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Research paper

Service-Aware Resource Scheduling for Heterogeneous M2M Communication in 5G Networks

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Abstract

Heterogeneous Machine to Machine communication or massive machine type communication in 5G networks presents unique challenges due to diverse device types, service requirements, and scarce radio resources. The work proposes a Service-Aware Resource Scheduling (S-RS) scheme to optimize resource allocation while simultaneously considering both resource utilization and cell throughput. S-RS dynamically allocates resource blocks based on a combination of device priority, channel quality, and service type. Simulation results demonstrate optimal improvements compared to proportional fair, priority, and Best-CQI methods, achieving optimal resource utilization and cell throughput. Future directions for further research are discussed, including advanced service differentiation. Our findings may lay the groundwork for efficient and adaptable resource allocation for reliable M2M communication in 5G-enabled smart cities or smart homes.

Keywords: *5G NR; M2M; PRB; QoS; Resource Allocation; Uplink Scheduling.*

1. Introduction

Machine-to-machine (M2M) communication and the Internet of Things (IoT) are indeed revolutionizing how we interact with and manage user equipment (UEs) or Machine-type Devices (MTDs) or Machine-type Communication Devices (MTCDs), enabling a wide array of applications that enhance efficiency, productivity, safety, and reliability across different industries [1]. In real-time, the ability to remotely monitor and control UEs such as sensors, actuators in petrochemical plants, grid voltage controllers, and surgical robots represents a paradigm shift. As M2M continues to evolve, it has the potential to reshape industries, improve quality of life, and contribute to the development of innovative solutions across various domains [2].

M2M communication, where UEs exchange data autonomously without human intervention, has unique characteristics compared to traditional human-to-human (H2H) communication or human-to-machine (H2M) communication [3]. The M2M data characteristics include 1) Low data volume, where M2M UEs often transmit small amounts of sensor data, status updates, or control commands in uplink direction with 2) Low latency requirements, but some M2M applications, like industrial automation, require near real-time communication for timely response. 3) Time-driven transmission, where many M2M UEs transmit data periodically or based on specific events. These M2M UEs often have 4) Limited processing power and battery life, as UEs are usually optimized for tasks and have limited resources, requiring efficient communication protocols [4].

The M2M architecture dwells on the technology required to connect the device domain with the application domain [5]. The M2M network characteristics include 1) Massive UE connectivity, where M2M networks can potentially accommodate millions of connected UEs (10^6 UEs per square kilometer), creating network density and uplink resource management challenges with 2) Heterogeneous UEs, as different UE types with varying capabilities and communication requirements coexist in the same network [6], and 3) Limited user interaction, as most communication takes place directly between UEs with minimal human intervention and different quality of-service (QoS) requirements [7].

5G New Radio (NR) supports a mix of communication technologies, including enhanced Mobile Broadband (eMBB), mMTC, and Ultra-Reliable Low Latency Communication (URLLC). It allows the network to cater to different communication requirements [8]. Top priority is provided for URLLC applications to achieve low latency and high reliability (over 99.999%) to guaranteed QoS, as data rates and coverage are less crucial for URLLC applications because they typically involve smaller data packets and operate in controlled scenarios; second priority is with eMBB applications with high peak data rates, low latency, and wide coverage as massive UE support and energy efficiency are secondary as eMBB primarily caters to human-centric services with relatively fewer UEs [9]. In contrast, the least priority is provided to mMTC applications with massive UE support, low energy consumption, and wide area coverage, as mMTC applications cater to large-scale IoT deployments requiring long battery life for numerous UEs spread across diverse locations. Whereas, data rates and latency are less critical for mMTC, as these applications frequently transmit small amounts of uplink data and usually don’t require real-time response [10].

As mMTC has not received the same level of standardization effort as eMBB or URLLC, it remains a crucial and rapidly growing aspect of 5G NR, highlighting its significant potential and impact on industries where mMTC underpins numerous sectors like smart cities, logistics, and industrial automation [11], driving efficiency. Still, despite its importance, mMTC presents unique technical challenges like radio resource management, massive UE management, low power consumption, and reliable low-rate communication [12]. Thus, adaptive resource scheduling algorithms are necessary to cater to a diverse traffic of applications with varying QoS demands. For success in the ever-evolving M2M landscape, these strategies demand self-adaptability to navigate dynamic scenarios, robustness to overcome interference, scalability to handle diverse UEs, and the ability to function autonomously.

