Real Time QoS in WSN-based Network Coding and Reinforcement Learning

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In recent years, wireless sensor networks have experienced significant advancements, driven by a reduction in development costs. This rapid growth in WSNs has led to the emergence of various potential and emerging applications, including real-time applications, which pose challenges due to their substantial requirements. As the number of applications continues to increase, ensuring both reliable and real-time Quality of Service (QoS) communication in resource-constrained WSNs becomes a paramount concern. To address this challenge, we propose the use of network coding (NC), a novel research area applicable in diverse environments to overcome several shortcomings within a network. Additionally, we focus on the duty cycle, recognized as one of the most popular techniques for energy conservation. Specifically, we employ the Duty Cycle Learning Algorithm (DCLA) to determine the optimal duty cycle. To guarantee the expected real-time QoS and reliability, we introduce NCDCLA (Network Coding-based Duty Cycle Learning Algorithm). Through simulations in OPNET, our results demonstrate that our approach achieves commendable reliable performance.

Povzetek: Nova metoda NCDCLA za zagotavljanje zanesljivosti QoS v WSN je zasnovana kot kombinacija mrežnega kodiranja in algoritma za učenje delovnega cikla.

1 Introduction

Recent advancements in micro-electro-mechanical systems (MEMS) and wireless communications have garnered attention toward small sensor nodes communicating with each other using radio signals. These sensors are compact, possess limited processing and computing resources, and are cost-effective compared to traditional sensors. These sensor nodes are capable of sensing, measuring, and collecting information from the environment. Following a local decision-making process, they can transmit the sensed data to the user [1].

However, certain characteristics of WSN pose challenges due to limited resources such as energy, bandwidth, memory, processing power, and transmission power. Despite these constraints, WSNs have emerged as one of the most intriguing areas of research, given their diverse applications including military sensing, environmental monitoring, and target tracking. Consequently, some applications present significant challenges due to their extensive requirements in terms of:

- *Real time QoS*: Critical application must support such time bound called deadline. For this, data should be delivered before its deadline.
- *Reliability*: The reliability of a WSN is the probability that end-to-end communication is successfully completed. In other words, reliable data transfer ensures that packets reach their destination.
- *Energy efficient*: Energy consumption must be highly constrained.

For this reason, ensuring communication reliability in resource-constrained wireless sensor networks remains an open area of research to achieve a high degree of real-time Quality of Service (QoS).

To address these challenges, the utilization of network coding and duty cycle learning algorithms has been demonstrated to enhance the performance of wireless sensor networks. Network coding, a novel technique that has garnered significant interest in recent studies, was originally proposed in information theory in 2000 by Ahlswede et al. [2]. The core premise of network coding is that intermediate nodes, referred to as relays, engage in coding operations on the incoming data stream to generate outflows. These nodes recombine incoming data using operations such as the XOR operation. Consequently, network coding offers improvements over traditional routing, where nodes typically perform simple operations like receiving and retransmitting packets.

On the other hand, duty cycling is considered one of the most critical energy conservation techniques. Duty cycling involves periodically placing a node into sleep mode, which is an effective method for reducing energy dissipation in wireless sensor networks (WSNs) [3]. To ensure Quality of Service (QoS) levels, [4] proposed a Duty Cycle Learning Algorithm (DCLA) that adapts the duty cycle during runtime without the need for human intervention, aiming to minimize power consumption while balancing the probability of successful data delivery and meeting application delay constraints.

DCLA is a mechanism based on reinforcement learning (RL), an area of machine learning that enables machines and software agents to automatically determine ideal behavior within a specific context to maximize performance [5]. It has proven successful in addressing various functional challenges of wireless sensor networks, including energy awareness, real-time routing, query processing, event detection, localization, node clustering, and data aggregation [6].

Our challenge is to implement a new paradigm, NCD-CLA (Network Coding-based Duty Cycle Learning Algorithm) [7][8][9][10], which holds the potential to offer significant benefits across various communication network metrics, such as throughput, delay, energy efficiency, wireless resources, security, complexity, and resilience to link failures.

