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A Dynamic Even Distribution Resource Scheduling Mechanism Combined with Network Coding for Inter-LEO Satellite Networks

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LEO satellite networks have risen to the forefront of study with the dynamic topology changes, varying service requirements and intermittent inter-satellite links (ISLs). Resource scheduling mechanism is the key to determining communication efficiency. However, the state-of-the-art cannot achieve high resource efficiency under both heavy and burst traffic loads, and the applicability of parameters design is insufficient under intermittent ISLs. Considering this, we propose a dynamic even distribution mechanism combined with network coding DENC. This novel mechanism obtains the service requirements and allocates resources dynamically through the even distribution algorithm to balance between network maintenance overhead and idle resources waste, and improves the success probability of transmission based on network coding to balance between retransmission and redundancy. In this paper, we establish performance analysis and resource efficiency optimization models to optimize the parameters such as maintenance frequency and coding coefficient. Besides, we construct a system-level simulation platform. Mathematical and simulation results indicate that the DENC performs better than SAHN-MAC, ICSMA, CSMA-TDMA and HTM under dynamic service requirements and intermittent ISLs, and the resource efficiency can be improved by about 130%.

KEYWORDS
Inter-LEO satellite networks, Resource scheduling mechanism, Even distribution, Network coding

1 | INTRODUCTION

As the backbone of linking multi-domain clusters and providing worldwide operations, the Low Earth Orbit (LEO) satellite network plays a crucial role in getting decision-making benefits[1]. It is also one of the primary growth paths of 6G "ubiquitous coverage". Using microwave-based inter-satellite links (ISLs)[2] to connect satellites and establish an inter-satellite network (ISLN) can offer diverse connection pathways and leverage the benefits of satellite networks[1], which has caught the industry's interest.

Periodic changes in network topology[3], varying service requirements[4][5], and intermittent ISLs[6] are defining characteristics of ILSNs that provide challenges for resource scheduling mechanisms (RSMs) design. Due to the long distance of ISLs, the reservation-based RAM with multiple interactive negotiations incurs a substantial amount of overhead. So there are two different types of RSMs in ILSNs[7]: conflict-free RSMs[8][9] and contention-based RSMs[10][11]. Conflict-free RSMs (i.e. SAHN-MAC mechanism[9]) distributed resources to all nodes regardless of whether they need to transmit data. However, its resource efficiency decreased drastically when the service requirements were inhomogeneous, or the proportion of nodes transmitting data was small because of idle resources. In contention-based RSMs (i.e. ICSMA mechanism[11]), satellites competed for the channel, and data collisions prevented nodes from successfully competing when the proportion of nodes having data to send is large. Therefore, the above mechanism couldn't adapt to heavy and burst traffic loads.

Considering the dynamic service requirements, [12] noted that dynamic resource scheduling can further improve the resilience and adaptability of satellite networks. For example, [13] proposed a CSMA-TDMA protocol in which the allocation of CSMA and TDMA time slots was dynamically altered based on predicted traffic loads, adapting to the dynamic changes in service requirements. The studies above didn't consider the impact of intermittent ISLs.

One way to fulfil the transmission success probability restriction with intermittent ISLs is using retransmission technology, but the retransmission will bring a significant delay in intermittent ISLs[14][15]. Network coding mechanism provides a novel solution to increase the probability of successful transmission[16]. [17] proposed a hybrid transmission mechanism combined with network coding (HTM), which encoded k packets into n packets, and the recipient could succeed after receiving k of n packets. The simulation results showed that when the coding coefficient was 1.1, and the outage probability of ISLs was 10% to 30%, the performance of HTM was better than that of the ARQ mechanism. Unfortunately, the state-of-the-art only considered the data transmission process to design the coding coefficient, ignoring the influence of RAMs and the consensus impact brought by protocols. Therefore, it is still necessary to adjust the coding coefficient in the long-distance and intermittent ISLs.

Focusing on this, we investigate the features of ISLNs, including dynamic network topology, varying service requirements, and intermittent ISLs, and propose a dynamic even distribution RAM combined with network coding (DENC) to improve the adaptability of RAM. DENC obtains the service requirements through the even distribution algorithm based on the regular and predictable topology changes to balance between network maintenance overhead and idle resource waste. Then it improves the successful probability of data transmission based on network coding to balance between retransmission and redundancy overhead. The main contributions in this paper are summarized as follows.

