Towards Achieving an Efficient ADR Scheme for LoRaWAN: A Review of the Constrained Optimisation Approach

Rachel Kufakunesu[1], Gerhard P. Hancke[1,2], Adnan M. Abu-Mahfouz [1,3]

[1]*Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria 0002, South Africa*
[2]*Nanjing University of Posts and Telecommunications, Nanjing 210023, China*
[3]*Council for Scientific and Industrial Research (CSIR), Pretoria, 0184, South Africa*
[1]`rachel.kufakunesu@tuks.co.za`

Abstract—**Long Range Wide Area Network (LoRaWAN) is a networking technology that is rapidly growing in the Internet of Things (IoT) implementations under Low Power Wide Area Networks (LPWAN). The main goal of LoRaWAN is to optimise the coverage range, capacity, cost and battery life of the network. A vital LoRaWAN characteristic is the Adaptive Data Rate (ADR) algorithm that minimises energy utilisation and maximises throughput by regulating the bit rate, based on the link budget for individual end devices in the LoRaWAN. ADR regulates the transmission parameters, specifically Bandwidth (BW), Spreading Factor (SF), Transmission Power (TP) and Coding Rate (CR). The current spurt in IoT deployments has resulted in diverse QoS requirements, metrics, and implementation strategies. We present a comprehensive review of the constrained optimisation methods used to enhance ADR schemes for LoRaWAN technology. We highlight the strengths and drawbacks and computational complexity of the approaches. We provide a comparison of the optimisation techniques and identify research challenges and potential future study.**

***Keywords*— Adaptive Data Rate, Computational Complexity, Constrained Optimisation, Internet of Things, LoRaWAN,**

I. INTRODUCTION

Numerous organisations in various industries are increasingly adopting the Internet of Things (IoT) to improve their functionality and improve decision making to improve the customer experience. Consequently, an accretion in devices connecting to the internet has ensued. These end devices (EDs) are required to have the capability of acquiring an Internet Protocol (IP) address and capable of data transfer over a network. Long Range Wide Area Network (LoRaWAN) is a Low Power Wide Area Network (LPWAN) that operates in the unlicensed industrial, scientific, and medical (ISM) frequency bands connected in a star network topology. A characteristic of LoRaWAN is low power consumption, low data rate (small data packets) and long-range communication up to five kilometres in urban locations and up to forty kilometres in rural locations [1].

The LoRaWAN network incorporates five core elements: the end devices also called end nodes, the gateway (GW), the network server (NS), the Join Server (JS) and application servers (AS) configured in a star topology architecture as shown in Fig I. The LoRa ED consists of a wireless transceiver and sensor nodes that send packets to several GWs within its locality utilising LoRa radio frequency (RF) modulation. GWs draw their power from the mains and can connect to the internet and comprise of radio components with transmitters and microprocessors for information processing. The cloud-based NS receives data packets from each GW which it consecutively transmits to the characteristic Application Server (AS). Where multiple GWs are available in a network, it is possible for one ED to send data to all the GWs. GWs are capable of concurrently listening to multiple frequencies in each SF.

The Adaptive Data Rate (ADR) scheme is an essential feature in LoRaWAN. Its objective is to minimise power utilisation and maximise throughput by regulating the bit rate depending on the link budget for each ED in the LoRaWAN. ADR regulates the transmission parameters, specifically transmission power (TP), spreading factor (SF), bandwidth (BW) and coding rate (CR) depending on the link budget. Optimising the ADR reduces airtime and increases network capacity and improves energy efficiency. The upsurge in IoT implementations has resulted in a wide variety of quality of service (QoS) specifications, benchmarks, and deployment methods. As such, ADR schemes have been implemented using different approaches. This paper looks at the constrained optimisation methods used to enhance the ADR schemes for LoRaWAN technologies. The key contributions of this paper are defined as follows:

- An overview of the ADR scheme and a comprehensive review of its parameters.
- An investigation of the constrained optimisation techniques that enhance the ADR schemes which are proposed in literature.
- A discussion of the strengths, drawbacks, and computational complexity of the optimisation techniques.
- Identification of research challenges and open issues for farther study.

