

Towards Ambient Internet of Things in 5G: What does Medium Access Control Scheduling cost?

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Abstract—The positioning of medical instruments, which are equipped with battery-free devices, is a challenging task in hospitals. Therefore, this paper presents novel insights into the Medium Access Control (MAC) protocol that is optimized for Ambient Internet of Things (A-IoT) devices to enable access to fifth generation (5G) networks and low-level data exchange. By emulating the physical layer via a USB connection, the energy consumption and time behavior of the Contention-Based Random Access (CBRA) and the device to reader (D2R) Upper Layer Data Transfer procedure are investigated on MAC layer depending on different key parameters, such as the number of access occasions and the D2R transport block size (TBS), respectively. Based on the Raspberry Pi Pico 2 W, the Nordic Power Profiler Kit II, a USB-UART adapter, and a Lenovo Thinkpad X260, the results show that the network access via CBRA procedure can take up to 229 s with an energy consumption of 16,482 mWs, if the number of access occasions is set to its maximum value. On the other hand, the transmission of 4,096 B can require up to 26 s with an energy consumption of 1,675 mWs using the D2R Upper Layer Data Transfer procedure, if the D2R TBS is set to its minimum value. Additionally, the latter procedure is completed 0.36% faster, if the RISC-V Hazard3 processor is used instead of the ARM Cortex-M33. However, the latter consumes 4.86% less energy than the former during upper layer data transmissions.

Index Terms—5G, Ambient IoT, MAC, energy consumption

I. INTRODUCTION

THE online management and positioning of medical instruments, for instance, orthopedic forceps or knives, require a new class of devices that can be attached to them. This is due to certain conditions that are described by the *3rd Generation Partnership Project (3GPP)* in [1]. According to [1], medical instruments always need to be cleaned and sterilized under high pressure, extremely high or low temperatures in environments with high humidity. Therefore, the replacement of batteries, as is currently done with conventional *Internet of Things (IoT) devices*, will not longer be possible, which is why battery-free devices are needed. As a consequence, the device size and its cost can also be reduced ([1]).

This new class of devices without or with limited energy storage is introduced by the 3GPP as *Ambient Internet of Things (A-IoT) devices* as part of the latest Release 19 standards to pave the way for new applications in current 5G and future 6G networks ([2], [3]). Based on *energy harvesting*, these A-IoT devices are powered by alternative energy sources,

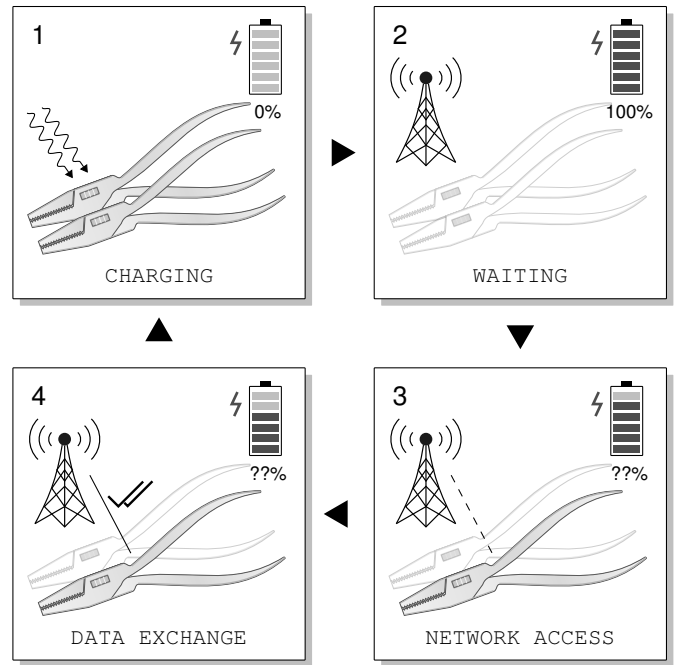


Fig. 1. Typical life cycle of an A-IoT device, for instance, when it is integrated into orthopedic forceps that are equipped with a solar panel as a power source: After the A-IoT device has stored enough energy in its internal capacitor during the first step, it is waiting for a trigger by the 5G network in the second step. In the third step, the A-IoT device is accessing the 5G network based on specific MAC procedures. If the network access has been successfully completed, the A-IoT device can exchange data with the 5G network in step four, for instance, for positioning purposes. When the A-IoT device is out of energy, charging is performed again starting from the first step ([2], [3]).

such as radio waves or solar energy. This leads to the need to significantly reduce the complexity of such A-IoT devices and their algorithms to decrease their overall energy consumption.

In this context, Figure 1 shows the four-step life cycle of A-IoT devices as part of orthopedic forceps that are equipped with a capacitor for minimal energy storage and a solar panel as a power source. At the beginning, the A-IoT device is charging its internal capacitor using its solar panel until it has stored enough energy. In the second step, the A-IoT device of both orthopedic forceps is waiting for a trigger from the 5G network. On *Medium Access Control (MAC)* layer, this trigger

is represented by a *Paging* message, which is not shown in Figure 1 and indicates if an A-IoT device is selected by the 5G network or not ([4]). In case of selection, the A-IoT device tries to access the 5G network depending on the contents of the received Paging message. This is illustrated in the third step of Figure 1, where one of both orthopedic forceps has been selected. If the network access is successful, the A-IoT device of the selected medical instrument can exchange data with the 5G network, as indicated in the fourth step of Figure 1. For instance, if positioning of the selected orthopedic forceps is desired, position-related data could be exchanged between the 5G network and the integrated A-IoT device.

