Afro-Asian Journal of Scientific Research (AAJSR)
المجلة الأفروآسيوية للبحث العلمي (AAJSR)
E-ISSN: 2959-6505
Volume 2, Issue 3, July - September 2024, Page No: 328-336
Website: https://aajsr.com/index.php/aajsr/index
SJIFactor 2023: 3.908 | معامل التأثير العربي (AIF) 2023: 0.51 | ISI 2023: 0.337

Strategies for Implementing LTE/LTE-A Wireless Networks

Ahmed A. Alsabri *
Department of Electrical, Electronic and Systems Engineering, College of Information Technology, University of Zawia, Alzawia, Libya

استراتيجيات تنفيذ شبكات LTE/LTE-A اللاسلكية

أحمد علي الصبري*
قسم الهندسة الكهربائية والإلكترونية والنظم، كلية تقنية المعلومات، جامعة الزاوية، الزاوية، ليبيا

*Corresponding author: ah.ali2060@gmail.com

Received: July 15, 2024	Accepted: August 24, 2024	Published: September 21, 2024

Abstract:
LTE-Advanced builds upon the foundational features of LTE, such as network architecture and radio interface, by incorporating additional enhancements to further optimize system performance. One of the critical and complex challenges presented by LTE technology is managing multiple users who require high data rates within a limited bandwidth in the same geographical area, all while maintaining low latency. To address this, multiple access techniques are employed, which allocate portions of the total system resources to each User Equipment (UE), enabling efficient sharing of available bandwidth. To significantly enhance system performance, particularly by increasing the spectral efficiency of the wireless interface and thereby expanding system capacity, the development of advanced resource allocation algorithms for scheduling is imperative. This paper provides a concise review of LTE and LTE-Advanced, with a particular focus on Carrier Aggregation techniques and downlink scheduling methodologies.

Keywords: 5G Network, Wireless Communication, 5G Technology, Fifth Generation Network.

الملخص
يبني LTE-Advanced على الميزات الأساسية لتقنيةLTE ، مثل بنية الشبكة وواجهة الراديو، من خلال إضافة تحسينات إضافية تهدف إلى تحسين أداء النظام بشكل أكبر. تتمثل إحدى التحديات الحرجة والمعقدة التي تواجه تقنية LTE في إدارة العديد من المستخدمين الذين يحتاجون إلى معدلات بيانات عالية ضمن نطاق ترددي محدود في نفس المنطقة الجغرافية، مع الحفاظ على زمن انتقال منخفض. لمواجهة هذا التحدي، يتم استخدام تقنيات الوصول المتعدد، التي تقوم بتخصيص أجزاء من موارد النظام الإجمالية لكل جهاز مستخدم (UE)، مما يتيح مشاركة فعّالة للنطاق الترددي المتاح بين الأجهزة. ولتحقيق تحسين كبير في أداء النظام، لا سيما من خلال زيادة الكفاءة الطيفية لواجهة الاتصال اللاسلكي وبالتالي تعزيز قدرة النظام، فإن تطوير خوارزميات تخصيص الموارد المتقدمة لجدولة المهام أمر ضروري. توفر هذه الورقة مراجعة موجزة لتقنيتي LTE وLTE-Advanced، مع التركيز على تقنيات تجميع الحامل (Carrier Aggregation)ومنهجيات جدولة النظام في الوصلة الهابطة.

الكلمات المفتاحية: شبكة الجيل الخامس، الاتصالات اللاسلكية، تقنية الجيل الخامس، شبكة الجيل الخامس.

1. Introduction

The architectural framework and radio interface of LTE serve as the foundation for LTE-Advanced, which introduces additional features aimed at enhancing overall system performance. LTE technology presents a significant and complex challenge in managing multiple users who, within the constraints of limited bandwidth and the same geographical area, require high data rates while maintaining low latency. To address this, resource allocation techniques are employed, wherein segments of the total system resources are dynamically assigned to each User Equipment (UE), enabling efficient sharing of available bandwidth. Enhancing system performance, particularly by improving the spectral efficiency of the wireless interface and subsequently increasing system capacity, necessitates the development of advanced resource allocation algorithms for effective scheduling. This paper provided a comprehensive review of LTE and LTE-Advanced, with a focus on key techniques such as Carrier Aggregation and downlink system scheduling.