The remainder of the paper is organized as follows: In the next section, we summarize related work. Section 3 surveys several key technologies fundamental to our study of network coding and DCLA in WSN. We evaluate the performance of our approach in section 4 and conclude by outlining directions for our future work in section 5.

2 Related works

In recent years, network coding has been investigated as a method to achieve improvements in wireless networks [11]. Additionally, many researchers in the field of network coding have underscored the importance of this technique. Reference [12] outlines the two main benefits of this approach: potential throughput improvements and a high degree of robustness.

The effectiveness of a network-coding strategy depends on the context, and in the case of Wireless Sensor Networks (WSNs), it should leverage the broadcast nature of the medium while considering the capacity limitations of the nodes [13]. Furthermore, [14] proposed an enhanced AdapCode schema. This schema allows for the reduction of power consumption for the entire network and prolongs the lifetime of the network by minimizing packet communications throughout the code dissemination process.

The ultimate goal of the work described in [15] is to improve network efficiency and extend its lifetime. This solution reduces the overall volume of data transfer. Moreover, in [16], the authors described some drawbacks of applying network coding in real-world sensor network scenarios. However, authors [17] proposed and investigated the use of network coding to improve real-time performance in IEEE 802.15.4-based wireless sensor networks. They developed a performance model that analytically characterizes the real-time performance of a single M/M/1 node with network coding.

According to the network coding technique for packet encoding, [18] proposed the NCQ-DD routing protocol, which can efficiently conserve bandwidth and node energy to improve the efficiency and accuracy of data transmission. The delivery rate of packet groups is also enhanced. [19] analyzed two robust implementations of network coding for transmission in sensor networks. Wang X. et al. [20] suggested a network coding-based approach in data dissemination to achieve rapid dissemination, thereby reducing energy consumption and decreasing delay.

Additionally, [21] introduced CodeDrip, a data dissemination protocol for Wireless Sensor Networks. The main concept behind this protocol is to apply Network Coding to the dissemination process, reducing the number of transmitted messages and consequently saving energy consumption. CodeDrip requires additional space in the packet to store message IDs and buffers to store combined messages. These overheads can be controlled by specifying the maximum number of messages that can be decoded and the maximum buffer size. Moreover, [22] investigated the concept of network coding in Wireless Sensor Networks (WSN) and presented Re-CoZi, a packet transport mechanism that uses medium-aware advanced acknowledgment mechanisms to provide reliable network coding-based communications over lossy environments. Also, Lie Wang et al. [23] proposed a multirate network coding scheme to improve the energy efficiency of WSNs. This scheme can enhance energy efficiency in three aspects: reducing the number of re-encoding nodes without compromising the performance of network coding, transmitting more data in a transmission period, and working over a very small finite field.

To achieve energy efficiency in WSN, [24] proposed DutyCode, a network coding-friendly MAC protocol that implements packet streaming and allows the application to decide when a node can sleep. Through analysis and real system implementation, it is demonstrated that DutyCode does not incur higher overhead and achieves 20-30% more energy savings compared to network coding-based solutions that do not use duty-cycling.

Duty cycle has demonstrated efficiency in numerous studies aimed at balancing objectives to ultimately extend the lifetime. Several works aim to adapt the service cycle mechanism to enhance performance. Euhana et al. [25] proposed OWR, a practical opportunistic routing scheme based on duty cycle, which exhibits significant improvements in terms of energy efficiency, delay, and resilience to sink dynamics. Sukumar and Aditya [26] introduced a QoS-aware MAC protocol in which the MAC layer utilizes the network layer's next-hop information for better adaptation of the duty cycle based on DSS delay. Smita and Prabha [27] suggested a MAC protocol with adaptive duty cycle that gradually adjusts the contention window, offering very high throughput and low delay characteristics. Pangun et al. [28] proposed an adaptive optimal duty cycle algorithm running on top of the IEEE 802.15.4 medium access control to minimize power consumption while meeting reliability and delay requirements. However, the adaptation of the duty cycle introduces the possibility of two cases: a small duty cycle increasing the delay and a higher duty cycle reducing energy efficiency. For this reason, the adaptation of the duty cycle becomes crucial.