However, it should be mentioned that the shown life cycle in Figure 1 is simplified in terms of its state transitions. On the one hand, a new Paging message will stop the data exchange of an already connected A-IoT device to force accessing the 5G network with new parameters, as illustrated in the third step of Figure 1. On the other hand, if the A-IoT device is out of energy, it will cancel the current procedure and returns to the charging state directly regardless of its current state ([4]).

The latter case leads to the questions of how long does it take to access the network and how much energy is consumed until the network access is completed on MAC layer to prevent the energy from running out before the data exchange with the target 5G network can be initiated. The same questions can also be applied to the data exchange, whose energy consumption and time behavior on MAC layer are also unknown so far. Therefore, the paper at hand presents two contributions:

- ① **Prototypical implementation** of a MAC scheduler for an A-IoT device with support of all defined procedures according to the latest 3GPP specification ([4]).
- ② **Systematic investigation** of the Contention-Based Random Access and the Upper Layer Data Transfer procedures on MAC layer depending on the number of access occasions n_{ao} and the D2R transport block size N_{TBS}^{D2R} in terms of energy consumption and time behavior on the ARM, as well as the RISC-V processor of the Raspberry Pi Pico 2 W using the Nordic Power Profiler Kit II.

In the following, Section II gives an overview of related work. Afterwards, Section III summarizes the working principle of the Contention-based Random Access and the Upper Layer Data Transfer procedures, and highlights the key parameters that are important for the further cost estimations. Based on this, the experimental setup and the achieved results are considered in the Sections IV and V, respectively. Finally, Section VI summarizes the key points of this paper.

In order to improve the readability of each section, Table I and Table II summarize the most frequently used abbreviations, and the defined mathematical symbols, respectively.

II. RELATED WORK

The importance of A-IoT devices has already been addressed in other works and was examined there from various perspectives. For instance, Moloudi et al. give an overview of the current standardization process of the A-IoT device

TABLE I
OVERVIEW OF SELECTED ABBREVIATIONS

Short	Long
3GPP	3rd Generation Partnership Project
A-IoT	Ambient Internet of Things
CBRA	Contention-Based Random Access
CFA	Contention-Free Access
D2R	Device to Reader
MAC	Medium Access Control
R2D	Reader to Device
TBS	Transport Block Size

TABLE II
OVERVIEW OF DEFINED MATHEMATICAL SYMBOLS

Symbol	Description
n_{cnt}	access occasion counter value
n_{ao}	number of access occasions
X	number of time domain resources of access occasions
N_{sf}	number of potential small frequency shift factors
Δt_{at}	time interval to send consecutive Access Trigger messages [ms]
t_{base}	base time value as impact factor of Δt_{at} [ms]
n_{sz}	size of upper layer data to be transmitted by the A-IoT device [B]
M_i	set of measurements including current and time value pairs
n_i	sample size of a recorded measurement series M_i
T_i, t_i	estimated time behavior of an A-IoT MAC procedure [s]
E_i	estimated energy consumption of an A-IoT MAC procedure [mWs]
N_{TBS}^{D2R}	D2R transport block size [B]
U_{src}	voltage applied to the A-IoT device [V]
m	number of repetitions of an A-IoT MAC procedure
$\bar{I}_i$	estimated average current of the measurement series M_i [mA]
$\bar{P}, \bar{P}_{mac}$	sample mean of the electric power based on $\bar{I}_i$ and U_{src} [mW]
$\bar{X}, S^2$	point estimators for statistical description of t_i and E_i metrics
$\sigma_{\bar{x}}$	standard error representing the variance of the sample mean $\bar{X}$
≈ 0.005	quantile of the standard normal distribution

communication on physical layer ([5]). The authors discuss different aspects related to data transmission on physical layer, such as waveform and modulation schemes for D2R and R2D transmissions. In contrast, the paper at hand is addressing MAC procedures that are located on top of the physical layer.

Kim et al. provide insights into the current A-IoT architecture within the scope of 5G networks in [6]. More specifically, they address different A-IoT device types, multiple architecture options, as well as A-IoT device identification and security aspects. Additionally, the authors mention several challenges, for instance, that energy efficiency is one of the most important challenges, so that mechanisms must be developed to minimize the overall energy consumption. The paper at hand addresses this challenge by investigating two MAC procedures in a real-world environment to find out how much energy is consumed depending on different key parameters.

Similar to [6], Shen et al. also summarize the current state of

research in the area of A-IoT devices in [7]. As in [5], they are also discussing several physical layer aspects, such as different physical channel procedures, and the frame structure of R2D and D2R messages. Shen et al. also describe higher layer procedures to enable network access and data transmission, as well as different aspects regarding energy limitations of A-IoT devices, for instance, the impact of D2R segmentation.

However, it appears that their descriptions no longer comply with current 3GPP standards. Therefore, the paper at hand provides an A-IoT MAC scheduling implementation that fully supports the latest 3GPP specification ([4]). Based on the developed MAC scheduler, this paper addresses the D2R segmentation in context of data transmission, and the CBRA network access procedure that are investigated in terms of their time behavior and energy consumption in a real-world test environment depending on different key parameters, such as the D2R TBS, to extend the findings of [7].