LTE and LTE-A require access to a wide frequency range to meet high data demands. A crucial step is selecting the appropriate spectrum bands and ensuring optimal utilization through techniques like carrier aggregation. Spectrum refarming, or reassigning underused spectrum, is also essential for smooth transitions from older technologies (e.g., 3G). Moreover, Efficient network planning is critical for ensuring coverage, capacity, and quality of service (QoS). This includes cell site selection, antenna placement, and network dimensioning to handle high traffic volumes, particularly in urban areas. Propagation modeling tools help design networks that account for obstacles and interference. In this direction, techniques such as Multiple Input Multiple Output (MIMO) and beamforming are central to LTE-A for increasing spectral efficiency and network capacity. Implementing MIMO allows networks to support more users with the same bandwidth, improving data throughput without needing additional spectrum.

Furthermore, LTE-A leverages carrier aggregation to combine multiple frequency bands, significantly enhancing the network's bandwidth and allowing for faster data rates. Strategies for integrating this into an existing network depend on the availability of contiguous or non-contiguous frequency blocks. with this context, seamless handover between cells and networks (LTE, LTE-A, and legacy systems) is vital for maintaining uninterrupted service, particularly in high-speed mobility scenarios (e.g., vehicular). Implementing strategies like self-organizing networks (SONs) helps automate and optimize handover processes. However, traffic prioritization and quality of service policies must ensure that critical applications (like VoLTE) receive the required bandwidth and latency while efficiently managing non-critical traffic. Policy and Charging Control (PCC) strategies help ensure that LTE/LTE-A networks maintain high service quality. In this regard, LTE/LTE-A networks must include advanced security protocols to protect against threats such as eavesdropping, denial-of-service attacks, and unauthorized access. Employing robust encryption, secure authentication methods, and intrusion detection systems (IDS) is key.

As matter of fact, tools like network function virtualization (NFV) and software-defined networking (SDN) play a critical role in optimizing LTE/LTE-A networks. These technologies enable flexible network management and the dynamic allocation of resources to address capacity demands in real-time. It is clear that, the Evolved Packet Core (EPC) Integration is a critical component in LTE/LTE-A networks, facilitating efficient data routing and user authentication. Integrating the EPC with legacy core networks ensures smooth transitions and supports hybrid network environments during the rollout of LTE-A. Voice over LTE (VoLTE) requires careful integration with the IP Multimedia Subsystem (IMS) to deliver high-quality voice services. Strategies for implementing VoLTE involve ensuring low latency, high QoS, and interoperability with legacy voice networks (e.g., 3G). LTE-A networks must be designed to coexist with emerging 5G technologies. This involves planning for network upgrades, ensuring backward compatibility, and leveraging existing LTE infrastructure for non-standalone 5G deployments.

2. LTE and LTE-Advanced

In recent years, mobile networks have experienced substantial growth, expanding from basic voice and text communication to providing a wide range of services such as internet browsing, multimedia downloads, and video streaming. This expansion is driven by the increasing demand for higher data rates, which directly determine the range, quality, and efficiency of the services offered. To accommodate this demand, mobile networks have progressively increased bandwidth and transmission speeds. For example, the Second Generation (2G) Global System for Mobile Communication (GSM) utilized a 200 kHz channel to achieve data rates of 9.6 Kbps, mainly supporting voice communication but also providing several tens of kilobits per second for data traffic (Maloberti 1989; Halonen et al. 2022). In 2001, the Third Generation (3G) wireless system, known as Wideband Code Division Multiple Access (WCDMA), introduced a 5 MHz bandwidth, offering downlink speeds of up to 2 Mbps and uplink speeds of 768 Kbps (Honkasalo et al. 2022).

The technical specifications for Long-Term Evolution (LTE) were announced in December 2008 as part of 3GPP Release 8. This first LTE release supported radio-network latencies of less than 5 ms and peak data rates of 300 Mbps. The use of Multiple Input Multiple Output (MIMO) technology enabled LTE to achieve these high data rates. Furthermore, LTE is designed to operate in various bandwidths and supports both Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD) modes. As an enhancement of LTE, LTE-Advanced (LTE-A) was introduced, offering backward compatibility with LTE, ensuring a seamless transition for users with minimal conversion costs. The upgrade from LTE to LTE-A is analogous to the transition from WCDMA to High-Speed Packet Access (HSPA), making it an efficient evolution for operators and users alike.

