE or user equipment is a user or a machine that connects to the eNodeB to access the network [80]–[82].

The primary duties of an eNB are radio resource management, encryption and compression of IP data packets, and selection of an MME. The eNB performs radio resource scheduling at its MAC. The MME is part of the core network that deals with user authentication, session management, and mobility management. This entity keeps track of the user device, and there can only be one MME connected to a device at a time. The S-GW takes care of the data packet routing, forwarding, and manages mobility between LTE and other networks [83]–[85]. This component also allows for the replication of user data for lawful interception. The P-GW provides a facility to connect the UE with an external network

i.e., the Internet. The P-GW also enforces the charging policy and allows for packet analysis or interception. The HSS is the master database for all users, and it is typically stored in a single node. This component helps in the authentication and authorization of users for the services offered by the network [34], [80].

B. LTE PACKET SCHEDULER STRUCTURE

In any cellular communication technology such as LTE, multiple devices contends for limited resources offered by the network operator’s infrastructure. The distribution of these resources to numerous devices over the radio channel consists of assigning time slots and frequency channels to these devices. This process of assigning time and frequency to devices is called radio resource scheduling. The algorithms used for this allocation are instrumental in providing optimal services to end-users and applications [74], [77].

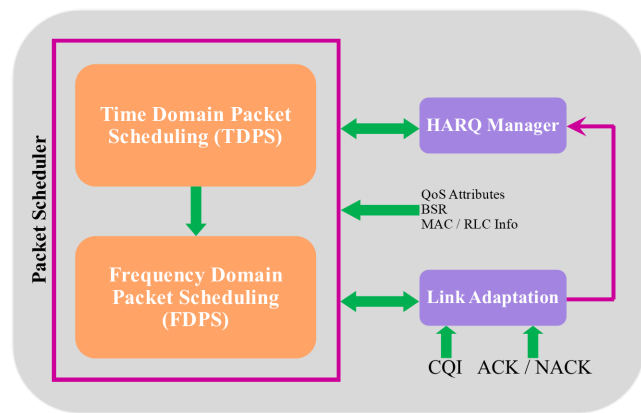


FIGURE 6. Block diagram of LTE packet scheduler.

Packet scheduling is performed by the packet scheduler at eNB. Fig. 6 shows the functional diagram of the LTE packet scheduler. The scheduler performs the scheduling task in both the time domain and frequency domain. In the first phase, Time Domain Packet Scheduler (TDPS) scheduler selects a sufficient number of devices that can be assigned the resources [86], [87]. The selection of the devices by the TDPS scheduler is performed based on some criteria such as device priority, channel quality, Buffer Status Report (BSR), etc. After selecting eligible UEs, TDPS passes the list (list of RNTIs) of selected UEs to the Frequency Domain Packet Scheduler (FDPS) for the further resource allocation process. The FDPS assigns the physical resources to UEs as per the device and channel status and device requirements [71], [80], [88].

LTE packet scheduler also performs the task related to the Hybrid Automatic Repeat Request (HARQ) management for failed packet transmission, link adaptation based on the packet’s feedback (ACKs/NACKs) and Channel Quality Index (CQI) to adjust the transmission rate, transmit power level, Modulation and Coding Schemes (MCS) for error-free transmission. Packet scheduler also receive inputs about QoS, BSR, and Medium Access Control (MAC) & Radio Link

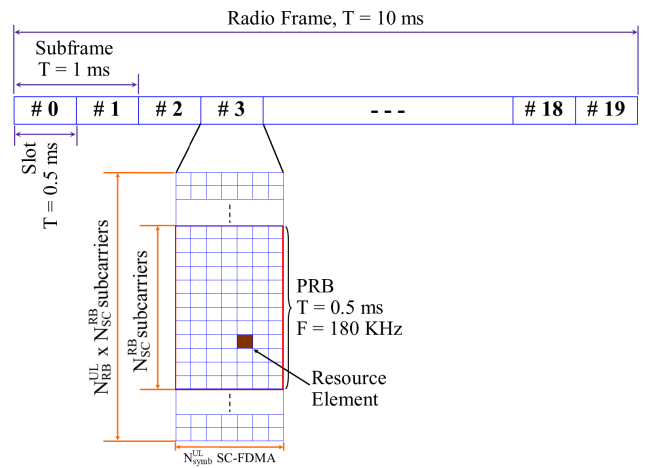


FIGURE 7. LTE radio frame structure.

Control (RLC) information to perform efficient scheduling decisions [74], [80].

C. LTE RADIO FRAME STRUCTURE

LTE communication uses OFDMA in the downlink and SC-FDMA in the uplink channel. The data in both the uplink and downlink is transmitted as frames of 10ms duration, as shown in Fig. 7. Each frame is further divided into 10 subframes of length 1ms each. The duration of the subframe is known as the transmission time interval (TTI), and each such subframe is further divided into two slots of 0.5ms duration each. The resource units are allocated in slots of 0.5ms long in the time domain and 180KHz bandwidth in frequency domain [89]–[91]. The block of 0.5 ms long in the time domain and 180KHz wide in the frequency domain is called Physical Resource Block (PRB). The PRB is the minimum unit that can be allocated to a UE, and resources are allocated in multiple PRBs. Each PRB is a grid of 12×6 or 12×7 Resource Element (RE) comprises of 12 subcarriers of 15KHz each in the frequency domain and 6 (extended CP) or 7 (Normal CP) symbols in the time domain [74], [80], [92].

The number of PRBs in uplink is in the range of 6 to 100 depending on the bandwidth. LTE provides a facility of flexible bandwidth from 1.4 MHz to 20 MHz. Thus the bandwidth of 1.4 MHz provides 6 PRBs of $0.5\text{ms} \times 180\text{KHz}$, and bandwidth 20MHz provides 100 PRBs of $0.5\text{ms} \times 180\text{KHz}$. The most basic modulation unit is a resource element, a single block of 12×7 grid of a PRB, and contains one symbol of 15khz. Each resource element may contain 2 or more bits depending upon the modulation and coding scheme (2 bits in QPSK, 4 bits in 16QAM) [31], [93], [94].

D. LTE RESOURCE SCHEDULING

The LTE packet scheduler is a MAC layer functionality of eNB, which is responsible for packet scheduling and physical resource sharing decisions. When a UE sends a scheduling request (SR) to eNB, the packet scheduler assigns the required resources to that UE based on the received

information from UE and network such as BSR, a sounding reference signal (SRS), and available resource [95]. Physical resource scheduling decisions depend on various attributes such as QoS attributes, CQI, fairness, energy efficiency, spectral efficiency as per the objective of the scheduling objective. Fig. 8 shows schematic diagram of LTE scheduling process [96]–[98].

Whenever a UE or a machine has data in its buffer for transmission, it sends a BSR packet as an uplink resource scheduling request to the eNB over Physical Uplink Control Channel (PUCCH). BSR reporting interval can be configured to send periodically or data availability in UE’s buffer [99]–[101]. Upon receiving scheduling requests over PUCCH from UE, the scheduler allocates m available physical resources to n requesting UEs, using a specified algorithm according to received reference signals and algorithm’s objective and sends scheduling grant information in Downlink Control Information-0 (DCI0) format to UE. The scheduling grant contains information about MCS, frame number, transmit power, etc. If a UE_i received scheduling grant in n^{th} frame, then the UE_i can send data in $(n + 4)^{th}$ frame over Physical Uplink Shared Channel (PUSCH) [102]–[106]. PUCCH and PUSCH are logical channels in the MAC layer, as shown in Fig. 8.

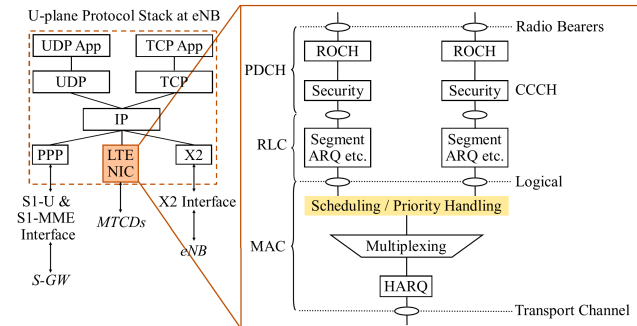


FIGURE 8. Schematic diagram of LTE scheduling process.

