NEW CAP REDUCTION MECHANISMS FOR IEEE 802.15.4 DSME TO SUPPORT FLUCTUATING TRAFFIC IN IOT SYSTEMS

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ABSTRACT

In 2015, the IEEE 802.15.4 standard was expanded by the Deterministic and Synchronous Multi-Channel Extension (DSME) to increase reliability, scalability and energy-efficiency in industrial applications. The extension offers a TDMA/FDMA-based channel access, where time is divided into two alternating phases, a contention access period (CAP) and a contention free period (CFP). During the CAP, transmission slots can be allocated offering an exclusive access to the shared medium during the CFP. The fraction $\tau$ of CFP’s time slots in a dataframe is a critical value, because it directly influences agility and throughput. A high throughput demands that the CFP is much longer than the CAP, i.e., a high value of the fraction $\tau$, because application data is only sent during the CFP. High agility is given if the expected waiting time to send a CAP message is short and that the length of the CAPs are sufficiently long to accommodate necessary (de)allocations of GTSs, i.e., a low value of the fraction $\tau$. Once DSME is configured according to the needs of an application, the fraction $\tau$ can only assume one of two values and cannot be changed at run-time. In this paper, we propose two extensions of DSME that allow to adopt $\tau$ to the current traffic pattern. We show theoretically and through simulations that the proposed extensions provide a high degree of responsiveness to traffic fluctuations while keeping the throughput high.

List of Symbols

| Notation | Description |
|----------|-------------|
| $aUB$    | aUnitBackoffPeriod (symbols) |
| $BE$     | CSMA/CA backoff exponent |
| $BI$     | Beacon interval |
| $BO$     | Beacon order |
| $CAP$    | Contention access period |
| $CFP$    | Contention free period |
| $GTS$    | Guaranteed time slot |
| $MD$     | Multisuperframe duration |
| $MO$     | Multisuperframe order |
| $SO$     | Superframe order |

| Proprietary Parameters |
|------------------------|
| $CM$                   | CAPs per multisuperframe |
### Notation Description

| Notation | Description |
|----------|-------------|
| CTM      | CAP’s time slots per multisuperframe |
| GB       | GTSs per beacon interval |
| GS       | GTSs per superframe |
| MB       | Multisuperframes per beacon interval |
| \( N_{\text{CAP}} \) | Expected number of time slots to send a CAP message |
| \( p_{\text{CAP}} \) | Probability of generating a packet during the CAP |
| SB       | Superframes per beacon interval |
| SbC      | Symbols per CAP |
| SbS      | Symbols per superframe |
| SM       | Superframes per multisuperframe |
| TB       | Time slots per beacon interval |
| \( T_{\text{CAP}} \) | Expected time to send a CAP message (symbols) |
| \( T_{\text{Ch}} \) | Expected channel access time (symbols) |
| \( T_{\text{ChCAP}} \) | Expected channel access time for a packet generated during the CAP (symbols) |
| \( T_{\text{ChCFP}} \) | Expected channel access time for a packet generated during the CFP (symbols) |
| TM       | Time slots per multisuperframe |
| TS       | Time slots per superframe |
| \( \alpha \) | Smoothing parameter of OpenDSME scheduler |
| \( \delta \) | Packets per second |
| \( \eta \) | Ratio of superframes to CAPs per multisuperframe |
| \( \tau \) | Fraction of CFP’s time slots a dataframe |

### 1 Introduction

The IEEE 802.15.4 standard is the leading adopted networking specification for applications of the Internet of Things (IoT). While the specification has been primarily designed with the goal of lowering the energy consumption of devices, recent extensions focus on improving reliability, robustness and latency. To ensure transmission reliability and the timeliness of wireless communication various MAC protocols have been devised. The main objective is to prevent interference caused by concurrently transmitting devices out- and inside of the network. A common approach against the former type of interference is frequency hopping, whereas reservation schemes are a means against the latter type. The underlying idea of reservations is to exclusively reserve some resources – time, frequency, etc. – for each node so that no interference occurs. Examples are SDMA, FDMA, and TDMA schemes. While these schemes can provide a high degree of reliability they also have some downsides. The main issue is when and how to perform reservations. They can be made statically or dynamically and they can be performed in a distributed fashion or by a central entity.

Static schedules have the disadvantage that the topology and the traffic characteristics must be known up front. If traffic patterns change over time, then this can lead to a waste of resources when reservations are not fully utilized or on the other hand to a shortage of resources implicating an increase of latency or in the worst case a buffer overflow and hence, lost packets. To support fluctuating traffic patterns such as bursts of packets in a timely manner, reservations must be made dynamically and in a distributed fashion. To allow all nodes to make new reservations or withdraw existing ones at all times, IEEE 802.15.4 provides a mode where time is divided into two parts: contention free period (CFP) and a contention access period (CAP). The handling of reservations is done during the CAP while the CFP is divided into time slots of equal length called guaranteed time slots (GTS). A pair consisting of a GTS and a valid frequency can be reserved for a particular link in such a way that links which have been allotted the same pair are spatially separated such that no interference occurs. Access to the channel in the CAP is managed by a CSMA/CA protocol.

In order to have a network-wide understanding of the two periods, time is organized with a fixed frame structure, where frames set out the times for the CFP and the CAP. Furthermore, a time synchronization mechanism is provided that guarantees that all nodes have a common understanding of the frame structure, i.e., each frame starts for each node at the same time. Such a scheme called Deterministic Synchronous Multichannel Extension (DSME) was set up in the IEEE 802.15.4e extension \[4\]. The big advantage of DSME is that the slot allocation mechanism transparently guarantees conflict free schedules, i.e., users are freed from this elaborate task. Various integral configuration parameters such \( SO, MO, BO \) of DSME allow to define the length of a slot, the internal structure of a frame, and the frequency...
of time synchronization. The values of these parameters have to be chosen according to the needs of the application, e.g., size of data packets, latency, etc. See [11] for a discussion.

The objectives of a high degree of agility and a high throughput are conflicting. A high throughput demands that the CFP is much larger than the CAP, because application data is only sent during the CFP. Thus, the fraction $\tau$ of CFP’s time slots in a dataframe is a critical value and each application demands its dedicated fraction. High agility is given if the expected waiting time $T_{\text{CAP}}$ to send a CAP message is short and that the length of the CAPs are sufficiently long to accommodate the necessary (de)allocations of GTSs.

Currently, the IEEE 802.15.4 DSME has defined two standard operating modes: CAP reduction, i.e., CR and no CAP reduction, i.e., NCR. The fraction $\tau$ in NCR mode corresponds to $\tau/16$ and in CR mode increases to $(15 - 8(2^{\text{MO-2}}))/16$, i.e., $\tau = 0.4375, 0.6875, 0.8125$. From these values it is clear that these two operating modes offer extremely different fractions. This does not allow an optimal usage of resources for a wide spectrum of applications. If the fraction $\tau$ is high, then there is little time to make new reservations or to withdraw existing reservations. Thus, high fluctuations are not well supported. On the other hand, in times with constant traffic rates there is no need for a large CAP and valuable time lies wasted. The problem is intensified by the fact that the configuration parameters of DSME cannot be easily changed dynamically.

The goal of this work is to extend DSME such that the fraction $\tau$ can be changed with a fine granularity and that changes can be performed dynamically, i.e., after the deployment of the network. We present two new mechanisms that allow more flexibility in setting up the fraction $\tau$ and therefore provide a better support for dynamically varying traffic. The first mechanism – Alternating CR (ACR) – operates alternating between CR to NCR every $\tau$ and therefore the actual number of CFP’s time slots per $B/T$ varies depending on the operating mode that ACR is working. Then, ACR’s $\tau$ is the mean of fraction $\tau$-values of CR and NCR. The second mechanism – Dynamic CR (DCR) – allocates GTS in CAPs locally according to the GTS demands of individual nodes. The higher the demand for GTSs the shorter will be the available CAP in superframes. DCR allows in principle to adopt any fraction $\tau$-value between the fraction $\tau$-values of the two modes CR and no NCR. While ACR is far easier to implement and remains within the original standard, DCR is more flexible with respect to the fraction of CFP’s time slots in a dataframe.