Chao et al. describe the A-IoT architecture enhancements in current 5G and future cellular networks in [8]. More precisely, the authors primarily focus on challenges to integrate A-IoT functionalities into existing 5G networks, and summarize the current 3GPP standardization progress. In addition to A-IoT device management and registration, Chao et al. also mention that the 5G protocol stacks for communication must be simplified to reduce complexity of A-IoT devices, which corresponds to the latest 3GPP standards. According to [2] and [3], the protocol stack of an A-IoT device has been reduced to three layers: the physical, MAC and higher layers including an A-IoT optimized *Non-Access-Stratum* (NAS) layer that are specified in [9], [4], and [10], respectively. In contrast to [8], the paper at hand investigates the energy consumption and the time behavior of two A-IoT optimized MAC procedures in accordance with [4] using a real-world test environment.

The overhead that is caused by the A-IoT optimized protocols, such as MAC and NAS, have already been initially studied by Van et al. in [11]. Based on 3GPP specifications, the authors compare the protocol overhead between previous 3GPP releases and give insight into the current 3GPP standardization process, similar to [6], and [7]. Additionally, they compare the payload of different A-IoT NAS procedures and their impact on the A-IoT MAC layer depending on different key parameters, such as security values.

However, Van et al. do not describe how they measure these overheads. Compared to [11], the paper at hand also investigates the A-IoT MAC protocol overhead of two procedures by varying different key parameters, such as the number of access occasion during the CBRA procedure, or the D2R TBS while data transmissions. In contrast to Van et al., the NAS layer is largely ignored, while the MAC protocol is examined in a more precise manner based on a real-world test environment.

Wu et al. study the energy harvesting of multiple A-IoT devices during an inventory procedure in [12]. Similar to the paper at hand, the authors also investigate the CBRA and data transmission procedure on MAC layer, and provide time, as well as energy consumption results. However, Wu et al. use a simulation approach to examine the behavior of A-IoT

devices. In contrast, the paper at hand demonstrates real-world experiments on a single A-IoT device based on a wider range of different key parameters that impact the CBRA and the D2R Upper Layer Data Transfer procedure on MAC layer.

III. INVESTIGATED MAC PROCEDURES AND THEIR KEY PARAMETERS FOR COST ESTIMATION

This section focuses on three A-IoT MAC procedures and their key parameters that are crucial for the further investigations in terms of energy consumption and time behavior. More precisely, the following MAC procedures are considered in accordance with the corresponding 3GPP specification in [4]:

- ① **A-IoT Paging** procedure that is used by the 5G network to select an A-IoT device or a group of them. In case of selection, a network access procedure is performed.
- ② **Contention-Based Random Access (CBRA)** procedure that can be used by A-IoT devices to access the 5G network. Alternatively, the *Contention-Free Access (CFA)* procedure can be used, if the 5G network is indicating this via an A-IoT Paging message. However, due to its low complexity, CFA is out of scope of this paper.
- ③ **A-IoT Upper Layer Data Transfer** procedure that is used by an A-IoT device to exchange upper layer data with the 5G network. However, the paper at hand is only focusing on D2R transmissions including D2R segmentation. Therefore, the A-IoT device is only sending upper layer data to the target 5G network.

In this context, Figure 2 shows a sequence of six steps to clarify the relationship between these MAC procedures. Additionally, the left side of Figure 2 also highlights the examined metrics of this paper, which are defined as follows:

- (A) **time behavior** that describes the required time to:
 - complete a CBRA procedure including the processing of an initially received A-IoT Paging message with CBRA indication that triggers this procedure and is addressed to the A-IoT device (t_{cbra}). The CBRA procedure is examined depending on the assigned number of access occasions n_{ao} .
 - complete the D2R transmission including D2R segmentation of upper layer data of n_{sz} byte (t_{d2r}). The D2R segmentation procedure based on the assigned D2R transport block size $N_{\text{TBS}}^{\text{D2R}}$.
- (B) **energy consumption** that describes the consumed energy over the required time t_{cbra} (E_{cbra}) and t_{d2r} (E_{d2r}), respectively, to complete the corresponding MAC procedure. The energy E is generally calculated by

$$E = \bar{I} \cdot U \cdot t, \quad (1)$$

where t corresponds to t_{cbra} or t_{d2r} , respectively, $\bar{I}$ is the average current over t , and U is the applied voltage.

The contents of Figure 2 are also mentioned by other works, for instance, in [12]. However, to the best of the author's