LTE resource scheduling is divided into two categories. The first is dynamic or channel-dependent, and the other is static or channel-independent scheduling. Dynamic scheduling considers the channel quality between UE and eNB in scheduling decisions. Whereas static scheduling does not consider CQI in scheduling decisions. In LTE, 15 CQIs are defined by 3GPP, ranging from 1 to 15. CQI values are utilized to decide the modulation and coding rate for the transmission to achieve a lower Bit Error Rate (BER). Table 1 shows the 4 bit CQI table for LTE [107], [108].

LTE scheduling mechanism follows some constraints enforced by the LTE standard itself or by the limitation of the communicating UE. Some scheduling constraints and limitations are as following [80], [102], [109].

- **Resource Exclusiveness and Contiguity:**- A single PRB can only be allocated to a unique UE, and allocation of PRBs should be continued in the frequency domain for

TABLE 1. 4 bit CQI table [80].

CQI	Modulation	Code Rate (x1204)	Efficiency
0	Out of range		
1	QPSK	75	0.1523
2	QPSK	120	0.2344
3	QPSK	193	0.3770
4	QPSK	308	0.6016
5	QPSK	449	0.8770
6	QPSK	602	1.1758
7	16QAM	378	1.4766
8	16QAM	490	1.9141
9	16QAM	616	2.4063
10	64QAM	466	2.7305
11	64QAM	567	3.3223
12	64QAM	666	3.9023
13	64QAM	772	4.5234
14	64QAM	873	5.1152
15	64QAM	948	5.5547

a single UE.

$$R_{i,j} \cap R_{i',j} = \phi; \quad \forall i \in I, j \in J \quad (1)$$

where $R_{i,j}$ are PRB allocated to UE i and $R_{i',j}$ are PRB allocated to the UE i'

$$R_{i,j} = \phi \quad \forall j \geq m + 1 \text{ if } R_{i,m} = \phi \quad (2)$$

where $R_{i,j}$ refers to PRB j is allocated to UE i .

- **Power Constraint:**- The power assign to the transmission channel $P_{TX,i}$ should be more than the minimum power $P_{min,j}$ required for transmission with assigned resources i and cannot exceed the total power $P_{T,i}$ of UE i .

$$P_{min,j} < P_{TX,i} < P_{T,i}; \quad \forall i \in I, j \in J \quad (3)$$

A UE i should have equal power level for all PRBs allocated to the that UE in a TTI as follows.

$$P_{i,j}^{TX} = P_{i,j'}^{TX}; \quad \forall i \in I, j \in J \quad (4)$$

- **Throughput Constraint:**- Achieved throughput for a UE i should be greater than minimum required Guaranteed Bit Rate (GBR) $T_{GBR,i}$ and should be less than the maximum allowable throughput T_{max} in j^{th} TTI [80].

$$T_{GBR,i} \leq \frac{n_{RE,i} * b_{sym}}{TTI_j} \leq T_{max} \quad (5)$$

where $n_{RE,i}$ is the number of resource elements allocated to UE i , and b_{sym} is bits per symbol.

- **Delay Constraint:**- Achieved packet delay D_i for UE i should be less than the delay budget $D_{B,i}$.

$$\frac{D_i}{D_{B,i}} \leq 1 \quad (6)$$

- **Maximize Connected UEs:**- The scheduling schemes should maximize the connected UE $UE_{N,K}$ in k^{th} TTI.

$$\text{argmax } UE_{N,K} \quad (7)$$

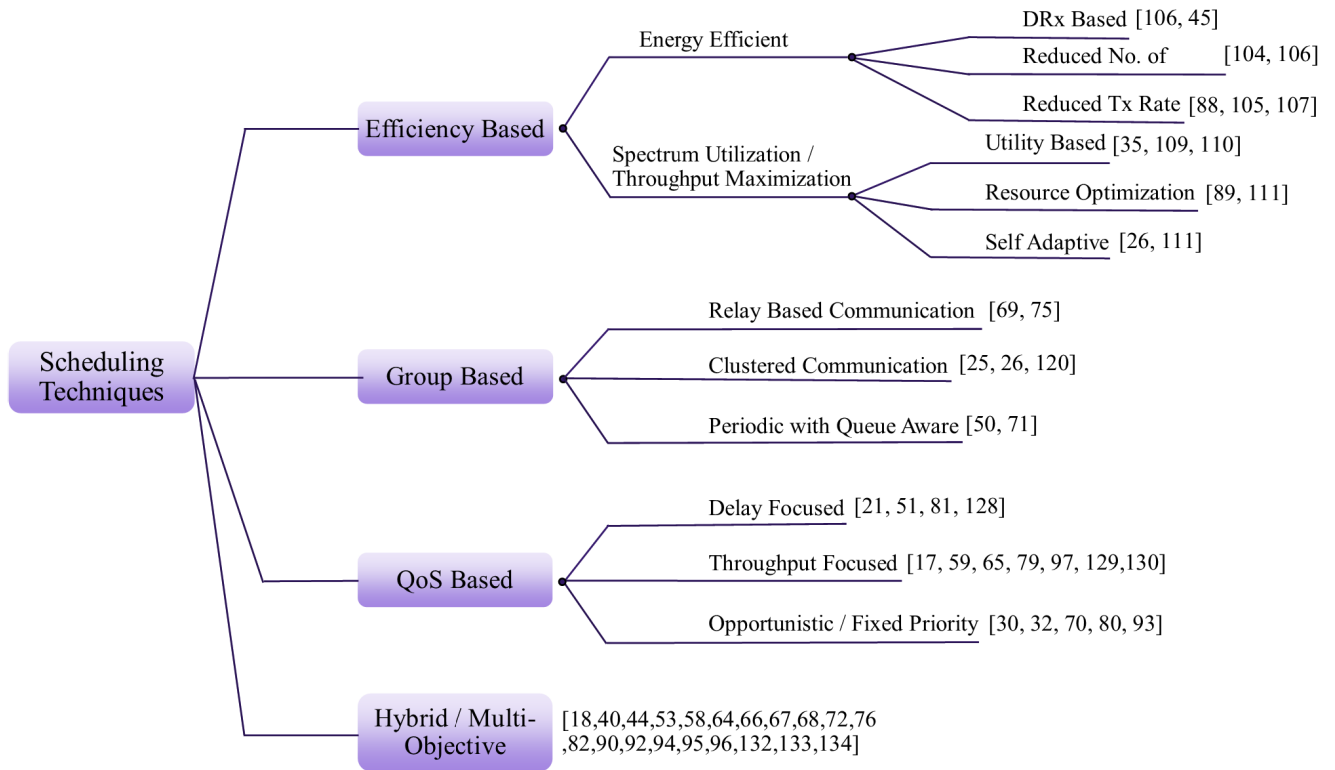


FIGURE 9. Taxonomy of LTE scheduling techniques.

- *Maximum Resource*:- The allocated resource $R_{max,i}$ to UE i cannot exceed the total available resources $R_{max,ava}$.

$$R_{max,i} \leq R_{max,ava} \tag{8}$$

E. CHALLENGES IN LTE SCHEDULING

There are many factors based on which the quality of allocation can be ascertained; namely, fairness, throughput, the fulfillment of QoS requirements, handling the massive number of devices, prevention of starvation, etc. [71], [110], [111]. There is a growing need to connect machines that communicate without human intervention. These machines communicate predominantly in the uplink direction and have a different set of QoS requirements than the H2H communication. The scheduling of M2M alongside H2H communication is a challenging problem [72], [112], [113].

IV. CLASSIFICATION OF SCHEDULING TECHNIQUES

In this section, we discuss selected physical resource scheduling techniques in the LTE network for M2M and H2H communication. All the scheduling techniques are classified depending on the focused objective of the scheduling. Fig. 9 shows the taxonomy of resource scheduling techniques.

A. EFFICIENCY-BASED TECHNIQUES

M2M devices have low processing capabilities and limited battery life. The majority of these devices are deployed with

fixed batteries. Some of these devices also serve real-time mission-critical applications. Due to this nature of M2M communications, suitable radio resource allocation techniques are required to provide the energy efficiency and throughput needed for these devices. These can be classified into two categories based on what they optimize: namely energy efficient, spectrally efficient, and throughput focused resource scheduling techniques [114]–[117].

1) ENERGY EFFICIENT TECHNIQUES

These algorithms aim to minimize energy consumption in MTCs individually or for the whole network. One approach is to give preference in the allocation of resource blocks to the MTC that has the best channel quality to increase throughput and decrease power consumption. The transmission rate depends on the quality of the channel between the UE and eNB [103], [118], [119]. For the poor channel condition, a sufficient data rate can be achieved using high transmit power (P_{tx}) and using MCS such as 16QAM/64QAM. Thus the transmit power P_{tx} of UE can be seen as one of the link adaptation schemes. Some applications can work efficiently with flexible data rates. For such cases, the energy efficiency of a UE can be increased with a lower data rate. In practice, the data rate of radio-link between the UE and eNB is controlled by Modulation and Coding rate [106], [120], [121]. Fig. 10 shows the relationship among the transmit power P_{tx} , data rate T_{tx} , and transmission channel quality.