We demonstrate, through a theoretical analysis and a series of simulations, that the two approaches considerably expand the flexibility of DSME. The evaluation was made in terms of packet reception rate, mean queue length and the maximum number of allocated GTSs. We show that data collection applications with different demands with respect to agility and throughput can be satisfied by choosing the right strategy. We believe that this work considerably broadens the range of applications that can be optimally supported by DSME.

2 Related Work

A comparative performance analysis of IEEE 802.15.4 and DSME has been carried out in several works [2, 5, 8, 10]. The analysis in [2] and [8] also covers the Time-Slotted Channel Hopping (TSCH) MAC layer. The former work shows that DSME and TSCH outperform IEEE 802.15.4 in scenarios with real-time requirements. The study of DSME shows that CR improves latency and throughput in applications with strict demands. At the same time the energy consumption is higher than NCR mode, since nodes operate in high duty cycles. The latter work remarks the effectiveness of the multichannel feature of DSME in terms of delay. Furthermore, simulation results demonstrate an increased network throughput of about 7% with CR compared to NCR. This is, CR rises GTS bandwidth and enhances the scalability of the system.

Jeon et al. evaluate in [5] single and multihop topologies. In both cases, the reachable throughput in DSME is higher (e.g. in multihop topology is about twelve times when CR is enabled) than the throughput obtained in IEEE 802.15.4. A scenario under interference from IEEE 802.11b wireless networks is analyzed in [10]. Mainly, given the channel diversity capability of DSME, the adaptability to varying traffic load conditions, and the robustness of DSME to interference from wireless LANs (WLANs), it is demonstrated a better performance of DSME over IEEE 802.15.4. This finding is supported by an almost invariant frame error rate (FER) for DSME. Even enabling CR improves slightly the FER, since interference over channels does not change. In terms of throughput, the CR mechanism shows a better performance for all tested cases.

A simulative evaluation of DSME in openDSME [7] is made by F. Kauer in [6]. Results evidence the influence of the parameter $\text{MO}$ in conjunction with CR in the overall network throughput. This is, throughput increases with increasing $\text{MO}$. However, higher values of $\text{MO}$ represent not only a larger number of available GTS, but also a severe reduction of the total CAP phase, in which the network is unable to handle the amount of management traffic. In terms of energy consumption, it is shown that for higher $\text{MO}$ the total power consumed by nodes is reduced.
Regarding the impact of CR in DSME, Vallati et al. [13] analyze it from the perspective of network formation. The authors propose an active backoff mechanism and appropriate selection of configuration parameters, that along with CR aim to reduce setup time up to a 60%. In the same direction, a dynamic multisuperframe tuning technique (DynaMO) in conjunction with CR is proposed in [9]. DynaMO was evaluated in openDSME showing a latency reduction up to 15-30% in a large scale networks.

3 Overview of DSME

DSME is a deterministic and synchronous MAC-layer protocol, which guarantees global synchronization and network parameter dissemination through beacon messages. The essential parameters are beacon order (BO), multisuperframe order (MO) and superframe order (SO). Beacons are repeated over time every beacon interval (BI), with a duration of $BI = 15.36 \times 2^{BO}$ seconds. A BI structures time by grouping superframes (SF) into multisuperframes (MSF) as illustrated in Fig. 1. The number of multisuperframes in a BI and the number of superframes in a MSF is calculated as $MB = 2^{BO-MO}$ and $SM = 2^{MO-SO}$ respectively. A SF is further divided in 16 equally sized slots: the first one is for beacon transmission, the subsequent eight slots form the contention access period (CAP) and the remaining seven slots the contention free period (CFP).

DSME operates in the 2.4 GHz band and can use 16 channels with 5 MHz channel spacing with a transmission rate of 62.5 ksymbol/s each (i.e. bit rate of 250 kb/s). In the CAP, the PAN coordinator selects one channel, $C_{CAP}$, that is used by all network nodes to exchange control messages via CSMA/CA. In the CFP, nodes communicate through guaranteed time slots (GTS), which are spread over time and frequency providing exclusive access to the shared medium. A schedule of allocated GTSs is repeated every MSF [4].

The distributed (de)allocation of a GTS between a neighboring pair of nodes is performed in the CAP and follows a 3-way handshake as depicted in Fig. 2. Nodes A and B exchange three messages, a unicast GTS Request and two broadcasts GTS Response and GTS Notify. The GTS negotiation guarantees a common collision-free selection of the tuple (channel, superframe, GTS id). Once neighbors of A and B detect slot inconsistencies by checking their own GTS schedules, the allocation is rolled-back and started again.

The available GTS bandwidth per MSF in NCR mode is $7 \times (2^{MO-SO})$ GTS. It can be increased by enabling the CR mechanism, in which only the CAP of the first SF of each MSF is enabled. Other CAPs are no longer part of the contention access period but belong to the CFP, as illustrated in Fig. 3. Thus, the total number of available GTSs per MSF in CR mode equals $7 + 15 \times (2^{MO-SO} - 1)$ GTS [4].

3.1 OpenDSME at Glance

openDSME [6] is an open-source project that implements features and functionalities of IEEE 802.15.4 DSME in OMNET++. For the development of new CAP reduction mechanisms the scheduling module and the management
of the DSME data structures *allocation counter table* (ACT) and *slot allocation bitmap* (SAB) are of interest. The first one is a distributed scheduling algorithm called *Traffic-Aware and Predictive Scheduling* (TPS). It is based on an exponentially weighted moving average filter, which uses a smoothing parameter $\alpha$ to estimate the required GTSs with respect to the traffic demand per link. A hysteresis feature is utilized to enforce a reduction of the management traffic. Once a link is established between two neighboring nodes, TPS keeps one slot until the *DSME-GTS expiration* timer expires. In openDSME a schedule is updated every *MSF*. The second feature of interest is a module that handles GTS status updates when a GTS negotiation is performed. It ensures the consistency of the ACT and SAB at every point of the negotiation.

4 The Proposed CAP Reduction Mechanisms

The use of CR increases throughput at the cost of reducing the number of the CAPs per *MSF*. As noted in different works [6, 13], a severe reduction of the CAP phase reduces the capability of the network to perform GTS negotiations required to meet fluctuating network traffic demands. This effect is intensified for large-scale networks and higher values of $MO$ since contention is higher and $T_{CAP}$ is prolonged. Shorter CAPs reduce the possibilities for GTS (de)allocations which in turn leads to lower responsiveness and adaptability of the network to changing conditions, e.g., external interference. Therefore, it is necessary to provide a sufficiently long time for exchanging channel states and based on that to schedule GTSs efficiently [12]. Moreover, as noted by Gomes et al. [3], a failure point of DSME is the use of only one channel for sending beacons and control messages in the CAP. Therefore, a mechanism that does not completely rely on the information sent through beacons or in the CAP improves the reliability and robustness of the network.

We propose two CAP reduction mechanisms to overcome these drawbacks. ACR, as explained in Sect. 4.1, works with little modifications of IEEE 802.15.4e DSME standard and offers an efficient but limited way of expanding the number of available GTSs by alternating between CR and NCR.

On the other hand, DCR extends CR, where CAPs shrink and expand dynamically based on the traffic demand of the network. It is fully described in Sect. 4.2.

