# Network Coding in TDMA-based Scheduling for Fluctuating Linear Wireless Sensor Networks

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***Abstract*—Wireless sensor networks have been applied in diverse applications, from facility monitoring to localized event surveillance, e.g., in power distribution grids of developing regions where traditional cables are not feasible. Linear wireless sensor networks are employed in such situations, where nodes link through lossy tandem links. Sensors generate and send data packets through intermediaries to reach network endpoints, where gateways forward aggregated data to a central server. Our previous research introduced a TDMA-based framework to ensure stable, cost-effective deployment, optimize delivery efficiency, and feature a proactive loss recovery mechanism in lossy links. However, as link loss increases, maintaining a high successful delivery probability that all packets from all nodes to the server becomes more challenging. Besides, the number of packets generated at sensors can fluctuate and sometimes exceed downstream link capacity, resulting in unrecovered packet losses. This paper investigates the benefit of using network coding schemes to enhance data transmission reliability in linear multi-hop wireless sensor networks, especially in a high link loss rate and packet fluctuation situations. The simulation results show a significant improvement in overall successful delivery probability and fairness (small deviations of success delivery probability among nodes) compared to the previous method in scenarios with a high link loss rate and moderate packet fluctuation.**

***Index Terms*—Linear Wireless Sensor Network, Packet Fluctuation, Network Coding, TDMA-based scheduling**

## I. Introduction

Linear multi-hop wireless networks [1] have gained significant attention due to their cost-effectiveness, quick deployment, and ability to establish connections and coverage in areas where single-hop networks fall short. They excel in scenarios requiring extensive area monitoring and data collection, especially when conventional communication infrastructures are unavailable or economically unfeasible. These networks find application in facility monitoring and local event surveillance within power distribution grids, particularly in areas where wired connections are impractical, as shown in Fig. 1. However, these environments are prone to packet loss due to various factors like attenuation, fading, and interference among nearby sensors. To address these challenges, lost packets are typically recovered using proactive methods such as Forward Erasure Correction (FEC) or reactive approaches like Automatic Repeat-reQuest (ARQ). Concurrent transmissions are managed through Media Access Control (MAC) protocols, which can use scheduling-based mechanisms like Time Division Multiple Access (TDMA) [2], [3] or contention-based strategies like Carrier Sense Multiple Access (CSMA) [4].

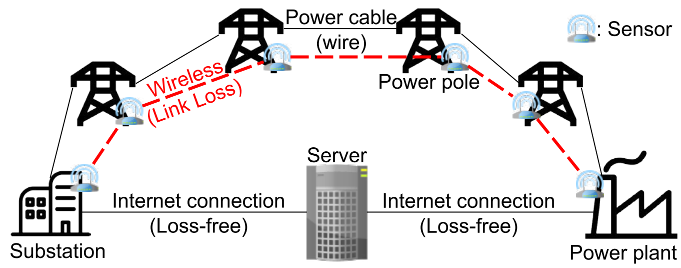


Fig. 1. Distribution grid and local event monitoring in areas with developing infrastructure using wireless sensors.

Figure 1 demonstrates a simple linear multi-hop wireless network setup. It includes monitoring sensors on power poles, establishing wireless interlinks, and cyclically generating monitoring data packets sent to a central management server. These stationary sensors are linearly connected through unreliable channels. In this framework, each sensor has a dual role: generates data packets at regular intervals and acts as a relay by sending packets toward the network's edge with controlled redundant transmissions. Two gateways at the network's ends connect to the central server via a reliable channel, ensuring seamless data transmission. This architecture is efficient for transmitting monitoring data over long distances, making it suitable for applications like power distribution grid management and other scenarios requiring extensive monitoring in challenging environments.

In the context of proximate sensor nodes using mid-range wireless links prone to loss, packet exchange aims to maintain network stability cost-effectively. Traditional network research has focused on managing packet flows temporally (scheduling) and spatially (routing or frequency allocation) to prevent interference during concurrent transmissions. However, this can be challenging with conflict graphs representing link interference [5]. Tandem topologies offer a more favorable framework for

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handling routing path models and conflict graphs, simplifying scheduling and routing optimization due to their inherent structure and improving network performance feasibility.