LTE-A meets all the requirements set by the International Mobile Telecommunications-Advanced (IMT-Advanced) standard, utilizing advanced technology components such as extended spectrum flexibility, coordinated multipoint transmission-reception, enhanced multi-antenna solutions, and advanced repeaters/relays. With approximately 90% of the global mobile subscriptions adhering to the 3rd Generation Partnership Project (3GPP) standards, most mobile operators have adopted 3GPP LTE-A, making it the de facto standard for advanced mobile communications. Upgraded technologies like WCDMA, HSPA+, and LTE all align with 3GPP specifications, and LTE-A has consistently met the performance targets set by IMT-Advanced (3GPP 2011c).

LTE-A demands larger bandwidths than its predecessors, as its carrier aggregation technique allows for the combination of various LTE carrier bandwidths, each up to 20 MHz, to achieve an overall operating bandwidth of up to 100 MHz. Carrier aggregation is considered the most effective method for increasing peak data rates and meeting IMT-Advanced standards. Each carrier is known as a Component Carrier (CC), and the aggregation model can be either continuous and symmetric, termed Carrier Aggregation (CA), or discontinuous and asymmetric, referred to as Spectrum Aggregation (Shen et al. 2022; Chen et al. 2023). This section highlights the evolution from 2G to LTE-A, showcasing the progressive technological advancements that have increased data rates and bandwidth while ensuring backward compatibility and scalability. These developments lay the groundwork for future mobile technologies and the eventual transition to 5G

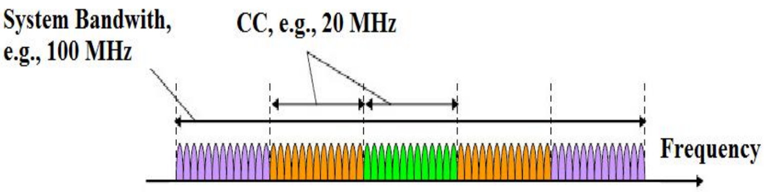

Figure (1): Wider bandwidth.

The primary goal of LTE-Advanced is to achieve data rates of up to 1 Gbps in 4G networks, with carrier aggregation technology being a key feature integrated into the LTE-Advanced standard (3GPP 2012). Although 3GPP has not explicitly outlined a strategy for carrier management and scheduling, the implementation of these components is left to network operators' discretion. In LTE-Advanced, the management of component carriers (CCs) is handled by the Radio Resource Control (RRC) layer, which governs carrier assignment and the selection of component carriers. LTE-Advanced allows for a maximum of five component carriers to be aggregated, enabling operators to maximize bandwidth utilization (Shen et al. 2022). This spectrum flexibility empowers network providers to efficiently utilize the entire spectrum assigned to them by regulatory authorities for LTE-A, as illustrated in Figure 2.

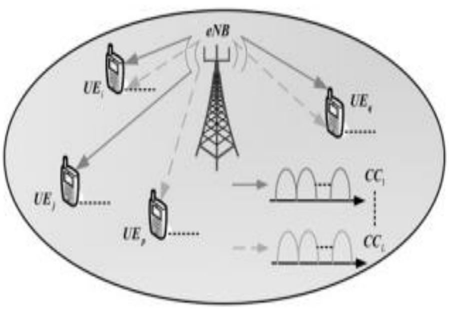

Figure (2): The downlink OFDMA-based CA system.

In LTE-A networks, all scheduling decisions, whether for downlink or uplink, are made by the Evolved NodeB (eNB), which is equivalent to the Base Station (BS) in previous mobile network generations. The time-frequency resource grid, which forms the basis of the downlink physical layer in the Media Access

Control (MAC), consists of multiple Resource Blocks (RBs), each further subdivided into several resource elements. The key component within the eNB responsible for assigning time and frequency resources to different users in the cell is the scheduler (Tugbiyele, 2021). The scheduler assigns Resource Blocks, which are the smallest allocatable units, to users.

Scheduling in the LTE-A downlink system is influenced by several factors, including the dynamic variations of channel conditions, ensuring that frequency and time resources are allocated to users experiencing better channel quality. Additionally, the Quality of Service (QoS) requirements in a multi-user communication system are dynamic, making the selection of the scheduling algorithm critical to maintaining both high throughput and fairness among users. Figure 3 illustrates the downlink scheduler in an LTE-Advanced system (Brown M. L., 2023). The downlink scheduler allocates resources to users based on their channel quality, QoS needs, and fairness considerations. Following the scheduler's decision, the eNB transmits data and scheduling signals based on the results (Zhang et al., 2019).