4.1 Alternating CAP-Reduction (ACR)

ACR operates alternating between NCR and CR every beacon interval. The alternation is not initiated by a central node, e.g., by broadcasting new configuration parameters into the network. Instead nodes know from information encoded in the beacons when to switch mode. The advantage of ACR is a higher GTS bandwidth compared to NCR with the minimum effect on CSMA traffic. That is because switching between CR and NCR is performed systematically, and nodes do not have to exchange additional control messages during the CAP to trigger a change of the operating mode. Moreover, latency does not increase because of a frame structure realignment after each change of the operating mode (i.e., from NCR to CR and vice versa). An advantage of ACR is that it allows to increase the fraction $\tau$ without changing the configuration parameters $SO$, $MO$, and $BO$ because these usually have to be chosen according to the needs of an application.

As part of the initialization, any node except for the root node (i.e. PAN coordinator), which operates in ACR, starts operating in CR to guarantee that CAP phases will be enabled for CSMA traffic and will not be affected by self-interference given by TDMA traffic from nodes already operating in ACR. Then, after association, nodes receive a beacon message from their parents (e.g. PAN coordinator or coordinators), in which the cap reduction field is retrieved to initialize the network’s operating mode (i.e. NCR or CR). This is also done in subsequent *BI*s. Since nodes know when *BI*s start, the implementation of the alternating behavior of ACR is straightforward. Synchronization is also guaranteed considering that all beacons exchanged in the network are allocated within a *BI*.
Instead of drastically reducing the CAP frequency per MSF, as the case for CR, ACR proposes to enable CR in a way that nodes can autonomously and temporarily increase their throughput or can sleep if no data packets are to be sent. Fig. 4 exemplifies the frame structure of ACR for the case $MO = SO + 1$ and $BO = MO$. This is, two $SF$s constitute a $MSF$ and the $BI$’s length equals that of a $MSF$. ACR does not increase the potential GTS bandwidth provided by CR. In fact, the fraction $\tau$ is incremented by the factor $2.14((2^{MO-SO} - 1)/(2^{MO-SO} + 1))$ compared to the fraction $\tau$ of NCR.

### 4.1.1 Scheduling of GTSs.

GTSs in ACR are classified according to the type of access period they belong to: contention access period GTSs (CAP-GTS) or contention free period GTSs (CFP-GTS) (as depicted in Fig. 4). They form the GTS bandwidth and its usage can be addressed in two ways: by defining separate schedules according to flow priorities or by allocating GTSs from the reduced CAPs as overprovisioning. The first approach introduces the concept of flows, that at higher layers (e.g. routing) allow to manage different schedules depending on the priority of packets that should be sent (i.e. high priority for flows with a period of $T_{flow} \leq BI$ seconds and low priority otherwise). This flow differentiation can be achieved with separate schedules by allocating GTSs from the CFPs (CFP-GTS) to high priority and CAP-GTS to low priority flows respectively. The second approach schedules CAP-GTS to deliver queued packets or to perform packet retransmissions as soon as possible. For the evaluation in this work, the second alternative is tested.

### 4.1.2 Specifics of ACR implementation in openDSME.

The implementation relies on the management of enhanced beacon information sent every $BI$. Specifically, the CAP reduction field (i.e. bit 6) contained in the DSME Superframe Specification of the DSME PAN Descriptor IE. In conjunction with the CAP reduction field, ACR introduces a local Boolean variable in the BeaconManager module to enable the alternating behavior after reception of the first beacon message. Thus, nodes can determine the operating mode for the next $BI$s. Reliability is guaranteed through verification of the operating mode via the cap reduction field of beacon messages received from the corresponding parent node. Another implementation aspect is the (de)allocation of GTSs from reduced CAPs, i.e., CAP-GTSs. In this work, CAP-GTSs are used to deliver queued packets or perform packet retransmissions. Therefore, the scheduler of OpenDSME makes no difference between CFP-GTSs and CAP-GTSs to estimate the number of required slots. However, allocation of CFP-GTS has priority over CAP-GTS given their higher frequency. Once all CFP-GTSs are allocated, CAP-GTSs are negotiated. Deallocation of GTSs follow the opposite order, i.e., a CAP-GTS have a higher priority than a CFP-GTS.

### 4.2 CAP-Dynamic Reduction (DCR)

DCR starts in NCR mode and is triggered when all GTSs in the CFPs are depleted, i.e., allocated. At this point, DCR allocates additional GTSs during CAPs through the standard DSME 3-way handshake. For this, two allocating nodes, $v$ and $w$, negotiate a GTS during the last time slot of a random $SF$’s CAP, shrinking it from that moment on. The last slot is chosen because GTS negotiations are triggered at the start of CAPs in openDSME and thus the first slots of a CAP are usually busier than the last slots. Choosing a random CAP ensures that CAPs are reduced evenly and about the same time is available for GTS negotiations during all portions of a $MSF$. Thereby, DCR does not affect the first CAP of a $MSF$. The channel $C$, is chosen so that $C \neq C_{\text{CAP}}$. Therefore, communication during the new GTS does not interfere with regular CAP traffic. All nodes, except $v$ and $w$, can use the CAP normally with the restriction that they cannot communicate with $v$ or $w$ during the allocated GTS. This means, DCR reduces CAPs locally, as illustrated in Fig. 6. After the first allocation of DCR, node $v$ and node $H_C$ have reduced their CAP by one slot, while node $w$ can use one less CAP slot for communication with them but all CAP slots for communication with other nodes. The rest of the network remains unaffected. Optionally, $w$ can hold back messages to node $H_C$ during the allocated GTS and
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Figure 5: Frame structure using DCR \((MO - SO = 1)\). The allocation order for GTSs during the CAP is illustrated.

send those during the next CAP to reduce traffic. Without this optimization, messages to \(v\) or node \(H_c\) would be lost, since they listen on a different a frequency. The message would then be repeated in the next CAP.

Based on the traffic demand of the network, DCR continues allocating additional GTSs during CAPs until CR mode is reached. That means, the first CAP of every MSF is not affected to ensure that GTSs can be deallocated again. This way, up to \(8 \times (2^{MO-1} - SO - 1)\) additional GTSs can be allocated. The resulting frame structure of DCR is illustrated in Fig. 5, where the first CAP of a MSF is immutable, while GTSs can be allocated in the other CAPs, starting with the last time slot of a CAP. The deallocation of GTSs works exactly the opposite way until all GTSs in CAPs are deallocated. However, as illustrated in Fig. 5, CAPs can become fragmented during GTS deallocation, e.g., if the first and third GTS allocation was done by one node and the second GTS allocation was done by another node. Then, the deallocation of the second GTS results in a split CAP. A solution for this is the relocation of the third GTS to a later time slot. This behavior is currently not implemented, but also not mandatory as timers are stopped outside of CAP slots and therefore no timeouts for CAP messages should occur.

4.2.1 Scheduling of GTSs.

The above mentioned modification of CR provides opportunities for more sophisticated scheduling algorithms. For example, a scheduler could decide to allocate additional GTSs during the CAP if the traffic demand is high but deallocate GTSs again if the PRR of the CAP traffic falls below a certain threshold, e.g., when traffic fluctuations appear. Additionally, a modification of the scheduler has to be done. It has to be ensured that GTSs during the CFP and CAP are managed according to the description above. That means, the scheduler first allocates GTSs during the CFP until they are depleted and then starts allocating additional GTSs during the CAP.