The remainder of the paper is organised as follows: Section II provides an overview of the ADR scheme in LoRaWAN, describing how the algorithm works. Section III describes a typical system model, Section IV presents a review of the constrained-optimisation techniques. Section V features a discussion of strengths, drawbacks, and computational complexity of the optimisation method. Section VI concludes this paper.

II. TECHNOLOGICAL OVERVIEW

The ADR scheme was developed into LoRaWAN to enable the management of the ED transmission parameters to increase the packet delivery ratio (PDR). The uplink (UL) data transmitted from the ED to the GW is determined by the transmission parameter settings that are controlled by the ADR algorithm. The ADR algorithm manages the data rate and TP of EDs centred on the link budget approximation in the UL data packet and the maximal signal-to-noise ratio (SNR) essential for correctly decoding data packets at the current data rate.

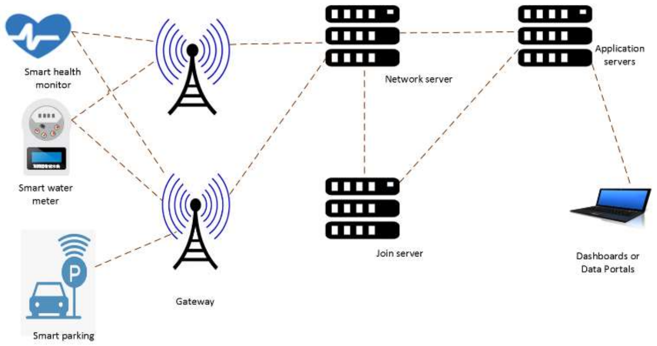

Figure I. LoRaWAN Architecture[2]

Where stationary EDs are concerned, ADR is managed by the NS subject to the historical information of the UL packets received from the EDs, termed "Network-managed ADR or Static ADR". This network-regulated ADR scheme would not function with mobile EDs due to channel degradation that arises when the mobile ED changes position. Where mobile EDs are considered, the ADR mechanism is effected "blindly" on the ED side, called "Blind ADR". In LoRaWAN networks, GWs use adaptive modulation techniques with multi-channel multi-modem transceivers in order to receive several data packets from the channels. Every distinct signal utilises a different SF, with the spread spectrum providing the orthogonal separation. This method offers advantages in managing the data rate [3].

In LoRaWAN, the ADR algorithm adaptively adjusts the transmission parameters attempting to extend the battery lifespan and maximise throughput. That is achieved by adjusting the data rate and TP for each ED in the LoRa network. Varying the SF adjusts the data rate, thus optimising the network performance. Past performance of each ED is the basis of data rate selection dependent on the transmission parameters. By optimising the data rates, time on air (ToA) and energy consumption, battery life is prolonged, and the overall capacity of the network is enhanced, thus increasing the lifespan of the EDs. The ADR algorithm is implemented in the LoRaWAN network to independently regulate the TP and data rate for all the EDs. LoRaWAN network performance is directly affected by power consumption in the EDs since the end devices have limited battery capacity. Because of the LoRaWAN Regional Parameters and Specifications [4, 5] EDs must cater for specific data rates farther compounding the power constraint predicament since the SNR values must cross certain thresholds and power levels. Because the EDs must respond to the channel conditions in the network, it implies they must be able to control the data rates and TP accordingly.

There is a procedure that EDs must follow to achieve optimal data rates [5]. Firstly, the ED requests the NS to manage data rate adaptation by selecting the ADR bit in an UL message header. Thereafter, the ED receives LinkADRReq MAC commands from the NS which specify the adjustment of its SF and TP and hence its data rate. The ED then confirms to the NS each part of the requested settings in a LinkADRAns MAC command. If the ED does not receive any DL packet within the ADR_ACK_LIMIT uplinks and the existing data rate is higher than the minimal data rate, all successive ULs are transmitted with an ADR acknowledgment request bit (ADRACKReq) set. If no DL message is received from the NS the ED does not receive any DL within ADR_ACK_DELAY successive ULs, the ED attempts to recover connectivity by shifting to the subsequent lower data rate delivering an expanded range. Consequently, whenever the ADR_ACK_DELAY is attained, the ED lowers the data rate by one step. The ED utilises its internal counter (ADR_ACK_CNT) which is reset whenever it receives a DL message from the NS. The transmission parameters that need to be allocated in order to optimally adjust the data rate are explained below.