Our previous studies [6]–[8] introduced a centralized scheduling framework to devise a static time-slot allocation for redundant packet transmission. A central scheduler collects all parameters, including network topology, data collection cycle duration, transmission bandwidth, packet loss rates, and the number of packets generated at each node (sensor). The scheduler, then, formulates optimal TDMA-based scheduling with a proactive approach involving redundant packet transmission, addressing challenges arising from loss-prone links, and subsequently implementing this schedule across network nodes The previous works adopt a straightforward FEC method, wherein the same packet is transmitted repeatedly [7], [8], and the coded packets generated through a simple inter-packet XOR coding are sent [6]. Furthermore, as demonstrated in [9], our methods on a simple linear multi-hop network can be extended to more general networks composed of multiple linear multi-hop networks, such as a Y-shaped sensor network with three egress gateways. However, these simple repeat methods are a discrete duplication of packets, resulting in sensitivity to the order of losses. If a substantial of lost packets originate from a single original packet, the success probability of that packet's arrival significantly decreases. Besides, while the packet loss rate of each link generally remains stable, the number of packets generated by a sensor may fluctuate cyclically, leading to the number of required duplicated packets determined by the optimal schedule being higher than the downstream link capacity. This issue causes weakness in recovering the losses.

This paper introduces a Network Coding approach for better efficiency in a proactive loss recovery to mitigate the adverse effect of fluctuation in packet generation. Network Coding combines a set of packets into interconnected combination packets [10]. Consequently, Network Coding is unaffected by any order-specific lost packets; as long as the count of received combination packets equals or is greater than that of the original packets, successful decoding and reception of all original packets is ensured. This distinctive attribute helps the Network Coding scheme achieve a high success probability across scenarios characterized by substantial link loss rates, a large number of packets generated per sensor, and high degree packet fluctuations, compared to the previous schemes.

The rest of this paper is organized as follows. Sect. II reviews the scheduling based on TDMA. . Sect. III explains the Network coding approach. Simulation results and evaluation is discussed in Sect. IV, and the conclusion is given in Sect. V.

## II. TDMA SCHEDULING

### A. System model

This section introduces a conceptual framework where multiple nodes send the collected sensor data to a server via gateways, as shown in Fig. 1. This framework is termed a linear multi-hop wireless communication model, aiming to create a topology with gateways at both ends, as shown in Fig. 2. This architecture can include any nodes between the gateways (represented as $N$, with a specific example here being $N = 8$) for collecting and transmitting data from sensor nodes to the server. The key characteristics of this model are described below and summarized in Table I.

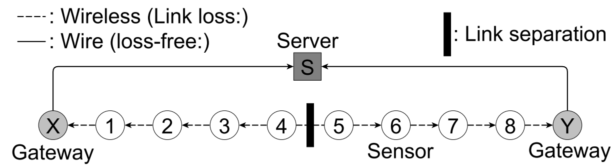



Fig. 2. Linear Wireless Sensor Network model.

TABLE I
TERMINOLOGY DESCRIPTION

| Term | Description |
|---|---|
| $N$ | Node total in the network. |
| $i$ | Node identification ($0 < i \leq N$). |
| $j$ | Link identification ($0 < i \leq N{+}1$). |
| $r_i$ | Generated packet total at Node $i$ in one cycle period. |
| $q_j$ | Link $j$'s loss rate. |
| $T$ | Total time-slots of one cycle. |
| $s_{i,j}$ | The number of redundant transmissions generated for a single original packet at node $i$ on link $j$. |

- The network has $N$ nodes indexed 1 to $N$.
- The wireless link total between nodes and between nodes and gateway (GW) at both ends is $N$+1 and can be indexed by $j$ (1 to $N{+}1$).
- Node $i$ generates total packet of $r_i$ in one cycle. There are $T$ time-slots in one cycle. The basic schedule is made to prevent two adjacent nodes from transmitting simultaneously in the same direction to avoid radio interference. Note that this "two-hop rule" is just an example, and the following formulation can be easily changed according to the rule on simultaneous transmissions by adjacent nodes.
- The lossy link $j$ has the link loss rate of $q_j$ ($0 < q_j \leq 1$).
- Nodes relay all the packets to the network ends (GW X and Y) with a store-and-forward mechanism. The packets are then forwarded to a central server S through a reliable infrastructure network (loss-free links).