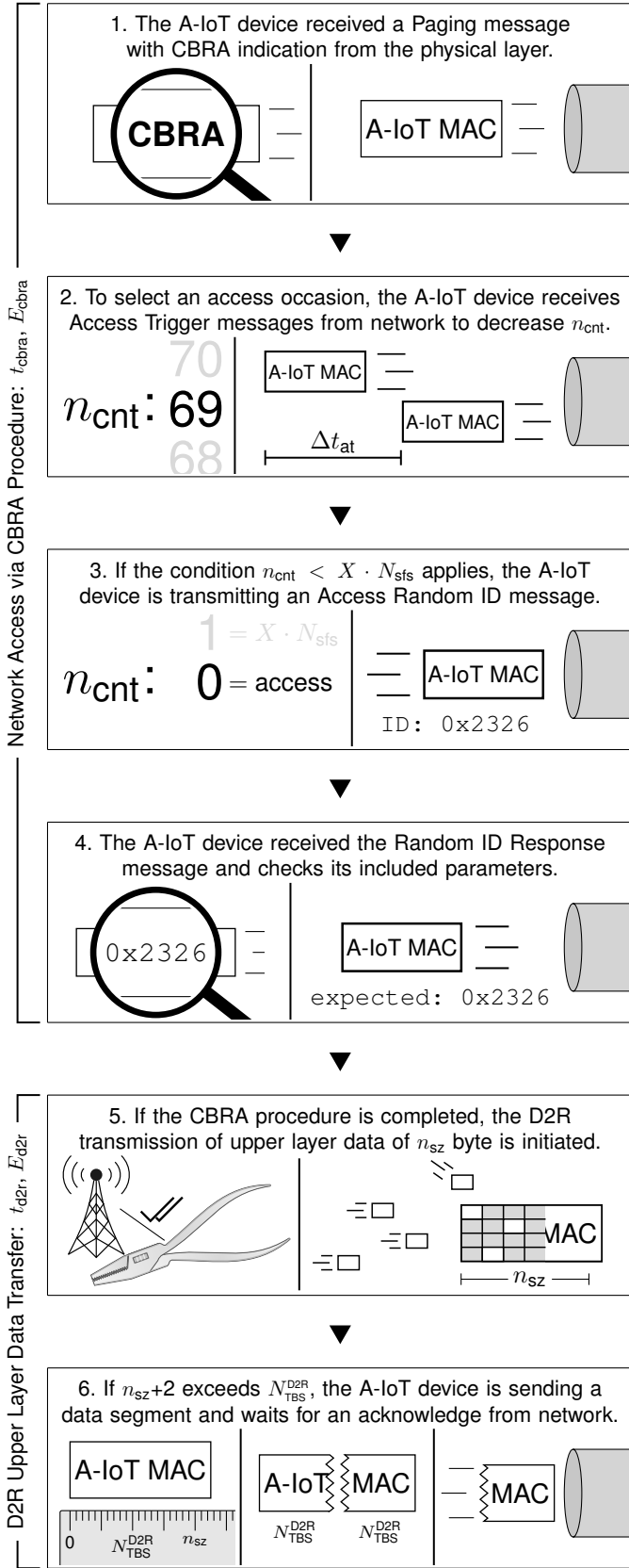


Fig. 2. Analysis of the time behavior t and the energy consumption E of the CBRA network access (first to fourth step), and the D2R Upper Layer Data Transfer procedure (fifth to sixth step) for an A-IoT device on MAC layer

knowledge, the paper at hand describes these MAC procedures in more detail based on the latest 3GPP standards ([2], [4]).

If the 5G network decides to select an A-IoT device, the network is sending an A-IoT Paging message over a *5G base station (gNB)*. As mentioned in [3], a gNB that interacts with an A-IoT device is also referred to as an *A-IoT reader*.

After the A-IoT device received an A-IoT Paging message with CBRA indication, as shown in the first step of Figure 2, the included main parameters that have a significant impact on the time behavior metric are the number of time domain resources of access occasions X , the number of potential small frequency shift factors N_{sfs} , and the number of access occasions n_{ao} . According to [4], the A-IoT device is using these values to initiate the CBRA procedure, if it is selected. Within this paper, the A-IoT device is always selected. Additionally, it is assumed that a *Paging ID* and a Security Parameter are included to increase the processing time of an A-IoT Paging message, as well as the time behavior metric t_{cbra} .

When the A-IoT device initiates the CBRA procedure, it must select a suitable access occasion first. For this purpose, the A-IoT device generates a random access occasion counter value n_{cnt} depending on the number of access occasions n_{ao} :

$$n_{cnt} := \{i \mid i \in \mathbb{N}_0, 0 \leq i < n_{ao}\}. \quad (2)$$

Based on the counter value n_{cnt} , the A-IoT device is waiting for *Access Trigger* messages from the network, as shown in the second step of Figure 2. Each time when an Access Trigger message is received, the A-IoT device decreases n_{cnt} by

$$n_{cnt} = n_{cnt} - X \cdot N_{sfs} \quad (3)$$

until the following equation

$$n_{cnt} < X \cdot N_{sfs} \quad (4)$$

applies. For instance, the counter value n_{cnt} is decreased from 70 to 69 due to a received Access Trigger message in the second step of Figure 2, where Equation (4) does not apply.

In order to ensure a balance between the processing of an Access Trigger message by the A-IoT device and the transmission of consecutive Access Trigger messages by the A-IoT reader using the shortest possible time interval Δt_{at} , the paper at hand proposes the following relationship:

$$\Delta t_{at} := \frac{t_{base}}{\log_2(n_{ao})}, \quad (5)$$

where $\log_2(n_{ao})$ represents the access occasion index as encoded in the corresponding A-IoT Paging message, and t_{base} that corresponds to the base time value with

$$t_{base} = 150 \text{ ms}. \quad (6)$$

To increase the time until Equation (4) applies to get a worst-case estimation of t_{cbra} , it is assumed that X and N_{sfs} are set to their lower boundaries. According to the A-IoT MAC protocol specification in [4], the following values are assigned:

$$X = 1 \text{ and } N_{sfs} = 1. \quad (7)$$

If Equation (4) applies, the A-IoT device is using its counter value n_{cnt} to select a suitable access occasion, and generates an *Access Random ID* message that is sent to the 5G network. For instance, the third step of Figure 2 shows the case, where the counter value n_{cnt} reaches zero, so that Equation (4) becomes true. Consequently, an *Access Random ID* message including the random ID 0×2326 is transmitted to the network.