A. *Bandwidth*

Bandwidth is a significant variable in LoRa modulation. LoRa symbols comprise of 2^{SF} chirps, spreading the entire frequency domain. BW is defined as a series of frequencies inside some specified transmission band [6]. Large figures of BW provide larger transmission data rates that imply smaller ToAs, resulting in diminished sensitivity due to the auxiliary noise incorporated. A smaller BW delivers greater sensitivity though it realises decreased data rates. While the choice of BW could range between 7.8 kHz and 500 kHz, the standard LoRaWAN operates at either 500 kHz, 250 kHz, or 125 kHz (BW500, BW250 and BW125) depending on the regional parameters [4].

B. *Spreading Factor*

SF is the number of raw bits that is encoded to a symbol to improve the signal-to-noise ratio (SNR), which improves sensitivity and range. However, SF results in increased ToA. The formulation 2^{SF} symbolizes the number of chips held by each symbol [2]. The spreading factor symbolises the correlation between the chip rate and the baseband data rate. The SF values for LoRaWAN range from 7 to 12, implying that, increasing the SF value increases the strength of the wireless signal which in turn increases the sensitivity of the GW, decreasing the data rate consequently. Contrastingly, reducing the SF results in an increase in the data rate, causing the data packets being transmitted to require higher TP for proper decoding at the GW. When the data signal is faint, EDs use a larger SF resulting in a longer ToA as shown in Table 1, using 125khz bandwidth and 20 bytes payload and a code rate of 4/5.

The value of SF is also affected by the distance from the GW. The farther away the ED is from the GW the weaker the data signal and hence the greater the SF value. In general, increasing the bandwidth decreases the receiver sensitivity, while increasing the spreading factor improves the receiver sensitivity. SF is the significant parameter that improves QoS[7]. Theoretically spreading factors are orthogonal but in real deployments there are interferences that are experienced which decrease performance levels. Co-SF interference is interference emanating from EDs utilising the same SF on the same channel, while inter-SF interference results from EDs on the same channel but using different SFs [8].

TABLE I
EFFECT OF SPREADING FACTOR ON BIT RATE, TIME ON AIR AND SENSITIVITY

Spreading Factor	Bit Rate(kb/s)	Time on Air(ms)	Receiver Sensitivity(dBm)
7	5.47	61.7	-123.0
8	3.13	113.2	-126.0
9	1.76	205.8	-129.0
10	0.98	370.7	-132.0
11	0.54	695.5	-132.5
12	0.29	1318.9	-137.0

C. Code Rate

LoRa uses Forward Error Correction (FEC) error coding to increase the strength of the wireless link. This form of error correction introduces extra bits in the LoRa payload which is dependent on the CR variable in the PHY layer. The LoRa modem utilises CR to render enhanced insulation from spurts of interference and decoding errors. LoRa allows CR specifications to be either 4/5, 4/6, 4/7 or 4/8. Fixing a high CR value denotes larger number of error correction bits, providing improved protection for the message sent. Nevertheless, the drawback is an increase in ToA which results in decreased battery lifespan. GWs that maintain SF and BW constant while varying CR, can still communicate with the EDs by the use of explicit headers, given that the payload's CR is resident in the packet header. The default CR setting is 4/5 [9]. Equation (1) below states the link between data transmission rate, CR, BW, and SF [10].

$$R_b = SF * \frac{BW}{2^{SF}} * CR, \tag{1}$$

where:
SF = spreading factor
BW = modulation bandwidth
CR = code rate.

By tuning the transmission parameters mentioned earlier, the end-to-end attributes, namely, data rate, communication range, error correction capacity become variable [9]. Theoretically, it is possible to configure SF, BW and CR, but practically according to the LoRaWAN regional parameters specifications, the SF and BW combination forms the data rate [9]. The regional parameters paper stipulates the different regulatory requirements of LoRaWAN dependent on the network locale.

