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Research Article

Constrained Adaptive Exponential Backoff: An Algorithm for Effective RTO Estimation in CoAP

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Abstract: The Constrained Application Protocol (CoAP) has become a widely adopted communication standard for the Internet of Things (IoT) and wireless sensor networks (WSNs). However, its default congestion control mechanism, based on binary exponential backoff (BEB), lacks adaptability to dynamic network conditions. This limitation often results in excessive retransmissions, increased latency, and inefficient energy consumption, particularly in resource-constrained environments. To address these challenges, this study proposes a novel Constrained Adaptive Exponential Backoff (CAEB) algorithm designed to enhance retransmission timeout (RTO) estimation through an adaptive, lightweight approach. CAEB integrates a logarithmic adjustment mechanism and weighting factors based on retransmission count and active node density, enabling real-time adaptability while maintaining computational simplicity. The proposed algorithm was implemented and evaluated in the Cooja simulator using the Contiki operating system under both continuous and periodic traffic scenarios. The experimental results demonstrated that CAEB consistently achieved lower flow completion time, higher throughput, and reduced packet loss and retransmissions compared with BEB, with these improvements confirmed as statistically significant based on the two-sample t-tests ($p < 0.05$) and the Holm–Bonferroni correction method. These findings highlight the effectiveness of CAEB in mitigating congestion and improving reliability in constrained IoT networks. The proposed algorithm not only advances methodological approaches for RTO estimation but also offers practical implications for energy-efficient and scalable IoT communication systems, particularly in applications such as smart agriculture, environmental monitoring, and structural health monitoring, where timely and reliable data delivery is critical.

Keywords: Adaptive backoff algorithm; Constrained adaptive exponential backoff; Constrained application protocol; Congestion control; RTO estimation

1. Introduction

Constrained application protocol (CoAP) is a communication protocol that relies on message exchange and has been widely used in Internet of Things (IoT) devices, especially in wireless sensor networks (WSNs). However, these devices typically operate under resource constraints (Akpakwu et al., 2025; Makarem et al., 2022; Bhalerao et al., 2016; Hassan et al., 2016; Shelby et al., 2014), e.g., limited processing capabilities, small memory capacities, and restricted sources of energy (Verma et al., 2024; Bansal and Kumar, 2020; Bolettieri et al., 2017; Bormann et al., 2014; Yuan et al., 2014). Since WSNs have been widely used across different domains, accurate and reliable communication under resource-constrained environments has also become a critical consideration, especially for IoT devices that require high accuracy and timely response. In this

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regard, CoAP's reliable message transmission plays a crucial role during critical operational periods. CoAP uses message retransmission based on an estimated retransmission timeout (RTO), which determines the time interval before message retransmission if no acknowledgment is received. This mechanism ensures reliable communication and efficient energy use (Wang et al., 2024; Pham et al., 2022; Akpakwu et al., 2021; Swarna and Godhavari, 2020; Akpakwu et al., 2019; Suwannapong and Khunboa, 2019; Betzler et al., 2016; Järvinen et al., 2015). However, the default RTO estimator in CoAP, which relies on the binary exponential backoff (BEB) algorithm that increases the RTO value in a fixed exponential manner, often lacks adaptability to changing network conditions. This limitation can result in unnecessary retransmissions when the RTO is underestimated and excessive delays when the RTO is overestimated, both of which contribute to insufficient energy use due to poor system performance (Hasan and Alisa, 2023; Lim, 2020; Singh et al., 2018; Kovatsch et al., 2014; Lee et al., 2013; Zhu et al., 2011).