Afterwards, the A-IoT device is waiting for a *Random ID Response* message from the 5G network, which includes an individual *Access Stratum* identifier that is needed to exchange upper layer data with the 5G network. If the Random ID Response message contains the same identifier as transmitted by the A-IoT device in the previous step, the latter accepts the Random ID Response message to complete the CBRA procedure. As an example, the fourth step of Figure 2 shows that the previously transmitted random ID 0×2326 is echoed by the 5G network. Then, the A-IoT device can initiate the D2R transmission of upper layer data, if available. As indicated in the fifth step of Figure 2, the upper layer data size is set to n_{sz} byte. Within this paper, n_{sz} corresponds to

$$n_{\text{sz}} = 2^{12} = 4,096 \text{ B} . \quad (8)$$

This value has been chosen because it exceeds the maximum D2R TBS of 125 byte ([4]). Therefore, the A-IoT device initiates the D2R Segmentation procedure, as shown in the sixth step of Figure 2. The initiation of the D2R segmentation mechanism enables a worst-case estimation of the D2R transmission time t_{d2r} depending on different D2R TBS values.

After the A-IoT device received a *R2D Upper Layer Data Transfer* message as an acknowledgment from the 5G network to indicate the reception of a upper layer data segment of size $N_{\text{TBS}}^{\text{D2R}}$ byte, the A-IoT device is sending the next data segment using the D2R Segmentation procedure. Therefore, the sixth step of Figure 2 is repeated until the transmission of the upper layer data of size n_{sz} is successfully completed. This repetition mechanism is not shown in Figure 2.

IV. HOW IS MAC SCHEDULING EXAMINED ON A POTENTIAL A-IoT DEVICE?

Based on the described A-IoT MAC procedures in Section III, this section gives an overview of the real-world test environment that is used to investigate the time behavior and the energy consumption metrics of the CBRA and the D2R Upper Layer Data Transfer procedure on MAC layer.

In this context, Figure 3 shows the experimental setup that consists of four main components: the Raspberry Pi Pico 2 W, the Nordic Power Profiler Kit II, a USB-UART adapter and a Lenovo Thinkpad X260. While the Raspberry Pi Pico 2 W represents the A-IoT device, the Nordic Profiler Kit II is acting as a power source and measures the current of the former over time. The USB-UART adapter is used to emulate the physical layer by a serial connection. The Lenovo Thinkpad X260 represents the A-IoT reader that is sending R2D messages to the Raspberry Pi Pico 2 W over the UART interface.

In order to assign a piece of program code to a set of measurement samples, the Nordic Power Profiler Kit II offers

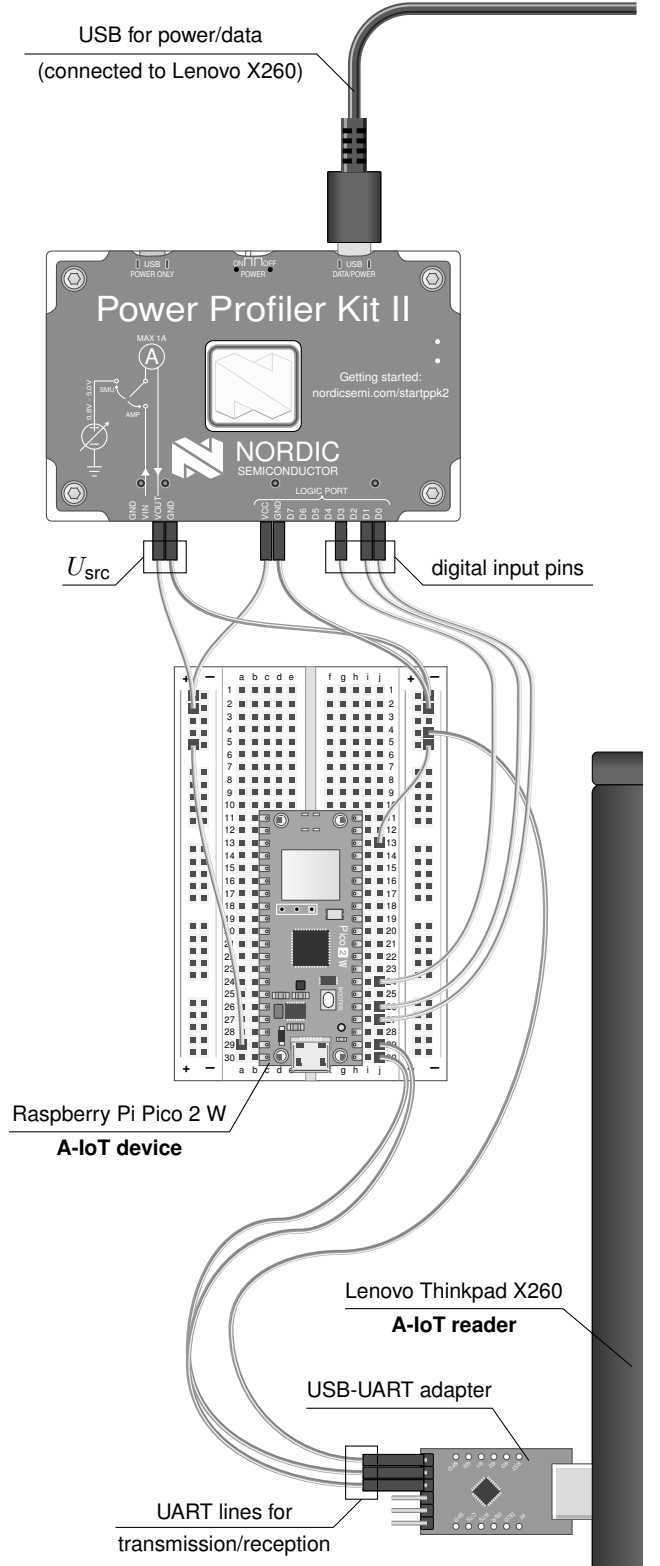


Fig. 3. Experimental setup to investigate the energy consumption and the time behavior of selected A-IoT MAC procedures using a Raspberry Pi Pico 2 W as a potential A-IoT device (middle), a Nordic Power Profiler Kit II to record the formers current over time (above), a USB-UART serial adapter to emulate the physical layer (below), and a Lenovo Thinkpad X260 that is acting as an A-IoT reader (below, right).