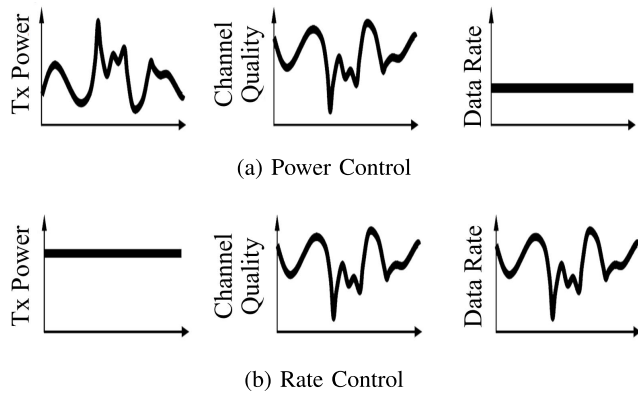


FIGURE 10. Power and rate control in LTE.

The LTE network provides two methods to control the UEs' power consumption: "Closed-Loop Power Control" and "Open-Loop Power Control." The Closed-Loop power control mechanism uses the feedback provided by the UEs to the eNB through sounding reference signals [122]. These SR signals give information about the path gain and shadowing through the path between the UE and the eNB and are used to calculate the Signal-to-Interference plus Noise Ratio (SINR), which is employed to make decisions about the MCS and transmit power required for the transmission. MCS affects the amount of information transmitted per transmission and the power consumption [73], [106]. The power-control for the PUCCH is defined as follows.

$$P_{PUCCH} = \min\{P_{max,c}^{Tx}, P_{0,PUCCH} + PL_{DL} + \Delta_{Format} + \delta\} \quad (9)$$

And the power-control for PUSCH is defined as follows.

$$P_{PUSCH,c} = \min\{P_{max,c}^{Tx} - P_{PUCCH}, P_{0,PUSCH} + \alpha \cdot PL_{DL} + 10 \cdot \log(M) + \Delta_{MCS} + \delta\} \quad (10)$$

where; $P_{max,c}^{Tx}$ is per-carrier maximum transmit power, $P_{PUSCH,c}$ is allocated power for PUSCH over carrier c , $P_{0,PUCCH}$ is the target received power, P_{PUCCH} is allocated power for PUCCH, $P_{0,PUSCH}$ is cell-specific parameter, PL_{DL} is downlink path loss, α is partial path-loss compensation, Δ_{Format} is P_{tx} power offset, and δ is explicit power-control commands. The Δ_{MCS} shows the requirements of different transmit power level for the different MCS. The term $10 \cdot \log(M)$ reflects the power required per resource block. Larger resource block size required more power to transmit data. Thus, (9) and (10) show that the transmission rate and resource block size affect the power consumption of transmitter [73].

Discontinuous Reception (DRx) scheme is also used to improve the UE's energy efficiency, in which UE only consumes power when it is transmitting or receiving data to or from eNB; otherwise, it gets in sleep mode and consumes very little power. A UE can be configured to monitor PDCCH discontinuously. DRx can be set in two ways Long DRx and Short DRx as per the requirements of

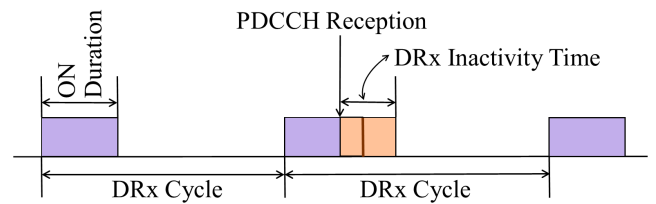


FIGURE 11. DRx scheme with PDCCH reception.

the UE's application. DRx scheme maintains various timers such as on duration timer, DRx inactivity timer, and DRx re-transmission timer. DRx mechanism set the time offset and set or reset the timers as per the configurations [73], [109]. A typical DRx scheme with PDCCH reception is shown in Fig. 11 - Rekhissa et al. [123] proposed two energy-efficient uplink allocation strategies in H2H / M2M co-existence scenario by modifying Carrier-By-Carrier (CBC) and Recursive Maximum Expansion (RME) algorithms for UEs as well as MTCs. The authors define UE metrics for each RBs and allocate RBs such that RB_i is allocated to the UE, which has the highest metric for the i_{th} RB. CBC approach consists of choosing the best CQI and allocating the corresponding RB to the MTC, this process of allocation is repeated until no one UE is remaining or all RBs are assigned. RME recursively expands allocation toward the left/right of an allocated RB for a device.

Azari et al. [124] model energy consumption and network lifetimes based on transmission and circuit energy consumption and proposed an algorithm that maximizes network lifetime by allocating devices that have the most effect on network lifetime first. The authors define network lifetime as shortest, longest, and average individual lifetime and expected lifetime metric as follows.

$$L(t) \triangleq \frac{E(t)}{\varepsilon_s + \varepsilon_d} T \quad (11)$$

where $E(t)$ is the remaining power, T is reporting interval, ε_s is static power use, and ε_d is the average power of UE. The authors modeled the problem as Min-Max optimization and proposed variations of this algorithm that work with limited Channel State Information (CSI). Results demonstrate that the spectral efficiency and energy efficiency show an inverse trend, i.e., Increasing data sent in each resource block increases spectral efficiency and decreases energy efficiency.

In [125], the authors modeled machines' energy consumption as a constraint minimization problem and defined it as follows.

$$\min \sum_{f=1}^T \sum_{n=1}^N E^n(f) \quad (12)$$

where $E^n(f)$ is a function of the device's power consumption in data transmission state and signal transmission state. When the device is not in any transmission state, it goes into a sleep state. The authors consider devices as sensory nodes and proposed two energy-efficient scheduling algorithms.

The first algorithm is used when the distance between eNB and device is long, it schedules data that has short deadlines first and tries all possible allocations of RBs to reduce power consumption. The second algorithm minimizes the number of active sub-frames to achieve efficiency and is used when the distance between the device and eNB is short. The algorithms were compared with EDF, WF²Q, and Chen's algorithm and were found to consume less energy with satisfactory fairness and scheduling success ratios.

In [61], Azari *et al.* proposed an energy-efficient scheme to enhance the lifetime of the network using an optimum size cluster. The expected lifetime of a cluster is defined as the ratio of remaining power to the average power consumption of nodes in each duty cycle and is expressed as follows.

$$L_c = \frac{E_0}{\frac{1}{g}E_h + (1 - \frac{1}{g})E_m} T_c \quad (13)$$

where E_0 is the remaining power, g is cluster size, E_h is the average power consumption of cluster head, and E_m is the average power consumption of other devices in the cluster. The authors reduce the energy consumption by selecting an optimum value for g . And proposed a distributed clustering scheme for massive M2M devices by modeling power consumption and creating clusters of optimal size. The authors also proposed a lifetime-aware scheduling technique that maximizes network lifetime. Results indicate that this technique consumes less energy than standard scheduling schemes.

In [126], the authors proposed an energy-efficient scheduling technique for small data transmissions in an LTE network. The proposed algorithm selects an optimal MCS according to the payload size to achieve energy efficiency. The authors defined the energy efficiency of a UE as the ratio of the number of transmitted payloads bits L by UE to the energy consumed by the UE in the transmission E_T and are calculated as follows.

$$\eta = \frac{L}{E_T} \quad (14)$$

The simulation results show that their approach maximizes the battery lifetime of MTCs. The authors also suggested a simple PRB allocation in which all necessary PRBs are allocated to send the entire packet, which maximizes energy efficiency. In [107], the problem is reduced to an NP-hard mixed-integer linear fractional programming problem consisting of MCS assignment, allocation of resources, and power, and data scheduling. The authors achieved the global optimum using Charnes-Cooper transformation and another technique called Glover linearization scheme to obtain the global optimum. The authors compared the performance of their technique with Greedy and EES [125], and results indicate that their technique outperforms both in terms of packet dropping ratio and provides optimal energy efficiency when the number of resource blocks is limited.