The aforementioned challenges and limitations have driven efforts to improve RTO estimation. Previous studies have predominantly focused on modifying the baseline algorithms for the transmission control protocol (TCP), e.g., Jacobson's algorithm (Jacobson, 1988), and the approach outlined in RFC6298 (Paxson et al., 2025). Although proven effective in traditional network environments, they often encounter congestion issues when applied to highly constrained conditions, such as those in WSNs. Later, algorithms that can improve the RTO estimation by incorporating different computational methods have been proposed (Deshmukh and Raisinghani, 2022). However, concerns regarding processing and memory resource requirements remain a barrier to actual communication. Real-time communication or high-frequency data transmission is not always necessary in many IoT devices comprising large numbers of nodes because the observed data often exhibit slow variation over time (Kurniawati et al., 2023; Naeim et al., 2023). In some cases, the data follow identifiable patterns that can be analyzed using observations collected periodically. Examples can be drawn from Smart Agriculture (Zhang et al., 2024) uses technologies and advanced data analytics to enhance agricultural products, reduce operational costs, and mitigate environmental impacts. In environmental monitoring applications (Amerson et al., 2022), sensor networks collect and analyze data such as air and water quality, noise levels, and climate changes. Another related application is wildlife tracking (Horback et al., 2012), which uses IoT-based systems to track animal movement patterns and behaviors, thus allowing for better understanding of migration paths and conservation needs. The other application is structural health monitoring (SHM) (Muttillo et al., 2020), in which IoT and smart sensing technologies can help assess the structural integrity of buildings and bridges over time.

The present study, therefore, proposes the Constrained Adaptive Exponential Backoff (CAEB) algorithm to address the limitations of the already-existing RTO estimators. The algorithm provides an adaptive, lightweight solution that aligns with the resource constraints of IoT devices and has been developed based on real-time analysis of network conditions, e.g., the number of active nodes, current congestion levels, and communication patterns typically observed in IoT devices where real-time or immediate response is often not required, and data transmissions tend to follow identifiable patterns (i.e., period of high and low transmission activity or network traffic density). By considering the aforementioned factors, the proposed algorithm can predict and adapt to the communication patterns observed in a network.

With regard to the significance of the study, CAEB can provide more efficient RTO estimation in CoAP-based communication. This algorithm serves as an alternative to the traditional CoAP that relies on a fixed exponential increase in RTO and hence fails to adapt effectively to changing conditions in IoT networks, causing either excessive delay due to overly conservative RTO estimates or network congestion due to early retransmissions. Additionally, when the number of nodes in the network increases, the packet collision likelihood also increases, which negatively affects the overall communication efficiency. CAEB can solve this problem by estimating the RTO according to the retransmission count and the number of active nodes in the network. This adaptive behavior can mitigate packet collisions and enhance the overall network performance, particularly in large-scale networks with many devices that require stable communication despite fluctuating traffic scenarios. The implementation and experiment of CAEB in the Cooja simulator within the Contiki operational system is also significant. Moreover, the efficiency of the proposed algorithm has been validated and compared to existing algorithms using statistical analysis of key performance metrics, including flow completion time (FCT), throughput, packet loss, and total number of retransmissions.

2. Methods, Background, and Related Work

2.1 Congestion Control in the CoAP

CoAP is an application-layer protocol specially designed for communication under constrained resources, such as in IoT devices with limited memory and processing and energy resources. CoAP features a lightweight architecture and facilitates simple message formats, making it suitable for communication in constrained networks (Shelby et al., 2014). It relies on the user datagram protocol (UDP), i.e., the transport layer protocol for rapid data transmission but with minimal overhead. However, additional mechanisms are required to ensure data integrity and handle network congestion and packet loss during transmission due to the unreliable nature of UDP (Bormann et al., 2012). CoAP incorporates a default CoAP to regulate packet transmission rates using the BEB algorithm to determine the RTO value to address these challenges. The default CoAP operation is illustrated in Figure 1.

2.2 Related Work

As CoAP is designed to operate in constrained environments, such as IoT devices and WSNs, these devices or networks often encounter congestion due to limited bandwidth, energy constraints, and high packet loss rates. Consequently, several congestion control mechanisms have been developed to solve these problems in CoAP-based communication. This section provides an overview of each backoff algorithm as part of congestion control mechanisms, along with their efficiency and limitations.

Betzler et al., 2016 proposed the CoAP simple congestion control/advanced (CoCoA) mechanism, aiming to improve the CoAP congestion control mechanism by refining the RTO estimation. CoCoA includes three key components: (1) round-trip time (RTT) measurement, (2) RTO backoff calculation, and (3) RTO aging mechanism. These components can improve the adaptability of CoAP message transmission under varying network congestion and align with IoT device communication patterns. CoCoA is superior to the default CoAP in terms of throughput, settling time, and fairness under varying network conditions. However, CoCoA has some limitations, particularly in terms of increased memory use due to its complexity. Furthermore, the study lacks an analysis of the trade-off between performance gains and resource use.