2. Background

Cellular networks can deliver diverse M2M/mMTC services because of Radio Resource Management (RRM) protocols [13]. RRM protocols act like traffic controllers, ensuring UEs receive reliable connections by allocating time and frequency resources efficiently. Scheduling is the process of assigning resources to UEs for transmitting and receiving data [14].

a) Resources in 5G NR

The 5G NR system organizes time and frequency resources into a grid. The resource in 5G NR is characterized as 1.) Resource Elements (REs), consists of one subcarrier spaced at a specific subcarrier spacing (SCS) and transmitted for one OFDM symbol duration [15]. 2.) Physical Resource Blocks (PRBs) or Resource Blocks (RBs) consists of 12 subcarriers (same as LTE) in the frequency domain and one slot in the time domain. RBs are used for describing the mapping of physical channels to REs and used for scheduling and assigning resources to UE for data transmission. One resource grid is created for one antenna port and numerology [16]. Figure 1, presents the resource grid concerning to PRBs or RBs and RE in 5G NR.

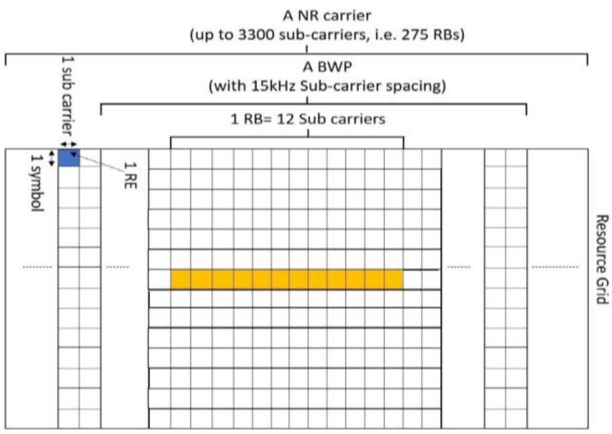

Fig. 1: Resource Grid in 5G NR.

b) Overview of 5G NR Numerology

In 5G NR, numerology refers to the set of parameters that define the structure of the radio frame and the SCS [17]. The overview of the frame structure in the time domain is as 1) Radio Frame, which is the basic unit of time, lasting 10 ms (inherited from LTE), 2) Sub-frame, where each frame is divided into 10 sub-frames, each lasting 1 ms, and 3) Slot, where sub-frames can be further divided into slots, which depends on the chosen numerology. Slots are the fundamental unit for resource allocation in the frame. 4) OFDM Symbol, which is the building block of data transmission and is fixed in each slot, the number of symbols is 14 with normal cyclic prefix (CP) and 12 with extended CP. Table I presents the 5G NR numerology parameters [18].

Table 1: 5G NR Numerology Parameters

Numerology (μ)	0	1	2	3	4
Subcarrier Spacing (SCS) ($2^{\mu} \times 15$ kHz)	15	30	60	120	240
Slots per Sub-frame (2^{μ})	1	2	4	8	16
Slots per Frame ($10 \times 2^{\mu}$)	10	20	40	80	160
Symbols per Slot	14	14	14 /12	14	14
Slot Duration (ms)	1	0.5	0.25	0.125	0.625

c) Resource Scheduling Overview

The scheduling phase in the uplink channel of 5G NR relies on several key elements, as a few of them are: 1.) Buffer Status Reports (BSRs): UEs regularly transmit BSRs through dedicated control channels (PUCCH) to inform the BS (gNB) about their buffer status [19]. The information allows the gNB to assess the urgency and requirements of each UE before allocating resources [20]. 2.) Physical Uplink Control Channel (PUCCH): PUCCH carries control information (including BSRs) from UEs to the gNB, utilizing short, flexible-length transmissions [21]. 3.) Physical Downlink Control Channel (PDCCH): PDCCH carries scheduling grants from the gNB to UEs, indicating allocated resources like time slots, frequency bands, and modulation schemes. 4.) HARQ Feedback, After the UE transmits data, the gNB provides Hybrid Automatic Repeat Request (HARQ) feedback to the UE. HARQ is a mechanism that manages retransmissions to ensure reliable data delivery [22].