3 NCDCLA protocol design

In this section, the system model of NCDCLA is described. NCDCLA aims to enhance real-time communication in IEEE 802.15.4 beacon-enabled mode. NCDCLA is integrated into the MAC sublayer and the application layer. The duty cycle adaptation algorithm is incorporated into the MAC sublayer, while network coding is integrated into the application layer.

3.1 Markov decision process and reinforcement learning

Markov decision processes (MDPs) provide a mathematical framework for modeling decision-making in situations where outcomes are partly random and partly under the control of a decision maker. MDPs are an intuitive and fundamental formalism for reinforcement learning (RL).

This algorithm consists of a sequence of numbered steps (S, A, T, R):

- S: is a discrete set of environment states $S = \{s_1, s_2, \dots, s_n\}$
- A: is a set of actions from each state $A = \{a_1, a_2, \dots, a_n\}$
- T: is the transition probability from state s to a successor state s'
- $R(a, s)$: is the reward function

In the process of reinforcement learning, an agent interacts with its environment through rewards. At each step t, the agent chooses an action a from the set of actions available and a reward r. The agent seeks to maximize the total reward it accumulates in the long run. The agent is guided by a coordinator that, at first glance, selects a set of states such as the energy-saving level l.

The DCLA agent employs a reinforcement learning technique known as Q-learning to find the optimal policy Π^* which is represented by the value function in a two-dimensional table indexed by state-action pairs. Mathematically, the optimal policy is defined as:

$$\Pi^*(s) = argmax(Q^*(s, a)) \tag{1}$$

After each step t, the Q value is updated as follows :

$$Q_{(t+1)}(s, a) = Q_t(s, a) + \alpha[R(s, a) - Q_t(s, a)] \tag{2}$$

Every new Q value is computed as the sum of the old value and a correction term α. $R(s, a)$ is the reward function and is defined as follows:

$$R(s, a) = r_t + \gamma max_{a' \in A(s')} Q(s_{(t+1)}, a_{(t+1)}) \tag{3}$$

The idea is to maximize exploration by selecting random actions during a large number of iterations, allowing for several cycles of reward exploration from the initial state to a goal state. At each passage, the algorithm reinforces the quality of the action that leads to rewards for $nbCycle$. The algorithm stops when all possible states are visited, and the exploration rate $TauxExp$ decreases to a probability of ϵ determining the optimal Q function Q^*. The pseudo-code for the duty cycle learning algorithm is defined as follows:

Algorithm 1 $Q\_Learning$

```
Input: $l, s, \gamma$
Output: $\Pi$
Begin
$Q(s, a) \leftarrow 0$
for $1 < i < nbCycle$ do
    $currentState \leftarrow l$
    for $1 < j < nbAction$ do
        $s \leftarrow currentState$
        $TauxExp \leftarrow random(0, 1)$
        if $TauxExp < \epsilon$ then
            $a \leftarrow randomAction(s)$
        else
            $a \leftarrow argmax_{a'}(Q(s, a'))$
        end if
        $s' \leftarrow a(s)$
        Rewards_Evaluation ($\Pi$)
        $Q(s_t, a_t) = Q(s_t, a_t) + \alpha[r_t + \gamma \cdot max_a Q(s_{t+1}, a_{t+1}) - Q(s_t, a_t)]$
        if $s' = desiredState$ then
            $Exit$
        end if
    end for
end for
End
```

$$r_t = r_e + r_u + r_d + r_o \tag{4}$$

The reward r_t in reinforcement learning is computed as the sum of four components: energy r_e, super frame utilization r_u, delay r_d, and queue occupation r_o rewards.This computation enables the DCLA agent to learn the optimal duty cycle. The pseudo-code for the evaluation of rewards is defined as follows:

3.2 Network coding

The fundamental assumption of network coding is that intermediate nodes, referred to as relays, are utilized to perform coding operations on the incoming stream, resulting in outflows. These nodes recombine incoming data using the XOR operation. Network coding offers advancements beyond traditional routing, where nodes typically perform only simple operations such as receiving and retransmitting packets.

fig. 1 depicts the system model of the network coding. There are two sources A, B, and one destination (sink).