FASOR was introduced as a novel RTO estimation mechanism integrated into CoAP and designed for IoT devices under network environments with high link error rates and congestion. FASOR comprises three key features: (1) fast RTO calculation, (2) slow RTO, and (3) a novel retransmission timer backoff logic that adapts to current network conditions. Experiments that compare this algorithm to the default CoAP and CoCoA algorithms reveal that FASOR can significantly reduce the flow completion time (FCT) and the total number of retransmissions, especially in scenarios characterized by buffer bloat and frequent link errors. However, further investigation is required to improve the robustness and general applicability of FASOR across a broader range of network conditions (Järvinen et al., 2018).

Another study introduces the improved CoAP in IoT devices using fuzzy logic with an adaptive retransmission timeout adjustment called FLCoCoA. This approach addresses the traditional CoAP limitations on handling highly dynamic and bursty traffic conditions. The FLCoCoA consists of (1) a multidimensional congestion estimator for real-time network condition assessment, (2) an adaptive initial RTO estimation based on relative signal strength indicators and trend analysis, and (3) a flexible backoff algorithm that adjusts backoff thresholds using fuzzy logic. Compared with other mechanisms, the experimental findings indicate that FLCoCoA can increase throughput, reduce transmission delays, and minimize retransmissions. This study, however, has the limitation of FLCoCoA's inability to support CoAP's non-confirmable mode and lacks evaluation under varying traffic scenarios (Aimtongkham et al., 2021).

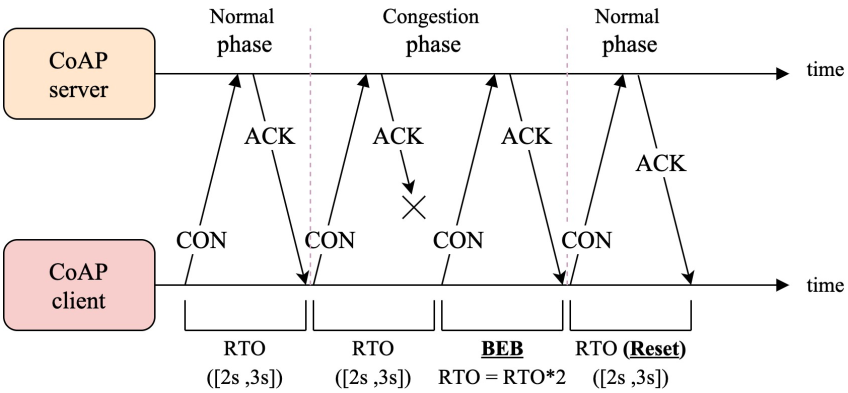

Figure 1 The default CoAP operation

The TNSB algorithm is developed based on the figure number theory and proposed as a technique for predicting RTO in CoAP congestion control mechanisms. Its objective is to support communication in resource-constrained IoT networks by reducing the probability of packet collisions and mitigating packet loss during network congestion. Its performance was evaluated in comparison to traditional backoff algorithms used in the Transmission Control Protocol (TCP), i.e., BEB, Exponential Feedback Backoff (EFB), Exponential Backoff with Acknowledgment (EBA), and Binary Increase Increment (BII). Comparisons were performed using the Cooja simulator and analyzed using statistical methods to identify differences among these groups. TNSB exhibits superior performance under medium to high congestion conditions, with higher throughput and reduced response time than other algorithms. However, no statistically significant differences were detected among the assessed parameters in low-congestion conditions. To clarify this point, TNSB may not consistently outperform existing algorithms in all network scenarios; therefore, the integration of supplementary mechanisms is required to improve the efficiency of TNSB in handling congestion across varying network environments (Jangkajit and Suwannapong, 2023).

Rathod and Tahiliani, 2020 introduced the geometric sequence technique (GST) as an alternative approach for more accurate RTO estimation because traditional approaches frequently encounter difficulties with numerous retransmission failures, resulting in excessive RTO values. The RTO is reset to its initial value upon successful message transmission or when retransmission attempts exceed the protocol-specified threshold, thus disregarding acquired information regarding current network conditions. GST solves this problem by slowly reducing RTO toward its initial value, based on the number of consecutive successful message transmissions. Experimental results conducted in both the Cooja simulator and real-world testbeds, i.e., FIT/IoT-LAB, demonstrate that GST can significantly decrease FCT and retransmissions while increasing throughput. However, GST relies heavily on multiple consecutive successful transmissions to lower RTO, which may hinder optimal recovery of performance following network congestion.

