Dynamic active period control in heterogeneous wireless sensor networks

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***Abstract*—Wireless sensor networks are now ubiquitous. Many of these networks consist of multiple types of sensor nodes, each with different functions and specifications, and are called heterogeneous wireless sensor networks [1]. IEEE 802.15.4 [2] is widely used as a communication standard in such networks, where the DC(Duty Cycle) plays a critical role in reducing power consumption. However, since the DC cannot be dynamically adjusted, changes in sensor types or the number of active nodes in heterogeneous environments can make it difficult to ensure communication quality while reducing power consumption.**

To address this, we propose a dynamic DC control method that extends the SDAAM (Superframe Duration Adaptation Algorithm using Markov Chain) [11] for heterogeneous environments. Our key contribution is the re-evaluation of the Markov chain model within SDAAM to account for diverse packet sizes and generation rates from different node types. By reformulating the state transition probabilities and the expected communication time, the proposed method accurately calculates the optimal superframe duration based on the network's real-time communication demands. This adaptive approach aims to maintain a high PDR(Packet Delivery Ratio) while reducing energy consumption and latency. Simulation results, conducted using the Castalia simulator [3], indicate that the proposed method is a promising and effective approach for achieving these objectives in heterogeneous environments.

***Index Terms*—Wireless sensor networks, Duty cycle, PDR, IEEE 802.15.4**

I. Introduction

With the development of IoT (Internet of Things) technology, WSNs (wireless sensor networks) have become increasingly important. In most WSNs, IEEE 802.15.4 [2] is widely used as a communication standard. This standard achieves low power consumption by adjusting the ratio of the active period to the total communication period, known as DC(Duty Cycle).

In actual WSNs, it is common for multiple types of sensors to coexist within the network, handling different data types, sizes, and transmission frequencies. Such networks are known as heterogeneous wireless sensor networks [1]. For example, in smart homes, temperature, humidity, motion, and light sensors are used to monitor the environment and maintain comfortable living conditions [10]. Furthermore, the number of sensors in use can fluctuate. Therefore, maintaining appropriate data control in such complex, heterogeneous environments is critically important.

Without dynamic and appropriate DC control, communication quality cannot be maintained, or conversely, it may become overspecified.

To address this issue, a method called TMP (Tele-Medicine Protocol) was proposed [5]. TMP dynamically controls the DC while maintaining an acceptable delay. However, its prioritization of delay reduction prevents it from guaranteeing a sufficient Packet Delivery Ratio (PDR). To overcome this limitation, subsequent studies have proposed dynamic DC control and scheduling methods that aim to maintain both low latency and high PDR. For instance, buffer-occupancy-based DC control has been proposed for IEEE 802.15.4 WSNs [4], [6]. Another approach, ADE-MAC (2021), dynamically adapts the DC based on observed traffic generation rates and node activity to balance delay and reliability [7]. A further method, the Superframe Duration Adaptation Algorithm using a Markov Chain (SDAAM), models all possible pre-communication states to calculate the expected transmission cycle time and determine an appropriate active period [11]. A key limitation of SDAAM, however, is its assumption of a homogeneous environment with only a single device type. More advanced methods address such complexity; for example, in industrial settings, the QMDE (2024) method designs TSCH schedules for multiple concurrent flows with diverse QoS requirements [8]. Finally, the technique of Listening Suspension in TSCH (2023) suppresses unnecessary idle listening in slow-rate data streams, thereby reducing energy waste without sacrificing PDR for high-rate sensors [9].

In this study, we propose a method that maintains both high transmission performance and low power consumption in dynamically varying heterogeneous environments.

II. Preliminaries

A. Related Works

In IEEE 802.15.4 beacon mode, a virtual time schedule called a superframe is used.

Figure 1 shows the structure of the superframe. The superframe consists of an active period called the superframe period and a sleep period called the inactive period. The superframe period consists of 16 slots of equal length. There is a time unit called aUnitBackoffPeriod that is even smaller than a slot, and