III. SYSTEM MODEL

A typical LoRaWAN system consists of a NS, GWs and EDs. EDs connect to the GWs within their vicinity and are configured with SF-TP combinations available from the ADR algorithm. The NS manages the spreading factor and transmission power of the EDs through the ADR commands so that packets can be correctly decoded from the GW. As such, the ADR algorithms are run on the NS. The EDs are stationary and can be homogenous or heterogenous (depending on the application) and generate data packets at a given rate. Interference is considered in the form of imperfect orthogonality and the capture effect. The EDs can be randomly or uniformly distributed around the GW which is located in the centre with a certain radius of coverage. To ensure successful transmission, the signal-to-noise ratio (SNR) must be above the reception threshold, the signal-to-interference ratio (SIR) must exceed the co-SF and inter-SF capture threshold in the presence of co-SF and inter-SF interference, respectively. In the event of packet collision of different SFs, a single signal will be successfully received if it's SIR is above its inter-SF capture threshold. If there are several signals with the same SFs transmitting on the same frequency simultaneously, the LoRa GW will successfully receive one of them provided its SIR exceeds 6dB for any SF. Channel propagation can be modelled using the different propagation models, for example Okumura-Hata model, Free Space Path Loss or Log-Distance Path Loss. An optimised ADR algorithm ensures proper ST and TP allocations resulting in an efficient network.

IV. REVIEW OF CONSTRAINED OPTIMISATION TECHNIQUES

Several optimisation methods have been developed for solving different types of optimisation problems. Because LoRaWAN has restrictions in terms of resource allocations, due to regional parameter regulations [4], constrained optimisation is a befitting method to improve ADR decision algorithms. The goals for LoRaWAN network determine what constraints the scheme will consider. Some networks want to optimise throughput, scalability, power consumption, communication robustness, coverage, and energy efficiency among other metrics. We review a body of work that utilises constrained optimisation to improve resource allocation that results in efficient ADR schemes.

The authors in [11] established a joint SF and TP assignment problem to maximise the minimum UL throughput of the EDs, based on co-SF and inter-SF interferences and TP constraints. Their SF allocation scheme hinges on the matching theory. After SFs have been assigned to EDs, the power distribution parameters are optimised to maximise the minimum throughput attained for each SF. The authors managed the intractability of the joint SF and power distribution problem by separating it into two distinct sub-problems: SF distribution while TP is constant, and TP allocation with constant SFs. The authors make the non-linear inequalities a tractable feasibility problem by implementing linear and quadratic approximation. Despite serious co-SF and inter-SF interferences, the results indicated that, the presented algorithms outperformed state-of-the-art algorithms, regarding minimal ED data rates, fairness, and mean ED throughput. Nonetheless, the model does not examine the optimisation of carrier frequencies (CFs) and the reduction of energy consumption according to the SF choice. Future work could consider load balancing and extending the proposed approach to multi-cell LoRaWANs which would assign EDs to the best GW in the case of multiple GWs.

The ADR mechanism that can efficiently optimize the packet error rate (PER) fairness within a LoRaWAN cell was proposed in [12]. The authors optimised the SF and TP per ED whilst avoiding near-far problems by assigning EDs lying on the edge of the cell to different channels. EDs pathloss values were used to arrange the EDs and divide them into homogenous clusters corresponding to the number of available channels. Each cluster was assigned a particular channel while within the cluster the proportion of EDs utilising the SFs is relative to $s/2^s$. This corresponds to the solution of the optimisation problem which seeks to minimise the maximum collision probability among all the spreading factors. The ADR mechanism computes the optimum SF assignment to apply for the purpose of minimising the collision probability. The algorithm allocates SFs and TP values optimally to EDs within a LoRaWAN cell such that there is no interference between the EDs. This scheme improves the PER of EDs farther from the GW. The results indicate that the PER can be decreased up to fifty percent for EDs farther away from the GW in a moderate contention setup. The global network PER is lowered by 42%. Energy consumption is reduced, and a wide network coverage provided, reducing the number of GWs required. The EDs are uniformly distributed around the GW and every ED can use all SFs and TPs. This means every ED in the network can reach the GW with each SF and each TP configuration. In a real-life network, this setup would be problematic because specific EDs can only employ a portion of the configuration settings which are prescribed by the radius from the GW. Future work could examine randomly distributed EDs and acknowledged traffic as they study unacknowledged traffic in this work.