2) THROUGHPUT AND SPECTRAL EFFICIENT TECHNIQUES

The spectral efficiency of a radio link is defined as the achieved data rate is over a fixed channel bandwidth. Spectral-efficiency is also termed as normalized throughput and measured in bits/second/Hz [131], [132]. Spectral efficiency and throughput efficiency are proportionally related to each other. It can be enhanced through resource optimization, spectrum sharing among multiple users [133], optimum allocation of MCS, and optimum resource grid size. These strategies are also related to the device's utility. The parameters which broadly affect the spectral efficiency of a radio link are MCS and SNR. Higher MCS and SNR give higher spectral efficiency [73], [134], [135]. 3GPP defines 15 MCS indexes ranging from 1 to 15. For a selected MCS index, a considerably sufficient SNIR is required at the receiver to maintain the BER acceptable. In LTE with Adaptive Modulation and Coding (AMC) the normalized throughput (T_N) is given as follows.

$$T_N = \begin{cases} 0 & SNR_r < SNR_{min} \\ \alpha \cdot \log_2(1 + SNR) & SNR_{min} < SNR_r < SNR_{max} \\ T_{max} & SNR_r > SNR_{max} \end{cases} \quad (15)$$

Theoretical throughput for LTE network can be defined as follows.

$$T_{the}(Bits/ms/TTI) = PRBs * REs * S_{TTI} * Bits_{MCS} \quad (16)$$

where $PRBs$ is the number of resource blocks in a given bandwidth, REs is the number of resource elements in a resource block, and S_{TTI} is the number of slots per TTI, and $Bits_{MCS}$ is the number of bits per symbol.

Fig. 12 shows the relationship among the SNR, MCS, and Throughput. Multiple approaches have been proposed for resource scheduling to increase throughput and spectral efficiency. For example, Yaacoub *et al.* [127] proposed a resource scheduling scheme to increase spectral efficiency and define UE's utility as a function of achievable throughput and the number of PRBs as follows.

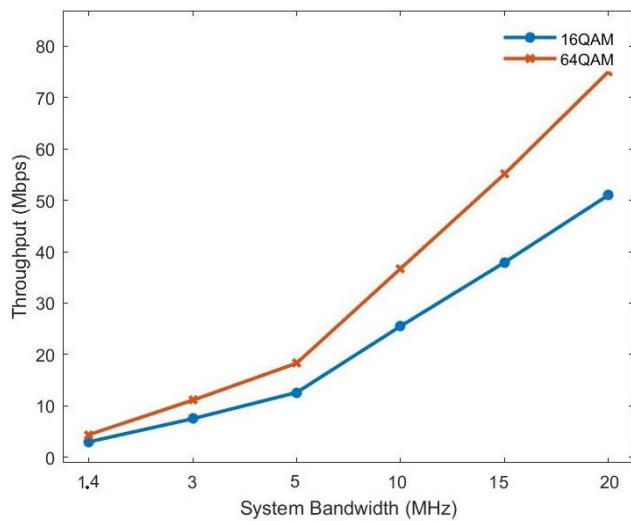
$$\max \sum_{k=1}^k \bigcup (R_k | I_{RB,k}) \quad (17)$$

where R_k and $I_{RB,k}$ are achievable throughput and allocation of RBs to the user k . The authors proposed an algorithm that greedily allocates each RB to a corresponding user, which causes a maximum increase in throughput. In [108], Lin *et al.* proposed a channel aware and buffer aware technique that sets priorities based on CQI and BSR values. The technique performs better compared to proportional fairness, purely opportunistic, and round-robin against fairness, throughput, and packet loss probability. Alawi *et al.* [45] proposed a scheme to meet the minimum rate and delay requirements of the user by considering MAC and physical layer information. The authors used the game-theoretic approach by applying two

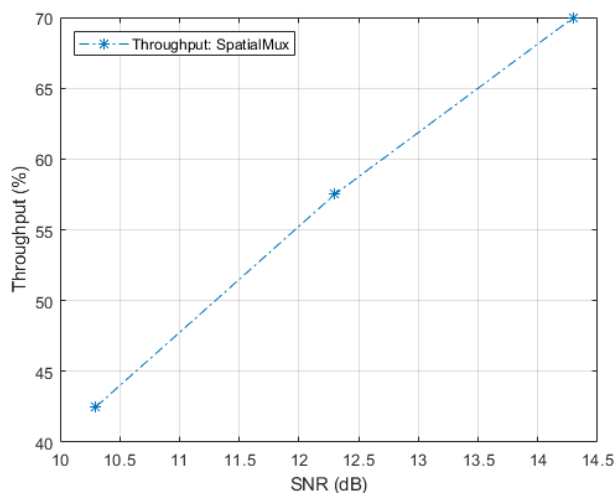
TABLE 2. Comparison of selected efficiency focused scheduling techniques.

Reference	Model / Approach	Cell Type	EE	SE	TE	QoS	IA	FA	Priority	CLO	M2M?
Rekhissa et al. [123]	Resource Partitioning	S/MC	✓	N	✓	×	×	×	CQI	×	M2M/H2H
Azari et al. [124]	Min-Max	S/MC	✓	✓	×	×	×	×	Energy	×	H2H
Shen et al. [125]	Reduced PRB	S/MC	✓	×	×	✓	×	✓	Delay	✓	M2M
Azari et al. [61]	Optimal Cluster Size	S/MC	✓	×	×	✓	×	×	Life Time	×	M2M
Wang et al. [126]	Optimal MCS	S/MC	✓	×	✓	×	×	×	None	×	M2M
Li et al. [107]	MILP	S/MC	✓	×	✓	×	×	×	None	✓	M2M
Yaacoub et al. [127]	Gready	S/MC	×	✓	✓	×	×	×	None	×	H2H
Lin et al. [108]	Gready	S/MC	×	×	✓	✓	×	✓	CQI / BSR	×	H2H
Alawi et al. [45]	Game-Theoretic	S/MC	×	✓	✓	×	×	×	Delay/GBR	✓	H2H
Wang et al. [128]	Game-Theoretic	S/MC	×	✓	✓	×	✓	×	None	×	M2M/H2H
Safdar et al. [129]	Game-Theoretic	S/FC	×	✓	×	×	×	×	None	×	H2H
Tseng et al. [130]	Genetic	S/MC	×	✓	✓	×	×	×	None	×	H2H

Note:- Macro Cell (MC) Femto Cell(FC), Single-Cell(S), Multi-Cell(Mu), Energy Efficient(EE), Spectrum Efficient (SE), Throughput Efficient (TE), QoS Support (QoS), Interference Avoidance (IA), Fairness Achievement (FA), Cross-Layer Optimization (CLO)



(a) Throughput vs MCS



(b) Throughput vs SNR

FIGURE 12. Relationship between MCS, SNR, and throughput.

cooperative games nontransferable utility (NTU) and Transferable utility(TU). The authors use the Nash bargaining solution for NTU and a coalition-based method for solving TU.

Similarly, Wang et al. [128] proposed a Nash Bargaining-based game-theoretic model for optimal resource allocation to maximize throughput as per the QoS of UEs and MTCs. The authors divide the problem into two sub-problems. The first is channel allocation and the second sub-problem is power allocation. The authors model the channel allocation problem as a matching problem between UEs and MTCs, where MTCs (max 2) share channels with a UE. The authors use an Exhausted algorithm and KM algorithm to solve this matching problem to maximize unit and system earnings. According to the paper, maximizing unit earning and system earning is equivalent to reducing interference in the common channel. The power allocation problem is solved by restricting the power of MTCs to a threshold value. The UEs are allocated power to maximize throughput using the Lagrangian multiplier method. Safdar et al. [129] proposed another approach where the authors use both cooperative and non-cooperative games for the femtocell environment.

Tseng et al. [130] proposed a genetic-algorithm-based technique that uses binary bit chromosome mutation based on fitness values. The fitness value is defined using resource block pairs. The selection procedure for next-generation parents is carried out using two methods: roulette wheel selection, which is similar to the Russian roulette in which larger blocks are allocated to chromosomes with larger fitness values, and Tournament selection method in which random mating is performed, and the best performing offspring becomes the subsequent parent. The procedure continues until either the desired convergent rate is obtained or the number of generations reaches a threshold number. The authors compare their algorithm against the random allocation method, and their algorithm performed better in terms of throughput and packet service rates over the range of N_u (number of users).