Overall, the literature review reflects continuous efforts to develop CoAP congestion control mechanisms through various backoff algorithms, each of which primarily aims to optimize communication efficiency in constrained networks. These algorithms were also evaluated across different network environments and traffic conditions. However, the choice of a suitable backoff algorithm is influenced by the specific characteristics of the network and the requirements and communication patterns of the target application.

3. Proposed Algorithm

Our proposed algorithm, CAEB, builds upon the BEB algorithm, which exhibits limited adaptability under varying network conditions. CAEB incorporates an adaptive factor (F) and uses randomization and logarithmic function to estimate RTO based on observed network congestion levels. The estimation relies on the number of nodes currently engaged in communication within the network. The primary objective of CAEB is to enhance the efficacy of CoAP-based communication in IoT environments, especially when the number of devices and network congestion are increasing. To clarify this point, the proposed algorithm aims to reduce packet loss and the number of transmission attempts while maintaining a high throughput.

CAEB uses randomized delay mechanisms to reduce network congestion caused by communication between nodes. The process is outlined in Algorithm 1. This algorithm begins with the retransmission timeout initial (RTOinit), which is randomly selected within the range of 2–3 s during message exchange. In scenarios where the source node fails to receive an Acknowledgment (ACK) message, subsequent retransmissions adopt the retransmission timeout overall (RTOoverall) calculated from Equation (1) to replace the initial RTO value. The RTOoverall is adjusted by multiplying RTOinit by 2 to the power of the product of the retransmission count (i) and the adaptive factor (F), as shown in Equation (2). In this regard, F is defined to have a positive value and constrained within an appropriate bounded range (with lower and upper limits) to prevent the transmission delay from unnecessarily increasing to the extent that it degrades overall performance. Additionally, F exhibits a monotonic increasing property, that is, F correspondingly increases in a continuous way and does not decrease under the same conditions because the number of retransmissions increases or the density of the network grows. This modification can increase the waiting period before the next retransmissions, allowing more time for a response from the destination node, thereby decreasing traffic congestion. RTOoverall is allowed to increase up to its maximum threshold, i.e., when the number of retransmission attempts reaches four, but it must not exceed four times the total number of nodes in the network. Importantly, if a message is successfully communicated, the current value of RTOoverall is retained for that particular transmission associated with the new Message ID, but it is later reset to RTOinit upon confirmation of successful communication.

The $RTO_{overall}$ is calculated using Equation (1).

$$RTO_{overall} = RTO_{init} \times 2^{(i \times F)} \tag{1}$$

F is determined from Equation (2) as follows:

$$F = w_n \times \log_2(N) + w_r \times i \tag{2}$$

N is the total number of devices or nodes in the network

i Number of retransmission attempts

w_n the weighting factor (set to 0.2) to regulate the backoff growth according to the network's number of nodes

w_r the weighting factor (set to 0.1) to regulate the backoff growth according to the number of RT attempts.

Figure 2 illustrates the overall operation of the CAEB during the normal and congestion phases. This technique resembles the default CoAP, as shown in Figure 1, but the key distinction lies in the RTO handing. In other words, unlike the default CoAP, CAEB does not reset the RTO upon receiving the ACK message resulting from the retransmission. Instead, the existing RTO value is retained for the next transmission attempt (see RTO (Retained) in Figure 2). The RTO does not reset until the ACK message is successfully obtained from the first transmission of a new communication instance. Therefore, the principle allows CAEB to maintain the RTO value that reflects the prevailing network congestion level. This can, in turn, prevent the timeout from decreasing too rapidly and enhance the likelihood of successful message transmission, especially for nodes to transmit CON messages to the destination nodes.

