Evaluating the Impact of the Adaptive Data Rate Algorithm in LoRaWAN

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) has emerged as a prominent communication system for Low Power Wide Area Networks (LPWAN) in the context of Internet of Things (IoT) implementations. This technology is designed to prioritise key factors such as battery lifespan, network capacity, coverage range, and deployment cost. LoRaWAN achieves these objectives through the use of an Adaptive Data Rate (ADR) algorithm that dynamically optimises data rate, time-on-air, and energy utilisation. In this research, we conduct simulation studies to investigate the influence of different methods of averaging Signal-to-Noise Ratio (SNR) history on the behaviour of the ADR scheme in LoRaWAN. Our primary objective is to present a comprehensive performance analysis of ADR and gain insights into how it enhances the overall performance of LoRaWAN networks. To evaluate its effectiveness, we employ four distinct metrics to measure the impact of the ADR scheme. By presenting comprehensive findings, the results of our study provide valuable insights into the functioning of ADR schemes in LoRaWAN networks enhancing the understanding of how ADR can better cater to the diverse requirements of real-world IoT applications.**

***Keywords*— Adaptive Data Rate, Internet of Things, LoRa, LoRaWAN, LPWAN**

I. INTRODUCTION

The adoption of the Internet of Things (IoT) has gained significant traction across diverse industries, aiming to enhance operational efficiency, facilitate informed decision-making, and elevate the overall customer experience. As a consequence, there has been a notable proliferation of connected devices accessing the Internet. These devices, commonly known as end devices (EDs), necessitate the ability to obtain an Internet Protocol (IP) address and enable the transmission of data over a network. Long Range Wide Area Network (LoRaWAN), operating within unlicensed industrial, scientific, and medical (ISM) frequency bands, is a Low Power Wide Area Network (LPWAN) architecture that adopts a star network topology. LoRaWAN is characterised by its low energy expenditure, reduced data rate for handling small data frames, and remarkable communication range of up to five kilometres in urban environments and up to forty kilometres in rural areas [1].

The LoRaWAN network comprises five fundamental components, namely the end devices, the gateway (GW), the network server (NS), the Join Server (JS), and the application servers (AS), all configured in a star topology architecture [2], as depicted in Fig.1. The LoRa end devices are equipped with wireless transceivers and sensor nodes, enabling them to transmit packets to multiple gateways within their range, utilising LoRa radio frequency (RF) modulation. The GWs, which are mains powered, possess the capability of internet connectivity and consist of radio components encompassing transmitters and microprocessors for efficient data processing. The network server (NS) is cloud based and receives data packets from every gateway, subsequently relaying them to the corresponding application server (AS) responsible for their specific functions. In scenarios where multiple gateways exist within a network, it is feasible for a single end device to transmit data to all the gateways simultaneously. The gateways have the capability of simultaneously monitoring multiple frequencies in each spreading factor (SF).

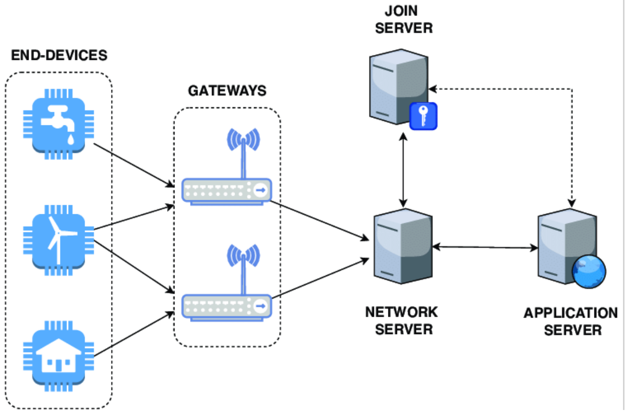

Figure 1: LoRaWAN Architecture [3]

An intrinsic and essential functionality of LoRaWAN is its Adaptive Data Rate (ADR) algorithm. The primary purpose of this mechanism is to optimise energy utilisation while maximising the capacity of data transmission by dynamically controlling the data rate cording to the link budget for each specific ED within the LoRaWAN network. ADR effectively controls the transmission parameters, namely Bandwidth (BW), Spreading Factor (SF), Transmission Power (TP), and Coding Rate (CR). By fine-tuning ADR, the network's capacity can be significantly enhanced, as data packets transmitted using different SFs are orthogonal and can be concurrently received, resulting in a reduction in airtime utilisation.