4.2.2 Specifics of the DCR implementation in openDSME.

It must be mentioned that there is a storage overhead for DCR because it requires larger data structures (SAB and ACT) for storing information about the \(8 \times (2^{MO-1} - SO - 1)\) additional GTSs. Even if no CR is active, nodes must use the SAB and the ACT of the CR mode for storing their GTS information. That is because the size of the structures in DSME cannot be changed dynamically but they are determined during network configuration. There is no way to estimate if slots will be allocated during the CAP using DCR, since the decision is purely based on the current traffic demand of the network, so that the data structures always have to include the potential GTSs during the CAPs. At last, it has to be said that DCR is not conform with the IEEE 802.15.4 standard and openDSME requires larger code modifications to allow the allocation of GTSs during the CAP. For example, the transceiver cannot be turned on and set to a single frequency for the duration of the whole CAP anymore, but it has to be checked if the next time slot is a GTS and the frequency has to be adapted accordingly. This changes how GTSs are handled. The default behavior at the end of a GTS is to turn off the transceiver. Now, if the GTS was inside a CAP, the frequency has to be switched back to \(C_{CAP}\) and the transceiver has to stay on. This does not increase energy-consumption as the transceiver of nodes must be turned on during the whole CAP.

4.3 An example of ACR and DCR in DSME

Fig. 6 shows an example of how the two proposed CAP reduction mechanisms work. Here two nodes \((v\) and \(w)\) send messages to the coordinator \((H_c)\). The GTS during the CFP are already completely allocated, as illustrated in the schedules for the two mechanisms.

With ACR, nodes switch between CR and NCR every \(BI\), and information about the current operating mode is retrieved through beacons received from \(H_c\). As it is shown in this example, during the \(BI\) at time \(t\), represented in the first row, nodes operate in NCR. During that \(BI\), a total number of 28 GTSs can be allocated. Then, during the next \(BI\) at time \(t + BI\), in the second row, nodes alternate their frame structure to CR with a maximum of 44 usable GTSs. This alternating behavior allows nodes to allocate extra GTSs in the extended CFPs. ACR would even work if the beacon from \(H_c\) is not heard by, e.g., \(v\) because nodes also keep track of time themselves and can switch between CR and
**Figure 6:** Example of ACR and DCR making more GTS resources available in a network with 3 nodes ($BO - MO = 1, MO - SO = 1$).

NCR autonomously after they heard the first beacon, immediately after the association to the network is completed. Additionally, ACR allows static schedules because the frame structure is completely deterministic (i.e. every BI, the frame structure switches from CR to NCR or vice versa).

For DCR, additional GTS resources are created through the DSME 3-way handshake when all GTSs during CFPs are allocated. Here, $v$ allocates an additional GTS with $H_c$. For the new GTS, the CAPs of $H_c$ and $v$ are locally reduced and a GTS is allocated on a different channel than $C_{CAP}$. This way, $w$ can continue using all CAP slots for communication with nodes other than $v$ and $H_c$ (which are not shown here). The benefit is that the number of additionally created GTSs is a direct effect of the traffic load and therefore no unused GTS during the CAP occur.

## 5 Metrics and Hypotheses

There is a number of relevant metrics for the evaluation of the proposed CAP reduction mechanisms. These include, at an abstract level, the adaptability of DSME with respect to time varying traffic and the fraction of CFP’s time slots in a dataframe, i.e., the fraction $\tau$. Adaptability refers the time for (de)allocating a GTS. That is because the proposed mechanisms try to increase the potential throughput while maintaining responsiveness and reliability. For the simulative evaluation also the packet reception ratio (PRR), mean queue length, the maximum number of allocated GTS and dwell time are relevant as they indirectly represent adaptability and throughput of DSME.

It can be expected that overall performance of the described CAP reduction mechanisms strongly depends on the difference $MO - SO$, since the two parameters directly control the number of SF per MSF and thus the frequency of the CAPs per MSF. An analysis of this difference can be made considering two cases: Varying MO while fixing SO or varying SO while fixing MO. The former keeps the slot length constant and for each increment of MO, the length of the MSF as well as the number of CAPs per MSF is doubled. The latter preserves the length of the MSF, and each increment of SO doubles the slot length and halves the number of CAPs per MSF.

In case of CR the CAP frequency per MSF is always equals 1. Therefore, for a fixed SO, increasing MO means enlarging the MSF length and thus increasing $T_{CAP}$. In other words, as the difference between MO and SO increases, CR performs worse as there are not enough CAPs to (de)allocate all GTSs in time. For a fixed MO, decreasing the value of SO increases SM by reducing the length of the SF and therefore the length of CAPs. Thus, as the difference between MO and SO increases, CR’s performance degrades, because the reduction of time in CAPs diminishes the capability of the network to (de)allocate GTSs to adapt rapidly to fluctuating traffic.

On the other hand, differences between MO and SO should not have an strong effect for NCR. This is, because either fixing SO or MO, the number of CAPs per time stays invariant. In some scenarios (e.g. highly varying traffic), MO could be an influencing parameter because it determines the period in which the scheduler updates the number of required GTSs to adapt to traffic changes in the network. Thus, the higher MO the lower the responsiveness of the network to rapid traffic changes over time. In case of the scheduler of openDSME, it uses hysteresis and a smoothing
parameter, $\alpha$, to manage effectively such traffic fluctuations in the network. Therefore, the parameters $MO$ and $SO$ should not have a significant influence on NCR as stated above.

In ACR, the alternation between CR and NCR every $BI$ guarantees that the average amount of time in CAPs is enough to accomplish the required GTS (de)allocations to meet traffic demands. Moreover, the scheduling strategy guarantees stability because it first allocates CFP-GTS and then CAP-GTS, which are less frequent over time. Therefore, as well as NCR, we do not expect higher changes in ACR’s performance given by differences between $MO$ and $SO$. DCR should converge to CR or NCR, depending on which one performs better, and should even exhibit a better performance for a large difference between $MO$ and $SO$.

### 6 Theoretical Evaluation

The goal of the proposed CAP reduction mechanisms is to increase the throughput while maintaining adaptability to time varying traffic. We consider mainly two metrics:

1. the fraction $\tau$ and
2. the adaptability of DSME expressed in two correlated variables:
   - the expected time to send a CAP message, $N_{CAP}$, on time slot level and
   - the expected channel access time, $T_{Ch}$, on symbol level, that a node has to wait to perform a GTS negotiation during the next CAP.

Both metrics strongly depend on the average number of CAPs per $MSF$, $CM$, and the average number of CAP’s time slots per $MSF$, $CTM$. For example, CR mode is characterized by $CM = 1$ and $CTM = 8$, a single CAP per $MSF$ with 8 time slots. Thus, CR heavily sacrifices adaptability for a higher throughput, which is especially problematic if not all GTSs are utilized, because they could have been used for CAP traffic. The proposed mechanisms attempt to overcome this problem by modifying $CM$ (ACR) and $CTM$ (DCR) in an appropriate manner.

#### 6.1 The fraction $\tau$ of CFP’s time slots in a dataframe

The parameter $\tau$, can be calculated based on $CM$ and $CTM$ as

$$
\tau = \frac{TM - CTM - SM}{TM},
$$

where $TM = 16 \times SM$ is the total number of time slots in a $MSF$. Subtraction of $SM$ is required to account for $SM$ beacon slots per $MSF$. Therefore, the fraction $\tau$ increases for decreasing values of $CTM$, as illustrated in Tbl.2. NCR is independent of $MO$, while CR converges towards 93.75% as $MO$ increases. ACR offers a compromise between NCR and CR. Similarly, DCR dynamically adapts the time for sending packets with the lower bound equal to NCR and the upper bound equal to CR.

| $MO$  | NCR   | CR     | ACR   | DCR              |
|-------|-------|--------|-------|------------------|
| 4     | 43.75% | 68.75% | 56.25% | 43.75% - 68.75%  |
| 5     | 43.75% | 81.25% | 62.5%  | 43.75% - 81.25%  |
| 6     | 43.75% | 87.5%  | 65.63% | 43.75% - 87.5%   |
| 7     | 43.75% | 90.06% | 67.19% | 43.75% - 90.06%  |

Table 2: Values of the fraction $\tau$ for sending packets with NCR, CR, ACR, and DCR for $SO = 3$ and $4 \leq MO \leq 7$.