- We propose a dynamic even distribution RAM combined with network coding considering the features of ISLNs, such as dynamic network topology, varying service requirements and intermittent ISLs. DENC first leverages the periodic knowledge of ILSN's topology to evenly distribute the resources to maintain the network. So the service requirements can be obtained through regular network maintenance, then resources are distributed equally based on the service requirements to meet the dynamic service. In addition, DENC employs network coding to reduce the failure probability and retransmission overhead due to intermittent ISLs and network maintenance consensus error and improve resource efficiency.

- We establish performance analysis models to analyze performance under different proportion of nodes with service requirements and outage probabilities of ISLs. On this basis, a resource efficiency optimization model is established to optimize the parameters to balance between network maintenance overhead and idle resource waste, retransmission and redundancy. In particular, considering the fact that the consensus probability of network maintenance has not been evaluated in state-of-the-art[18], we analyze the network maintenance consensus probability using multi-agent consensus theory[19].
- A Visio Studio (VS)-based platform is constructed for system-level simulation to simulate the performance of DENC. Mathematical and simulation results indicate that the DENC performs better than SAHN-MAC[9], ICSMA[11], CSMA-TDMA[13] and HTM[17] under dynamic service requirements and intermittent ISLs, and the resource efficiency can be improved by about 130%.

The article is organized as follows: The first part is the introduction, in which we introduce the background and research objectives. The network structure of this paper is described in Section 2. Section 3 shows the critical process and frame structure of DENC. Section 4 describes the performance analysis models of DENC, and optimizing mechanical parameters is achieved by establishing a resource efficiency optimization model. To verify the model's accuracy and DENC's applicability, we build a simulation platform based on VS, and compare the performance of different RAMs in Section 5. Section 6 summarizes the whole paper.

2 | NETWORK STRUCTURE OF INTER-LEO SATELLITE NETWORK

As a typical LEO satellite constellation with ISLs, Iridium[20] serves a valuable reference for future design. We implement the RAM based on the polar constellation and microwave ISLs referring to the Iridium constellation. The ILSN structure in a time slice is shown in Figure 1. We consider that the constellation topology within a time slice[21] will not change. The red line indicates the connectivity of some nodes in a time slice in the figure.

The satellite network has M polar orbital planes, and there are N_o LEO satellites on each plane. The orbit altitude of the constellation $L_o = 780km$. The satellite operates in half-duplex mode. Each satellite has 2 inter-plane ISLs and $N_i - 2$ intra-plane ISLs. The maximum number of network hops is $H_{net} = \lceil M/2 \rceil \cdot \lceil N_o/2 \rceil$.

For ISLs in the same orbit, the link distance is

$$L_{\mathrm{v}} = \sqrt{2}(R + L_{\mathrm{o}})\sqrt{1 - \cos(\frac{360^0}{N_{\mathrm{o}}})} \tag{1}$$

where R is the radius of the earth.

For ISLs with neighboring different orbits, the link distance is

$$L_{\mathrm{h}} = \sqrt{2}(R + L_{\mathrm{o}})\sqrt{1 - \cos(\frac{360^\circ}{2M})} \times \cos(lat) \tag{2}$$

where lat indicates the latitude of the ISL.

The unequal distribution of ground stations and users causes dynamic changes in service demands of satellites[5]. The proportion of nodes with service requirements is p_{sr} within a time slice. The outage probability of ISLs is p_{out} considering the influence of the free space propagation loss and interference from ground[6].

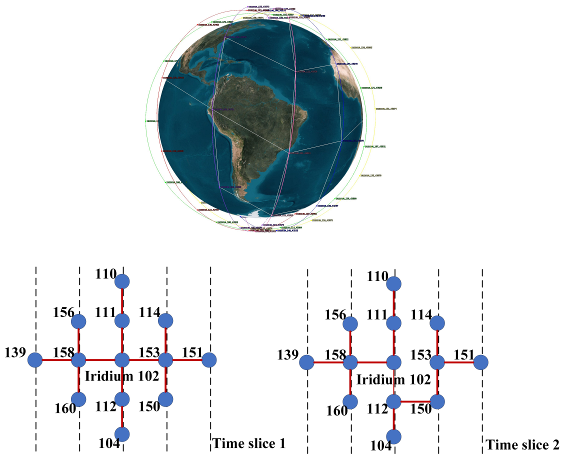

FIGURE 1 LEO Satellite Network Structure. ISLs between the Iridium 102 and its 2-hop neighbors are shown as red lines in different time slices when $Ni = 4$.

3 | DESIGN OF DENC

The ILSN has the characteristics of dynamic but periodic topology changes, which can be used to evenly divide the resources according to the topology connectivity without multiple interactive negotiations or competitions. Therefore, we optimize the RAM based on even distribution RAM[22].