ADR acts as a technique for controlling the uplink (UL) transmission settings of LoRa devices in accordance with the prevailing link budget. To use ADR, it must first be enabled at the ED side. In literature, various approaches have been utilised to implement and analyse ADR algorithms in LoRa implementations, including mathematical models, simulations, and testbed experiments. However, a notable challenge associated with the ADR algorithm is the absence of explicit instructions in the LoRa specification regarding how the NS should communicate rate adaptation instructions to EDs.

Consequently, there exists a gap in ADR implementation, as companies often maintain their implementations proprietary, resulting in the proposal of numerous distinct ADR schemes. The proliferation of IoT deployments introduces diverse Quality of Service (QoS) prescriptions, metrics, and deployment strategies, further complicating the reliability and suitability of ADR schemes. Various methods, including mathematical models, simulations, and testbeds, are used in the literature-presented LoRa implementations to implement and evaluate ADR strategies. [4-6]. In our work, the different methods of averaging the signal-to-noise-ratio (SNR) of the twenty "most recently received packets" received at the gateway are evaluated to determine the superior method. We investigate the effect of the different SNR history averaging methods on the performance of the standard ADR algorithm in relation to energy utilisation, interference rate and packet reception rate.

The following are the primary contributions of this article are defined as follows:

- An overview of the ADR scheme and a brief review of its parameters.
- An evaluation of the performance of LoRaWAN and ADR.
- A detailed analysis on the performance of ADR in relation to various performance metrics.

The remainder of the article is organised as follows: Section II provides technological overview on LoRaWAN ADR, Section III introduces the simulation of the LoRaWAN network under ns-3, Section IV presents the performance analysis and simulation result. Section V concludes this paper.

II. TECHNOLOGICAL OVERVIEW

The LoRaWAN Adaptive Data Rate involves leveraging real-time measurements, network control, and adaptive algorithms to optimise the transmission parameters for each end device in the network, resulting in improved network efficiency, range, and reliability. The link budget plays a crucial role in determining the quality of the communication channel. It considers factors like transmit power, path loss, fading, and noise. ADR utilises measurements of the Signal-to-Noise Ratio (SNR), which indicates the quality of the received signal relative to background noise. Higher SNR values indicate better signal quality. By monitoring SNR, ADR assesses the channel conditions and can make informed decisions about transmission parameters. The ADR scheme is made up of two algorithms, one operating on the ED side and the other on the NS side.

ADR analyses real-time SNR and channel quality indicator measurements to determine the optimal transmission parameters for each ED. These algorithms consider factors such as desired range, reliability, and energy consumption. By dynamically adjusting parameters like spreading factor, data rate, and transmission power, ADR optimises the communication link for every ED, resulting in improved network performance. ADR is controlled by the LoRaWAN network server, which collects and analyses data from the EDs via the GW. The network server determines the appropriate transmission parameters for each end-device based on the network-wide requirements and individual device characteristics. LoRaWAN EDs join the network the Over-the-Air Activation (OTAA) process during which the NS configures the initial transmission parameters for each device. The ADR can then be enabled to dynamically adjust these parameters as needed, based on real-time measurements and network requirements.

The achievement of optimal data rates in EDs requires adherence to a specific procedural framework [7]. Initially, the ED initiates a request to the NS for data rate adaptation by setting the ADR bit in the header of an uplink (UL) message. Subsequently, the NS transmits LinkADRReq (Link Adaptive Data Rate Request) MAC commands to the ED, which outline the necessary adjustments to its spreading factor and transmission power, thereby influencing its data rate. The ED acknowledges each component of the requested settings to the NS through a LinkADRAns (Link Adaptive Data Rate Answer) MAC command. In the event that the ED fails to receive any downlink (DL) packets within the specified ADR_ACK_LIMIT during consecutive uplinks, while maintaining a data rate higher than the minimum threshold, all subsequent ULs are transmitted with an ADR acknowledgment request bit (ADRACKReq) enabled. If no downlink message is transmitted from the NS within a consecutive sequence of ULs defined by ADR_ACK_DELAY, the ED initiates a recovery process by transitioning to the subsequent lower data rate, that extends the communication range. Consequently, upon reaching the ADR_ACK_DELAY threshold, the ED reduces the data rate by one step. To facilitate this functionality, the ED relies on an internal counter known as ADR_ACK_CNT, which resets upon receiving a downlink message from the network server.