Algorithm 2 Rewards_Evaluation

```
**Input:**$r_t$
**Output:**$s_t$
**Begin**
$sum \longleftarrow 0$
**for** $s \in S$ **do**
    **for** $i = 0toa = |s|$ **do**
        $sum \longleftarrow sum + r_t(s_t, \Pi(s))$
        $s_t \longleftarrow Q(s, \Pi(s))$
    **end for**
**end for**
**End**
```

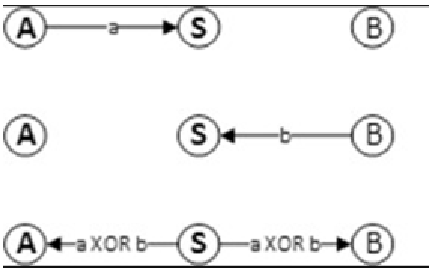

Figure 1: System model of network coding

Both sources broadcast their data messages to the relay S and to the destination. The relay combines the incoming data a and b to produce the data message $a \oplus b$. Next, the relay sends $a \oplus b$ to the sink.

Following the principle of traditional routing, we have four transmission units. However, with the model presented in Figure 1, we have three transmission units. Therefore, the gain is 3/4. Network coding provides benefits in terms of delay because the data will be transmitted after three transmissions instead of four transmissions. It also offers benefits in energy consumption because the relay broadcasts the input data after combining only once. Additionally, it provides benefits in bandwidth because the channel will be occupied for a shorter duration.

In our scheme, the packet coding operation is performed by the PAN coordinator. The network coding model consists of two interfaces, Sender and Receiver, representing the PAN coordinator operating the concepts of network coding. The transmitting interface sends the packet that has undergone network coding to the sink. The receiving interface sends the incoming packets to the nc_proc function precisely via the nc_value attribute to code them, and then the combined packet will be relayed to the sink as an output stream.

In addition, the transmitter interface contains other parameters such as $Bitsize_of_NC_value$ and $Output_NC_value$. The first parameter defines the code size used in network coding operations (in our case, equal to 2), and the second parameter indicates how the nc_value is calculated. The latter is randomly taken as a zero value (in other cases, it can be a specified number). Thus, there is another parameter, $Timeout_value$, that is responsible for the waiting time in the queue before the packets are coded. If the incoming packets are directly processed, then $Timeout_value$ is set to zero.

The pseudo-code of network coding is defined as follows:

Algorithm 3 *nc_proc*

```
**Input:**$P_i$
**Output:**$P_e$
**Begin**
**if** $Bitsize\_of\_NC\_value = 1$ **then**
    send packet without coding
    $Timeout\_value \longleftarrow 0$
**end if**
**for** each packet $P_i$ in queue **do**
    **if** $Bitsize\_of\_NC\_value = 2$ **then**
        coding paquet with XOR operator
        $P_e \longleftarrow P_i \otimes P_{i+1}$
        $Timeout\_value \longleftarrow 0$
    **else**
        coding the two first packet with XOR operator
        $P_e \longleftarrow P_i \otimes P_{i+1}$
        $Timeout\_value \longleftarrow Timeout\_value + 1$
    **end if**
    send coding packet to sink
**end for**
**End**
```

In this scheme, the principle of network coding involves the agent coordinator encoding all received packets. Subsequently, it relays the encoded packet to the sink.

3.3 NCDCLA

A system model of NCDCLA is considered with N sensor nodes scattered uniformly in an area. The nodes are named based on their role in the network. The nodes are differentiated into three groups:

- Sink: receives and decodes data
- Agent Coordinator (AC): encodes data received and retransmit the generated data to the sink. AC are duty cycle learning algorithm enabled
- Node (N): Senor node senses, gathers and transmits data to the AC.