Different standard algorithms like proportional fair, priority algorithm, and Best-CQI prioritize varying aspects, catering to diverse scenarios. Effective scheduling technique with BSRs, buffer size, PUCCH, and PDCCH plays a crucial role in optimizing radio resource utilization and cell throughput, maintaining optimal fairness and QoS for different service types with minimum latency for real-time applications, and adapting to network dynamics and channel variations.

3. Motivation and contribution

The emergence of 5G NR brings a new era of communication with high speed, low latency, and massive heterogeneous UE connectivity. Each mMTC service has distinct data rates, latency, reliability, and connectivity requirements, with dynamic network conditions where traffic patterns, UE locations, and channel conditions (CQI) constantly change. Existing resource scheduling approaches cannot optimally adapt to these dynamics, leading to sub-optimal resource allocation and potential performance degradation.

The presented article suggests a novel resource scheduling algorithm with the following key contributions:

- Service awareness: Our proposed algorithm incorporates service (5QI) differentiation by considering the diverse QoS requirements of different M2M/mMTC applications operating within the network.
- Optimized resource scheduling: The algorithm employs an efficient uplink scheduling mechanism that balances throughput and resource utilization while maintaining the required QoS for each service type.
- Dynamic adaptation: The algorithm leverages real-time network information (CQI) and traffic patterns to dynamically adjust resource allocation based on changing demands, particularly in dense network scenarios.
- 5G NR compatibility: The algorithm is designed to be compatible with the 5G NR framework, leveraging its features with 5G NR numerology to further enhance resource scheduling efficiency and cater to diverse service requirements.

The rest of the paper is structured as follows: Section IV provides an overview of related works. Section V details the proposed uplink scheduling algorithm. The analysis of the results is covered in Section VI, while Section VII constitutes the conclusion of the paper.

4. Related works

A comprehensive analysis of 5G RRM schemes is presented, focusing on fairness, resource utilization, throughput, energy efficiency, QoS needs, and interference. The analysis by [23] demonstrates the need for adaptable RRM approaches due to the increasing UE density and heterogeneity in 5G networks, but has limitations such as computational complexity, signaling overhead, and feasibility in highly dense and dynamic networks. To address the increasing number of connected UEs and enhance scheduling and spectral efficiency, the authors [24]-propose dual Non-Orthogonal Multiple Access (NOMA) and Orthogonal Multiple Access (OMA) for uplink scheduling and partially manage the limitations of NOMA and OMA in dense networks.

The authors [25] identify severe packet collisions as a key factor hampering performance and propose a frame division, joint access control, and sub channel resource allocation scheme to address the challenge but with limitations as assuming idealized channel conditions and perfect synchronization, which may not capture real-world variability, while [26] explore the suitability of Narrowband Internet of Things (NB-IoT) for low-rate, delay-tolerant applications, highlighting its four-step Random Access (RA) mechanism but limitations with assumption of non-overlapping transmission opportunities groups might not always hold in practical implementations and focus on per-user success probability. The authors [27] present a cognitive unmanned aerial vehicle (CUAV)-aided pairings for supporting both mMTC and URLLC services. The analysis is derived from latency, energy efficiency, and data rate, but Interference mitigation is not discussed.

The authors [28] propose a mixed reservation and priority-based resource allocation strategy with network slicing, aiming to improve resource utilization. The analysis concludes that a mixed strategy is suitable for URLLC and mMTC traffic, while the reservation-only methodology is suitable for eMBB traffic. but the model did not consider propagation environments or operational frequencies, while [29] addresses the heterogeneous service scheduling challenge by proposing two algorithms, the Iterative Greedy Algorithm (IGA) and the Resource Partitioning and Assignment (RPA) algorithm, to maximize admitted UEs while satisfying data transfer and latency constraints. The analysis considers a 5G system with flexible numerologies and discretizes available time-frequency resources into REs, but RPA's resource allocation efficiency decreases with increasing number of sub-bands.