In [13] the authors developed a method that reduces data collision and energy usage. This approach increased the data extraction rate (DER) and improved QoS of the LoRaWAN. They generated optimum SF and CF settings using the Mixed Integer Linear Programming (MILP) optimisation method. They demonstrated the effectiveness of the method for different network sizes using LoRaSim simulation. Their system model presumed that BW and CR are held constant whilst varying CF and SF to compute ToA to maximise packet success probability. They used the following assessment metrics to evaluate the network performance, such as, DER, number of collisions and system energy utilisation. The results proved that MILP optimised the allocation of SF and CF pairs giving more than six percentage increment in DER in contrast to the benchmark LoRaWAN ADR while the number of collisions were found to be thirteen times less. The overall energy usage of the network decreased nearly threefold compared to the equal-distribution and random dynamic allocation strategies. The strength of their approach lies in its backward compatibility with the standard ADR scheme, indicating that the solution can be implemented in off-the-shelf LoRa designs. Farther study could involve expanding the optimisation technique to much wider coverage and a greater number of GWs.

An investigation of energy efficient resource allocation was performed in [14]. The authors jointly optimised SF and TP allocation to maximise system energy efficiency (SEE) and minimal energy efficiency (MEE)of individual EDs. They constructed two optimisation problems, farther decomposing them into three sub-problems constituting user scheduling, SF allocation and TP assignment. They used an iterative power assignment process derived from the general fractional programming and proposed a sequential convex programming. The results demonstrate that the propositioned matching algorithm and power assignment scheme outperforms the current schemes regarding SEE and MEE.

MARCO is a Mixed Integer Linear Programming optimisation model for resource allocation for LoRaWAN introduced in [15]. They also introduce CORRECT, a heuristic for adaptive resource allocation which dynamically adjust the LoRaWAN parameters to reduce interference and packet collisions, thus maximising channel utilisation and delivered packets. They use a heuristic and an optimisation framework for resource allocation which models transmission parameters to maximise channel utilisation, minimising collisions meanwhile considering signal strength utilising the ED location. The simulation results obtained demonstrated that the CORRECT heuristic produces results approximating the optimum achieved by the MARCO model, optimising the assignment of transmission parameters reducing collisions and improving the overall network performance. Particularly, the CORRECT heuristic improves DER almost twelve percent compared to the ADR heuristic, and for other heuristics, this difference is even more considerable. CORRECT reduces the number of collisions up to three times compared to the standard ADR scheme adopted for LoRaWAN. Although the heuristic CORRECT shows the best DER results, the energy consumption is substantial in comparison.

The gradient projection optimisation method was employed in [16] to enhance the ADR scheme to optimise throughput. The authors propose a contention-aware ADR scheme which achieves considerably higher throughput than the standard ADR because of load balancing. The data rate is regulated by way of incrementing the number of EDs in the network using small SFs. Even though this scheme improves gross throughput, the drawback is that transmission success ratio declines which renders it unideal for applications that have reliability as a QoS requirement.

The authors in [17] proposed a LoRa network slicing and configuration mechanism to optimise resource allocation. They employed a slice-based SF and TP configuration optimization. The authors developed a novel slicing optimisation technique termed TOPG which is formulated on the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Geometric Mean Method (GMM). The proposed method efficiently configures SF and TP parameters improving the performance of each slice with respect to QoS, reliability and power utilisation. From the results the authors illustrated that TOPG outperformed static and adaptive configuration strategies, improved the performance of LoRa slices in terms of reliability as well as the proportion of EDs that achieved their throughput and delay requirements. The drawback is that this approach performing slicing over LoRaWAN introduces overheads, resulting in reduction in network resources. The authors did not do the computational cost analysis of their proposed algorithm.