First of all, due to the fluctuating service requirements of ILSNs, we first acquire service requirements via network maintenance and dynamically allocate resources to improve the flexibility of RAM. The data resources are allocated according to the maintained service requirements. Then we use a network coding mechanism and adjust the coding coefficient to improve the transmission success probability of and decrease the retransmission delay. Based on the above methods, we can realize the trade-off between network maintenance overhead and idle resources waste, retransmission and redundancy overhead.

3.1 | Frame structure and message structure

Considering that the DENC needs network maintenance and adopts network coding for transmission, the frame structure of DENC is shown in Figure 2. We divide each frame into $C_{sat} + D_{sat}$ time slots, where C_{sat} denotes the number of control slots for transmitting network maintenance information, and D_{sat} denotes the number of data slots for data transmissions. The number of control and data slots in each frame is determined according to the resource efficiency optimization model in Section 4.4.

The duration of effective transmission in each data slot of DENC is 8.28ms[20], which is consistent with the slot duration of Iridium. Considering the impact of long delay caused by ISL distance and the coding coefficient of slots, the duration of a slot is set as the sum of transmission delay and protection interval. That is, the duration of the control slot is $T_{\text{sat-c}} = T_{\text{guard-is}} + \alpha_{\text{NC-c}} T_{\text{sat-data}}$ and the duration of the data slot is $T_{\text{sat-d}} = T_{\text{guard-is}} + \alpha_{\text{NC-d}} T_{\text{sat-data}}$. Taking the maximum distance difference between adjacent nodes as the ISL distance difference, we can get the protection interval is $T_{\text{guard-is}} = [\max(L_{\text{v}}, L_{\text{h}}) - \min(L_{\text{v}}, L_{\text{h}})]/(3 \times 10^8)$.

The DENC needs to conduct network maintenance through control messages and obtain service requirements

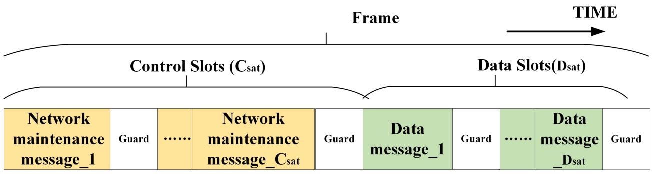

FIGURE 2 Frame structure of DENC with C_{sat} control slots (marked with yellow boxes) and D_{sat} data slots (marked with green boxes).

information. The network maintenance message structure is shown in Figure 3. Network maintenance messages include node ID, service requirements, neighbor set, etc.

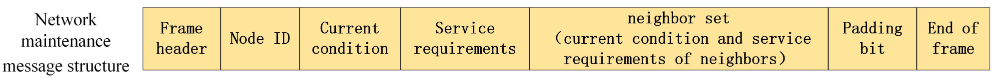

FIGURE 3 Network maintenance message structure of DMNC.

3.2 | Process of DENC

The critical process of DENC is shown in Figure 4.

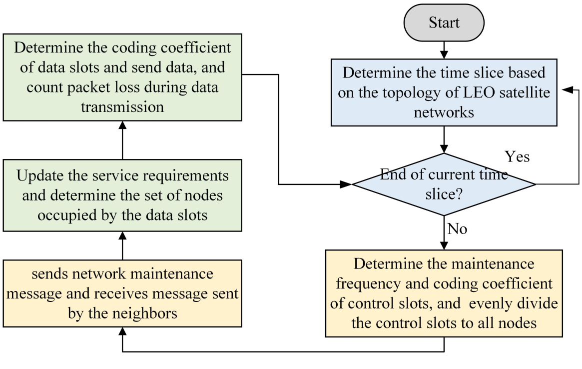

FIGURE 4 The process of DENC, mainly includes the network maintenance and data transmission process.

(1) Determine the maintenance frequency (the number of control slots in each frame) and the coding coefficient of control slots, based on service requirements and transmission success probability determined from the previous time slice. With the connectedness of nodes of the current time slice, control slots are equally divided for all nodes. Each node needs to be allocated at least one control slot.

(2) The node transmits the network maintenance message according to the chosen coding coefficient in the allocated control slots, receives the network maintenance message from neighbors, and forwards the neighbors' information until it spreads across the whole network (that is, the farthest node's information is received).

(3) The coding coefficient of data slots is defined by the statistical success probability of data transmission in the preceding time slice. After network maintenance, data slots are allocated according to the service needs. If the network maintenance information of a node is not received before the network maintenance is completed, resources

are still allocated to the node. If the service demand of the node is not received after the network maintenance process is completed or if the received network maintenance information of the node shows that there is no service demand, resources will not be allocated to it.