The authors [30] propose a simulated M2M smart city application model, utilizing networked UEs. Performance metrics of packet loss rate, packet delay budget and average delay are analyzed for large-scale MTC over cellular networks while [31] proposes a Group-Based and Energy Aware (GBEA) algorithm for M2M communication optimizing resource allocation by considering delay, energy, and fairness, and demonstrates increased performance in throughput, delay sensitivity, and energy consumption but the algorithm efficiency needs to be optimized for large-scale networks whereas [32] explores the uplink resource scheduling problem for smart city critical and essential applications by proposing a fairness and priority-based uplink resource scheduling scheme for M2M communication, leveraging 5G NR numerology.

The authors [33] address IoT connectivity and dynamic resource management using Deep Reinforcement Learning (DRL) for better throughput but have high computational complexity during training and potential struggle with convergence under dynamic scenarios as computational complexity strains resource-limited UEs. The authors [34] introduce the 5G-QoERA dataset to address the lack of comprehensive real-world data for analyzing 5G technology performance, but focus on video streaming applications to assess Quality of Experience (QoE), which may not capture the other 5G applications and services.

The reviewed literature reveals various approaches for 5G resource management from NOMA/OMA scheduling strategies to network slicing and DRL solutions. However, existing works focus on specific scenarios with idealized assumptions, suffer from computational complexity limitations, or lack a comprehensive consideration of the impact of M2M communication on other diverse UE requirements. To address these gaps, we introduce an uplink physical resource scheduling approach accommodating M2M communications, ensuring QoS fulfillment while minimizing their impact on other UE requirements.

5. System model and problem formulation

A scenario for the resource scheduling process is formulated to allocate PRBs to N UEs with varying services, CQI values, 5QI, priorities, traffic patterns, and QoS requirements. The allocation is performed by a gNB within each transmission time interval (TTI). Figure 2(a) represents the ~~network~~ system model considering a 5G network with gNB, various UE types (U1, U2, E1, E2), and M2M UEs (M1, M2, M3) with varying data in their buffers awaiting transmission. In our scenario, we deploy 100 to 500 UEs engaging in 5G mMTC applications and place them randomly. Figure 2(b) lists the smart home application settings and traffic characteristics of different UE types, showing transaction rates from 1 per minute (security systems) to 1 per day (appliances), with payload sizes ranging from 8 bytes to 2017 bytes, creating a realistic M2M traffic environment for evaluating our service-aware scheduling algorithm. Each UE operates within a network to transmit information to the gNB. The necessary simulation parameters are listed in Table II.

Algorithm (pseudo code): 5G-S-RS

The algorithm aims to allocate available PRBs among multiple UEs with optimal resource utilization and cell throughput.

Input: $K = \{k_1, k_2, \ldots, k_N\}$ is set of N M2M UEs, M is total number of available PRBs, S_k is sub-carrier spacing, T_k is TTI, C_k is channel quality indicator for UE k, $P = \{p_1, p_2, \ldots, p_N\}$ is set of priorities for UEs in K, B_k is buffer-status report for UE k, 5QI is the QoS class identifier for each request, MCS Matrix is the mapping between CQI and MCS, Qpr is the queue of pending requests, Qsr is the scheduled queue for the current scheduling period.

Result: Set of K UEs with Mapped RBs.

Steps:

Initialization:

- Get UE requests, define available RBs (M), initialize scheduled queue, and count pending requests (Cpr).

Resource availability check:

- If enough resources (Cpr < M): Schedule all requests.

Otherwise:

- Update Virtual Queueing (v5QI) based on CQI, priority, and request parameters.

Scheduling loop:

- Iterate M times:
- Select and remove the highest priority request.
- Map RBs to the selected request.
- Calculate MCS and TBS (Transport Block Size).