The path model involves finding a separation link creating two directed paths (left and right). Assuming a simple Repeating Transmission method (RT) [7] to recover losses, our previous studies calculate an optimal schedule and assess performance for each possible separation link position using the methods described in Sections II-B and II-C. This exhaustive evaluation helps choose the best separation link location. For example, in Fig. 2, the separation link is between nodes 4 and 5. Left Nodes send packets to Gateway X, while those on the right send packets to Gateway Y. This setup is called an "$l{-}r$ Model," where "$l$" represents the nodes before the separation link, and "$r$" represents those after it. Figure 2 is a 4-4 Model example.

In this model, the task is to deliver a cumulative total of $\sum_{i=1}^{N} r_i$ packets to server S. Each node $i$ demands to maximize the probability that all $r_i$ packets reach a gateway

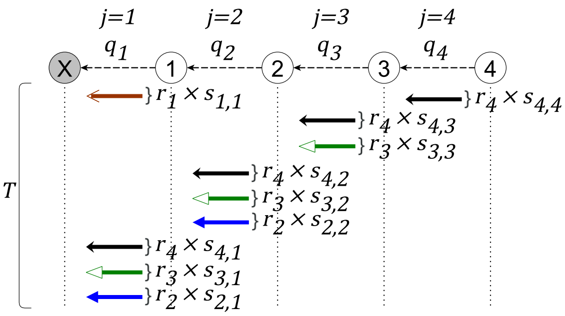



Fig. 3. Left side of the separation link in 4-4 Model.

within a cycle time while ensuring fairness among nodes. A meticulous schedule is created to maximize the overall delivery probability, accounting for packet losses on any link. The central scheduler computes a TDMA-based schedule, requiring knowledge of parameters like the number of slots within a cycle ($T$), link loss rate ($q_j$), and packet generation rate ($r_i$). However, this paper does not detail the implementation of the derived schedule at individual nodes.

### *B. Time-slot allocation*

Strategically allocating time-slots prevents interference among adjacent links within the interference range while reserving sufficient time-slots for each packet to be transmitted over a lossy link. Our prior study used a simple RT method [7] to recover losses. Node $i$ sends the multiple repetitions of packets to the next node, either from the previous one or generated locally. For link $j$, allocating $r_i \times s_{i,j}$ time-slots is necessary to accommodate these transmissions, where $s_{i,j}$ is the number of repetitions. Figure 3 illustrates the time-slot allocation for the left side of the separation link in the 4-4 Model. This allocation method is applicable across different $l{-}r$ Models, showcasing its adaptability and versatility.

### *C. Maximize the successful delivery probability*

The optimal schedule is independently calculated for each separated segment. The left segment includes nodes with $i \le n$, while the right segment has nodes with $i > n$, where $n$ represents the count of left-side nodes. Using the 4-4 Model shown in Fig. 3 as an example, we explain how to derive an optimal slot allocation on the left segment. For each node $i$, the success probability of delivering all packets to server S is determined using (1). The combined product of these probabilities across all left-side nodes is expressed by (2).

$$M(i) = \prod_{j=1}^{i} \left(1 - q_j^{s_{i,j}}\right)^{r_i} \tag{1}$$

$$M_{\mathit{left}} = \prod_{i=1}^{n} M(i) \tag{2}$$

If concurrent transmissions from nodes separated by two hops are permissible, the total $T$ time-slots in a cycle period adhere to (3) for the left-side segment. As exemplified in

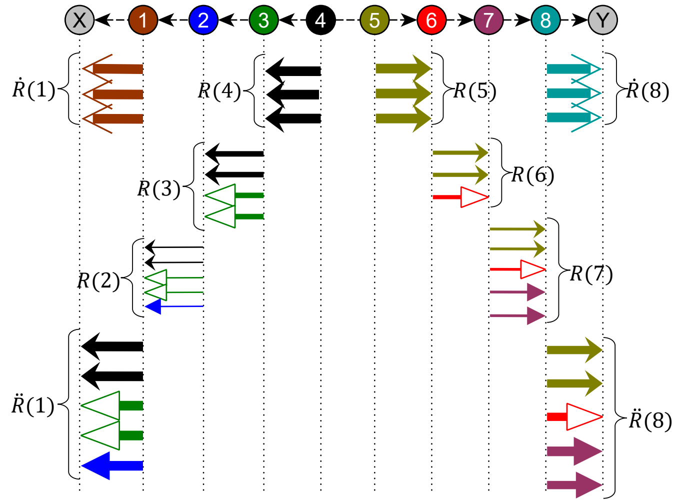



Fig. 4. Example of simultaneous transmission in 4-4 Model.