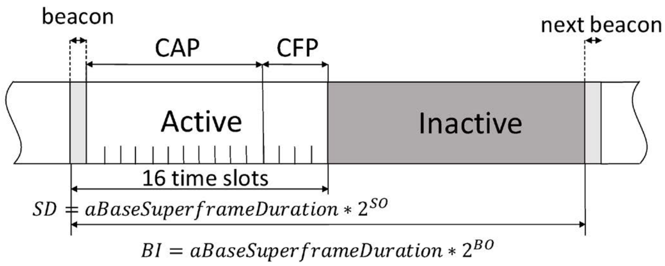

Fig. 1. Structure of the Superframe

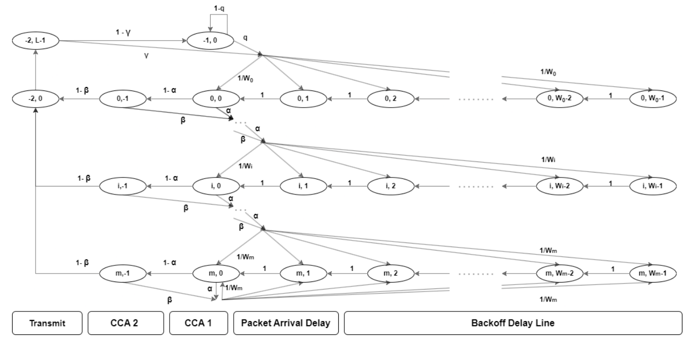

Fig. 2. Markov chain model of IEEE802.15.4

each slot consists of 60 aUnitBackoffPeriods. The beacon period and superframe period are determined by variables called BO (Beacon Order) and SO (Superframe Order), respectively, and are expressed by the following equation1 and equation2.

$$BI = aBaseSuperFrameDuration \times 2^{BO} \tag{1}$$

$$SD = aBaseSuperFrameDuration \times 2^{SO} \tag{2}$$

BO and SO are expressed as integers, and the value of BO in particular is generally 6. The value of SO is between 0 and 6.

DC is the ratio of the active period to the total Superframe, so it is maximum when SO is 6 and minimum when SO is 0.

During the active period, communication uses the CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) method. Each sensor node waits for the backoff period before transmitting data. The backoff period is calculated using a variable called BE (Backoff Exponent), resulting in a duration equal to aUnitBackOffPeriod multiplied by a random integer between 0 and $2^{BE}-1$. After the backoff period ends, each sensor node initiates a CCA (Clear Channel Assessment). If the channel is assessed as clear in two consecutive CCA attempts, the sensor node begins data transmission. If the channel is assessed as busy in either of the two CCA attempts, the BE is incremented, and the backoff process is repeated.

When data transmission is successful, the sink node sends an acknowledgment signal called ACK, completing the communication. If no ACK is received after a certain period due to data collisions, the sensor node determines the transmission failed and attempts to resend the data.

B. Markov chain model of IEEE802.15.4

Each state has an i representing NB (Number of Backoffs) and a k representing the backoff counter until communication occurs, with the probability expressed as $b_{i,k}$. Here, when the value of k is 1, it indicates the first CCA is congested. when the value of k is 2, it indicates a communication state, and $(-1, 0)$ indicates no packet to transmit.

In Figure2, α is the probability of detecting channel congestion during the first CCA, β is the probability of detecting congestion during the second CCA, and γ is the packet collision probability. q represents the data generation probability. The probability of each state is calculated using the property that the sum of all possible states' probabilities equals 1.

III. Proposed Method

We propose an extension of the dynamic DC control method based on the SDAAM for heterogeneous WSNs. SDAAM models all possible communication states as a Markov chain, estimates the expected time required for all nodes to complete a single transmission, and derives an appropriate active period. This approach enables adaptive DC control according to the number of devices. However, the original SDAAM was designed for homogeneous networks with a single device type, which limits its applicability.

In this study, we extend SDAAM to heterogeneous WSNs by redefining the probability of packet transmission during the active period and recalculating the expected communication time in the Markov chain. The PAN Coordinator, a FFD (Full Function Device, performs the calculation and uses the corresponding SO based on the result."

The probability that an RFD(Reduced Function Device) i attempts to transmit is given by Equation 3.

$$\tau_i = \frac{1-P_i^{m+1}}{1-P_i} b_{0,0}^{(i)}, \quad P_i = \alpha_i + \beta_i - \alpha_i\beta_i \tag{3}$$

Here, m denotes the maximum number of CSMA backoffs.