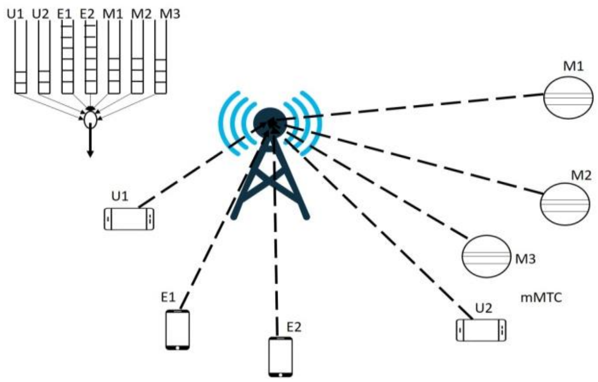

Fig. 2: A). System Model.

IN-HOME M2M DEVICES TRAFFIC PARAMETERS

Device	Transaction rate	Transaction size (bytes)	Devices per home	Distribution
Home security system	1 per 10 min	20	1	Poisson
Elderly sensor devices	1 per min	128	0.1	Poisson/uniform
Refrigerator	1 per hour	30	1	Poisson/uniform
Clothes washer	1 per day	8	1	Poisson/uniform
Clothes dryer	1 per day	8	1	Poisson/uniform
Dishwasher	1 per day	8	1	Poisson/uniform
Freezer	1 per day	30	1	Poisson/uniform
Stove/oven	1 per day	8	1	Poisson/uniform
Microwave	1 per day	8	1	Poisson/uniform
Coffee maker	1 per day	8	1	Poisson/uniform
Toaster oven	1 per day	8	1	Poisson/uniform
Plug in electric vehicles in smart grids	1 per 1.15 hours	97.6	2	Poisson/uniform
Smart meter	1 per 2.5 hours	2017	3	Poisson/uniform

Fig. 2: B). Smart Home UE Traffic Parameters [35]

Table 2: Simulation Parameters

Parameter	Value
Number of Antennas	1
Network Type	Single Cell
Channel Bandwidth (MHz)	5
Sub-carrier Spacing (kHz)	15
Number of RBs	25
Subcarrier per RB	12
Video Bitrate (kbps)	242
Application Packet Size	200 Bytes
Scenario	Urban Macro
Frame Configuration (ms)	10
No. of Sub-frame per Frame	10
No. of UEs	[100, ... , 500]
UE Placement	Random

6. Results and discussion

The performance of the proposed uplink scheduling algorithm is assessed by comparing it with the proportional fair (PF), priority algorithm (PS) [36], and BestCQI scheduling algorithm. Our proposed method delivers performance advantages over PS while maintaining optimal performance compared to optimal methods. During simulations, we utilize two key performance metrics to gauge the effectiveness of the proposed uplink scheduling algorithm:

1) Average cell throughput: The cell throughput refers to the total amount of data successfully transmitted per unit time in Mbps by a cell. It is a crucial metric for evaluating the system's capacity and effectiveness in 5G networks. We study BestCQI, which prioritizes UEs with the best CQI and offers the highest throughput, while PF balances throughput with fairness by considering both CQI and UE requirements. Thus, offers high throughput. The PS solely relies on UE priority, regardless of CQI leads to the lowest throughput. These outcomes are illustrated in Fig. 3. The proposed algorithm achieves 88-91% of BestCQI, 91-92% of PF performance while delivering 13% better throughput than PS.
2) Average resource utilization: Average resource utilization reflects the ratio of RBs utilized to the available RBs during a TTI and reflects how effectively PRBs are used during a TTI. It is a crucial metric for measuring network efficiency. There can be trade-offs between different factors; maximizing resource utilization might come at the cost of fairness or QoS. As depicted in Fig. 4, the BestCQI algorithm leads to the highest resource utilization but potentially neglects fairness, whereas PF achieves high resource utilization and optimal fairness while the PS approach offers the lowest resource utilization, whereas the proposed algorithm utilizes both CQI and 5QI and aims for a balance between optimal utilization and fairness delivers 26% better resource utilization than PS, with only 6-8% gap from optimal methods.