The processing flowchart of NCDCLA is defined as follows in Figure 2.

4 Experimental results

4.1 Simulation models

In this section, we assess our proposed scheme using OPNET simulator v14.5 [29]. For the simulation, we examine a small network comprising 10 Micaz nodes randomly

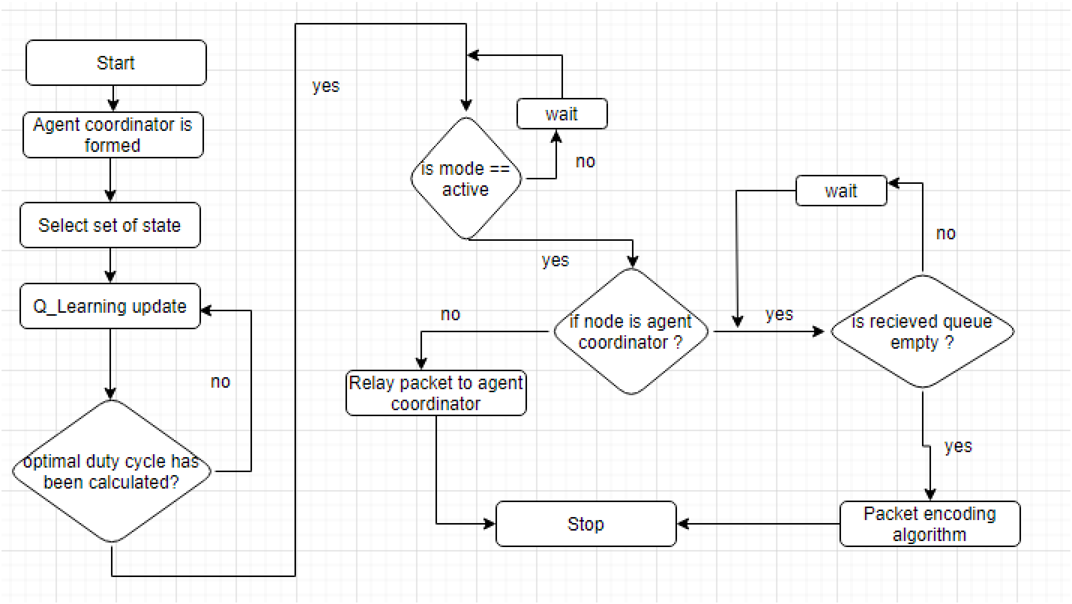

Figure 2: Flow chart of NCDCLA

placed within a 1000x1000m area. The primary parameters utilized in the simulations are provided in Table 1.

Parameter	Value
Data Rate (Kbps)	250
Packet size (bits)	120
Number of node	10
Initial energy (mAh)	16
Learning rate α	0.1
Discount factor γ	0.5
Bitsize_NC_value	2
Output_NC_value	0
Timeout_value (s)	0

Table 1: Parameters used by the NCDCLA simulations

A set of performance metrics is considered, including energy consumed, energy remaining, end-to-end delay, packet delivery rate, throughput, bit error rate, and signal-to-noise ratio. The definitions of these metrics are given below:

- Energy Consumed: The total energy used by all nodes in the network.
- Energy Remaining: The total energy remaining for all nodes in the network.
- End-to-End Delay: The total sum of transferred packets across a network from the source to the sink node.
- Throughput: The rate of successfully received data packets by the node per unit time.
- Packet Delivery Ratio: The ratio of packets successfully delivered to the sink node compared to the total number of packets sent by all sensor nodes in the network.
- Packet Loss Rate: Corresponds to the acceptance or rejection of a packet, respectively.
- Retransmission Attempts: The number of retransmissions due to collision or channel errors.
- Transmission Success: Indicates the success of transmitting a packet.

4.2 Performance of NCDCLA

The simulation results provide a comparison among IEEE 802.15.4, network coding with duty cycle, and NCDCLA.