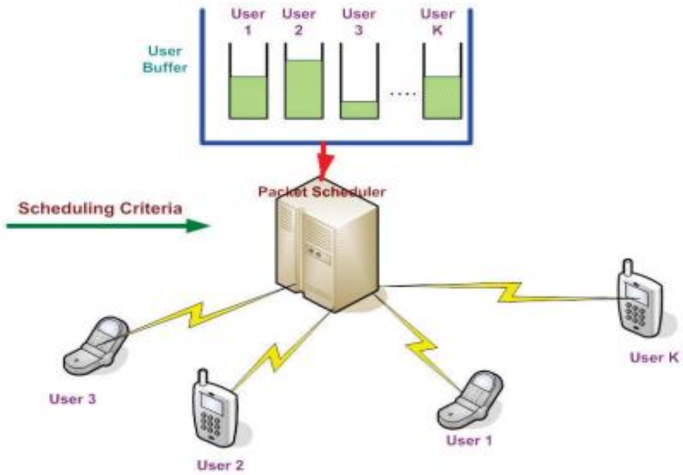

Figure (3): General packet scheduling system for downlink wireless system.

With the updates introduced in Release 9 of the latest LTE specifications, LTE-Advanced (LTE-A) has evolved into the equivalent of LTE Versions 10 and 11. Much like the IMT-Advanced standard, LTE-Advanced continues to progress, offering significant enhancements in system performance over LTE. LTE-Advanced supports peak data rates of up to 1 Gbps on the downlink and 500 Mbps on the uplink, compared to LTE's peak of 100 Mbps downlink and 50 Mbps uplink. In addition to substantial improvements in performance for both cells and users, LTE-Advanced optimizes spectrum utilization and boosts power efficiency for both users and infrastructure. To achieve these performance improvements (Dalibor, 2023), several key technological features of LTE-A are being introduced:

- Wider Bandwidth Assistance: LTE-A aggregates multiple LTE carrier bandwidths, each not exceeding 20 MHz, to form a combined operational bandwidth of up to 100 MHz. Carrier aggregation has emerged as the most effective technique for increasing peak data rates to fully comply with IMT-Advanced requirements (Shen et al., 2022). Each individual carrier is referred to as a Component Carrier (CC). When these CCs are continuous and symmetric, the model is known as Carrier Aggregation. In contrast, when the CCs are discontinuous and asymmetric, the model is termed Spectrum Aggregation (Chen et al., 2023). LTE-A allows for a maximum of five component carriers (Shen et al., 2022). This spectrum flexibility provides network operators with a distinct advantage, enabling them to fully utilize all available spectrum assigned to them by government regulators for LTE-A deployment, as illustrated in Figure 4.

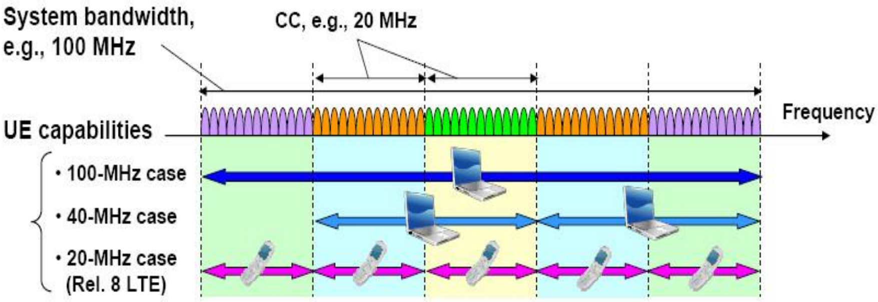

Figure (4): Wider bandwidth (Nakamura 2019).