(4) Nodes with service requirements send data under the chosen coding coefficient in the allocated data slots. Based on the service demand within this time slice, calculate the number of control slots in each frame of next time slice. Concurrently, the packet loss in the current time slice is counted as the current link quality, and the coding coefficient parameters for the subsequent period are computed based on the prediction findings.

(5) When the next time slice arrives, repeat the preceding steps to conduct dynamic network maintenance and data transmission.

4 | PERFORMANCE ANALYSIS MODEL OF DENC

In this section, we establish the network maintenance consensus model and the transmission success probability model to analyze mechanism performance, taking into account the influence of network parameters (the number of nodes in ILSN), service parameters (the proportion of nodes with service requirements) and channel parameters (outage probability of ISLs). On this basis, the scheduling cycle and resource efficiency optimization models are established, and the ideal maintenance frequency and coding coefficient are calculated to enhance performance.

4.1 | Overhead and consensus probability of network maintenance

DENC meets service requirements by performing periodic network maintenance. A node's network maintenance message must be broadcast to the whole network. If the frame required for a node to receive all nodes' information is considered a scheduling cycle, the number of control slots utilized in that cycle is

$$C_{\text{sat-all}} = \frac{H_{\text{net}}}{\bar{H}_{\text{nbr}}} \left(N_{\text{nbr}} + 1 \right) \tag{3}$$

where $N_{\text{nbr}}+1$ represents the number of H_{nbr}-hop neighbors, $H_{\text{nbr}} = 3$[23]; $\bar{H}_{\text{nbr}}$ is the number of hops that the network maintenance message can spread after each frame of control message is sent. Considering that the transmitting order of each node is random after the control slots resources are equally divided, $\bar{H}_{\text{nbr}} = 1.75$.

Section 3.2 explains how DENC utilizes network coding to increase the transmission success probability. When network coding is adopted to encode K_{NC} packets into M_{NC} packets, the failure probability of transmission is

$$p_{\text{out-NC}} = \sum_{m=0}^{K_{\text{NC}}-1} C_{M_{\text{NC}}}^{m} \left(1 - p_{\text{out-is}}\right)^{m} {p_{\text{out-is}}}^{M_{\text{NC}}-m} \tag{4}$$

According to the frame structure described in Section 3.1, each control slot may hold one network maintenance message, so $K_{\text{NC-c}} = 1$. Further, we can get $\alpha_{\text{NC-c}} = M_{\text{NC-c}}/K_{\text{NC-c}}$. For network maintenance messages, the failure probability of transmission is

$$p_{\text{out-NC-c}} = M_{\text{NC-c}} {p_{\text{out-is}}}^{M_{\text{NC-c}}} \tag{5}$$

Network maintenance may fail to be transmitted because of intermittent ISLs, leading to a conflict of resource scheduling results and raising the failure probability of data transmission. Therefore, we analyze the consensus probability of network maintenance, that is, the probability that the node information can be accurately maintained.

Based on the multi-agent consensus analysis theory[19], we use a maintenance matrix to describe the neighbor maintenance outcomes and assess the network maintenance consensus probability based on this matrix. In the topology maintenance matrix, 0 indicates that the network maintenance message is lost, while 1 indicates that the network maintenance message is successfully received. Take the network information maintained by a node as an example for analysis. For a H_i-hop neighbor of a node, the probability that its maintenance matrix value is 1 is $1-[1-(1-p_{\text{out-nc-c}})^{Hi}]^{N_{\text{nm}}}$, where N_{nm} indicates the average received times of network maintenance information of H_i-hop neighbors.

$$N_{\text{nm}} = \left\lfloor \frac{H_{\text{net}}/\bar{H}_{\text{nbr}}}{H_i/\bar{H}_{\text{nbr}}} \right\rfloor \tag{6}$$

It can be obtained that the mean value is $E_{\text{sat}} = 1-[1-(1-p_{\text{out-nc-c}})^{Hi}]^{N_{\text{nm}}}$, and the variance is $D_{\text{sat}} = \{1-[1-(1-p_{\text{out-nc-c}})^{Hi}]^{N_{\text{nm}}}\}\cdot[1-(1-p_{\text{out-nc-c}})^{Hi}]^{N_{\text{nm}}}$. The binomial distribution can approximate to the normal distribution. If the maintenance consensus threshold is θ_{sat}, the maintenance success probability of hop neighbors is

$$p_{\text{con-is,i}} = \Phi\left(\frac{\theta_{\text{sat}} - E_{\text{sat}}}{\sqrt{D_{\text{sat}}}}\right) \tag{7}$$