Ensuring end-to-end delay is a crucial Quality of Service (QoS) parameter for forwarding data in a time-constrained Wireless Sensor Networks (WSNs) environment. This parameter is defined as the total delay, including MAC delay and queuing delay, between the sending and reception of a packet.

Scheme	Queuing delay(s)	MAC delay(s)
IEEE 802.15.4	0,013	0,029
NC+ duty cycle	0,00016	0,00093
NCDCLA	0,000077	0,000064

Table 2: Comparisons of performance

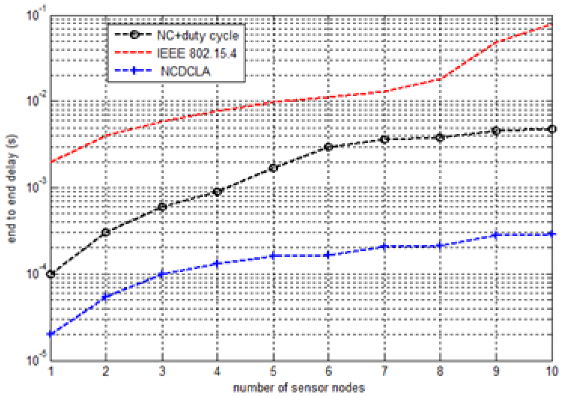

Figure 3: The average end-to-end delay

fig. 3 shows the average end-to-end delay. Based on the results, we observed that NCDCLA exhibits slightly lower end-to-end delay compared to other schemes. Similarly, table 2 presents the MAC delay and queuing delay of our scenario with 10 nodes. We observed that the queuing delay and MAC delay of NCDCLA are lower than those of other schemes because NCDCLA adapts the duty cycle, taking into account the parameter of end-to-end delay. Additionally, network coding (NC) reduces the average end-to-end delay.

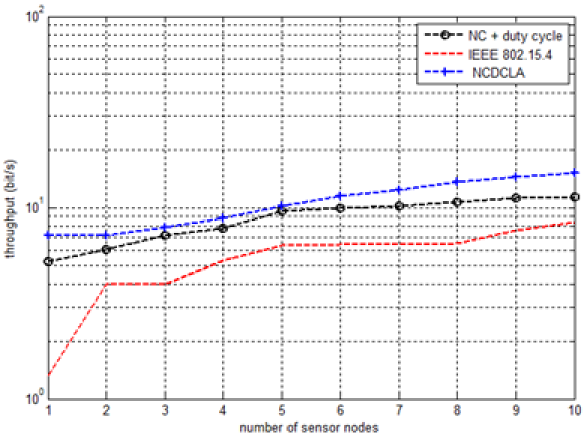

Figure 4: The average throughput

In this scenario, we calculate the average throughput. As depicted in Figure 4, we can observe that as the number of sensor nodes increases, the average throughput also increases. Thus, we confirm that throughput is directly proportional to the increased number of sensor nodes. Additionally, we observed that NCDCLA exhibits slightly higher throughput compared to other schemes because the utilization of network coding could potentially double the throughput.

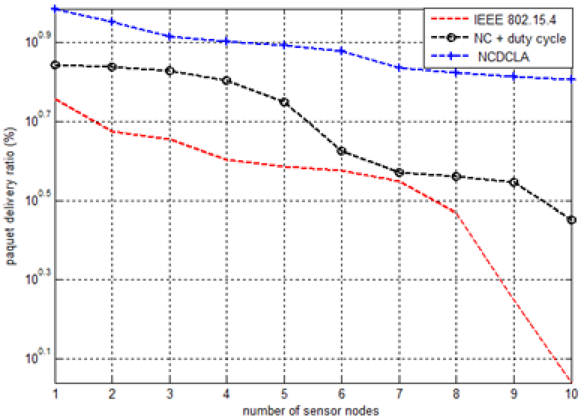

Figure 5: The average packet delivery ratio

Primarily, the packet delivery ratio is another significant parameter for evaluating the performance of QoS. Figure 5 illustrates the average packet delivery ratio. According to these results, we observed that NCDCLA has a higher packet delivery ratio compared to other schemes. NCDCLA achieves 80% when the number of sensor nodes is 10, whereas NC with duty cycle and IEEE 802.15.4 achieve 39% and 28%, respectively.