In [18] they investigated power allocation, and propositioned an algorithm centred on Markov decision process (MDP). They formulate a user grouping problem using a many to one matching problem. They grouped EDs into available channels and used a Markov Decision Process-based algorithm to allocate power to achieve an optimal throughput for each ED in the same channel. They develop transmission parameter assignment in wireless powered Internet of Things systems into a joint optimisation problem that optimises channel assignment and dynamic power distribution, where MDP is implemented to model the uncertainty of the harvested energy and channel conditions. To make the problem tractable, it is divided into two segments: a) allocation of EDs to available channels and b) optimising TP allocation of EDs allocated to a corresponding channel in the same time frame. The results showed that the propositioned method achieved close to optimum performance and is superior to methods that use random channel allocation but still maintains much lower computational complexity. In this paper, the authors solve the MDP-based power allocation using dynamic programming which requires known model information. Future research could look into model-free methods to solve MDP problems.

Narieda *et al.* in [19] present a performance improvement method utilising SF allocations for LoRaWAN. The authors construct the optimisation problem for the SF assignment to maximise the packet reception probability (PRP) encompassed in the average energy utilisation constraint per ED and the sensitivity constraint. By solving the optimisation problem, the network performance is improved under these constraints considering each ED individually. The authors developed a method that solves the optimisation problem using distributed genetic algorithm, a method which is metaheuristic. This method enhances the system performance by allocating the SFs to ED under the given constraints. It assumes static EDs whose quantity is constant in the network. The authors consider imperfect orthogonality of the SF in the derivation of the PRP in the LoRaWAN. The results obtained show that the PRP performance of the developed approach is more proficient and utilises a reduced mean energy for all the EDs in comparison with existent algorithms. Farther study could focus on energy usage per ED instead of averaging all the EDs.

V. DISCUSSION

Different performance metrics are used to optimise transmission parameters to achieve specific objectives such as throughput [11, 16-18], scalability [12] and energy consumption [13, 15, 19] . Table II highlights the different objectives and metrics used in the optimisation approaches under review. Energy and throughput efficiency are common objectives for optimisation while the RSS and coverage stand out as metrics. Multi-objective optimisation requires the formulated problem to divided into subproblems in order to deal with intractability[11, 14, 18]. For the references whose objective is throughput, [17] outperforms the rest of the algorithms because of the dynamic inter-slicing configuration whose performance is superior, followed by the contention aware ADR algorithm in [16] due to the load balancing effect using the gradient projection method. This is then followed by [18] whose proposed channel allocation algorithm outperforms the random channel assignment approach by ninety percent while offering better time efficiency. [11] is ranked the least performing as it achieves throughput fairness but because the approach does not optimise CFs, it compromises energy consumption. For the energy efficiency objective, the approach in [15] makes gains in the global network performance, but loses for having a higher energy consumption compared to the other approaches being considered. Ref [13] results are very closely optimum, although the runtime becomes more protracted as the number of EDs in the network increases. The algorithm proposed by [19] is superior as it presents the best PRP performance with the least average energy consumption.

Looking at the computational complexity of the approaches reviewed in this paper, Ref [11]shows the running time of the proposed SF algorithm is upper bounded by $\boldsymbol{O}(\boldsymbol{NM}+\boldsymbol{Q}^2+\boldsymbol{M})^2$. When considering a real life LoRaWAN network, the complexity of the matching algorithm is not a limitation since the algorithm functions on the network server whose computational capability is extensive. In [12] they capped the amount of EDs at one thousand as a result of the computer memory restriction. All the parameters required to be transmitted to the EDs result in a $\boldsymbol{O}(\boldsymbol{n}^2)$ memory utilisation. In [13] the Approximation Algorithm sustains a linear complexity time $\boldsymbol{O}(\boldsymbol{n}) = \mathbf{111}\boldsymbol{n} + \mathbf{57}$ in the worst-case scenario. The design of the algorithm is such that it functions in the LoRaWAN Application Layer with EDs that have a time complexity equal to the ADR algorithm, such that the suggested optimisation problem would not trigger any significant computation overhead, neither in the EDs nor in the NS. Ordinarily, the implementation of the algorithm utilises below 20 kB of memory, 4 kB in most cases while 20 kB would be the worst-case scenario. This is inconsequential considering that most commercial off-the-shelf EDs include at least 128 kB of flash memory [20].