eight digital input pins that can be set to high or low voltage levels to indicate the start and the end of a piece of program code, respectively. As shown in the middle of Figure 3, three of these input pins are used. While each of the CBRA, and the D2R Upper Layer Data Transfer procedure is assigned to one of these pins, the third input pin is used to indicate, if the developed MAC scheduler, whose source code is publicly available in [13], is running or not. In the latter case, either data is exchanged over the emulated physical layer using UART or the device is waiting for R2D messages from the A-IoT reader.

For testing both MAC procedures, whose steps are shown in Figure 2, the Raspberry Pi Pico 2 W is powered by the Nordic Power Profiler Kit II with a voltage U_{src} of

$$U_{\text{src}} = 5 \text{ V} , \quad (9)$$

while the current I is sampled with 100 kHz during runtime of the Raspberry Pi Pico 2 W. The processor cores of the latter run at the default clock speed of 150 MHz, while the A-IoT MAC scheduler is only running on one core at the same time. Additionally, the time behavior and the energy consumption metric are investigated on both of its built-in processors: on the Arm Cortex-M33 and on the Hazard3 RISC-V processor.

In order to evaluate the time behavior t , as well as the energy consumption E using statistical methods, the sequence of steps shown in Figure 2 is repeated m times with

$$m = 35 , \quad (10)$$

depending on the number of access occasions n_{ao} and the D2R transport block size $N_{\text{TBS}}^{\text{D2R}}$ that are set to

$$n_{\text{ao}} \in \{2^k \mid k \in \mathbb{N}_0, 0 \leq k \leq 15\} , \quad (11)$$

and

$$N_{\text{TBS}}^{\text{D2R}} \in \{3, 6, 12, 24, 48, 96, 125\} , \quad (12)$$

respectively. Based on this, it is assumed that for each repetition, two measurement series M_{cbra} and M_{d2r} are recorded including n_{cbra} and n_{d2r} samples, respectively. Therefore, let

$$M_i := \{(I_1, T_1), (I_2, T_2), \dots, (I_{n_i}, T_{n_i}) \mid n_i \in \mathbb{N}^+\} \quad (13)$$

a set of n_i independent random variable pairs, where each of these pairs represents a taken sample that consists of the current I_j and its assigned timestamp T_j .

Due to the fact that the used Nordic Power Profiler Kit II assigns a timestamp to each recorded current I_j , the time behavior of both MAC procedures t_{cbra} and t_{d2r} can be calculated by subtracting the first and the last timestamp of the corresponding measurement series M_i as follows:

$$T_i = T_{n_i} - T_1 . \quad (14)$$

Furthermore, the sample mean $\bar{I}_i$ of each measurement series M_i can be calculated by applying

$$\bar{I}_i = \frac{1}{n_i} \sum_{j=1}^{n_i} I_j , \quad (15)$$

where I_j corresponds to the j -th sample of the measurement series M_i including n_i samples to estimate the average current

$\bar{I}$. Applying the Equations (9), (14) and (15) to (1), the energy consumption E_i of the measurement series M_i is defined by

$$E_i = U_{\text{src}} \cdot \bar{I}_i \cdot T_i . \quad (16)$$

Finally, m values of the time behavior t_i and the energy consumption E_i have been determined for the CBRA, and the D2R Upper Layer Data Transfer procedure depending on the number of access occasions n_{ao} , and the D2R TBS $N_{\text{TBS}}^{\text{D2R}}$, respectively. Based on the sample mean $\bar{X}$ and the sample variance S^2 that are calculated for both metrics by applying

$$\bar{X} = \frac{1}{m} \sum_{j=1}^m X_j \quad \text{and} \quad (17)$$

$$S^2 = \frac{1}{m-1} \sum_{j=1}^m (X_j - \bar{X})^2 , \quad (18)$$

respectively, the time behavior t and the energy consumption E of the investigated CBRA and D2R Upper Layer Data Transfer procedure can be described statistically.

Due to Equation (10), the sample size m is larger than 30. Based on the *Central Limit Theorem (CLT)*, it can be assumed that the sample mean $\bar{X}$ is normally distributed with

$$\bar{X} \sim \mathcal{N}(\mu, \sigma_{\bar{x}}^2) , \quad (19)$$

where μ represents the true mean value and $\sigma_{\bar{x}}$ corresponds to the *standard error*, which can be estimated by

$$\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{m}} = \frac{|\sqrt{S^2}|}{\sqrt{m}} . \quad (20)$$

Due to the fact that the point estimators $\bar{X}$ and S^2 are *unbiased*, their expected values $E[\bar{X}]$ and $E[S^2]$ correspond to the true mean μ and variance σ^2 , respectively. This allows the construction of a 99% *confidence interval* that also quantifies the *uncertainty* implicitly by applying the following equation:

$$[\bar{x} - z_{0.005} \cdot \sigma_{\bar{x}}, \bar{x} + z_{0.005} \cdot \sigma_{\bar{x}}] . \quad (21)$$