B. GROUP-BASED TECHNIQUES

M2M communication has a massive number of connected devices and diverse traffic patterns. In some cases, data (i.e., sensory data) need not send immediately to the server due to high correlation or delay tolerance nature [136]. So the data can be preprocessed at intermediary nodes (i.e., MTCs) to reduce traffic and energy consumption of MTCs through

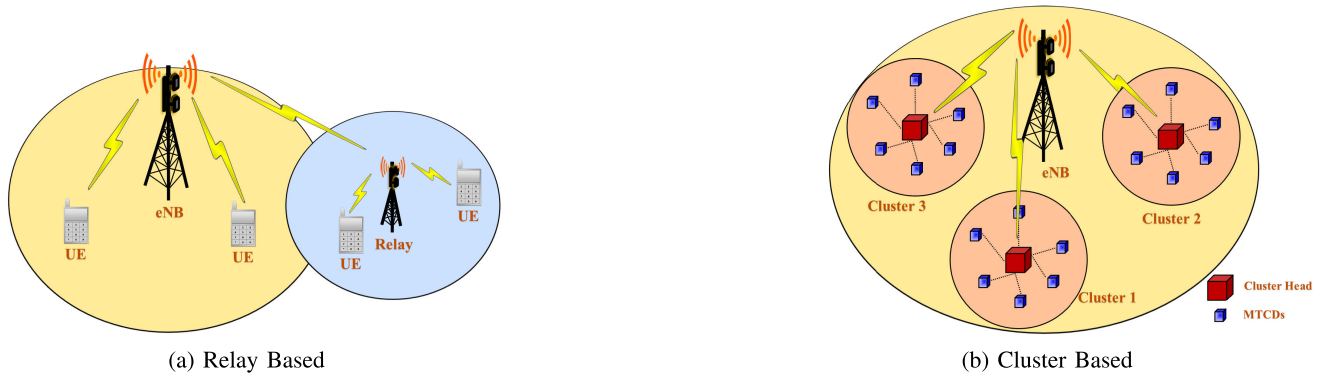


FIGURE 13. Group communication paradigms in LTE.

data aggregation and preprocessing [30], [31], [137]. For example, a temperature sensor sending temperature readings (T_s) every 30 seconds, but the temperature up to a threshold (T_{thr}) is acceptable. Then it is unnecessary to send readings if $T_s < T_{thr}$. These intermediary nodes are known as MTCGs or Aggregators [138], [139]. The main objectives of group communication in the LTE network are as follows.

- **Data Aggregation:-** When multiple MTCs transmit small packets and delay-tolerant co-related data then the data packets from different MTCs can be aggregated at an intermediary node and sends together to save bandwidth and to reduce frequent scheduling [30].
- **Connectivity Support:-** Gateways, which have the dual connectivity facility, can provide connectivity support to non-LTE devices [140].
- **Reduced Network Traffic:-** Unnecessary data transmission can be avoided through preprocessing of data at the gateway to reduce the network traffic, for example sending only the temperature readings which are above the threshold value [86].
- **Reduced Energy Consumption:-** Energy consumption can be optimized by limiting the frequency of packet transmission and reducing transmission-time [93].
- **QoS Support for MTCs:-** Gateway-based communication can provide QoS support to MTCs through preprocessing and intelligent decision approach [31].

The grouping of devices is generally based on the characteristics and requirements of devices, Which can be classified as the following criteria [89], [141].

- **QoS Requirements of Devices:-** The MTCs having the same QoS requirements can be grouped to support a QoS-aware scheduling decision [142].
- **Communication Protocol:-** MTCs can be grouped which have the same communication protocols such as WiFi, BLE, ZigBee, etc to support ease of connectivity with the gateway.
- **Data Generation and Traffic Pattern:-** MTCs which have the same data generation pattern (i.e, Time Trigger or Event Trigger) and same traffic characteristics (i.e.,

Periodic, Burst, Frequent) can be grouped to avoid the frequent scheduling task [143].

- **Payload Size:-** To support the data aggregation approach MTCs can be grouped based on the payload size (i.e, Small/Medium/Large).
- **Physical Layer Parameter:-** MTCs can be grouped based on the physical layer properties (i.e., Channel Quality, Tx power) to support better resource utilization.
- **Locality of Device:-** MTCs can be grouped based on the distance from different gateways. This approach can improve energy efficiency through short-range communication.

There are two types of group communication first is relay-based and cluster-based. In relay-based communication, relay serves as an eNB for the devices that are not directly able to communicate to the eNB. A UE can with higher capacity work as a relay. In cluster-based communication, a UE act as a cluster head and is responsible for forwarding data from UE to eNB and vice-versa [30], [141]. Fig. 13 shows typical group communication paradigm in LTE network. The research community has extensive work in group-based resource scheduling for the LTE network, mostly focused on energy consumption and data traffic.

In [141], Songsong *et al.* proposed a proportional fairness algorithm using user grouping. The algorithm groups devices based on the number of carriers they can be assigned. All the carriers having the same bandwidth are grouped into L aggregated carriers. Each aggregated carrier has V resource blocks. The power allocated to a carrier in a group carrier is given as $P_c = V/P_T$. Results indicate that this algorithm provides better fairness than proportional fairness (PF) with degradation in throughput. In [93] Ho *et al.* proposed an energy-conserving 2-hop transmission-based allocation scheme. The author defines the maximum achievable bit rate for each sub-carrier as follows.

$$f_{c_j} = \frac{r_{c_j}}{P_{c_j} + P_{cir}} = \frac{\log_2(1 + p_{c_j}|h_{c_j}|^2/N_0 * B_c)}{P_{c_j} + P_{cir}} \quad (18)$$

The author get power for the group coordinator by maximizing the Eq. (18) through iterative process. The authors

TABLE 3. Comparison of selected group-based scheduling techniques.

Reference	Model / Approach	Cell Type	EE	SE	TE	QoS	IA	FA	Priority	CLO	M2M?
Songsong et al. [141]	Carrier Aggregation	S/MC	×	✓	×	×	×	✓	None	×	H2H
Ho et al. [93]	Cooperative	S/MC	✓	✓	×	×	×	×	None	×	H2H
Gotsis et al. [89]	Probabilistic	S/MC	×	×	×	✓	×	×	QCI	×	H2H
Xu et al. [30]	QCI Clustering	S/MC	×	×	×	✓	×	×	Delay	×	H2H
Frank et al. [86]	Cooperative	S/MC	×	✓	×	×	✓	×	None	×	H2H
Hsu et al. [31]	QCI Clustering	S/MC	×	✓	×	✓	×	×	QCI	×	M2M/H2H
Bayat et al. [67]	Distributed Coalition	S/MC	✓	✓	×	✓	×	×	Delay	×	M2M

Note: Macro Cell (MC) Femto Cell(FC), Single-Cell(S), Multi-Cell(Mu), Energy Efficient(EE), Spectrum Efficient (SE), Throughput Efficient (TE), QoS Support (QoS), Interference Avoidance (IA), Fairness Achievement (FA), Cross-Layer Optimization (CLO)

also propose optimal number of coordinators in a group. Gotsis et al. [89] proposed a queue-aware QoS based scheduling technique. The UEs are grouped in L clusters based on the individual QoS requirements of UEs. Physical resources are shared among clusters rather directly to individual UE. The authors defined a probabilistic model such that the probability of violation δ of maximum delay threshold Δ is given as follows.

$$\delta = Prob\{W_q > \Delta\} \approx e^{-r.\theta(r).\Delta} \tag{19}$$

where, W_q is the experienced packet delay and θ is the QoS factor of the group. Xu et al. [30] propose a group-based scheme for Random Access (RA) and uplink scheduling procedure. A UE (M) can be a member of group (k) if it satisfy the following condition -

$$M_k = (n_{TB} * C_{TB})/C_{MTC} \tag{20}$$

where n_{TB} is the number of resource blocks allocated for transmission, C_{TB} , and C_{MTC} are the capacity of resource block and UE, respectively. The authors consider it a priority for a group of UE for uplink scheduling. The authors also propose a group paging scheme for resource allocation that improves delay and access probability. Frank et al. [86] defined a scheme to reduce the effects of cell-edge interference, which involves multiple adjacent base stations to communicate multi-cellular CSI reports through a fast back-haul network to a central scheduling unit. The authors proposed an interference aware uplink scheduling algorithm based on a proportional fairness approach to avoid inter-cell interference.

Hsu et al. [31] proposed an enhanced cooperative access class barring and traffic adaptive radio resource management (ECACB + TARRM) for M2M devices. This technique builds upon enhanced cooperative access class barring (CACB) to which the authors add support for UEs and TRRM. TRRM implies that UEs and MTCs use different PRBs, preambles, and MTC devices, which are clustered based on their data rates and random access rates. To determine better parameters for access class barring, the number of MTC devices is used as a factor over the factors used by CACB, that connect to an eNB.