- Multiple Input Multiple Output (MIMO): LTE-Advanced supports the use of multiple antennas at both the receiver and transmitter, employing MIMO techniques to offer various benefits, such as spatial diversity and spatial multiplexing. Spatial multiplexing enhances network capacity by transmitting different data streams simultaneously in parallel through separate antennas (Shen et al., 2022).
- Asymmetric Transmission Bandwidth: In previous 3GPP standards, including LTE, Frequency Division Duplex (FDD) mode allocated equal bandwidths for uplink and downlink transmissions (Afroz, 2022). However, in LTE-Advanced, the downlink bandwidth can differ from the uplink, reflecting the disparity between download and upload traffic volumes, as illustrated in Table 1 (Dahlman et al., 2020).
- Coordinated Multipoint Transmission and Reception (CoMP): CoMP is a technique used to increase user throughput and expand cell coverage by transmitting and receiving data through multiple coordinated cells. CoMP techniques are divided into two categories: Joint Processing (JP) and Coordinated Scheduling/Beamforming (CS/CB), both of which help improve signal quality and user experience (Nakamura, 2019).
- Relaying: A significant addition to the LTE-Advanced architecture is the Relay Node (RN), a network element that receives signals from an eNodeB and forwards them to extend the coverage area. The link from the eNodeB to the RN is called the backhaul link, and the link from the RN to the User Equipment (UE) is referred to as the access link (Chen et al., 2023). This relaying feature is crucial for enhancing coverage, especially in areas where direct signals from the eNodeB may not reach effectively.

Table (1): Overview of all new characteristics of LTE/LTE-A (Shen et al. 2012).

Technology	LTE	LTE-A
Peak data rate DownLink (DL)	150 Mbps	1 Gbps
Peak data rate UpLink (UL)	75 Mbps	500 Mbps
Transmission bandwidth DL	20 MHz	100 MHz
Transmission bandwidth UL	20 MHz	40 MHz (requirements as defined by ITU)
Mobility	Optimized for low speeds (< 15 km/hr) High performance at speeds up to 120 km/hr Maintain Links at speeds up to 350 km/hr	Same as that in LTE
Coverage	Full performance up to 5 km	Same as LTE requirement Should be optimized or deployment in local areas/micro cell environments
Scalable Band Widths	1.3,3,5,10 and 20 MHz	Up to 20 – 100 MHz
Capacity	200 active users per cell in 5 MHz	3 times higher than that in LTE

3. LTE-A Radio Resource Management

In LTE-Advanced (LTE-A), Radio Resource Management (RRM) is critical for ensuring the efficient allocation of available resources to users. RRM encompasses various strategies that control parameters such as transmit power, handover mechanisms, modulation schemes, and channel allocation. Additionally, it includes the use of error-coding schemes to manage the network resources effectively. RRM in LTE-A is dynamic, meaning that it adaptively adjusts the radio network parameters based on factors such as traffic load, user positions, and Quality of Service (QoS) requirements. Figure 5 provides a detailed overview of the key RRM features and their interaction through both signaling and data exchange. Below are the main concepts involved in the RRM process:

- Admission Control: The decision to admit a user into the network is based on the user's channel conditions, current cell load, and QoS requirements. Admission Control ensures that the network can handle additional users without degrading the quality of service for existing users.
- Component Carrier (CC) Assignment: Once a user is admitted, one or more available Component Carriers (CCs) are assigned to them based on their terminal type and traffic needs. This process ensures that users receive the appropriate bandwidth for their traffic requirements.
- Packet Scheduling: After CC assignment, the process of packet scheduling begins. In this stage, each user is allocated the available Physical Resource Blocks (PRBs). In LTE and LTE-A, the PRB is the smallest resource unit that can be allocated to a user at a given time.
- Link Adaptation: Link adaptation is the process where an appropriate Modulation and Coding Scheme (MCS) is selected for each user to meet spectral efficiency targets while maintaining a specific Block Error Rate (BLER). The selected MCS, along with the Multi-Input Multi-Output (MIMO) mode (if applicable), determines the performance of Layer 1 transmission on each CC.

By effectively managing these processes, RRM ensures that LTE-A networks maximize performance while meeting the varying demands of users in terms of data rates, QoS, and network conditions.