The maintenance consensus probability is

$$p_{\text{con-is}} = \frac{\sum_{i=1}^{H_{\text{net}}} N_i \cdot p_{\text{con-is},i}}{MN_o} = \frac{\sum_{i=1}^{H_{\text{net}}} N_i \cdot \Phi\left(\frac{\theta_{\text{sat}} - E_{\text{sat}}}{\sqrt{D_{\text{sat}}}}\right)}{MN_o} \tag{8}$$

4.2 | Transmission success probability of data messages

As mentioned in Sections 3.2, the DENC still allocates data slots to all nodes before network maintenance is completed. In the absence of network coding, each data slot may hold up to 3 Ping packets[1], so $K_{\text{NC-d}} = 3$. Further, we can get $\alpha_{\text{NC-d}} = M_{\text{NC-d}}/K_{\text{NC-d}}$. The transmission failure probability of data messages is

$$p_{\text{out-NC-d}} = \sum_{m=0}^{2} C_{M_{\text{NC-d}}}^{m} (1-p_{\text{out-is}})^m {p_{\text{out-is}}}^{M_{\text{NC-d}}-m} \tag{9}$$

DENC allocates data slot resources according to the maintained service requirements after network maintenance. Therefore, when the network maintenance is complete, the transmission success probability of data message is not only related to the outage probability of ISLs, but also the network maintenance consensus probability. The number of nodes not maintained but with service requirements is

$$N_{\text{uncon-is}} = (1-p_{\text{con-is}})p_{\text{sr}}N_{\text{nbr}} \tag{10}$$

After the network maintenance is completed, nodes with consensus maintenance and service requirements may be successfully transmitted if there is no collision with the nodes with inconsistent maintenance and no packet loss. So, the transmission success probability is

$$p_{\text{suc-NM}} = p_{\text{con-is}}(1-p_{\text{out-NC-d}}) \times \left(1 - \frac{1}{p_{\text{sr}}(1-p_{\text{fa}})p_{\text{con-is}}N_{\text{nbr}}+1}\right)^{N_{\text{uncon-is}}} \tag{11}$$

[1]When the transmission rate is 96 kbps[20], the packet length of each slot is $L_{\text{pak-is}} = 96 \times 8.28 = 794$bit. Each slot can accommodate three Ping packet data (32Byte).

4.3 | Scheduling cycle and resource efficiency of DENC

The scheduling cycle and resource efficiency of the DENC are analyzed in light of the impact of mechanism factors such as varied maintenance frequency and coding coefficients. When there are C_{sat} control slots in each frame, the scheduling cycle is

$$T_{\text{sat-DENC}} = \frac{C_{\text{sat-all}}}{C_{\text{sat}}} \times [(T_{\text{guard-is}} + \alpha_{\text{NC-c}} \times 8.28) + D_{\text{sat}}(T_{\text{guard-is}} + \alpha_{\text{NC-d}} \times 8.28)] \tag{12}$$

The resource efficiency is normalized as

$$\begin{aligned} \eta_{\text{sat-EMNC}} = & \frac{(\left\lceil \frac{C_{\text{sat-all}}}{C_{\text{sat}}} \right\rceil - 1)p_{\text{sr}}(1 - p_{\text{fa}})}{T_{\text{sat-DENC}}} \times \frac{(1 + D_{\text{sat}} - C_{\text{sat}})(1 - p_{\text{out-NC-d}})T_{\text{sat-data}}}{T_{\text{sat-DENC}}} \\ & + \frac{(C_{\text{sat-all}} - \left\lceil \frac{C_{\text{sat-all}}}{C_{\text{sat}}} \right\rceil + 1)(1 + D_{\text{sat}} - C_{\text{sat}})}{T_{\text{sat-DENC}}} \times \frac{p_{\text{suc-NM}} T_{\text{sat-data}}}{T_{\text{sat-DENC}}} \end{aligned} \tag{13}$$

4.4 | Resource efficiency optimization of DENC

The resource efficiency model of DENC reveals that the proportion of nodes with service requirements, outage rate of ISLs, maintenance frequency, and coding coefficient are the most influential resource efficiency characteristics. To further improve the performance of the DENC, considering the time slice constraints of ILSN, we establish an optimization model of resource efficiency to determine the optimal coding coefficient and maintenance frequency. The resource efficiency optimization model is stated as follows:

$$\begin{aligned} & \max : \eta_{\text{sat-EMNC}} \\ & s.t. : T_{\text{sat-EMNC}} \leq T_{\text{time-slicing}} \end{aligned} \tag{14}$$

5 | SIMULATION ANALYSIS AND PERFORMANCE COMPARISON

5.1 | Simulation platform setup

We build a system-level simulation platform based on VS and conduct mechanism performance simulation, as shown in Figure 5.