TABLE II
COMPARISON OF THE OPTIMISATION TECHNIQUES

Ref	**Objective**	**Metrics**	**Constraints**
[11]	Throughput	Channel fading, RSS	Co-SF, inter-SF, TP
[16]	Throughput	RSS, ToA	Number of EDs, TP
[17]	Throughput	RSS, PER, slice priority	Channel reservation, TP, data rate capacity
[18]	Throughput	Data rate, ToA	TP, time slots per frame, users that can access the channel
[12]	Scalability	Coverage range	SINR
[13]	Energy efficiency	DER	SF, CF
[15]	Energy efficiency	PDR, DER	Sensitivity, Number of EDs
[19]	Energy efficiency	Channel contention, PDR	Sensitivity, current consumption

The computational complexity in [14] is such that for the energy efficient power allocation for SEE the whole complexity to solve SEE is $\boldsymbol{O}(\boldsymbol{L}_{max}^{(1)} + (\boldsymbol{N} + \mathbf{1})^{3.5}\boldsymbol{\delta}^{(1)})$ where $L_{max}^{(1)}$ is the maximum iteration number and δ is the number of bits required to symbolise the entries in the optimisation problem. Concerning MEE, the computational complexity is $\boldsymbol{O}\left(\boldsymbol{log}_2\left(\boldsymbol{\epsilon}^{-1}(\boldsymbol{\eta}_{m,l}^{max} - \boldsymbol{\eta}_{m,l}^{min})\right)\boldsymbol{L}_{max}^{(2)}(\boldsymbol{N}^{3.5}\boldsymbol{\delta}^{(2)})\right)$, where $\eta_{m,l}$ is energy efficiency per ED. In [17], because the adaptive slicing and spreading factor-transmission power configuration algorithm is simple, it has a constant complexity of $\boldsymbol{O}(\mathbf{1})$. Notwithstanding, the global complexity of the proposed dynamic adaptive slicing and SF-TP algorithm and TOPG algorithm is $\boldsymbol{O}(\boldsymbol{n}^2)$. Complexity is decreased in TOPG as a consequence of the server narrowing the search space to SF values that acknowledge the guaranteed bit rate threshold. The computation time is shortened without the QoS performance being significantly affected.

VI. CONCLUSION

ADR schemes are continually being developed because numerous end devices are being added to the IoT network daily, resulting in new QoS requirements emerging. It is crucial in LoRaWAN to allocate transmission resources optimally as demands for scalability, throughput and energy efficiency and QoS requirements continue to grow. Different applications have different objectives and constraints and thus require unique resource allocation optimisation mechanisms to accomplish the desired optimisation goals. This paper reviewed several existing ADR schemes that employ constrained optimisation techniques and considered their strengths and drawbacks and how they impact network performance. The research lays the foundation for more efficient and efficacious ADR algorithms. The study revealed that although transmission parameters are standard, many different approaches are constantly being proposed to improve network performance and provide efficiency. Gaps in the literature were identified and future work on enhancing ADR schemes was proposed.

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REFERENCES

[1] M. Centenaro, L. Vangelista, A. Zanella, and M. Zorzi, "Long-range communications in unlicensed bands: The rising stars in the IoT and smart city scenarios," *IEEE Wireless Communications,* vol. 23, no. 5, pp. 60-67, 2016.

[2] L. Alliance, "LoRa and LoRaWAN-A Technical Overview," *White paper,* 2019.

[3] C. El Fehri, M. Kassab, S. Abdellatif, P. Berthou, and A. Belghith, "LoRa technology MAC layer operations and Research issues," *Procedia computer science,* vol. 130, pp. 1096-1101, 2018.