#### 6.2 Metrics to evaluate the adaptability of DSME

The adaptability of DSME is characterized by the expected time to allocate a new GTS, i.e., the expected time until a GTS-handshake can be conducted in a CAP. In contrast to the fraction $\tau$, which gives an idea of the maximum throughput of a system, adaptability gives an idea of how long it would take to allocate all required GTSs. Additionally, it provides an insight into how well the system adapts time-varying traffic. Therefore, we define the following two metrics to determine the agility of DSME:

#### 6.2.1 Expected time to send a CAP message on time slot level.

Since a time slot is a baseline unit in DSME’s frame structure, we consider it to estimate adaptability in terms of the expected number of time slots that a node should wait to send a CAP message, i.e. $N_{CAP}$. This value can be calculated per $MSF$ as
Thus, the expected number of time slots to send a CAP message in NCR is characterized by \( N_{\text{CAP}}(SM, 8 \times SM) \), which is independent of \( MO \) with a value of 2.25 time slots. For CR this value is given by \( N_{\text{CAP}}(1, 8) \) and is therefore dependent on the difference between \( MO \) and \( SO \). As shown in Tbl. 3, the expected waiting times to send a CAP message increase exponentially for an increasing \( MO \). For ACR, \( N_{\text{CAP}} \) is calculated as an average of the expected times for CR and NCR, since the first phase of ACR is CR and the second phase is NCR. The value amounts to \( 0.5 \times (N_{\text{CAP}}(SM, 8 \times SM) + N_{\text{CAP}}(1, 8)) \). DCR dynamically adjusts the number of additional GTSs between NCR and CR so that the expected times are bounded by the expected times of these mechanisms.

### 6.2.2 Expected channel access time on symbol level.

The expected channel access time for CAP messages on symbol level, i.e. \( T_{\text{Ch}} \), evaluates the adaptability of DSME as it describes the time until a node is able to send a CAP message and initiate a GTS (de)allocation. In the following, a single channel access without contention is considered where the corresponding packet is generated according to a uniform distribution on the interval \([0, MD]\). Two cases have to be considered: packet generation during the CFP and packet generation during the CAP. For the calculation, beacon slots are treated as CFP slots in which no data is sent.

#### During the CAP: The probability, \( p_{\text{CAP}} \), for generating a packet during a CAP is given by

\[
p_{\text{CAP}} = \frac{CTM}{TM}.
\]

The system can be discretized in time steps, \( aUB \), of \( aUnitBackoffPeriod \), the base duration for the CSMA/CA algorithm. If a packet is generated at the end of the CAP, its transmission is more likely to be shifted to the next CAP. The system can be discretized in time steps,

\[
N_{\text{CAP}}(CM, CTM) = \sum_{i=1}^{TM-CTM} \frac{i}{TM}.
\]

where \( BE \) is the backoff exponent of the CSMA/CA algorithm, \( SbS = 16 \times 60 \times 2^{SO} \) is the number of symbols per SF, \( SbC = \frac{CTM}{CM} \times 60 \times 2^{SO} \) is the number of symbols per CAP, and \( \eta = \frac{SM}{CM} \) is a stretching factor if \( CM < SM \) under the assumption that CAPs are evenly distributed in the MSF. In other words: Eq. (4) calculates the expected backoff from a given slot for all possible CSMA/CA backoff values. The total backoff, \( B \), equals to the CSMA/CA backoff \((i \times aUB)\) if there is enough space in the CAP. Otherwise, it includes the wait duration of the CFPs. In this case (Eq. (5), case otherwise), the first summand is the backoff until the next CAP from the time of the packet generation, the second summand is the remaining backoff time in a latter CAP, and the third term adds the backoff for multiple superframes if \( i \times aUB \) spans over multiple CAP phases. The expected channel access time, \( T_{\text{ChCAP}} \), for a packet generation during the CAP can then be calculated as

\[
T_{\text{ChCAP}} = \frac{\sum_{s=0}^{aUB \times CM} T_{b}(s)}{CTM/(aUB \times CM)}.
\]

#### During the CFP: When a packet is generated during the CFP, the expected channel access time is the combination of the expected time to send a CAP message, i.e. \( T_{\text{CAP}} \), and the expected CSMA/CA backoff time from slot 0. The
expected time to send a CAP message on symbol level is given by \( T_{\text{CAP}} = 0.5 \times (T_{\text{CAP,min}} + T_{\text{CAP,max}}) \), where \( T_{\text{CAP,min}} = 1 \) is the minimum time to send a CAP message and \( T_{\text{CAP,max}} \) is the maximum time to send a CAP message and given by

\[
T_{\text{CAP,max}} = \eta \times SbS - SbC
\]

The expected channel access time, \( T_{\text{ChCFP}} \), for a packet generated during the CFP is \( T_{\text{ChCFP}} = T_{\text{CAP}} + T_b(0) \).

The expected channel access time, \( T_{\text{Ch}} \), is then given by

\[
T_{\text{Ch}} = p_{\text{CAP}} \times T_{\text{ChCAP}} + (1 - p_{\text{CAP}}) \times T_{\text{ChCFP}}.
\]

The expected channel excess time for different values of \( CM \) and \( CTM \) is shown in Fig. 7. Here, one can see that ACR achieves a much lower expected channel access time than CR mode. Therefore, the adaptability with ACR is higher. It can be seen that the expected channel access time scales exponentially with a decreasing CAP frequency and ACR operates at the part where a good adaptability is still given. In contrast to that, DCR reduces the number of slots in individual CAPs. Therefore, the expected time to send a CAP message is always quite low. However, in extreme cases all CAP slots might be allocated and DCR performs as CR in terms of expected channel access time.

### 7 Scenario Description

A common DSME application scenario is data-collection using the converge-cast pattern. In this pattern, routing is performed along an oriented tree with the sink as the root. Therefore, we use this scenario as a use case. In particular we use a rooted binary tree topology with 31 nodes. We abstained from using an unbalanced tree to eliminate the influence of heavily skewed traffic. Also this topology allows to analyze the behavior of nodes with different loads, because the traffic load increases exponentially from the leaves to the sink. All nodes except the sink generate an average of \( \delta \) packets per second and forward them along the edges of the routing tree to the root. The packet generation follows a Poisson distribution with mean \( \lambda \) and a 1 second observation interval to model the dynamic behavior of nodes. Two packet generation patterns are considered:

1. Generation of packets with \( \lambda = \delta \) packets.
2. Generation of packets in bursts of size \( \delta \) and \( \lambda = 1 \) burst.

The first scenario allows the assessment of the network close to saturation because traffic is pretty stable. In the second scenario (bursty traffic), the proposed CAP reduction mechanisms have to (de)allocate GTSs continuously and adjust to the current traffic demand of the network.