The value ranges of the parameters of DENC are shown in Table 1.

5.2 | Simulation results

5.2.1 | Resource efficiency of DENC

(1) Impact of coding coefficient on resource efficiency

Take the proportion of nodes with service requirements $p_{\text{sr}} = 1$, and the maintenance frequency $C_{\text{sat}} = 2$ for example to simulate. Figure 6 depicts the resource efficiency of the DENC under different outage probabilities of ISLs and coding coefficients. Some optimal coding coefficients are shown in the figure. The point in the picture indicates the value based on the simulation platform. The line in the figure reflects the value based on the model presented above. It can be observed that the mathematical results and simulation results are congruent.

When the outage probability of ISLs $p_{\text{out-is}} = 0$, the highest resource efficiency can be achieved without adding

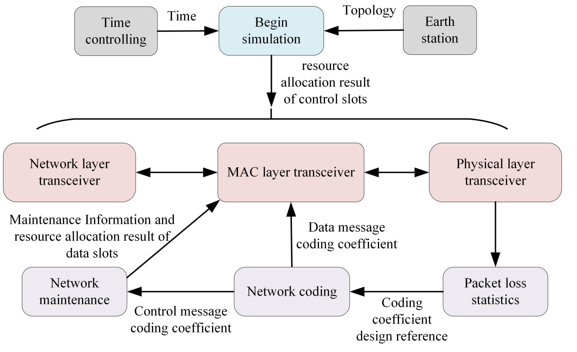

FIGURE 5 System-level simulation platform includes network coding module, network maintenance module, etc.

TABLE 1 Parameter value of VS-based simulation verification platform.

Parameter	Value
M	$M = 6$
N_o	$N_{\rm o} = 11$
N_i	$N_{\rm i} = 4$
$p_{\rm sr}$	$0 < p_{\rm sr} \leq 1$
$p_{\rm out-is}$	$0 \leq p_{\rm out-is} \leq 0.3$[6]
$T_{\rm sat-data}$	$T_{\rm sat-data} = 8.28$ms
$T_{\rm time-slicing}$	$T_{\rm time-slicing} = 213.93s$[21]
$C_{\rm sat}$	$1 \leq C_{\rm sat} < N_{\rm nbr} + 1$
$D_{\rm sat}$	$D_{\rm sat} = N_{\rm nbr} + 1$
$\theta_{\rm sat}$	$\theta_{\rm sat} = 1$
$\alpha_{\rm NC-c}$	$\alpha_{\rm NC-c} \geq 1$
$\alpha_{\rm NC-d}$	$\alpha_{\rm NC-d} \geq 1$

network coding, that is, the coding coefficient of control slots $\alpha_{\rm NC-c} = 1$ and coding coefficient of data slots $\alpha_{\rm NC-d} = 1$. When $p_{\rm out-is} > 0$,the resource efficiency first increases and then decreases with the increase of the coding coefficient increases. The reason is that as the coding coefficient increases, the transmission success probability and the consensus probability of network maintenance increase, leading the resource efficiency increases. However,suppose the coding coefficient is large. In that case, the gain of transmission success probability and network maintenance consensus probability is no longer obvious, and the coding redundancy increases, so the resource efficiency decreases. Besides, with the increased outage probability of ISLs, the resource efficiency under the same coding coefficient decreases. To ensure best resource efficiency, a larger coding coefficient is necessary. We can achieve a compromise between retransmission and coding redundancy costs by selecting the optimal coding coefficient.

(2) Impact of maintenance frequency on resource efficiency

Take $\alpha_{\rm NC-c} = 4$ and $\alpha_{\rm NC-d} = 1.33$ for example to simulate. The resource efficiency of the DENC under various maintenance frequencies is shown in Figure 7.