On the network server side, the determination of the Signal-to-Noise Ratio (SNR) value involves channel estimations based on the signal-to-noise ratio of the twenty most recently received data packets (ULs), starting from the instant the ADR bit is set on the ED side. Various ADR schemes employ different methods to obtain the SNR value from these ULs, including selecting the maximum value among the twenty ULs, choosing the minimum value from the twenty ULs, or calculating an average of the UL messages [8-10]. Slabicki et al in [11] developed a novel open-source framework called FloRa, built in OMNeT++ specifically designed for LoRa simulations. It was designed to simulate the physical and medium access control layers. FloRa's ADR algorithm substituted the maximum SNR determined over the last 20 frames with the average SNR. The modification resulted in enhanced delivery ratio and reduced energy utilisation when compared to standard ADR, particularly in channels with moderate to high variability. The ADR example developed in the ns-3 LoRaWAN module implements a minimum SNR for the ADR algorithm [12]. The algorithm showed better performance metrics when compared to the standard ADR [10].

In our research, we focus on investigating the impact of these three methods for obtaining the measured SNR value within the ADR scheme. Once the SNR value is determined, the "margin" is calculated, which represents the measured SNR minus the required SNR to demodulate a packet given the data rate, as expressed in (1). The margin determines the feasible adjustments to optimise the ADR scheme.

$$SNR_{margin} = SNR_{value} - SNR_{thresh} - D_{margin}, \tag{1}$$

where SNR_{value} is the (maximum, minimum or average) measured SNR of the twenty packets, SNR_{thresh} is the minimum SNR threshold, and D_{margin} is the device margin and is typically 10dB in most networks. Once the margin is computed, N_{step} which characterises the number of times the algorithm is executed is calculated using (2).

$$N_{step} = \text{int}\,(SNR_{margin} / 3), \quad (2)$$

Where int is the integer part of the result obtained.

III. LoRaWAN SIMULATION UNDER NS-3

To evaluate our experiments, we utilised the ns-3 LoRaWAN module accessible at [12]. Our network uses 200 EDs which periodically generate packets and transmit through up to 7 GWs to a network server. The aim of this investigation is to analyse the performance of LoRaWAN using standard ADR by evaluating the effect of modifying the calculation of SNR_{value}. The simulation parameters exploited in this research are presented in Table I. We utilised the energy model implementation in ns-3 for energy consumption estimation of a battery-powered ED. The following assumption on energy consumption is reflected in the framework. All device operations are represented as states, each with a value representing the amount of current drawn by the device at that state. We assume that the radio can be in one of three states—transmit, receive, or sleep [13].

TABLE I
PARAMETERS OF THE SIMULATION

Parameter	**Value**
Frequency	868MHz
Bandwidth	125kHz
Number of EDs	200
Network Radius	5000m
Number of GWs	1to 7
Number of NS	1
Channel Loss Model	Log Distance Propagation Loss Model
Carrier Frequency	868MHz
Initial Energy of EDs	10000J
Channel Bandwidth	125kHz
Simulation Time	3.3 hours
Application Data Interval	1 packet per 20min

IV. SIMULATION RESULTS AND DISCUSSION

In analysing the results, we used four metrics to measure network performance, namely, energy consumption, interference rate, undersensitivity rate, successful packet reception rate.

A. *Total Energy Consumption*

The total energy consumption in LoRaWAN networks is depended on the energy consumed in each state of the EDs, and it is the sum of the battery energy consumed by all nodes over the course of the simulation. In Fig. 2, we present the performance of three different history averaging methods for the ADR implementation in LoRaWAN, specifically in terms of the total energy consumption of the EDs.