The probabilities that RFD i senses a busy channel in the first CCA, the second CCA, and experiences packet collision are expressed in Equations 4, 5, and 6. L refers to the communication period.

$$\alpha_i = L \left\{ 1 - \prod_{j \neq i} (1-\tau_j)^{n_j} \right\} (1-\alpha_i)(1-\beta_i) \tag{4}$$

$$\beta_i = \left\{ 1 - \frac{1}{1 + \frac{1}{1-\prod_j (1-\tau_j)^{n_j}}} \right\} \left\{ 1 - \prod_{j \neq i} (1-\tau_j)^{n_j} \right\} \tag{5}$$

$$\gamma_i = 1 - \prod_{j \neq i} (1-\tau_j)^{n_j} \tag{6}$$

where n_j denotes the number of RFDs of type j.

By solving $(\alpha_i, \beta_i, \gamma_i)$ for each RFD type, the transmission probability, delay, and success probability can be derived individually. Furthermore, the overall network throughput and energy consumption can be obtained by aggregating the results of all RFD types.

To evaluate the proposed method, simulations were conducted in Castalia [3] using a heterogeneous WSN. The network consisted of one sink node and between 1 and 24 RFDs. Each RFD had distinct packet sizes and packet transmission interval, so that increasing the number of RFDs also increased the heterogeneity of the traffic load.

We evaluated our method, which estimates an appropriate SO to apply DC control, by measuring the PDR, power consumption and latency. For comparison, we also simulated fixed SO values without DC control. The evaluation consisted of two steps. First, we validated the analytical model by comparing the PDR obtained from simulations with fixed SO values (0–6) against the PDR calculated from our expressions. The close agreement confirms that the model can accurately predict an appropriate SO. Second, we applied DC control using the SO estimated by our model. Here, the SO adapts dynamically to the heterogeneous environment. Let this SO be denoted as SO_{active}. If T_{active} is the optimal active period for communication, derived from factors such as the packet size generated by RFDs and the beacon transmission time, then SO_{active} is given as Equation7.

$$\left\lceil \log_2 \left(\frac{T_{active}}{960} \right) \right\rceil \tag{7}$$

In Equation7, the denominator 960 is the number of aUnitBackOffPeriods for 16 slots.

IV. Experimental Results and Discussion

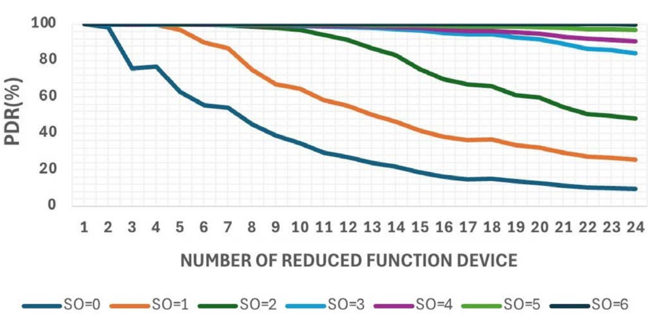

Fig. 3. PDR results obtained by Castalia

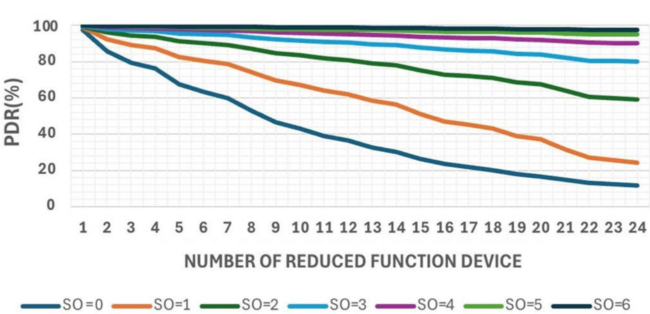

Fig. 4. PDR results obtained by Analysis

Figures 3 and 4 show the PDR for each node count as the number of RFDs increases from 1 to 24. Comparing the two figures, both simulation and analytical results exhibit similar trends, with the PDR decreasing as the number of RFDs increases.

When SO is 4 or higher, the PDR remains at a high level, and both analysis and Castalia show values close to 100%. This indicates that the analytical model continues to provide reasonable estimates in this region. In contrast, when SO is 3 or less, where the number of RFDs is small and the duty cycle is tighter, the shapes of the curves diverge between the two figures. Nevertheless, when comparing the average PDR values of Castalia and the analysis for each SO, the maximum difference is 6.11% at SO = 3, and the ratio of analytical to simulated PDR remains close to 1 across all SO values. Therefore, the SO values obtained from the analytical formula are considered valid for duty cycle control in heterogeneous WSNs.