Algorithm 1 Constrained Adaptive Exponential Backoff (CAEB)

```
Initialize random value from $[2s, 3s]$ to $RTO_{init}$
if transmitting a confirmable message then
    if maximum number of retry attempts has not been reached then
        if this is the first transmission then
            $RTO = RTO_{init}$
        else
            $RTO = RTO_{init} \times 2^{(i \times F)}$
            if the current $RTO$ is more than 64 then
                $RTO = N \times 4$
            end
        end
    end
end
if additional packet transmissions remain to be completed then
    $RTO = RTO_{increase}$
    if the transmission is successful then
        // reset the RTO to the default
        $RTO = RTO_{init}$
    end
end
```

CAEB adjusts the backoff time in accordance with network sizes, thereby preventing the RTO from growing too rapidly. This adjustment aligns with the relationship between the increase in the rate of RTO and the number of retransmission attempts, as shown in Figure 3. If the RTOinit is set to 3 s, the RTO reaches the maximum value of 57 s when the number of retransmissions reaches the upper bound of four attempts. This value is then reset to RTOinit when a new communication session is completed without requiring any retransmissions. The range of the RTO, from the maximum to the minimum, can be determined to guarantee that the transmitted packet delay remains within acceptable limits to avoid excessive message transmission delays.

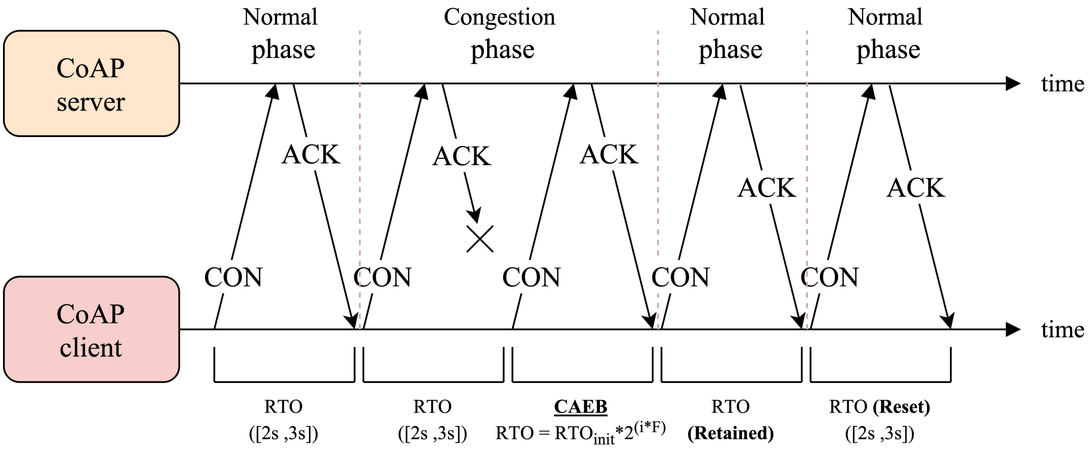

Figure 2 CAEB algorithm operation

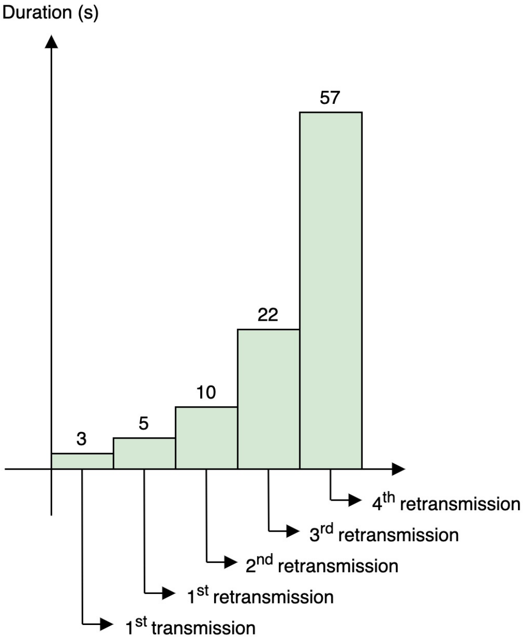

Figure 3 Increase in backoff time in relation to the number of retransmissions in CAEB

4. Evaluation Setup

This section presents information regarding the experimental design, including performance metrics and traffic scenarios used to compare the CAEB efficiency with the default CoAP.

4.1 Network and Simulation Setup

Figure 4 illustrates the grid network topology used for the backoff algorithm simulation and performance evaluation. In this study, the topology consisted of 16 nodes characterized by multipath structures and complex interconnections. The distance between adjacent notes was set to 10 m, and each node's transmission range was set to enable direct communication with its four adjacent nodes. This architecture also ensured that the internal nodes were more likely to become congested, yielding a real congestion scenario for the experiment.