Bayat et al. [67] proposed a distributed coalition forming algorithm that involves the rules called “merge-and-split.” The authors used data aggregation for machine-type

devices that has different delay requirements and proposed a game-theoretic approach using coalition games. The algorithm allows MTCs to organize into groups independently with each group head handling data to and from the machines in each group.

C. QUALITY OF SERVICE BASED TECHNIQUES

The M2M communication is different from the regular H2H communication in terms of the number of connected devices, packet size, frequency of data transmission, a broad range of delay budgets, throughput requirements, priority, etc. ETSI defines QoS class identifier for M2M communications in LTE [110], [144], [145], as shown in Table 4. As the M2M communication system has a massive number of devices with varying QoS requirements, therefore designing scheduling schemes for M2M communication over the cellular network is a challenging task [71], [146]. A massive number of MTC devices are infrequently sending varying sizes of data packets; the LTE bandwidth offers a limited number of physical resources and that are optimized for H2H communication [72]. Therefore, it is required to design a solution for M2M communication, which gives optimum utilization of the available physical resources while satisfying unique QoS requirements of M2M communication [98], [147], [148].

AI-Rawi et al. [149] proposed an opportunistic channel adaptive radio resource scheduling algorithm for dynamic traffic patterns based on the buffer sizes of users. The scheduler estimates the expected rate $\mu_{n,i}$ of device i if the resource block n is allocated to the device with given estimated throughput of x_i as follows.

$$y(t) = arg \max_y \sum_{i=1}^N \sum_{n=1}^C u_i(x_i) \mu_{n,i} y_{i,n} \tag{21}$$

The scheduler maximizes the Eq. (21) to find optimal allocation. The authors evaluated pruning, which is a process of recovering weaker bands for use by other UEs. The authors evaluated the effect of delays in receiving buffer information and concluded that it would result in better fairness, whereas limited buffer information would lead to inefficient resource usage. Delgado et al. [82] defined a utility function $\bigcup(R_k | S_k)$ as a function of throughput R_k and set of allotted resources S_k of device k and maximize the utility of the device for optimal

TABLE 4. QCI for M2M over LTE [109].

QCI	Bearer Class	Priority	Delay Budget	GBR	Example Service
1	GBR	2	1s	25 kbps	Delay and Throughput sensitive bandwidth applications - Actuators.
2	GBR	4	1s	10 kbps	Delay sensitive bandwidth applications - Sensors.
3	GBR	3	10s	50 kbps	Higher bandwidth applications - Infotainment Applications.
4	GBR	5	10s	25 kbps	High bandwidth applications - e-Health.
5	Non-GBR	1	100ms	—	Time sensitive application - Instant presence sensors.
6	Non-GBR	6	1 minute	—	Low demanding applications - Temperature monitoring .
7	Non-GBR	7	10 minutes	—	Low demanding applications - non-critical monitoring.
8	Non-GBR	8	1 hour	—	Low demanding applications - smart metering.
9	Non-GBR	9	1 day	—	Low demanding applications - Utility applications.

TABLE 5. Comparison of selected QoS-based scheduling techniques.

Reference	Model / Approach	Cell Type	EE	SE	TE	QoS	IA	FA	Priority	CLO	M2M?
Al-Rawi <i>et al.</i> [149]	Heuristic	S/MC	×	✓	×	✓	×	✓	Delay	×	H2H
Delgado <i>et al.</i> [82]	Greedy	S/MC	×	×	✓	✓	×	×	GBR	×	H2H
Afrin <i>et al.</i> [26]	Greedy	S/MC	×	×	×	✓	×	×	Delay	✓	H2H
Safa <i>et al.</i> [150]	Greedy	S/MC	×	×	×	✓	×	×	QCI	×	M2M
Mata <i>et al.</i> [76]	Genetic	S/MC	×	×	✓	✓	×	×	GNR/Delay	×	H2H
Maia <i>et al.</i> [112]	Deterministic	S/MC	×	✓	×	✓	×	✓	None	×	H2H/M2M
Afrin <i>et al.</i> [151]	Deterministic	S/MC	×	×	×	✓	×	×	Delay	×	M2M
Giluka <i>et al.</i> [87]	Utility Based	S/MC	×	×	✓	✓	×	×	GNR/Delay	×	H2H/M2M
Brown <i>et al.</i> [68]	MLHE	S/MC	×	×	×	✓	×	×	Delay	×	M2M
Agdhmadi <i>et al.</i> [152]	Flow Based	S/MC	×	×	✓	✓	×	×	GBR	×	M2M
Kumar <i>et al.</i> [99]	Queue Awareness	S/MC	×	×	×	✓	×	✓	Delay	×	M2M
Abdelsadek <i>et al.</i> [22]	Queueing Model	S/MC	×	✓	×	✓	×	×	Delay	×	H2H/M2M
Alaa <i>et al.</i> [35]	Queue Awareness	S/MC	×	✓	×	✓	×	×	Delay	×	H2H/M2M
Kumar <i>et al.</i> [100]	Queue Awareness	S/MC	×	✓	×	✓	×	×	Delay	×	M2M
Karadag <i>et al.</i> [98]	Graph Theory	S/MC	×	×	×	✓	×	×	Delay	×	M2M
Ouaissa <i>et al.</i> [116]	Heuristic	S/MC	×	✓	×	✓	×	×	QCI	×	M2M

Note:- Macro Cell (MC) Femto Cell(FC), Single-Cell(S), Multi-Cell(Mu), Energy Efficient(EE), Spectrum Efficient (SE), Throughput Efficient (TE), QoS Support (QoS), Interference Avoidance (IA), Fairness Achievement (FA), Cross-Layer Optimization (CLO)

allocation of resources as follows.

$$\max \sum_{k \in K} \bigcup (R_k | S_k) \tag{22}$$

The authors proposed two algorithms that aim to reduce delay while having a minimum throughput constraint. The authors use two highly scalable greedy heuristics based on the problem. Afrin *et al.* [26] defined an urgency metric U_i for the device i as a function of deadline d_i and BSR index B_i as follows.

$$U_i = \begin{cases} \frac{B_i}{\max(B)} * \frac{T_{SF}}{d_i-t} & \text{if } d_i-t > 1 \\ 1 & \text{Otherwise} \end{cases} \tag{23}$$

The devices are selected based on urgency metric U_i to improve the satisfaction of delay requirements. This approach allows the eNB to know the age of the oldest packet in their buffer using a new MAC control field in the MPDU. Afrin *et al.* [151] proposed a buffer-based adaptive semi-persistent scheduling (SPS) scheme, which does not have the same overheads as dynamic scheduling while offering the same flexibility. The authors examine the influence of semi-persistent scheduling on the QoS and compare it with fixed allocation SPS schemes. Safa *et al.* [150] proposed a technique that aims to satisfy delay requirements of M2M devices. The authors defined a QoS aware allocation metric

$\gamma_i^c(t)$ of a UE i for QoS introducer $\alpha_i(t)$ of UE as follows.

$$\gamma_i^c(t) = \frac{\lambda_i^c(t)}{\alpha_i(t)} \tag{24}$$

Their technique gives priority to the UEs having high priority data while not starving others. Mata *et al.* [76] proposed a genetic algorithm based approach to optimize for video streaming with focus on video chat. The authors defined PF metric $\lambda_n^m(t)$ as a ratio of instantaneously achieved data rate $r_n^m(t)$ to the long-term rate $R_n(t)$ for a user n with assigned resources m over a period of time t as follows.

$$\lambda_n^m(t) = \frac{r_n^m(t)}{R_n(t)} \tag{25}$$

The authors also defined a metric based on the HoL of the packets that resides in the UE’s buffer. Maia *et al.* [112] proposed an extension to the QoS classes for M2M in two groups, event-based and time-based. The authors try to control the effect of M2M communication on H2H communication by calculating the current demand of resources for H2H communication as a ratio of average resource allocated to the average buffer size and expressed as follows.

$$\widehat{B}_H(u, t) = \frac{BS_{u,t} * RB_{u,t-1}^{avg}}{BS_{u,t-1}^{avg}} \tag{26}$$