As discussed in Sect. 5 and Sect. 6 all CAP reduction mechanisms only depend on the difference \( MO - SO \). Therefore, either \( SO \) or \( MO \) can remain constant for simulation. We set \( SO \) to \( \delta \) so that a single packet with 127 bytes can be sent
per GTS. Furthermore, it insures that all CAPs have the same length for all configurations. If not stated otherwise, we also fixed $BO = 7$ to guarantee sufficiently many beacon slots in the network for all nodes to associate. The scenario is evaluated for $4 \leq MO \leq 7$. Each node’s queue is divided in a CAP queue of length $Q_{CAP}$, and a GTS queue of length $Q_{GTS}$, with a combined total capacity of 30 packets. Table 4 summarizes the setup of the simulation. For each configuration, 20 runs are conducted and results are shown with a 95% confidence level. Simulations are done using OMNeT++ and openDSME.

| Parameter | $SO$ | $MO$ | $BO$ | $\alpha$ | $Q_{CAP}$ | $Q_{GTS}$ | $\delta$ |
|-----------|------|------|------|----------|----------|----------|---------|
| Values    | 3    | [4, ..., 7] | 7    | 0.1      | 8        | 22       | [1, ..., 4] |

8 Simulative evaluation

In the following, we present a performance assessment of the proposed mechanisms by comparing them with NCR and CR. Performance metrics include the packet reception ratio (PRR), the mean queue length and the maximum number of GTSs allocated. Additionally, the adaptability to time varying traffic metric as explicated in Sect. 6 is also evaluated by simulation. It corresponds to the GTS-negotiation message dwell time. Dwell time is the time between the generation of a message and its transmission, including queuing delay. Therefore, it provides an insight into a system’s adaptability because the system adapts to changes in traffic faster by (de)allocating GTSs if the respective control messages have a lower dwell time.

8.1 Varying burst sizes

Fig. 8 shows the average packet reception ratio (PRR) for an increasing $\delta$ and different values of $MO$ with $\lambda = 1$ burst. For all methods, the PRR decreases for an increasing number of packets per burst. This is mainly due to the following reason: especially for smaller values of $MO$, there are not enough GTSs per second to accommodate all packets generated during a burst, leading to dropped packets as the queues fill up.

In case of CR, the frequency of CAPs decreases for an increasing $MO$, resulting in more contention during the remaining CAPs. Thus, the required GTSs cannot be allocated in time. This is the case of $MO = 5$, where fraction $\tau$ equals 81.25%. From this theoretical value, a high PRR was expected. However our results show that for an increasing number of packets per burst CR is very sensible to high traffic loads.

The performance of NCR is independent of $MO$, as already indicated by the theoretical analysis in Sect. 6. Therefore, the choice of CR or NCR depends largely on $MO$, as CR performs better than NCR for $MO = 4$ and $MO = 5$, but NCR performs better for $MO = 6$ and $MO = 7$. If $SO = MO = 3$, all mechanisms perform equally well, since there is only a single SF per MSF, which cannot be reduced by DCR or CR.

On the other hand, DCR performs similarly to CR for $MO = 4$ and outperforms CR and NCR for $MO \geq 5$. That is because DCR starts with NCR mode and therefore allocates GTSs as fast as possible (e.g., as fast as NCR) for larger values of $MO$ where there is only a small number of CAPs for CR. In addition, it reduces CAPs when all regular GTSs are already allocated so that it converges towards CR. However, the allocation of these additional resources has a slight time overhead, resulting in the performance gap between DCR and CR for $MO = 4$.

Similarly to CR, the performance of ACR depends on $MO$ but its influence is not as strong as for CR. For smaller values of $MO$, ACR’s PRR is about the average between values for CR and NCR. It corresponds to the theoretical analysis regarding $\tau$, with boundaries delimited by CR and NCR (e.g. $\tau = 56.25\%$ for $MO = 4$). For larger values of $MO$ (i.e. $MO \geq 6$), the PRR is less sensible to this parameter, performing even better than NCR. This is because of the alternating behavior every $BI$, which provides enough CAPs to perform the required GTS negotiations. Moreover, the fact that ACR allocates first CFP-GTS and then less frequent GTSs (i.e. CAP-GTS) is a key aspect in the performance of this mechanism.

All in all, ACR and DCR seem to be attractive alternatives to DSME under varying traffic patterns. The former because it combines the strengths of CR and NCR mechanisms in one approach. The latter because it dynamically adapts to the traffic demands of the network and (de)allocates additional GTSs during CAPs to increase reliability.

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8.2 Varying packet generation rates

The following figures show a performance assessment for different packet generation intervals, which correspond to $1/\delta$ seconds. Particularly, Fig. 9 depicts the PRR for different values of $MO$. As already explained in Sect. 8.1, the choice of CR and NCR largely depends on $MO$, with CR performing better for $MO \leq 5$ and NCR performing better for $MO \geq 6$. NCR, ACR and DCR provide a good performance for $\delta \leq 1$ and all values of $MO$. For $\delta > 1$ NCR is operating beyond the maximum capacity and ACR starts to reach the limits of the capacity of available GTSs. Therefore, performance of NCR and ACR is diminished. Contrary to NCR, ACR's PRR is also slightly affected by increasing $MO$. DCR performs significantly better than the other CAP reduction mechanisms, especially for larger values of $MO$. E.g., it achieves a PRR of 95% for $MO = 7$ and $\delta = 3$, while NCR achieves only about 48%, ACR about 67% and CR less than 2%.

The main reason for lost packets are queue drops. This is also reflected by the average queue length, as shown in Fig. 10. Here, nodes with the same distance from the sink are grouped together, as nodes closer to the sink experience more traffic than nodes further away from the sink. With a maximum $Q_{GTS}$ capacity of 22 packets, it is clearly visible that NCR operates close to the maximum queue capacity at nodes close to the sink for all values of $MO$. That is because the network is over-saturated for a packet generation interval of 0.33 seconds and no more GTSs are available for allocation. For ACR the network is close to the maximum capacity and therefore the average queue length for nodes closer to the sink is significantly higher and close to the maximum queue capacity (i.e. nodes up to 2 hops away from the sink node). This funneling effect is intensified for increasing $MO$, which reduces the frequency of CAPs per $MSF$ in $BI$s in which ACR operates in CR mode. On the other hand, the average queue length for CR increases with an increasing $MO$ because there are fewer CAPs per $MSF$. Consequently, the remaining CAPs are more congested and the required GTSs are not allocated in time. The average queue length for DCR is lower than 68% of the maximum queue capacity for all values of $MO$.

The maximum number of RX- and TX-GTSs allocated by the different CR mechanisms for $\delta = 3$ and different values of $MO$ is illustrated in Fig. 11. Nodes with the same distance to the sink are grouped together, as more GTSs are allocated closer to the sink. For $MO = 4$, less slots need to be allocated because the $MSF$- and thus the schedule of allocated GTSs - is repeated multiple times per packet generation interval. Theoretically, for $MO = 7$ and $\delta = 3$, the number of required GTSs at the sink node to successfully receive all packets generated in the network is about
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Figure 9: PRR of DCR, ACR, CR and NCR for different values of MO and $\delta$.

Figure 10: Average queue length per node for different values of MO and $\delta = 3$. Nodes with the same number of hops to the root are grouped together.
Figure 11: Maximum number of allocated GTSs per node for $MO = 4$, $MO = 7$ and $\delta = 3$. Nodes with the same number of hops to the root are grouped together.

180 GTSs per $BI$ (i.e. assuming that no packet was dropped from any queue). For NCR and CR the highest number of available GTSs per $BI$ amounts to 112 and 232 GTSs respectively. For ACR this value corresponds to the average between NCR and CR, which is about 172 GTSs per $BI$. However, given the funnelling effect that is inherent for data collection scenarios this assumption does not hold. That is, many packets are lost in nodes closer the sink node and therefore the number of allocated GTSs are a bit less than the theoretical value. That is the case for NCR, in which nodes 1 hop further require about 174 GTSs. However, only 112 GTSs can be negotiated. Therefore, about 90 GTSs are allocated at the sink node, which supports the obtained PRR with a value of 47%.

For NCR, one could expect a good performance of the network with these configuration parameters since the average number of available GTSs (i.e. 172 GTSs) should be sufficient to guarantee a low number of packet drops. However, this is not the case because the number of usable GTSs varies over a $BI$. That is, the number of usable GTSs is limited to 112 in one $BI$ – while operating in NCR – and extended to a maximum of 232 GTSs in the next $BI$ – while operating in CR. The effect of this drastic reduction of GTSs from one $BI$ to the other is observed in the large value of the average queue lengths for nodes close to the sink. That is, despite the fact that all usable GTSs are allocated, the higher number of queued packets in the $BI$ operating in NCR leads to queue overflows, specially for nodes closer to the sink node.