[4] L. Alliance, "LoRaWAN 1.1 regional parameters," *Technical Specification,* 2017.

[5] L. Alliance. "LoRaWAN 1.0. 3 specification." https://lora-alliance.org/resource-hub/lorawanr-specification-v103 (accessed May, 2021).

[6] A. Augustin, J. Yi, T. Clausen, and W. M. Townsley, "A study of LoRa: Long range & low power networks for the internet of things," *Sensors,* vol. 16, no. 9, p. 1466, 2016.

[7] M. A. Ertürk, M. A. Aydın, M. T. Büyükakkaşlar, and H. Evirgen, "A Survey on LoRaWAN Architecture, Protocol and Technologies," *Future Internet,* vol. 11, no. 10, p. 216, 2019.

[8] A. Waret, M. Kaneko, A. Guitton, and N. El Rachkidy, "LoRa throughput analysis with imperfect spreading factor orthogonality," *IEEE wireless communications letters,* vol. 8, no. 2, pp. 408-411, 2018.

[9] R. Sanchez-Iborra, J. Sanchez-Gomez, J. Ballesta-Viñas, M.-D. Cano, and A. F. Skarmeta, "Performance evaluation of LoRa considering scenario conditions," *Sensors,* vol. 18, no. 3, p. 772, 2018.

[10] Semtech, "Modulation basics application note AN1200. 22. Semtech Corporation-Wireless Sensing and Timing Products Division," Semtech, , 2015.

[11] L. Amichi, M. Kaneko, E. H. Fukuda, N. El Rachkidy, and A. Guitton, "Joint allocation strategies of power and spreading factors with imperfect orthogonality in LoRa networks," *IEEE Transactions on Communications,* 2020.

[12] B. Reynders, W. Meert, and S. Pollin, "Power and spreading factor control in low power wide area networks," in *2017 IEEE International Conference on Communications (ICC)*, 2017: IEEE, pp. 1-6.

[13] E. Sallum, N. Pereira, M. Alves, and M. Santos, "Improving Quality-of-Service in LoRa Low-Power Wide-Area Networks through Optimized Radio Resource Management," *Journal of Sensor and Actuator Networks,* vol. 9, no. 1, p. 10, 2020.

[14] B. Su, Z. Qin, and Q. Ni, "Energy Efficient Uplink Transmissions in LoRa Networks," *IEEE Transactions on Communications,* vol. 68, no. 8, pp. 4960-4972, 2020.

[15] J. Moraes *et al.*, "An Efficient Heuristic LoRaWAN Adaptive Resource Allocation for IoT Applications," in *2020 IEEE Symposium on Computers and Communications (ISCC)*, 2020: IEEE, pp. 1-6.

[16] S. Kim and Y. Yoo, "Contention-aware adaptive data rate for throughput optimization in LoRaWAN," *Sensors,* vol. 18, no. 6, p. 1716, 2018.

[17] S. Dawaliby, A. Bradai, and Y. Pousset, "Joint slice-based spreading factor and transmission power optimization in LoRa smart city networks," *Internet of Things,* p. 100121, 2019.

[18] X. Liu, Z. Qin, Y. Gao, and J. A. McCann, "Resource allocation in wireless powered IoT networks," *IEEE Internet of Things Journal,* vol. 6, no. 3, pp. 4935-4945, 2019.

[19] S. Narieda, T. Fujii, and K. Umebayashi, "Energy Constrained Optimization for Spreading Factor Allocation in LoRaWAN," *Sensors,* vol. 20, no. 16, p. 4417, 2020.

[20] Semtech. "MCU Memory Security and System Partitioning Considerations for Sensors for LoRaWAN® Networks." Semtech. https://lora-developers.semtech.com/library/tech-papers-and-guides/mcu-memory-management/download-mcu/ (accessed 5 June, 2021).

Rachel Kufakunesu received her BTech and MTech degrees in Electrical Engineering from the University of South Africa. She is currently pursuing a PhD in Electronic Engineering at the University of Pretoria. Her research interests are wireless sensor networks and low power wide area networks.