As shown in Figure 7(a), with the same network maintenance frequency, the resource efficiency of DENC im-

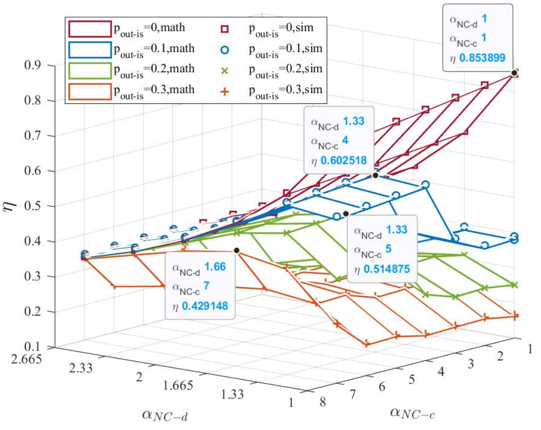

FIGURE 6 Resource efficiency of the DENC under different outage probabilities of ISLs and coding coefficients. As the coding coefficient increases, the resource efficiency rises first and then drops.

proves as the proportion of nodes with service needs increases. Moreover, it can be evident from Figure 7 that resource efficiency declines when the outage probability of ISLs rises, assuming the same network maintenance frequency and proportion of nodes with service requirements.

The arrows depicting appropriate network maintenance frequencies are shown in the diagram. As the proportion of nodes with service needs increases, the optimal network maintenance frequency decreases. This is because when the proportion of nodes with service requirements is low, if the network maintenance is not completed, data slots resources need to be allocated to all nodes, resulting in a severe waste of resources. Therefore, a higher network maintenance frequency is necessary to complete the network maintenance process as soon as possible and allocate resources based on the network maintenance information. However, when the proportion of nodes with service needs is relatively large and the network maintenance has not been completed, the data slots resources are allocated to all nodes with little resource waste. Therefore, it is no longer susceptible to the completion time of network maintenance. Considering the impact of the number of control slots on resource efficiency in each frame, we suggest that a minor network maintenance frequency is necessary under these circumstances to improve resource efficiency performance.

By comparing Figure 7(a), 7(b) and 7(c), it can be seen that when $p_{\text{out-is}} = 0.1$, the optimal network maintenance frequency is same as when $p_{\text{out-is}} = 0$. This is because with $\alpha_{\text{NC-c}} = 4$ and $\alpha_{\text{NC-d}} = 1.33$, the network maintenance consensus probability reaches 1 when $p_{\text{out-is}} = 0.1$. The network maintenance consensus error does not affect resource scheduling and data transmission. However, when $p_{\text{out-is}} \geq 0.2$, the optimal network maintenance frequency differs from when $p_{\text{out-is}} = 0$, and it is lower under the same proportion of nodes with service requirements. This is because the probability of resource allocation conflict is high when $p_{\text{out-is}} \geq 0.2$, resulting in a poor transmission success probability for data packets. Data transmission will not collide when network maintenance is not performed, notwithstanding the waste of resources caused by providing resources to nodes without service demands. Therefore, it is more likely to select minor network maintenance frequencies to minimize the proportion of resource allocation after network maintenance. We can achieve a trade-off between network maintenance overhead and idle resources waste by selecting the optimal maintenance frequency.

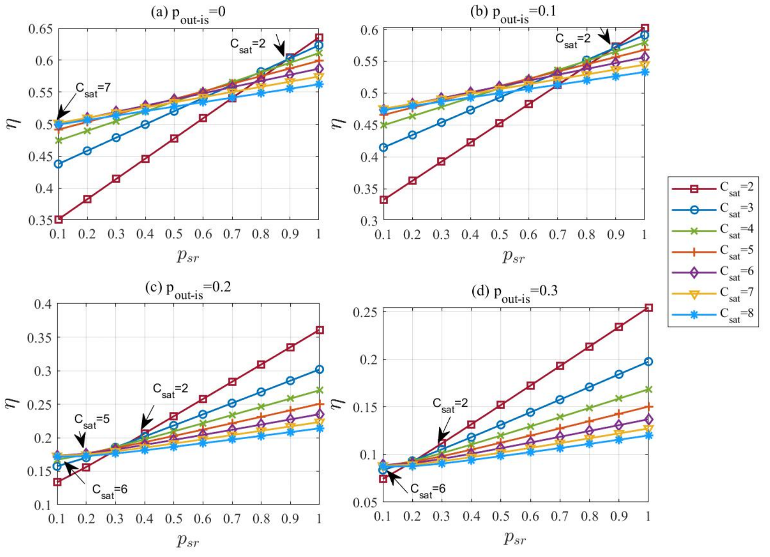

FIGURE 7 The resource efficiency of the DENC under various outage probabilities of ISLs, proportions of nodes with service requirements and maintenance frequencies.