Fig. 3, slots represented by $r_1{\times}s_{1,1} = r_4{\times}s_{4,4}$ facilitate simultaneous transmissions by nodes 1 and 4. Consequently, these slots should be singularly accounted for within $T$.

$$T = \sum_{i=n-2}^{n} \sum_{j=1}^{i} r_i \times s_{i,j} \tag{3}$$

The Lagrange multiplier method is applied to find an optimal time-slot allocation $\{s_{i,j}\}$, maximizing (2) while adhering to constraint (3). The real number solution of $s_{i,j}$ is found using an interim variable $\alpha$ in (4). Since $s_{1,1}$ and $s_{4,4}$ are tightly coupled by $r_1 \times s_{1,1} = r_4 \times s_{4,4}$, either $s_{1,1}$ or $s_{4,4}$ should be represented by (4), but not both, leading to having the two distinct cases. The optimal solution can be obtained by prioritizing either link 4 or link 1, ensuring feasibility in both scenarios. In a more extensive network with numerous nodes, a systematic and recursive approach can be separated into multiple small cases to be solved similarly.

$$s_{i,j} = -\frac{log(1 - \alpha \, log \, q_j)}{log \, q_j} \tag{4}$$

The optimal integer solution should be calculated which is near the obtained real number even though it may deviate from optimality. In the context of real-number solutions as (4), the optimal value of $s_{i,j}$ is uniform for all $i$. However, in the case of integer solutions, the total slot allocation on link $j$ needs to be divided among packets from different upstream nodes. This can result in divergent slot allocations among packets on the same link, as in Fig. 4. In this example, the total $\ddot{R}(1)$ slots allocated on link 1 for packets from Nodes 2, 3, and 4 show differential allocations, especially for Node 2.

## III. Network Coding Approach

### *A. Network Coding Theory*

In this paper, Network Coding (NC) enables individual nodes to transmit $C_{i,j}$ combination packets derived from the

$r_i$ original packets generated by Node $i$ over link $j$ (referred to as encoding). The combination packets are represented as $\mathbf{G}_{i,j} = \left[g_{i,1}^{(j)}, g_{i,2}^{(j)}, \ldots, g_{i,C_{ij}}^{(j)}\right]$, with $g_{i,n}^{(j)}$ specified in (5) for $n = 1, 2, \ldots, C_{ij}$. Here, $p_m$ refers to the $m$-th original packet in set $r_i$, and $\delta$ is the coefficient. If the number of lost combinations below $k = C_{i,j} - r_i$, the sink can recover all original packets without retransmission (known as decoding). $\delta$ is chosen through linear coding, and computations take place within a designated Galois field (e.g., $\mathbb{GF}(2^8)$) using XOR operations and a lookup table. This computational approach ensures manageable complexity, making it highly feasible for real-world system implementations.

$$g_{i,n}^{(j)} = \sum_{m=1}^{r_i} \delta_{n,m}^{(j)} \times p_m \tag{5}$$

### *B. Successful delivery probability in NC approach*

Before transmission, every packet produced at each node is encoded into combination packets $\mathbf{G}$. Consequently, the minimum requisite for successful decoding to $r_i$ original packets, which is referred to as successful delivery at Node $i$-1, is the arrival of at least $r_i$ combination packets to the subsequent node, particularly when considering the left side of the topology. For any given node $i$ positioned within the left side of the link separation, the probability of successfully delivering all packets over link $j$ adheres to (6), and to server S adheres to (7). The cumulative product of these probabilities across all nodes within the left side of the link separation is (8). Furthermore, the total $T$ time-slots within a single cycle period are expressed in (9).