Based on the current demand, resources are shared among H2H and M2M devices. Maia *et al.* [113] proposed a genetic algorithm-based method and introduced a new scheme of initialization, crossover, mutation, and a QoS aware fitness function. Kumar *et al.* [99] proposed a multi-class scheduler for MTCDs with different delay requirements. The authors classify M2M data into periodic update (PU) and event-driven (EU). The authors aimed to maximize utility by using heuristics and a sigmoid-based utility function for each device type. Their algorithm prioritizes ED data over PU data as long as PU deadlines are being met and makes sure that congestion due to failed updates is reduced. Kumar *et al.* [100] proposed a delay in optimal scheduling strategy in which multiple M2M devices communicate with an application server from multiple M2M aggregators. Giluka *et al.* [87] proposed a classification and prioritization scheme of M2M and H2H service flows based on QoS requirements. In a given class, H2H devices are given higher priority, while a limit is set a maximum limit for the assignment of radio resource blocks assigned to MTCDs. The authors define a utility of a QoS class C_i as follows.

$$C_i = \sum S(H) + \beta_i * \sum S(M) \quad (27)$$

where $S(H)$ and $S(M)$ are the satisfiability function of H2H and M2M communication requests. Agdhmadi *et al.* [152] proposed a scheme to provide QoS to Guaranteed Bit Rate (GBR) services based on QCI and using priorities for M2M. Erpek *et al.* [153] proposed a scheme that gives priority to delay-bound traffic over delay-sensitive traffic. The authors implement a utility proportional fairness policy based on the same. Brown *et al.* [68] proposed a predictive resource allocation scheme using on Maximum Likelihood Estimation (MLHE) and defined MLHE as follows.

$$\mathcal{L}(t_1, t_2, \dots, t_n) = Pr(t_1, t_2, \dots, t_n | \tau) = \{(t_1, t_2, \dots, t_n | \tau) \quad (28)$$

$$\Rightarrow \mathcal{L} = \begin{cases} \frac{a-b+1}{\sigma} & \text{if } a \geq b \\ 0 & \text{Otherwise} \end{cases} \quad (29)$$

where,

$$a = \min\{r_1 - 1, r_2 - 1 - \tau, \dots, r_n - 1 - (n-1)\tau\}$$

$$b = \max\{r_1 - \sigma, r_2 - \sigma - \tau, \dots, r_n - \sigma - (n-1)\tau\}$$

The authors used inter-sensor propagation time to determine when it will reach downstream sensors. This approach allows sensors to send fewer scheduling requests that reduce traffic and delay. Abdelsadek *et al.* [22] proposed a scheme, which considers the scheduler as M/D/1 queues model. The achieved throughput for the UEs u is given as follows.

$$Run = \begin{cases} \mu_u & \text{if } \mu_u \leq \lambda_u \\ \lambda_u & \text{if } \mu_u \geq \lambda_u \end{cases} \quad (30)$$

where λ_u and μ_u are the average arrival rate and average service rate, respectively. The authors improved the computational efficiency of the optimization problem. Alaa *et al.* [35]

proposed a non-preemptive queuing model and investigated the scheduling performance for different QoS classes of M2M and H2H devices with dynamic access grant time interval scheduling. The authors use the M/G/c/c model to improve bandwidth utilization and QoS satisfaction. Karadag *et al.* [98] proposed an optimization approach for MTCD transmissions considering the repetitive nature of these transmissions. The authors proposed semi-persistent scheduling and implement using the Depth-First approach and minimum frequency-fit approach to reduce the use of frequency bands used by MTCDs while maintaining delay requirements. The authors proposed a heuristic algorithm in polynomial time with fixed priority assignments to solve this problem. Ouaisa *et al.* [116] proposed a hybrid model of RR, First Maximum Expansion, and Maximum Throughput.

Abdalla *et al.* [2] proposed a technique that aims to retain the Quality-of-Experience (QoE) of UEs while processing the message requests of M2M devices. The authors proposed a new set of QCIs for M2M to ensure end-to-end QoS. Hassebo *et al.* [91] proposed a technique that aims to manage QoS requirements of M2M devices along with massive access while protecting H2H devices from a lapse in service quality. The authors used a semi-persistent approach for scheduling a large number of MTCDs while using typical dynamic scheduling for H2H devices.

D. HYBRID/MULTI-OBJECTIVE TECHNIQUES

In this category, we consider the scheduling algorithms which focus on more than one objective in combination with any scheduling objective like a priority, QoS, throughput, energy, and fairness. For example, Elhamy *et al.* [84] proposed a technique called "BAT" that aims to balance throughput and delay requirements. This technique is a hybrid technique that allocates M2M resources and UE at the same time interval using an RME like expansion method. Maia *et al.* [113] proposed a technique that aims to reduce congestion, satisfy QoS requirements, and ensure fairness of the allocation of M2M devices while minimizing the effect on H2H traffic. Their algorithm uses a state transition function with three states to evaluate the probability of allocation to M2M devices while optimizing for the said factors. Kwan *et al.* [101] proposed the classic throughput and fairness balancing approach called PF scheduler, which aimed to improve the fairness of Max-Rate scheduler while taking some loss in throughput. AlQahtani *et al.* [54] proposed a scheduling technique that borrows from RR and Best-CQI (B-CQI) to solve the fairness and throughput trade-off. RR provides ideal fairness, whereas B-CQI provides high data rates with weak fairness. Results by testing against RR and B-CQI indicated that the technique provides a balance between fairness and throughput. AlQahtani *et al.* [60] proposed a queuing-model based access strategy in the case of H2H and M2M coexistence. The authors evaluated the system performance using a continuous-time Markov-Chain model. Results indicate that this technique increases the overall resource utilization while decreasing blocking probability.

TABLE 6. Comparison of selected hybrid/multi-objective scheduling techniques.

Reference	Model / Approach	Cell Type	EE	SE	TE	QoS	IA	FA	Priority	CLO	M2M?
Elhamy <i>et al.</i> [84]	Weighted Sum	S/MC	×	✓	✓	✓	×	×	Delay	×	M2M/H2H
Maia <i>et al.</i> [113]	Weighted Sum	S/MC	×	✓	×	✓	×	✓	None	×	M2M/H2H
Kwan <i>et al.</i> [101]	Weighted Sum	S/MC	×	×	✓	×	×	✓	Max Weight	×	H2H
AlQahtani <i>et al.</i> [54]	Weighted Sum	S/MC	×	×	✓	×	×	✓	Max Weight	×	H2H
AlQahtani <i>et al.</i> [60]	Markov Chain	S/MC	×	✓	✓	×	×	×	None	×	M2M/H2H
Mardani <i>et al.</i> [114]	Fuzzy	S/MC	✓	×	×	×	×	×	None	×	M2M/H2H
Mardani <i>et al.</i> [115]	MINLP	S/MC	✓	×	✓	✓	×	×	Delay	×	H2H
Aijaz <i>et al.</i> [154]	MIP	S/MC	✓	×	✓	✓	×	×	Statistical QoS	×	M2M/H2H
Dawaliby <i>et al.</i> [81]	0/1 Knapsack	S/MC	×	×	✓	✓	×	×	Delay	×	H2H
Dawaliby <i>et al.</i> [109]	Memetic	S/MC	✓	×	×	✓	×	×	QCI	✓	M2M
Kalil <i>et al.</i> [94]	Genetic	S/MC	×	×	✓	×	×	✓	None	×	H2H
Tagarian <i>et al.</i> [155]	Genetic	S/MC	✓	×	×	✓	×	×	Delay	×	H2H
Fagan <i>et al.</i> [85]	Deep-Learning	S/MC	×	✓	×	×	×	×	GBR	×	M2M/H2H
Comsa <i>et al.</i> [75]	Neural Network	S/MC	×	×	✓	×	×	✓	None	×	H2H
Chen <i>et al.</i> [70]	Heuristic	S/MC	✓	✓	×	✓	×	×	QCI	×	H2H
Abrignani <i>et al.</i> [23]	Heuristic / MILP	S/MC	×	✓	✓	×	✓	×	None	×	H2H
Hamdoun <i>et al.</i> [90]	Game-Theoretic	S/MC	✓	✓	×	✓	×	×	Group QoS	×	M2M/H2H
Lin <i>et al.</i> [111]	Iterative	S/MC	✓	×	×	✓	×	×	Delay	×	M2M
Salam <i>et al.</i> [156]	Queue Awareness	S/MC	✓	×	✓	✓	×	×	Delay	×	M2M
Edemacu <i>et al.</i> [83]	Queueing Model	S/MC	×	×	×	✓	×	×	QCI	×	M2M/H2H

Note:- Macro Cell (MC) Femto Cell(FC), Single-Cell(S), Multi-Cell(Mu), Energy Efficient(EE), Spectrum Efficient (SE), Throughput Efficient (TE), QoS Support (QoS), Interference Avoidance (IA), Fairness Achievement (FA), Cross-Layer Optimization (CLO)

Mardani *et al.* [114] proposed a technique that aims to minimize energy consumption while maintaining QoS requirements of H2H devices. The authors used a fuzzy logic-based controller that anticipates and manages uncertainties and obtained an optimal bandwidth ratio for each type of service flow. Mardani *et al.* [115] proposed a technique that aims to maximize throughput, satisfy power budget constraints, and statistical QoS delay requirements. The authors defined the problem as a mixed-integer non-linear problem and proposed a solution using Lagrange multipliers. Aijaz *et al.* [154] proposed a technique that aims to minimize energy consumption and proposed statistical QoS provisioning for M2M and H2H devices. The authors defined the problem as a Mixed Integer Programming problem of maximizing effective energy efficiency in bits-per-joule capacity. The authors solved this using the Canonical Duality Theory. The authors also proposed another approach, where the authors proposed two low complexity heuristic techniques for the same.