5.2.2 | Resource efficiency performance comparison

The performance comparison between DENC, SAHN-MAC[9], ICSMA[11], CSMA-TDMA[13], and HTM[17] coupled with CAMA-TDMA under varying proportions of nodes with service requirements and outage probabilities of ISLs is shown in Figure 8, assuming that the settings of each mechanism are optimum[2]. The arrows in the diagram show some mechanism performance intersections, while the figure's red numbers depict the mechanism gain.

The resource efficiency of DENC, SAHN-MAC, CSMA-TDMA and HTM improves progressively as the proportion of nodes with service needs increases; however, the resource efficiency of ICSMA declines when collisions intensify.

As shown in Figure 8(a), when $p_{\text{out-is}} = 0$ and $p_{\text{sr}} < 0.9$, the resource efficiency of DENC is superior than that of HTM, and its resource efficiency can be enhanced by no more than 132%. DENC's resource efficiency is superior to that of CSMA-TDMA and SAHN-MAC, and its resource efficiency can be improved by about 109% at most. Because the DENC requires network maintenance to allocate resources, the resource efficiency benefit of DENC decreases as the proportion of nodes with service requirements increases. The coding coefficient of the DENC is 1 when $p_{\text{out-is}} = 0$, whereas HTM has a coding coefficient of 1.1, making the performance of the HTM inferior to that of the CSMA-TDMA.

When the outage probability of ISLs increases, SAHN-MAC, ICSMA and CSMA-TDMA must guarantee the transmission success probability by retransmission, resulting in a rapid decline in resource efficiency. As demonstrated in Figure 8(b), DENC's resource efficiency may be increased by up to 131% relative to HTM. Compared to the performance shown in Figure 8(a), the maximum gain of DENC's resource efficiency is diminished. Because in this circumstance, the HTM improves the transmission success probability by networking coding, but the DENC must improve the network maintenance consensus rate with additional control slot coding. As shown in Figure 8(c) and 8(d), the resource efficiency of DENC is better than that of HTM when $p_{\text{out-is}} = 0.2$. With the increased outage probability of ISLs, the resource efficiency of DENC rise to 130%.

[2]Take $K_{\text{NC-d}} = 9$ for comparison

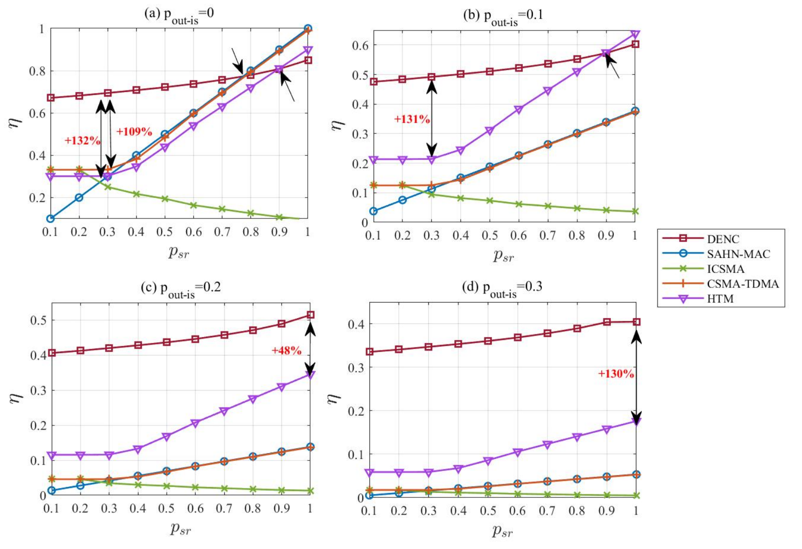

FIGURE 8 The performance comparison between DENC, SAHN-MAC, ICSMA, CSMA-TDMA, and HTM under different proportions of nodes with service requirements and outage probabilities of ISLs.

6 | CONCLUSION

Based on the analysis of existing resource scheduling mechanisms in uneven service requirements and intermittent ISLs, we propose a dynamic even distribution mechanism combined with network coding. This novel mechanism allocates resources based on network maintenance to meet the service requirements, and improves the transmission success probability based on network coding to reduce retransmission overhead. We establish performance analysis models and optimize the maintenance frequency as well as the coding coefficient to weigh the network maintenance overhead against idle resources waste, retransmission against redundancy overhead. Besides, we construct a system-level simulation platform to simulate the performance. Mathematical and simulation results indicate that the proposed mechanism performs better than SAHN-MAC, ICSMA, CSMA-TDMA and HTM under dynamic service requirements and intermittent ISLs, and the resource efficiency can be improved by about 130%.

DATA AVAILABILITY STATEMENT

The datasets analyzed during the current study are available from the corresponding authors on reasonable request.

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