While $\bar{x}$ and $\sigma_{\bar{x}}$ represent the sample mean and standard error of the target metric, respectively, $z_{0.005}$ corresponds to a *quantile* of the standard normal distribution that is equal to

$$z_{0.005} = 2.58 . \quad (22)$$

Due to the randomness of the generated access occasion counter value n_{cnt} , as defined by Equation (2), it is assumed that the sample variance S^2 of the time behavior t is larger for the CBRA than for the D2R Upper Layer Data Transfer procedure. Therefore, the sample mean of the electric power $\bar{P}$ is also taken into account by applying Equation (17) to the m values of the average current $\bar{I}_i$ and the voltage U_{src} :

$$\bar{P} = \frac{U_{\text{src}}}{m} \sum_{i=1}^m \bar{I}_i . \quad (23)$$

This allows a comparison of the energy consumption of both processors of the used Raspberry Pi Pico 2 W regardless of the random time behavior t of the CBRA procedure. In this

context, the electric power $\bar{P}_{\text{mac}}$ represents an estimation of the electric power $\bar{P}$ on MAC layer only, if the corresponding digital input pin of the Nordic Power Profiler Kit II, as indicated in the middle of Figure 3, is set to high. More specifically, $\bar{P}_{\text{mac}}$ based on a subset of the recorded currents I_i of the measurement series M_i that are tagged with a non-zero value of the corresponding digital input pin.

V. ARM VERSUS RISC-V: WHICH INSTRUCTION SET ARCHITECTURE COSTS LESS DURING MAC SCHEDULING?

This section deals with the achieved results of the CBRA and D2R Upper Layer Data Transfer procedures in terms of their time behavior and energy consumption. Based on the Raspberry Pi Pico 2 W's built-in ARM and RISC-V processors that are used to investigate the A-IoT MAC scheduling, three questions are addressed by the paper at hand:

- ① How long does it take until an A-IoT device completes the network access via CBRA procedure depending on the number of access occasions n_{ao} to exchange upper layer data with the 5G network, and how much energy is consumed by the A-IoT device during this time?
- ② Which impact does the D2R transport block size $N_{\text{TBS}}^{\text{D2R}}$ have on the time behavior and energy consumption of D2R transmissions of upper layer data of n_{sz} byte?
- ③ Which role does the instruction set architecture of the A-IoT device's processor play regarding the time and energy investigations of the previous two questions?

In this context, Figure 4 summarizes the achieved results of the A-IoT MAC procedure study. To ensure transparency and accessibility, the preprocessed raw data and their statistical parameters have been made publicly available in [13].

More precisely, Figure 4 shows four different diagrams that present a statistical evaluation of the time behavior t and the energy consumption E of the examined MAC procedures using 99% confidence intervals. While the two upper diagrams illustrate the results of the CBRA procedure performance depending on the number of access occasions n_{ao} , the lower two diagrams highlight both metrics for the D2R Upper Layer Data Transfer procedure depending on the D2R TBS $N_{\text{TBS}}^{\text{D2R}}$.

Due to the Equations (1) and (16), the energy consumption E depends on the time behavior t . Therefore, if t increases E also becomes larger, if the sample mean $\bar{t}$ remains largely constant. In terms of the CBRA procedure, the two upper diagrams show this expected behavior. While the time behavior t_{cbra} increases by 63.83% on average, if the number of access occasions n_{ao} is doubled, the corresponding energy consumption E_{cbra} also rises significantly by 63.95% on average. Due to the randomness of the time behavior t_{cbra} , the standard error $\sigma_{\bar{x}}$ also becomes larger, if the number of access occasions n_{ao} increases. This uncertainty is propagated through the system that is represented by Equation (16), causing the associated energy consumption to behave similarly in this context. Consequently, an A-IoT device can require up to 229 s with an energy consumption of 16,482 mW to access the 5G network