Despite ADR-SNR-MIN demonstrating better performance in other considered metrics, it consumes more energy compared to the other two methods. This suggests that ADR-SNR-MIN may not be the most energy-efficient option for LoRaWAN deployments, even though it may offer advantages in terms of other performance factors. On the other hand, ADR-SNR-MAX outperforms the other two methods in terms of energy consumption. The ADR algorithm optimises transmission power and spreading factor based on the distance between the EDs and their nearest GW. By utilising additional GWs, the energy utilisation of the LoRaWAN network can be minimised.

The results highlight the importance of considering energy efficiency when selecting the appropriate history averaging method for ADR implementation in LoRaWAN networks. While other metrics may be prioritised in certain scenarios, the overall energy consumption is a crucial factor in ensuring the longevity and sustainability of the network.

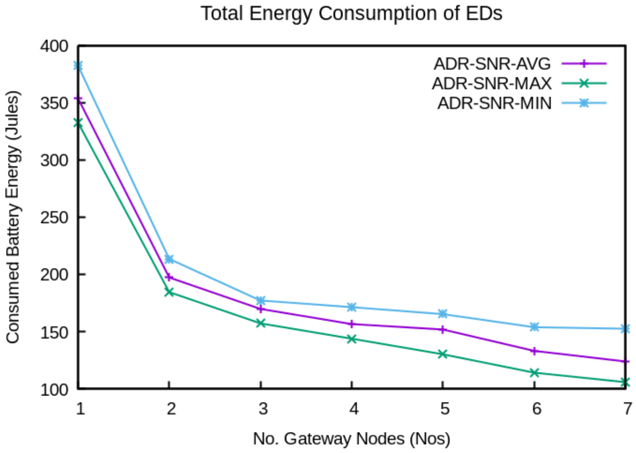

Figure 2: Comparison of Total Energy Consumption

B. *Successful Reception Rate*

The successful reception rate in LoRaWAN networks is defined as the ratio of total packets sent to the packets received successfully at the gateway. In Fig. 3, we present the performance of three different history averaging methods for the Adaptive Data Rate implementation in LoRaWAN, specifically in terms of the successful reception rate at the GW node. Among the three methods, ADR-SNR-MIN exhibits a notably high successful reception rate compared to the other averaging methods. This indicates that a larger proportion of packets sent are successfully received at the GW. Despite its higher interference rate in comparison to its counterparts, ADR-SNR-MIN proves to be the best performing method in terms of successful reception rate.

While a higher interference rate may suggest potential challenges in terms of packet transmission, the superior successful reception rate of ADR-SNR-MIN demonstrates its effectiveness in mitigating the impact of interference. This highlights the importance of considering the overall performance and reliability of the network, rather than solely focusing on the interference rate.

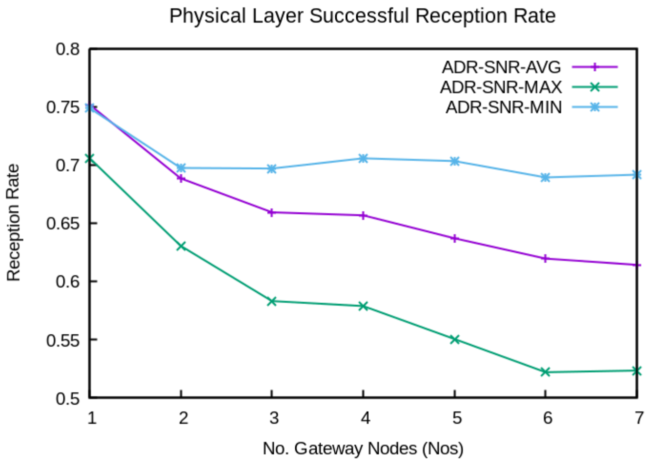

Figure 3: Comparison of Successful Reception Rate

C. *Interference/Collision Ratio*

The failure of packet reception at the gateway in LoRaWAN networks can be attributed to interference caused by overlapping packets. In Fig. 4, we present the performance of three different history averaging methods for the Adaptive Data Rate implementation in LoRaWAN, specifically in terms of the Interference/Collision Rate. Among the three methods, ADR-SNR-MAX demonstrates the lowest Interference/Collision Rate. This can be attributed to its larger Signal-to-Noise Ratio margin compared to the other two methods. The increased SNR margin provides a greater tolerance for interference and collisions, resulting in a lower rate of occurrence.