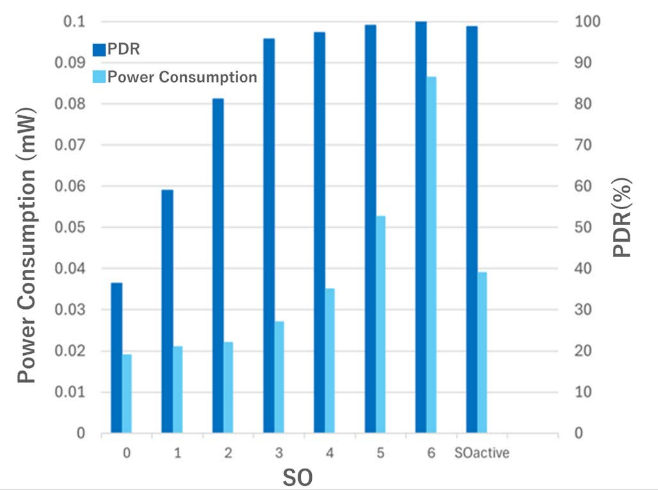

Fig. 5. Performance evaluation in SO_{active}

Figure 5 shows the comparison of PDR and power consumption between the simulations using duty-cycle control with SO_{active} and those without control using fixed SO values from 0 to 6. The average PDR is 98.78%, which is nearly equivalent to the case with $SO \geq 5$. The power consumption using SO_{active} is 25.9% less than that of a fixed SO of 5 and 54.9% less than with SO fixed at 6, confirming that the proposed method reduces energy consumption. For $SO \leq 4$, power consumption is lower than that of SO_{active}; however, the average PDR decreases sharply at $SO \leq 2$, and at $SO = 3$ or 4, RFDs with large packet sizes and high packet generation rates cannot maintain sufficiently high PDR. Based on these results, the proposed method appears to achieve an effective balance between communication quality and energy efficiency.

Figure 6 shows the distribution of packet delays observed during the simulation. The horizontal axis represents the SO value, while the vertical axis indicates the percentage of packets classified into each delay interval. For $SO \leq 2$, the majority of packets experience delays longer than 500ms.

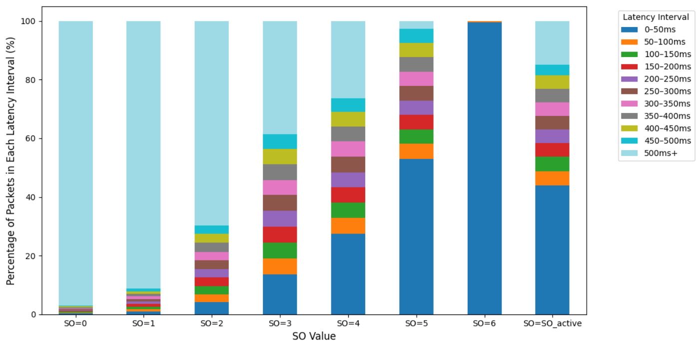

Fig. 6. Histogram of Latency by SO Value SO_{active}

This is because the short active period determined by the small duty cycle prevents immediate transmission, causing packets to remain queued and span across multiple beacon intervals before being processed. When SO is 3, 4, or 5, the proportion of packets with delays of 50–500 ms remains nearly unchanged, while the proportion of packets with delays of 0–50 ms increases exponentially. At $SO = 6$, almost all packets fall within the 0–50 ms range, achieving the minimum delay. Compared with $SO = 4$, the proposed method not only achieves a higher PDR and lower power consumption, but also suppresses delays more effectively. Nevertheless, the proportion of packets experiencing large delays remains significantly higher than that of $SO \geq 5$. As a result, the proposed method may lead to packet reordering or the inability to guarantee real-time delivery. Therefore, the proposed method can be considered practical in scenarios such as environmental monitoring, where each packet is timestamped or sequenced and strict real-time constraints are not required.

The experiments in this study were conducted with a network size of up to 24 nodes, and evaluations with larger-scale networks remain as future work. In particular, since Castalia does not provide a standard implementation of routing, large-scale simulations with tree-based topologies should be addressed in future studies. Moreover, this work did not fully evaluate certain QoS metrics, such as throughput, which should also be considered in future investigations.

V. Conclusion

We adapted the SDAAM method for star-based heterogeneous WSNs and proposed a duty-cycle control scheme. Simulation results demonstrated that the proposed method can reduce power consumption while maintaining a high packet delivery rate. In addition, the analysis of latency distribution showed that the method achieves practical delay performance for certain applications, although strict real-time constraints may not always be guaranteed.

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