For DCR, the largest number of GTS is allocated. Theoretically, CR could reach the same performance as DCR but it fails to allocate the GTS in time, as already explained. Still, DCR performs well for $MO \leq 7$ because it can allocate a large number of GTS at the start and then it successively reduces the CAPs to allocate the last remaining GTSs.

Similarly, Fig. 12 shows the average dwell time with one packet per second for messages sent during GTS negotiation, i.e., $GTS \ Request$, $GTS \ Response$ and $GTS \ Notify$. It can be seen that CR has the highest dwell time because there is only a single CAP per $MSF$, and GTS commands have to be queued for a long time. The dwell time exponentially increases for an increasing $MO$ as the duration of a MSF doubles when incrementing $MO$. ACR comes second in this ranking, which has a similar behavior as CR. Although ACR’s dwell time is influenced by the length of the MSF given by $MO$, this effect is diminished during the $BIs$ in which ACR operates in NCR. It should be noted, that although ACR’s waiting time is higher than DCR and NCR, it is still enough to guarantee adaptability to fluctuating traffic. The validation of ACR’s dwell time by simulation confirm the value estimated theoretically in Sec. 6 and A.2.3. This is the case for $MO = 4$ with an average dwell time of 42.80 ms against 44.64 ms from the theoretical model. In this case, the difference between both values comes from the way the estimation in the theoretical model was performed (i.e. average between NCR and CR). That is, the theoretical model does not take into account the scheduling mechanism implemented for ACR, which reduces on a small scale its dwell time.

DCR and NCR perform equally well, e.g., with an average dwell time of 17.08 ms and 18.06 ms, respectively. For NCR this matches with the value of about 17.28 ms from the theoretical models (Sec. 6 and A.2.1), which do not consider packet collisions. NCR has a higher dwell time than DCR because nodes are unable to allocate enough GTSs (network saturation) but still can send GTS commands for the required GTSs. This results in more congestion during the CAPs and the nodes backing of more frequently during the CSMA/CA algorithm. Both CAP reduction mechanisms are independent of $MO$ with the dwell time only marginally increasing for an increasing $MO$ because more GTSs are required initially for larger values of $MO$ resulting in more contention. For $MO = 3$ all mechanisms perform the same.
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8.3 Summary of results

The following statements summarize the most significant results from Sect. 6 and 8 without claim to completeness. It is assumed that the configuration parameters MO and SO are fixed before the simulation according to the needs of the application. We evaluated the capability of the proposed CAP reduction mechanisms to support fluctuating traffic in comparison with the NCR and CR modes provided by DSME. To this end, we tested two different packet generation patterns: varying burst sizes and varying packet generation rates with δ packets per second. Results are given from a data collection scenario for a binary tree topology with 31 nodes.

- **NCR** provides good adaptability for all values of MO − SO. However, for a large number of packets per second (δ > 2), NCR cannot provide a sufficient number of GTSs for sending all packets. This results in a large number of dropped packets due to full queues.

- **CR** performs well for MO − SO ≤ 2. Here, a single CAP per MSF is sufficient to allocate all required GTSs and CR still offers a higher throughput which increases the overall PRR. For MO − SO ≥ 3, the performance of CR diminishes since it is unable to allocate all GTS in time, resulting in large queues and packet loss.

- **ACR** offers a compromise between CR and NCR, which is reflected in its performance. For MO − SO ≤ 1, it performs as a middle ground between CR and NCR. For MO − SO ≥ 2, ACR starts to outperform the standard modes of DSME because it offers a higher adaptability than CR and a higher throughput than NCR.

- **DCR** achieves the best overall performance in terms of PRR, dwell time, and queue utilization for all differences MO − SO and different packet generation rates. That is because DCR starts in NCR mode which offers a high adaptability. Then it gradually and dynamically reduces the CAP to allow for a higher throughput. Notably, it manages to achieve a PRR of over 80% regardless of the value of MO − SO in a scenario without bursts and therefore outperforms the standard modes of DSME.

9 Conclusion

One of the pillars of the Internet of Things (IoT) is a robust and reliable wireless communication infrastructure. The IEEE 802.15.4 Deterministic and Synchronous Multi-Channel Extension (DSME) is a MAC protocol that guarantees reliability, scalability and energy-efficiency in WLANs. DSME offers a TDMA/FDMA-based channel access and provides the possibility to assign at run-time the resources time and frequency to individual links in a conflict free way. This allows a continuous distribution of the resources among the network nodes. This way the network can adopt itself to varying communication patterns. The redistribution of resources pursues two conflicting objectives, a high responsiveness towards bursts of packets on the one hand and an efficient utilization of the available bandwidth on the other hand. The first goal calls for a fast channel access for messages that (de)allocate resources. In terms of DSME this calls for long and frequent CAP phases. In contrast the second goal asks for frequent and long CFP phases, such that application packets can be sent with minimal delay and in high number. In DSME the balance between the goals agility and throughput is controlled by τ, the fraction of CFP’s time slots in a dataframe. A high value guarantees a high throughput. While a low value ensures that the expected waiting time to send a CAP message is short. Once DSME is configured according to the needs of an application there are only two different possible values for the fraction τ and these cannot be changed at run-time. In this paper, we proposed ACR and DCR as two extensions of DSME that allow to adopt the fraction τ to the current traffic pattern. We verified theoretically and through simulations that both provide a high degree of responsiveness to traffic fluctuations while keeping the throughput high.
first proposal can be implemented within the original specification the second one requires a deeper intervention. We believe that with these extensions more demanding IoT applications can be realized with IEEE 802.15.4.

The proposed mechanisms ACR and DCR provide the means to build IoT applications that can support fluctuating traffic including bursts. To fully exploit the possibilities they provide, a powerful dynamic scheduler is needed. While openDSME already provides such a scheduler which is based on an exponentially weighted moving average filter to estimate the required GTSs with respect to the traffic demand per link, it remains to develop Minimal Scheduling Functions (MSF) as defined in [1] by the 6TiSCH standardization group for TSCH. MSF is designed for best-effort traffic, where most traffic is periodic monitoring, with occasional bursts. We believe that the extensions proposed in this paper can be leveraged by future Minimal Scheduling Functions for DSME.

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A Analysis of Metrics

Two main metrics are

1. Adaptability to time varying traffic expressed as the expected time to send a CAP message on time slot level
2. Fraction $\tau$ of CFP’s time slots in a dataframe

Since the periodicity of the DSME frame structure is defined in multiples of a beacon interval ($BI$) (e.g. Period of ACR, $T_{ACR} = 2BI$), we analyse these metrics in a period interval for each operating mechanism (i.e. NCR, CR, ACR and DCR).

A.1 Definitions

Let consider the following superframe structures for a network operating in NCR mode (Fig. 13) and CR mode (Fig. 14). The former applies for all superframes of the DSME dataframe structure contained in a $BI$. The latter corresponds to superframes different to the first $SF$ of the first $MSF$ in a dataframe structure. The excluded $SF$ follows the structure depicted in Fig. 13.

Figure 13: DSME superframe structure with NCR

Figure 14: DSME superframe structure with CR

- $TS = 16$: number of time slots per superframe
- $SM = 2^{MO-SO}$: number of superframes per multi-superframe
- $SB = 2^{BO-SO}$: number of superframes per beacon interval
- $MB = 2^{BO-MO}$: number of multi-superframes per beacon interval
- $GB$: number of GTSs per beacon interval
- $GS$: number of GTSs per superframe

A.2 Adaptability to time varying traffic on time slot level

This metric can be characterized in terms of the expected number of time slots to send a CAP message, i.e. $N_{CAP}$. This is, the average waiting time on time slot level to (de)allocate a new GTS. A simple model is as follows: If a node wishes to allocate a new GTS at the beginning of slot number $i$ of a $MSF$, how many slots must the node wait to reach a CAP slot?. In the following, the formulation for NCR, CR, and ACR is presented.