The parameters listed in Table 1 were used to configure the Cooja simulator operating on Contiki OS 2.7 to test the performance of both the CAEB and BEB algorithms. A total of 10 repeated trials were conducted under different random seeds and initial conditions to mitigate bias from the stochastic characteristics of the simulation environment and to enhance the reliability of the results. Then, the results were averaged and recorded for further analysis and performance comparison.

4.2 Workload Definition

In the workload configuration, one node was assigned as the CoAP client to receive notification messages from 14 nodes acting as CoAP servers, following the role assignment illustrated in Figure 4. Each server sent CON messages with a fixed payload size, and the offered load was controlled by specifying the message generation rate/interval to realize the traffic conditions considered in this study. Each simulation run included a 60-second warm-up period during which no metrics were recorded to ensure measurement stability, followed by a measurement window in which all performance metrics (e.g., FCT, throughput, packet loss, and total retransmissions) were collected and aggregated across repeated runs.

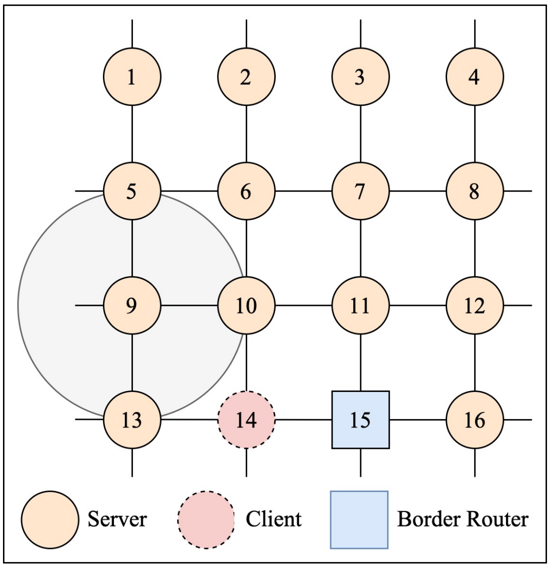

Figure 4 Grid network topology

4.3 Performance metrics

The evaluation of CoAP-based congestion control mechanisms requires careful consideration of several performance metrics to assess their impacts and efficiency in handling network congestion. In this study, the performance metrics were carefully selected according to the characteristics of message transmission, the structures of network topologies, and the intended application of CAEB. These metrics can provide insights into the congestion control mechanism's behaviors and performances under varying test conditions. The selected performance metrics are as follows:

4.3.1 Flow completion time (FCT)

The FCT defines the total duration of a complete communication cycle, which must send a message from the beginning to the successful communication. In the performance evaluation, a low FCT indicates the ability to effectively handle network congestion and promote faster message transmission.

4.3.2 Throughput

The throughput refers to the number of successfully sent messages over the network per unit of time. A higher throughput indicates better performance of the congestion control mechanism.

4.3.3 Packet Loss

Packet loss is the number of messages that are not successfully transmitted during communication within the network. In the CoAP context, message loss is generally attributed to network congestion. A lower packet loss means better congestion management and message transmission rate regulation.

4.3.4 Total number of retransmissions

The total number of retransmissions is the total number of times a message is sent due to unsuccessful transmission attempts. In terms of efficiency, a lower number of retransmissions means better RTO management and backoff algorithm.

Table 1 Experimental parameters

Parameter	Details
Mote	Zolertia (Z1)
Congestion mechanism	Default CoAP
Backoff algorithm	BEB, CAEB
Messaging model	Reliable message transmission
Wireless channel model	Unit disk graph model
Transport and network	UDP + uIPv6 + 6LoWPAN
Media access control	CSMA/CA
Radio duty cycling (RDC)	ContikiMAC/NullRDC
Physical	IEEE 802.15.4 PHY
Radio band	2.4 GHz
Transmission (TX) ratio	100%
UDP buffer size	256
Maximum retransmissions	4
RTO_{init}	2–3 s
Simulation time	600 s

4.4 Traffic Scenarios

The traffic scenarios used in the simulation play a crucial role in the experiment and evaluation of CoAP because they allow for the investigation of the performance of certain mechanisms under varying network conditions. In this study, two types of scenarios were used, namely, continuous traffic scenario and periodic traffic scenario, each of which can serve different purposes and has unique characteristics, as illustrated below:

4.4.1 Continuous traffic scenario

In this scenario„ the experiment simulated the behaviors of CAEB and BEB algorithms by configuring the clients to send messages continuously without any delays during transmissions. This setup was intended to simulate the condition of maximum or near-maximum resource use in the network, i.e., to make the network under high load and evaluate how each algorithm estimates the RTO under such conditions.