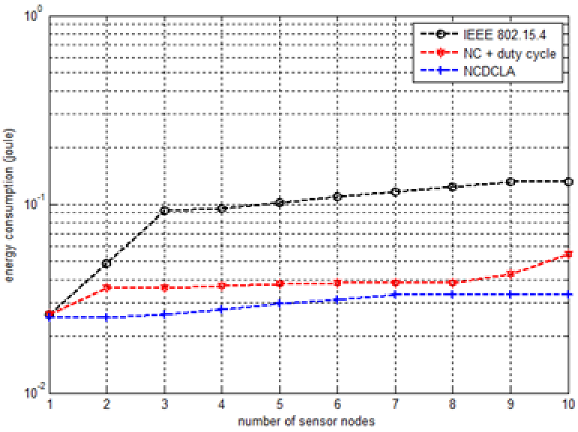

Figure 6: The average energy consumption

The energy consumption can significantly impact Quality of Service (QoS), making real-time applications particularly challenging due to their demanding requirements in terms of end-to-end delay, throughput, packet delivery ratio, and, concurrently, energy consumption and network lifetime.

fig. 6 displays the average energy consumption, where IEEE 802.15.4 exhibits slightly higher energy consumption compared to NC with duty cycle and NCDCLA. The lower energy consumption for NCDCLA and NC with duty cycle is attributed to the use of the duty cycle mechanism. Furthermore, NCDCLA demonstrates slightly lower energy

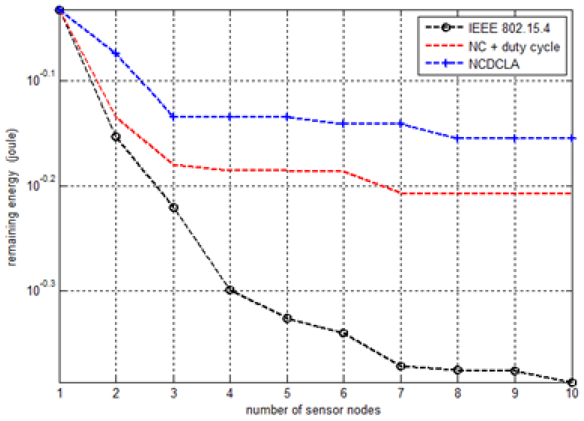

Figure 7: The average remaining energy

consumption than NC with duty cycle because network coding reduces the number of transmissions, and NCDCLA adapts the duty cycle to minimize energy consumption, thereby extending the network's lifetime, as illustrated in Figure 7.

Critical applications are sensitive to packet loss. Figure 8 shows the average packet loss ratio. It is evident that our scheme exhibits a slightly lower packet loss rate compared to other schemes. The lower packet loss rate for NCDCLA is attributed to the optimal duty cycle, which relies on packet loss rewards. Additionally, the concept of network coding contributes to reducing packet loss.

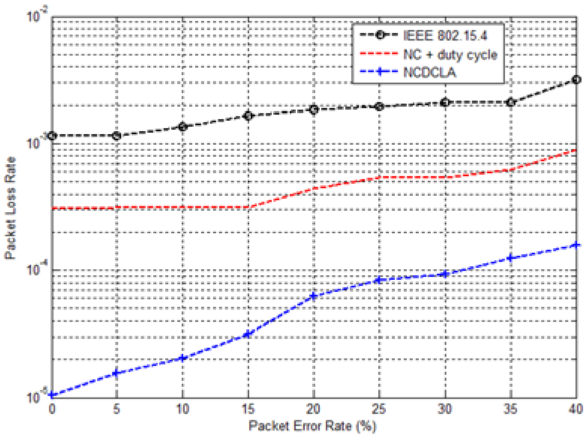

Figure 8: The average packet loss rate

fig. 9 displays the average retransmission attempts for packet error rate. As depicted in this figure, NCDCLA exhibits a slightly lower number of transmission attempts compared to other schemes. The lower number of retransmissions can be attributed to the use of network coding, which reduces the packet loss rate and increases the transmission success, and the optimal duty cycle, which aims to decrease the packet loss rate.