Furthermore, it is observed that the Interference/Collision rate decreases as the number of GW nodes increases. This is due to the availability of more transmission channels. With a larger number of GW nodes, the network can distribute the traffic across multiple channels, reducing the likelihood of interference and collisions between packets.

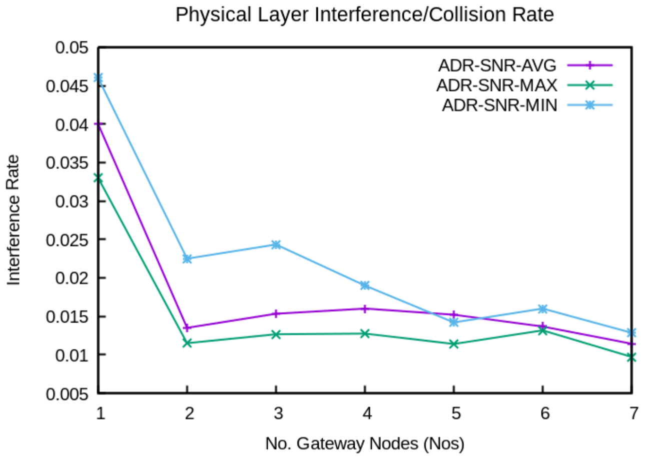

Figure 4: Comparison of Interference/Collision Rate

D. *Undersensitivity Rate*

The undersensitivity rate in LoRaWAN networks refers to the ratio of successfully received packets to the packets received with undersensitivity. Undersensitivity occurs when a packet arrives at the gateway with a power level lower than the sensitivity threshold. In Fig. 5, we present the performance of three different history averaging methods for the Adaptive Data Rate implementation in LoRaWAN, specifically in terms of the undersensitivity rate. Among the three methods, ADR-SNR-MIN demonstrates the lowest undersensitivity rate, indicating a higher proportion of packets successfully received at the GW. On the other hand, ADR-SNR-MAX exhibits the highest packet loss due to undersensitivity, indicating a larger number of packets that fail to meet the sensitivity threshold and are therefore not successfully received.

It is important to note that as the density of GW nodes increases, the undersensitivity rate tends to increase as well. This is because the packets from the EDs are transmitted to the physical layer of all GWs in the vicinity of the EDs. Consequently, the increased exposure to multiple GWs introduces a higher risk of undersensitivity.

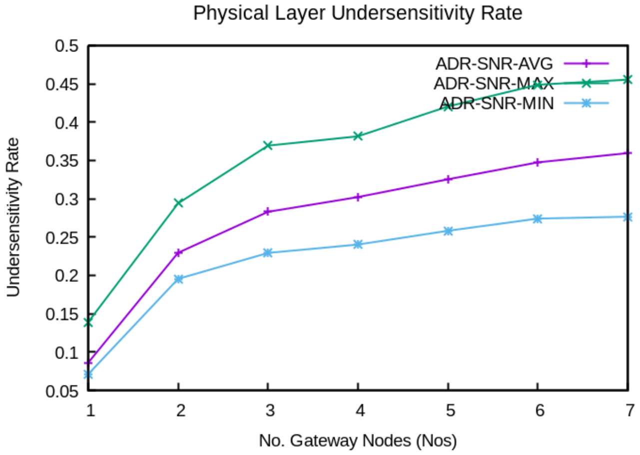

Figure 5: Comparison of Interference/Collision Rate

Based on the results presented, it can be concluded that the ADR-SNR-MIN packet history averaging method shows superior performance compared to the other two methods in terms of undersensitivity rate and successful reception rate. However, it is important to consider other factors such as energy consumption, interference and collision rate. While ADR-SNR-MIN demonstrates better undersensitivity rate and successful reception rate, it consumes more energy compared to the other methods. This higher energy consumption should be taken into account when considering the overall efficiency and battery lifetime of the LoRaWAN network.