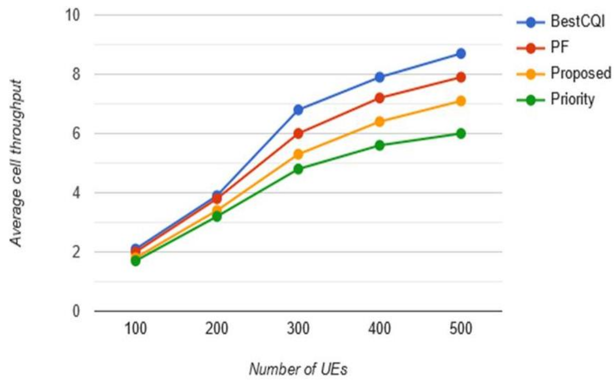

Fig. 3: Average Cell Throughput.

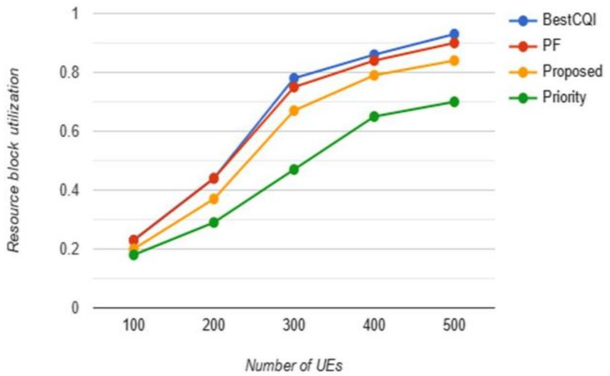

Fig. 4: Average Resource Utilization.

Our proposed method offers an optimal solution that: (1) Significantly outperforms PS (13-26% gains) (2) Provides service differentiation at optimal efficiency cost (6-9% trade-off), (3) Offers balanced performance suitable for M2M dense 5G deployments (4) Scalable advantage over PS increases with network density. The 6-9% efficiency loss compared to PF/BestCQI may be acceptable for accommodating the service-aware capabilities for M2M communications.

The proposed algorithm addresses key mMTC challenges by: (1) Service Differentiation: Dynamic priority assignment based on application types (2) Resource Efficiency: Optimal utilization of limited spectrum resources for massive connectivity scenarios (3) QoS Balancing: Simultaneous consideration of throughput maximization and service-specific requirements (4) Scalability: Demonstrated consistent performance scaling from 100 to 500 UEs with maintained efficiency ratios.

7. Conclusion

The work proposes a service-aware uplink scheduling algorithm (S-RS) for heterogeneous UEs in 5G networks, focusing on smart city applications. The proposed scheme dynamically allocates PRBs based on UE priority, traffic patterns, channel quality, and service type to maximize resource utilization and cell throughput while accommodating diverse M2M service requirements. Comprehensive simulation results across 100-500 UEs demonstrate that S-RS achieves an average improvement of 13.2% over PS and maintains an efficiency of 91-92% compared to optimal BestCQI/PF scheduling in throughput while achieving a 26.1% average improvement over PS and an efficiency of 92-94% compared to BestCQI/PF scheduling in PRB utilization. These results demonstrate that S-RS provides a balanced solution, significantly outperforming PS while maintaining near-optimal efficiency compared to other scheduling algorithms.

The proposed S-RS algorithm may enable smart city deployments by: (1) Supporting diverse M2M services, (2) Ensuring reliable connectivity for critical infrastructure applications, (3) Optimal spectrum usage in dense urban environments, and (4) Providing a scalable foundation for future IoT expansion.

8. Limitations

The limitations with the proposed work are: (1) Service-aware classification introduces 5-8% processing overhead compared to simpler scheduling methods, (2) Prioritizing M2M services may impact non-M2M UE performance under high load conditions impacting fairness, and (3) Performance depends on channel state information (CSI) and may degrade under imperfect CSI conditions. Future work would incorporate more granular service differentiation mechanisms, considering advanced QoS frameworks with multi-objective optimization to balance throughput, latency, energy efficiency, and fairness simultaneously with dynamic numerology where adaptive OFDM parameter selection will be based on service requirements.

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