Dawaliby *et al.* [81] proposed a technique that aims to maximize throughput and reduce delays in the case of LTE-M protocol. The authors model the problem to the 0/1 knapsack problem. Dawaliby *et al.* [109] proposed a technique that aims to minimize energy consumption while maintaining QoS requirements of M2M devices. The authors employ a cross-layer scheme using a Memetic-based algorithm the authors consider the QoS requirements while minimizing the energy consumption using discontinuous reception switching. Kalil *et al.* [94] evaluated a genetic algorithm that considers multiple constraints for the uplink scheduling problem. This approach is evaluated against the optimal allocation binary-integer programming problem (BIP). It offers comparable performance for low-population (<300 UEs) to the optimal solution while having comparatively lower time complexity.

Tagarian *et al.* [155] proposed a technique that aims to minimize energy consumption while maintaining delay QoS requirements of machines. The authors used a gateway-based approach where the use of clustering manages massive access. The optimization problem is solved using genetic algorithms for maximizing energy efficiency. To manage delay, the authors used an existing scheduling approach. Fagan *et al.* [85] applied a deep learning approach for downlink scheduling. The data set is derived using a genetic algorithm over many simulated random UE data reports and used to train the deep learning network. This approach allowed for approximating the genetic algorithm schedule without the delay of a genetic algorithm. Comsa *et al.* [75] proposed a scheduling scheme using the q-learning method to dynamically adjust the fairness and system capacity trade-off each transmission time interval. The proposed algorithm decides allocation using CQI for each class of users.

Chen *et al.* [70] proposed a heuristic technique that aims to minimize the energy consumption of MTCs while guaranteeing the QoS. The authors minimized MTCs’ energy consumption using lower modulation and coding and spatial reuse. Abrignani *et al.* [23] considered the problem of improving throughput while reducing resource usage and minimizing Inter-Cell Interference (ICI) in the case of a densely populated heterogeneous network. The authors modeled the problem to a Mixed Integer Linear Programming (MILP). The author’s employed a heuristics approach to solving MILP. The algorithm was compared against RR and found to perform better in terms of throughput.

Hamdoun *et al.* [90] considered an evolutionary game approach to preserve UE’s QoS while preserving the battery life of Machine Type Devices (MTDs). Here MTDs are in the same group share spectrum with a UE, which is matched

to it. The MTDs switch dynamically from non-cooperative to cooperative strategies. Results indicate that this adaptive technique performs better than a fixed discrete power allocation strategy as well as a non-cooperative strategy in terms of power consumption as well as QoS satisfaction. Salam *et al.* [156] proposed a technique to improve outage probability, energy efficiency, and system capacity called cooperative data aggregation scheme, which employs fixed data aggregators and mobile data aggregators. These aggregators serve M2M devices with varied QoS requirements. The authors also considered parameters of queuing delay and the number of devices not served in a class. Edema *et al.* [83] presented a study on existing Fixed access grant time interval (AGTI) and Time-controlled scheduling and proposed a dynamic AGTI scheme based on M2M and H2H traffic intensities focusing on resource utilization and QoS satisfaction. Lin *et al.* [111] proposed a technique that aims to minimize energy consumption while maintaining QoS requirements of M2M devices. Their algorithm used the concept of Multi-access edge computing. The authors considered packet processing time and travel time in latency calculation.

V. FUTURE RESEARCH DIRECTIONS

Although in the last decade, extensive research has been carried out by endeavors from industry and academia in the field of radio resource scheduling in LTE networks. Researchers have proposed various techniques to improve the efficiency of the scheduling process and optimizes the radio resources. With the emergence of M2M communication and recent developments in cellular technology, i.e., 5G-NR, there are lots of opportunities to work on the radio resource allocation problem. In this section, we provide future research directions for radio resource scheduling from the M2M perspective.

A. EFFICIENCY FOCUSED

Lots of research work exists in the literature about the efficiency-based approaches of resource scheduling in the LTE network for both H2H and M2M communication. As found in the literature, the spectrum is a scarce resource, and most of the MTCs are battery-operated. The M2M communication system has a massive number of devices. Therefore, there is still a scope of resource allocation schemes for Non-Orthogonal Multiple Access (NOMA) technology, which provides different power labels in resource allocation. NOMA is suitable for devices having various power labels and the co-existence of H2H and M2M communication. Spectrally efficient resource allocation has the opportunity to work with cooperative communication and cognitive radio communication.

B. GROUP-BASED

Cooperative communication and cognitive-radio communication support group communication and inter-cluster/group communication. There is a need to optimize the resource allocation process to work with cooperative and cognitive-radio communication. There is also the possibility of resource

allocation with mmWave beamforming to allocate resources to a group of devices efficiently. The massive-Multiple Input Multiple Output (massive-MIMO) is futuristic technology; there is a need to optimize the resource allocation for the MIMO communication model.

C. QOS FOCUSED

Although the QoS classes are well defined in the literature, they all are statically defined. So the resource allocation methodologies can be improved to support the dynamic QoS classes. mmWave can support QoS support with beamforming and relayed communication.

VI. LEARNINGS FROM STUDY

The study provides a comprehensive foundation of radio resource scheduling techniques in the LTE environment from the perspective of M2M communication. This study helps us identify the gaps in existing research work for potential future research in M2M radio resource scheduling and highlights the primary methodologies employed by researchers. Through this literature review, we get an overview of the fundamental architecture and the physical layer concepts of the LTE network. Also, it helps us to understand the basic architecture of M2M communication.

This review helps to understand the following critical aspects of the LTE radio resource allocation process.

- *Scheduling Metrics* - The scheduling metrics have a vital role in preferring or selecting a particular UE over others while assigning resources to the UEs.
- *Scheduling Objectives* - The study provides an insight into the scheduling objectives like efficiency, QoS, etc. that were focused on through previous research works.
- *Scheduling Methodologies* - The study helps to understand the pros and cons of previously employed approaches like game theory, queuing theory, etc. and provides direction towards the possibilities of implementing new methodologies in resource scheduling.
- *Constraints and Limitations* - In this literature review, we find out the constraints and limitations of LTE (i.e. resource exclusiveness and contiguity) and MTCs (i.e. power constraint), that draws a boundary for the resource scheduling process.
- *Parameters That Affect Scheduling Performance* - By comparing different scheduling work, we find out the parameters, i.e., MCS, number of PRBs, etc. that affect the performance of the scheduling methodology.
- *Current State of LTE Resource Scheduling* - This study helps us get an integrated and synthesized overview of the current state of the LTE scheduling.

VII. CONCLUSION

The study aimed to provide a comprehensive survey and classification of the scheduling strategies proposed by researchers for LTE/LTE-A networks from an M2M perspective. We classified scheduling strategies based on their aim for which the scheduling strategies are optimized. Most of the work in

efficiency-based approaches focused on the improvements in energy efficiency and throughput efficiency. However, some work is also focused on spectral efficiency and interference avoidance. In group-based scheduling approaches, most of the work focused on reducing uplink traffic and network coverage to achieve energy efficiency, spectrum reuse, interference control, and QoS support. In QoS-based scheduling approaches, the authors focused on the QoS of devices, mostly delay, and throughput. Some techniques supported the device's QCI. Some authors worked on defining QCIs for devices based on statistical priorities. In hybrid / multi-objective approaches, authors focused on satisfying multiple objectives in the combination of any purposes mentioned earlier. The authors implemented different modeling approaches, like game-theoretic, graph-theory, genetic-approach, constraint optimization, queuing-theory, greedy-approach, heuristic-methods, weighted-sum, deep-learning, neural-network, and fuzzy-logics, to achieve their objective of the work.

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