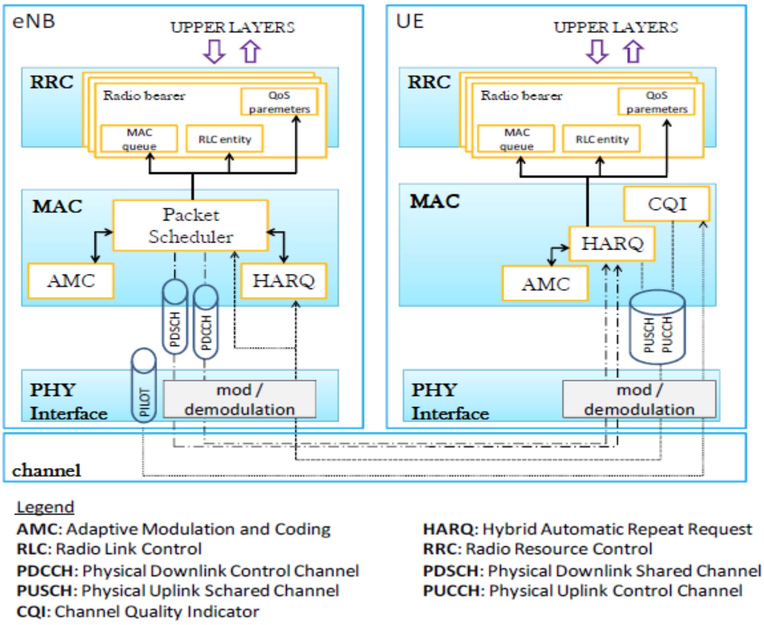

Figure (5): Interaction of the main RRM features.

A flowchart depicting the Radio Resource Management (RRM) process in LTE-Advanced (LTE-A) is shown in Figure 6. In this framework, RRM incorporates processes across multiple layers. At Layer 3, it includes Admission Control (AC), while Layer 2 handles Packet Scheduling (PS), Link Adaptation (LA), and Hybrid Automatic Repeat Request (HARQ) management. These processes are executed on a millisecond basis to quickly adapt to radio channel conditions, with all operations centralized at the eNodeB (eNB).

For a User Equipment (UE) to receive service from the eNB, it must first pass the Admission Control (AC) process, which evaluates the UE's Quality of Service (QoS) requirements, channel quality, and the current network load. Only when AC admits the UE will the eNB begin serving it. Once admitted, Packet Scheduling (PS) is responsible for allocating transmission and retransmission requests over the available resources.

At Layer 2, Link Adaptation (LA) works to maximize spectral efficiency while adhering to a specified Block Error Rate (BLER) constraint. The role of HARQ management is to improve transmission performance by combining retransmissions with previous transmissions. Finally, Layer 1 manages independent transmissions. This multi-layered approach ensures efficient allocation of radio resources, adaptability to channel conditions, and optimal service delivery to the users in an LTE-A network.

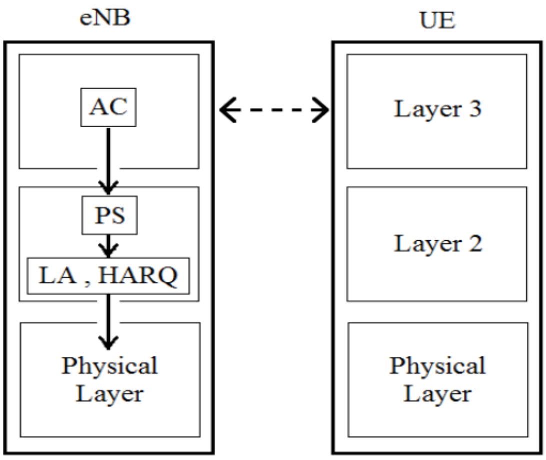

Figure (6): RRM in a single carrier LTE-Advanced system.

4. Key Scheduling Design Aspects

In LTE networks, designing an efficient dynamic resource-sharing scheme involves balancing decision optimality with computational complexity. Below are the key aspects that need to be considered in such a design:

- Complexity and Scalability: An LTE packet scheduler operates with a time granularity of 1 ms, meaning it must make resource allocation decisions during every Transmission Time Interval (TTI). Ensuring low computational complexity and scalability is crucial to minimize processing time and memory usage. Exhaustive search methods or solving complex non-linear optimization problems for resource allocation would be computationally expensive and time-consuming. To address this, most Frequency Domain Packet Scheduler (FDPS) decisions are based on per-Resource Block (RB) metrics, assigning each RB independently to the user with the highest metric (Nakamura, 2019).
- Buffer Status: Buffer status provides information on the pending packets to be served, directly influencing the scheduling process. Application bitrate, such as 242 Kbps for video and 8.4 Kbps for VoIP, is highly correlated with buffer status. The scheduler must account for queue length and Head-Of-Line (HOL) packet delays when determining scheduling priorities. For example, VoIP packets generally have smaller queues compared to video packets.
- Spectral Efficiency: Maximizing spectral efficiency, measured in bits per second per Hertz (bit/s/Hz), is one of the primary objectives in LTE scheduling. A policy aiming to serve users with the best channel conditions typically yields the highest spectral efficiency. This metric is often evaluated using the "user goodput," which measures the actual data rate excluding packet retransmissions and Layer 2 overheads due to physical errors (Shen et al., 2022).
- Packet Delays: Ensuring minimal packet delays is critical for maintaining QoS in delay-sensitive applications like VoIP and video streaming. Efficient scheduling schemes are designed to minimize packet delays, ensuring that applications requiring low latency can function correctly.
- Fairness: While maximizing overall cell throughput enhances spectral efficiency, it can lead to unfair resource distribution among users, particularly for those at the cell edge who experience poor channel conditions. Fairness is a key design consideration that must be integrated into the scheduling metric to ensure that all users, regardless of their location, receive adequate service. Quantifying the fairness level helps determine the balance between efficiency and equity in resource distribution (Arias R., 2023).

- QoS Provisioning: Quality of Service (QoS) provisioning is critical in next-generation mobile networks, particularly in all-IP architectures. LTE networks rely on QoS Class Identifiers (QCIs) to map QoS-constrained flows to dedicated radio bearers. QoS-aware schedulers must account for parameters such as packet loss rate, maximum delivery delay, and minimum guaranteed bitrate, depending on the application and service being provided (Nakamura, 2019).
- Type of Service: LTE services can be categorized into Real-Time (RT) and Non-Real-Time (NRT) types. Defining the type of service is essential for determining scheduling priority. For example, dynamic resource allocation is crucial for real-time services like video conferencing, whereas minor delays in non-real-time services like SMS are acceptable without impacting user experience.

These aspects ensure that the scheduling process in LTE networks not only maximizes spectral efficiency and throughput but also provides fairness, QoS, and scalability, allowing the network to efficiently handle varying user demands and traffic types.

5. Challenges Encountered in Implementing Scheduling in LTE-A

Implementing scheduling in LTE-Advanced (LTE-A) introduces several new challenges, particularly in terms of Radio Resource Management (RRM) and the increased complexity of the network. Below are the key challenges that need to be addressed:

- Quicker Computations: LTE-A's advanced architecture, which includes a greater number of Transport Blocks (TBs), Resource Blocks (RBs), and Component Carriers (CCs), demands faster processing capabilities across network elements such as User Equipment (UE) and eNodeB. Efficient simulations for scheduling tasks must be designed to ensure that the network can process scheduling decisions quickly enough to maintain smooth operations and meet real-time demands.
- User Mode Transitions: Scheduling in LTE-A must now accommodate more complex user behavior, including transitions between various modes such as Coordinated Multipoint (CoMP) and relaying. Active users may switch modes during their session, and the eNodeB must recognize these transitions in real time and optimize the user's performance accordingly. This requires dynamic scheduling solutions that can adjust to changing user conditions and enhance overall system efficiency (Vaishnav, 2023).
- Increased Complexity: New LTE-A features like CoMP and Multi-User MIMO (MU-MIMO) introduce higher levels of complexity, particularly regarding the coordination between multiple users and eNodeBs. The serving cell must act as a control unit, similar to the role of a Base Station Controller (BSC) or Radio Network Controller (RNC) in previous systems, to collect data from neighboring cells and active users. The eNodeB must then efficiently allocate resources and schedule tasks based on the collected information (Vaishnav, 2023).
- New Algorithms: One of the main challenges in LTE-A scheduling is the development of entirely new algorithms optimized for its specific requirements. Most current scheduling algorithms are modified versions of the Proportional Fair (PF) algorithm, but LTE-A demands algorithms that address both user-specific and system-wide needs while incorporating new features such as CoMP, carrier aggregation, and advanced MIMO configurations.

These challenges highlight the need for innovations in scheduling algorithms, processing capabilities, and network coordination mechanisms to fully realize the potential of LTE-A and ensure optimal network performance.