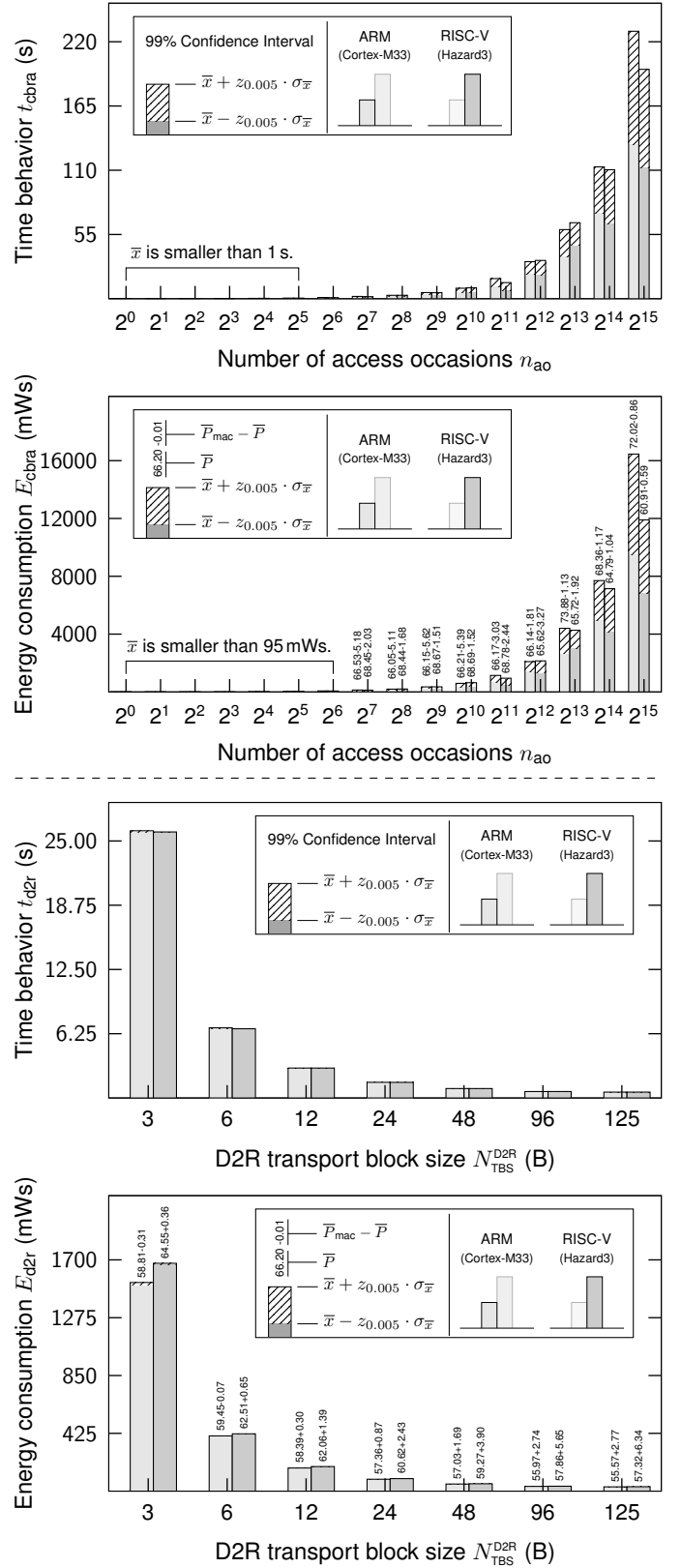


Fig. 4. Results of the MAC scheduling study on the Raspberry Pi Pico 2 W: While the CBRA procedure's time behavior and energy consumption depending on the number of access occasions n_{ao} are shown in the two upper diagrams, the lower two diagrams show both metrics for the D2R Upper Layer Data Transfer procedure depending on the D2R TBS $N_{\text{TBS}}^{\text{D2R}}$.

in a worst-case scenario, where n_{ao} is set to its maximum value, and a dynamic time interval Δt_{at} for consecutive Access Trigger messages, as defined by Equation (5), is applied.

In comparison with the CBRA procedure, the 99% confidence intervals of the time behavior t_{d2r} and the corresponding energy consumption E_{d2r} of the D2R Upper Layer Data Transfer procedure, which are illustrated in the lower two diagrams of Figure 4, have a significantly lower standard error $\sigma_{\bar{x}}$ due to the lack of randomness. Additionally, the time behavior t_{d2r} decreases by 50.02% on average, while the corresponding energy consumption E_{d2r} is reduced by 50.85%, if the D2R TBS N_{TBS}^{D2R} is doubled, and the upper layer data size n_{sz} is constant, as defined by Equation (8). In a worst-case scenario, an A-IoT device can take up to 26 s with an energy consumption of 1,675 mWs to send n_{sz} byte of upper layer data, when the D2R TBS is set to its minimum of three byte.

Based on the achieved results that are shown in Figure 4, the selection of the instruction set architecture appears to have a significant impact on both examined metrics. In context of the CBRA procedure, a comparison between both processors of the Raspberry Pi Pico 2 W would not be meaningful due to the randomness of the time behavior t . However, the electric power $\bar{P}$ of the ARM Cortex-M33 is lower than that of the RISC-V Hazard3 processor, if the number of access occasions n_{ao} is less than 2^{12} . Otherwise, the latter performs better.

In contrast, the D2R Upper Layer Data Transfer procedure behaves different on both processors. While the RISC-V Hazard3 completes the procedure 0.36% faster on average than the ARM Cortex-M33 processor, the latter has a lower electric power $\bar{P}$. Therefore, the energy consumption E_{d2r} of the ARM Cortex-M33 is 4.86% lower on average than that of the RISC-V Hazard3, as indicated by the lowest diagram of Figure 4.

VI. CONCLUSION

This paper presents a study around the A-IoT MAC protocol that based on the latest 3GPP specifications, where the CBRA, as well as the D2R Upper Layer Data Transfer procedure have been investigated depending on the number of access occasions, and the D2R transport block size, respectively. The results show that the 5G network access can take up to 229 s, while the transmission of 4,096 B can require up to 26 s, if a Raspberry Pi Pico 2 W is used as an A-IoT device. In addition, the latter's built-in RISC-V Hazard3 processor can transmit upper layer data slightly faster than the built-in ARM Cortex-M33, but at the cost of a higher energy consumption.

However, the achieved results should be only considered as a starting point, because A-IoT devices should not exceed a few hundred microwatts in terms of power ([5]). Additionally, the physical layer was emulated, and the taken measurement series are relatively small. Therefore, future work could address these issues and try to adjust, for instance, the time interval Δt_{at} to improve the MAC scheduling performance.

ACKNOWLEDGMENT

This work was supported by the PICANT-BOS project that is funded by the German Federal Ministry of the Interior

represented by the German Federal Agency for Public Safety Digital Radio (grant: 16BEC0009).

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