4.4.2 Periodic Traffic Scenario

In this scenario„ the experiment simulated message transmissions at fixed intervals by configuring the clients to send a message every 1 s. This setup resembles IoT application environments, such as smart metering, environment monitoring, or sensor networks. The goal is to investigate the effectiveness of the mechanisms under investigation in handling congestion and how well they adapt to regular, time-based message flows.

5. Performance Evaluation

The simulation and performance evaluation under the defined traffic scenarios are divided into four sections, each of which aligns with a specific performance metric. The experiments compare the performance of CAEB and BEB in dealing with congestion using FCT, throughput, packet loss, and the total number of retransmissions. The study focused on whether the observed differences in performance across these metrics were statistically significant by conducting a two-sample t-test. Data analysis was conducted using statistical software to test the hypothesis at a significance level of 0.05 ($p = 0.05$). Moreover, to control errors from multiple comparisons, the Holm-Bonferroni correction method was applied to mitigate the family-wise error rate and decrease the likelihood of false positives.

5.1 FCT

Figure 5 shows a comparison of FCT. According to the performance analysis, the FCT values for both CAEB and BEB were significantly different under both continuous and periodic traffic scenarios. The FCT value of CAEB was lower than that of BEB, indicating that CAEB outperformed BEB in terms of adaptability and response to network congestion. In other words, the use of the adaptive backoff algorithm enabled CAEB to handle congestion more effectively than BEB, which used the static backoff approach.

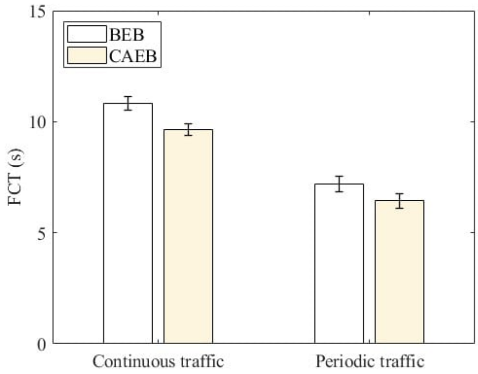

Figure 5 Comparison of FCT results in the Cooja simulator

5.2 Throughput

Figure 6 shows that the throughput values of both CAEB and BEB across two traffic scenarios also exhibited a statistically significant difference; that is, CAEB can achieve higher throughput than BEB. The overall performance comparison between CAEB and BEB using throughput as a performance metric shows that CAEB achieved a significantly higher throughput than BEB. This result can reflect the ability of the system to manage RTO more effectively. In this regard, CAEB can maintain RTO values that are consistent with the network congestion level and prevent them from rapidly decreasing. Consequently, CAEB helps avoid oscillations in RTO values. Additionally, it can improve network resource utilization and decrease unnecessary retransmissions. The experimental results from both traffic scenarios consistently reveal CAEB's superior performance, suggesting its tendency to yield more stable and higher throughput than BEB due to a more appropriate distribution of backoff time that better aligns with real network conditions.

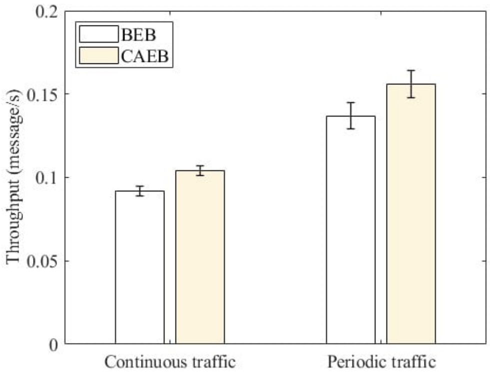

Figure 6 Throughput of the BEB and CAEB

5.3 Packet Loss

Figure 7 illustrates the comparison of the average packet loss between CAEB and BEB. The evaluation of packet loss performance in both traffic scenarios varied considerably; specifically, CAEB consistently yielded lower packet loss. This underscored CAEB's superiority over BEB in handling network congestion because it can adaptively allocate backoff intervals based on node context and retransmission, thereby minimizing message loss. Although CAEB exhibited a slight increase in computing complexity, it can perform better than BEB in terms of fairness and reliability. Notably, under continuous traffic conditions, CAEB can increase RTO more appropriately in accordance with node density, thereby reducing collisions and repeated transmission failures.