6. Conclusion

In this paper, the composition and key features of LTE and LTE-Advanced (LTE-A) have been thoroughly discussed, offering essential knowledge for understanding these technologies. The main specifications of LTE and LTE-A were presented, emphasizing the role of Carrier Aggregation (CA) technology in supporting future IMT-Advanced mobile systems with very high data rates. Additionally, the paper provided an overview of CA technology's potential in enabling high-speed communications. Opportunistic and optimal scheduling algorithms, which leverage multiuser diversity to maximize throughput, were also examined. However, these techniques often fail to ensure consistent access for users with poor channel conditions, leading to a lack of general fairness in scheduling. Despite efforts by opportunistic schedulers to balance fairness and high bitrate performance, an optimal trade-off has yet to be achieved. Furthermore, this paper addressed the various challenges in implementing scheduling mechanisms in LTE-A, highlighting the need for more effective solutions to enhance system performance.

References

1. Halonen, T., J. Romero & J. Melero. 2023. GSM, GPRS and EDGE performance: evolution towards 3G/UMTS Ed.: John Wiley & Sons.
2. Honkasalo, H., K. Pehkonen, M. T. NieMi & A. T. Leino 2022. WCDMA and WLAN for 3G and beyond. *Wireless Communica*tions, IEEE9(2): 14-18.
3. Iosif, O. & I. Banica 2011. On the analysis of packet scheduling in downlink 3GPP LTE system. *CTRQ 2011, The Fourth International Conference on Communication Theory, Reliability, and Quality of Service*. pp. 99-102.
4. Maloberti, A. 1989. Radio transmission interface of the digital pan European mobile system. *Vehicular Technology Conference, 1989, IEEE 39th*. pp. 712-717.
5. Chen, W., H. Yu & W. Feng 2023. A Self-adaptive Packet Scheduling Algorithm for Hybrid-traffic in Heterogeneous Wireless Networks. *International Journal of Future Generation Communication and Networking* **7**(6).
6. Zhang, L., K. Zheng, W. Wang & L. Huang 2019. Performance analysis on carrier scheduling schemes in the long-term evolution-advanced system with carrier aggregation. *IET communications***5**(5): 612-619.
7. Vaishnav, S. & T. Dholariya 2023. Performance analysis of 8× 8 MIMO system for LTE-A in Nakagami-m Fading Channel. *Communications and Signal Processing (ICCSP), 2014 International Conference on*. pp. 091-094.
8. Afroz, F., K. Sandrasegaran& P. Ghosal 2022. Performance analysis of PF, M-LWDF and EXP/PF packet scheduling algorithms in 3GPP LTE downlink. *Telecommunication Networks and Applications Conference (ATNAC), 2014 Australasian*. pp. 87-92.
9. Shen, Z., A. Papasakellariou, J. Montojo, D. Gerstenberger& F. Xu 2022. Overview of 3GPP LTE-advanced carrier aggregation for 4G wireless communications. *Communications Magazine,* IEEE50 (2): 122-130.
10. Nakamura, T., S. Nagata, A. Benjebbour, Y. Kishiyama, T. Hai, S. Xiaodong, Y. Ning& L. Nan 2019. Trends in small cell enhancements in LTE advanced. *Communications* Magazine, IEEE51 (2): 98-105.
11. Dahlman, E., S. Parkvall& J. Skold. 2020. 4G: LTE/LTE-advanced for mobile broadband Ed.: Academic press.
12. Arias R., M. Deshmukh, I. Mauro, D. O'Halloran, M. Spelman, H. Galal, and N. Ratan (2023). "The Impact of 5G: Creating New Value across Industries and Society," World Economic Forum Whitepaper, 2020.
13. Brown M. L., S. H. Chang, S. D. Delacourt, R. B. Engelman, M. J. Gardner, A. M. Gomez, D. A. Gross, and A. J. Reynolds (2023) 5G and Government: A Regulatory Roadmap: Wiley Law.
14. Chen, S., Qin F, Hu B., Li X. Chen Z.., *User centric Ultra-dense Networks for 5G*, in *User-Centric Ultra-Dense Networks for 5G*. 2019, Springer. p. 1-3.
15. DaliborVavruška Petr Očko (2023). How to approach 5G POLICIES. Ministry of Trade and Industry.
16. Tugbiyele, K., Increasing 4G Network Infrastructure to Improve E-Commerce. 2021, the George Washington University.
17. Watts J. T. (2022) "A Framework for an Open, Trusted, and Resilient 5G Global Telecommunications Network," The Atlantic Council, 2020.