Furthermore, retransmission attempts can impact energy consumption. As illustrated in Figure 10, NCDCLA demonstrates slightly lower energy consumption. However, IEEE 802.15.4 and NC with duty cycle exhibit a higher level of energy consumption.

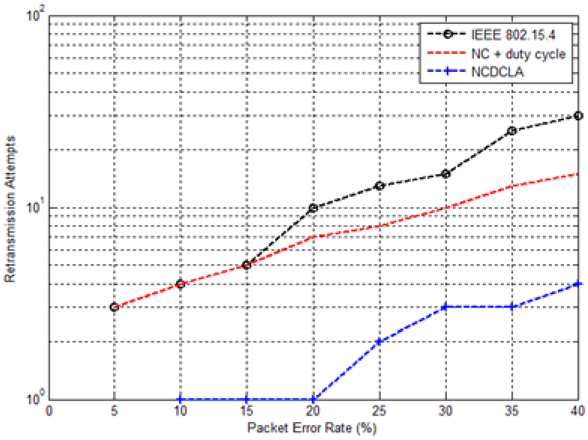

Figure 9: The average retransmission attempts

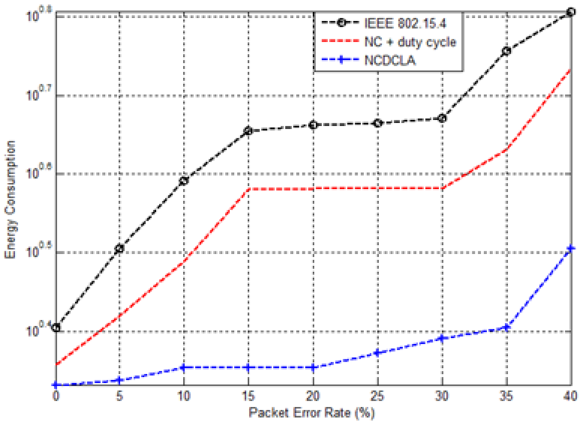

Figure 10: The average energy consumption

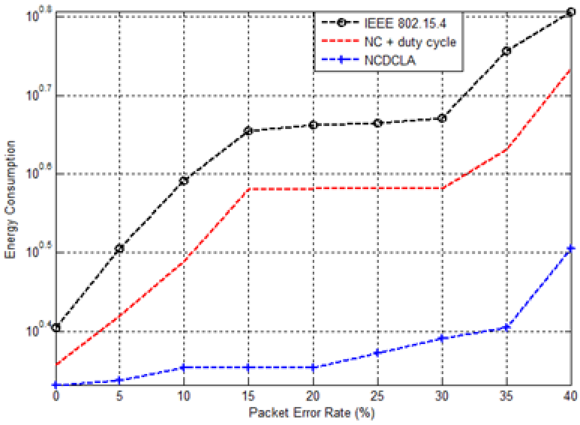

Figure 11: The average transmission success

fig. 11 illustrates the average transmission success. Based on the results, it is observed that as the packet error rate increases, the transmission success decreases. However, NCDCLA exhibits a higher transmission success compared to other schemes. When the packet error rate is 40%, NCDCLA achieves a transmission success rate of 55%, whereas IEEE 802.15.4 and NC with duty cycle achieve 24% and 30%, respectively.

5 Conclusion

Evolving technology has spurred a growing demand for real-time applications in wireless sensor networks. Consequently, supporting Quality of Service (QoS) has become a pivotal challenge. In this paper, we introduce a novel scheme, Network Coding and Duty Cycle Learning Algorithm (NCDCLA), designed to address QoS concerns in Wireless Sensor Networks (WSN). The simulation results demonstrate that NCDCLA significantly enhances performance across various metrics, including energy efficiency, delay, throughput, packet delivery ratio, packet loss rate, and transmission success.

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