Furthermore, ADR-SNR-MIN exhibits a higher interference and collision rate compared to the other methods. This indicates a potential trade-off between successful packet reception and the level of interference and collisions experienced in the network. The impact of this increased interference and collision rate on the overall network performance and reliability should be carefully evaluated, especially in scenarios with high network traffic or dense deployment of devices.

Therefore, while ADR-SNR-MIN shows advantages in terms of undersensitivity rate and successful reception rate, it is important to consider the trade-offs associated with energy consumption and interference/collision rate. ADR-SNR-AVG provides a balance in performance when considering the performance metrics. the A comprehensive analysis considering all these factors will facilitate the selection of the most suitable packet history averaging method for a specific LoRaWAN deployment, ensuring a balance between performance, energy efficiency, and network reliability.

V. CONCLUSION

In this paper, the evaluation of the network performance of a LoRaWAN network with an enabled ADR algorithm was conducted. The different methods of averaging the SNR of the twenty most recently received packets received at the GW are evaluated to determine the superior method. By examining different Signal-to-Noise Ratio history averaging methods, the research aimed to understand how the ADR algorithm optimises the performance of these networks. The study's findings shed light on the reliability and suitability of ADR schemes in LoRaWAN networks. By utilising four different metrics to evaluate performance, the research provided a comprehensive analysis of the ADR's effectiveness and efficiency in terms of data rate optimisation, interference and energy utilisation. The findings of this study make a contribution to an enhanced knowledge of the adaptive data rate's impact on the performance of LoRaWAN networks, offering insights into its suitability for diverse IoT applications. These findings, combined with other techniques can improve the resource allocation of the LoRaWAN ADR algorithms.

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Rachel Kufakunesu (Graduate Student Member, IEEE) received her B. Tech and M. Tech 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, low power wide area networks, Internet of Things and artificial intelligence. She is working with the Advanced Sensor Networks research group - investigating how advanced wireless sensor networks and communication solutions can contribute to solving existing problems and challenges.

Gerhard P. Hancke (M'88, SM'00, F'16, LF'19) received the B.Sc., B.Eng. and M.Eng. from the University of Stellenbosch, and the D.Eng. from the University of Pretoria (UP). He is a Professor with the Department of Electrical, Electronic and Computer Engineering at the University of Pretoria, South Africa, and the Colleges for Automation and Artificial Intelligence at the Nanjing University of Posts and Telecommunications, China. He is recognised internationally as a pioneer and leading scholar in Industrial Wireless Sensor Network (IWSN) research, and was elevated to IEEE Fellow "for contributions to wireless sensor networks". He co-edited a textbook, Industrial Wireless Sensor Networks: Applications, Protocols and Standards (2013), the first on the topic. He initiated and co-edited the first Special Section on Industrial Wireless Sensor Networks in the IEEE Transactions on Industrial Electronics in 2009 and the IEEE Transactions on Industrial Informatics (TII) in 2013. He has acted as AE and GE for TII, TIE and IEEE Access, Co-EiC for TII (2019-2022), and Senior Editor for IEEE Access (2019-2022). Currently, he is the Editor-in-Chief of the IEEE Transactions on Industrial Informatics (from January 2023).

Adnan M. Abu-Mahfouz (Senior Member, IEEE) received the M.Eng. and Ph.D. degrees in computer engineering from the University of Pretoria, Pretoria, South Africa, in 2005 and 2011, respectively. He is currently a Chief Researcher and the Centre Manager of the Emerging Digital Technologies for 4IR (EDT4IR) Research Centre, Council for Scientific and Industrial Research, Pretoria; an Extraordinary Professor with University of Pretoria; a Professor Extraordinaire with the Tshwane University of Technology, Pretoria, South Africa. His research interests are wireless sensor and actuator network, low power wide area networks, software-defined wireless sensor network, cognitive radio, network security, network management, and sensor/actuator node development. Prof Abu-Mahfouz is a Section Editor-in-Chief with the Journal of Sensor and Actuator Networks, an Associate Editor at IEEE INTERNET OF THINGS, IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS, IEEE TRANSACTIONS ON CYBERNETICS and IEEE ACCESS, and a member of many IEEE technical communities.