5.4 Total number of retransmissions

Figure 8 illustrates the statistically significant difference in the overall number of retransmissions between the two algorithms. In other words, CAEB consistently yielded fewer retransmissions than BEB across both traffic scenarios. The results demonstrate that the dynamic backoff adjustment of CAEB, informed by $\log_2(N)$ and the number of retransmission attempts, facilitated a decrease in total retransmissions, even under high-density network conditions. This adaptive tendency allowed CAEB to reduce redundant message transmissions more efficiently.

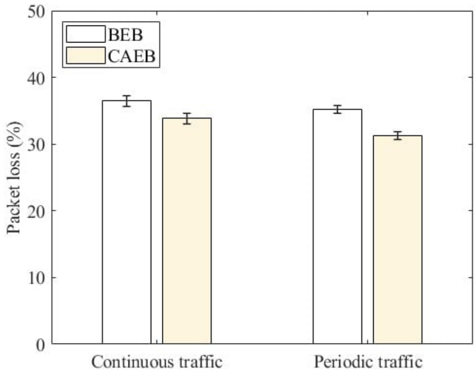

Figure 7 Packet loss of the BEB and CAEB

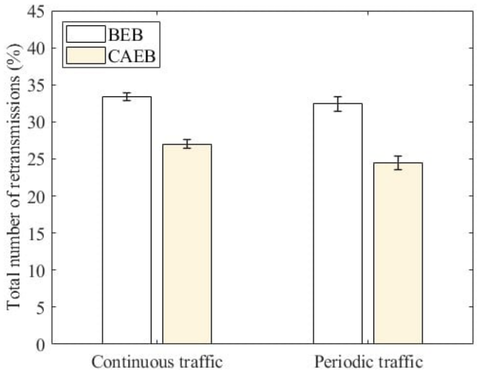

Figure 8 Comparison between the total number of retransmissions of BEB and CAEB

6. Conclusions and Future Work

This study addressed the long-standing limitation of the binary exponential backoff (BEB) mechanism used in the constrained application protocol (CoAP), which often fails to adapt effectively to changing congestion conditions in resource-constrained IoT networks. To overcome excessive retransmissions, latency, and inefficient energy use associated with BEB, we proposed the Constrained Adaptive Exponential Backoff (CAEB) algorithm, a lightweight yet adaptive approach for estimating retransmission timeout (RTO). CAEB integrates logarithmic weighting and adaptive factors based on retransmission count and active node density, allowing the RTO to reflect real-time network conditions while remaining computationally simple for constrained devices. The proposed algorithm was implemented and tested in the Cooja simulator with the Contiki operating system under both continuous and periodic traffic scenarios. The experimental analysis demonstrated that CAEB consistently outperformed the conventional BEB approach in terms of faster message completion, higher throughput, fewer packet losses, and fewer retransmissions, with all improvements validated as statistically significant through two-sample t-tests ($p < 0.05$) and the Holm-Bonferroni correction method to mitigate the family-wise error rate. These findings confirm that adaptive backoff mechanisms can substantially improve CoAP-based communication's efficiency, reliability, and scalability in diverse IoT applications, such as smart agriculture, environmental monitoring, and structural health monitoring. Beyond its immediate performance gains, CAEB contributes to the advancement of congestion control research by offering a practical, resource-aware strategy for estimating RTO in dynamic IoT environments. Future work should validate CAEB in large-scale real-world deployments, examine its robustness under highly heterogeneous traffic patterns, and explore hybrid cross-layer approaches to further optimize network stability and energy efficiency.

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Author Contributions

C.S.: conceptualization, investigation, reviewing, methodology, research design, data curation, data analysis, and editing; K.S.: investigation, methodology, and writing an original draft; S.S.: conceptualization, data curation, writing—reviewing and editing, funding acquisition, and project administration. All authors have read and approved the published version of the manuscript.

Conflict of Interest

The authors have no conflicts of interest to declare.

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