A.2.1 NCR.

For each beacon in a $SF$, the waiting time is one time slot. Therefore, for all beacons in a $BI$ the total waiting time is

$$t_1 = SB \times 1$$  \hspace{1cm} (9)

For the CFP time slots in a $SF$, the waiting time is

$$\sum_{i=9}^{TS-1} TS + 1 - i,$$
and then the total waiting time for all CFP time slots in a BI is:

\[ t_2 = SB \times \sum_{i=2}^{TS-8} i \]

From (9) and (10):

\[ t_{total} = t_1 + t_2 = SB \times \sum_{i=1}^{TS-8} i = \frac{SB(TS-8)(TS-7)}{2} \]

Thus, the average waiting time over a BI is:

\[ t_{avg} = \frac{t_1}{SB \times TS} = \frac{SB(TS-8)(TS-7)}{2TS} \]

The only influencing parameter is \( SO \). The following table exemplifies the waiting time in a superframe structure as shown in Fig.1. We can focus on a single SF, because they are repeated over a BI.

| Slot-number | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|-------------|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|
| Waiting time| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8  | 7  | 6  | 5  | 4  | 3  | 2  |

| Slot-number | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
|-------------|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|
| Waiting time| 0  | 0  | 0  | 0  | 0  | 0  | 0  | 8  | 7  | 6  | 5  | 4  | 3  | 2  | 1  |

Hence, the expected waiting time is \( 72/32 = 2.25 \) slots as computed in (12).

### A.2.2 CR.

Only the first SF in a MSF has CAP and the waiting time for its beacon is one time slot. Since there are \( MB \) MSFs, the total waiting time is:

\[ t_1 = MB \times 1 \]

For the other time slots, in all \( MB \) MSFs, the waiting time amounts to:

\[ t_2 = MB \times \sum_{i=0}^{SM \times N-1} (SM \times TS + 1 - i) \]

\[ = MB \times \sum_{i=2}^{SM \times TS-8} i \]

From (13) and (14):

\[ t_{total} = t_1 + t_2 = MB \times \sum_{i=1}^{SM \times TS-8} i = \frac{MB(SM \times TS - 8)(SM \times TS - 7)}{2} \]

From (11) and (13) the average waiting time over a BI is:

\[ t_{avg} = \frac{t_1 + t_2}{SB \times TS} = \frac{MB}{SB \times TS} \cdot \frac{(SM \times TS - 8)(SM \times TS - 7)}{2} \]

\[ = \frac{(SM \cdot TS - 8)(SM \cdot TS - 7)}{2SM \cdot TS} \]
Since $TS = 16$:

$$t_{avg} = 2^{MO-SO+3} + 1.75/2^{MO-SO} - 7.5 \text{ (slots)} \quad (17)$$

For the example shown in Fig. 3 with $MO - SO = 1$ the individual waiting times are as follows

| Slot-number | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|-------------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Waiting time| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 24 | 23 | 22 | 21 | 20 | 19 | 18 | 17 |

| Slot-number | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
|-------------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Waiting time| 16 | 15 | 14 | 13 | 12 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 |

Then, the expected waiting time is $300/32 = 9.375$ slots, that corresponds with the expression found in (17).

### A.2.3 ACR.

In this case a period equals $2BI$. Then, the expected time corresponds to an average of the waiting time for CR (11) and NCR (15) in a $BI$. Then, the total waiting time is:

$$t_{total} = t_{NCR} + t_{CR} = MB \times \sum_{i=1}^{SM \times TS-8} \frac{MB(SM \times TS - 8)(SM \times TS - 7)}{2} \quad (18)$$

From (18) the average waiting time is

$$t_{avg} = \frac{t_1 + t_2}{2 \times SB \times TS} = \frac{SB}{2 \times SB \times TS} \frac{(TS - 8)(TS - 7)}{2} + \frac{MB}{2 \times SB \times TS} \frac{(SM \times TS - 8)(SM \times TS - 7)}{2}$$

$$= \frac{(TS - 8)(TS - 7)}{4TS} + \frac{(SM \cdot TS - 8)(SM \cdot TS - 7)}{4SM \cdot TS} \quad (19)$$

Since $TS = 16$:

$$t_{avg} = 2^{MO-SO+2} + 0.875/2^{MO-SO} - 2.625 \text{ (slots)} \quad (20)$$

For the example in Fig. 4 of ACR the expected waiting time is 5.8125 slots, this value matches with the formula calculated in (20).

For the variant DCR the computation is a bit more difficult, given the dynamism that this mechanism uses. This is, the number of GTSs is changing over time.

The unit for the expected waiting time is time slots, depending on the value of $SO$ this can be converted into ms. This calculation does not respect the fact, that a slot negotiation takes more than one time slot, i.e., if a slot allocation is triggered at the beginning of the last CAP’s time slot, then it will take more time compared to triggering at the beginning of the first CAP’s time slot. Respecting this fact may lead to very difficult computations.

### A.3 Fraction $τ$ of CFP’s time slots in a dataframe

This metric is defined as the fraction of CFP’s time slots in a dataframe, which is bounded in a $BI$. In the following, the formulation for NCR, CR, and ACR is presented.

### A.3.1 NCR.

For each superframe the total number of GTSs is

$$GS = \sum_{i=9}^{TS-1} slot_i = TS - 9$$
Given that the frame structure is the same in all superframes. The total number of GTS per BI is calculated as

\[ GB = SB \times GS \]
\[ = SB \times (TS - 9) \]

Thus, the fraction of CFP’s time slots in a BI is estimated as

\[ \tau = \frac{GB}{SB \times TS} \]
\[ = \frac{SB \times (TS - 9)}{SB \times TS} \]
\[ = \frac{(TS - 9)}{TS} \] \hspace{1cm} (21)

Since \( TS = 16 \), \( \tau = 7/16 = 0.4375 \) and it is independent of values of \( SO, MO, BO \).

### A.3.2 CR.

For CFP’s time slots, the baseline is the number of GTSs per MSF. Then, the total number of GTSs per BI amounts to:

\[ GB = MB \times \sum_{i=0}^{SM \times TS - 1} slot_i - (SM - 1) \times slot_0 \]
\[ = MB \times (SM \times (TS - 1) - 8) \]

The calculation of the fraction \( \tau \) is

\[ \tau = \frac{GB}{SB \times TS} \]
\[ = \frac{MB \times (SM \times (TS - 1) - 8)}{SB \times TS} \]
\[ = \frac{(TS - 1) - 8 \times 2^{SO-MO}}{TS} \] \hspace{1cm} (22)

Since \( TS = 16 \):
\[ \tau = 0.9375 - 2^{(SO-MO-1)} \] \hspace{1cm} (23)

### A.3.3 ACR.

This estimation is made by calculating the average of the fraction \( \tau \) for NCR and CR in 2BI. Then, the fraction of CFP’s time slots in a dataframe is

\[ \tau = \frac{SB \times (TS - 9) + MB \times (SM \times (TS - 1) - 8)}{2 \times SB \times TS} \]
\[ = \frac{SB \cdot ((TS - 9) + 2^{SO-MO}) \times (SM \times (TS - 1) - 8)}{2 \times SB \times TS} \]
\[ = \frac{2TS - 10 - 2^{(SO-MO+3)}}{2TS} \]

Since \( TS = 16 \):
\[ \tau = 0.6875 - 2^{(SO-MO-2)} \] \hspace{1cm} (24)