$$M_{NC}(i,j) = \sum_{k=r_i}^{C_{i,j}} \binom{C_{i,j}}{k} \times (1-q_j)^k \times q_j^{C_{i,j}-k} \tag{6}$$

$$M_{NC}(i) = \prod_{j=1}^{i} M_{NC}(i,j) \tag{7}$$

$$M_{NC_{left}} = \prod_{i=1}^{n} M_{NC}(i) \tag{8}$$

$$T_{NC} = \sum_{i=n-2}^{n} \sum_{j=1}^{i} C_{i,j} \tag{9}$$

### *C. Maximize successful delivery probability in NC approach*

Using the Lagrange multiplier method to find an optimal time-slot allocation $\{C_{i,j}\}$ in this scenario is impractical because the complex form of the objective function in (6) hinders a continuous relaxation. Therefore, a numerical technique is employed in lieu of this, leveraging two solutions derived from sub-problems corresponding to the RT scheme. These serve as initial values, set through straightforward assignments, i.e., $C_{i,j}^{init} \approx r_i \times s_{i,j}$, the number of (coded) packets sent of Node $i$ at link $j$ (approximate operator here due to integer solution as mentioned in Sect. II-C), to find the optimal solution within the NC scheme. Subsequently, a comparative analysis identifies the superior $C_{i,j}$ from the integer points generated initially $C_{i,j}^{init}$ to maximize $M_{NC_{left}}$ as formulated in (8).

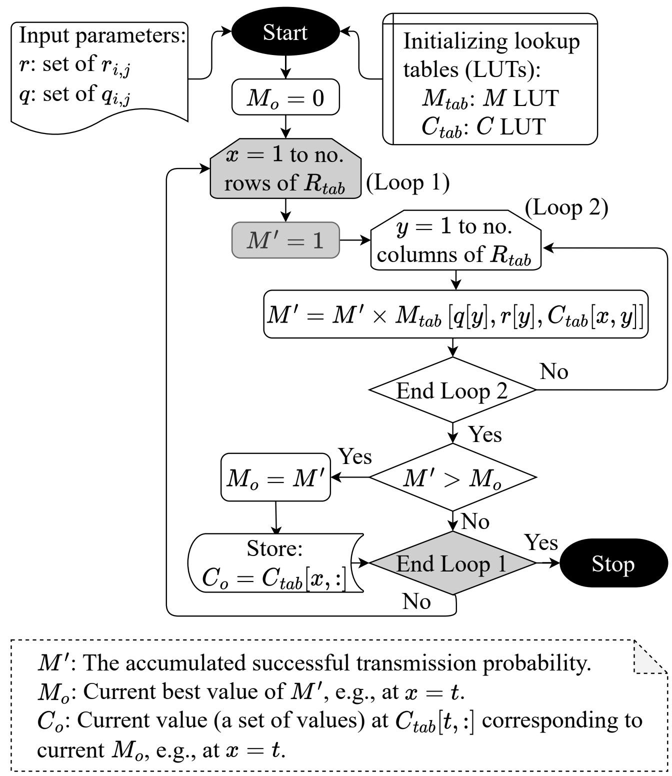



Fig. 5. Example of simultaneous transmission in 4-4 Model.

In this study, the search spans values of $C_{i,j}^{init} + \sigma$ where $\sigma = \{-3, -2, -1, 0, 1, 2, 3\}$ in pursuit of the optimal solution. In this paper's 4-4 Model, considering each side of the link separation, e.g., the left side is shown in Fig. 3, there are 9 $R_{i,j}$ cases. The comprehensive search encompasses $7^9$ (40,353,607) times. The search duration may be quick (several seconds) or slow (several minutes), depending on the hardware performance of the controller. However, leveraging look-up tables (LUTs) can significantly speed up the process; moreover, the number of look-ups is not equal to $7^9$ but 430,569 (calculated on simulation). The considering cases only belong to the total set cases of $\{\sigma_t\} = \{\sigma_1, \sigma_2, \sigma_3, \ldots, \sigma_9\}$ where $\sum\{\sigma_t\} = 0$ to let $T$ unchanged and $\sigma_t = \{-3, -2, -1, 0, 1, 2, 3\}$.

The flowchart in Fig. 5 shows the searching process in a $M_{tab}$ 3D-LUT, storing all pre-calculated probability based on (6) for all feasible cases with the size of total-link-loss-cases $\times$ total-$r_{i,j}$-case $\times$ total-$C_{i,j}$-cases and a $C_{tab}$ 2D-LUT storing all occurrences of $C_{i,j} + \sigma$ where $\sigma = \{-3, -2, -1, 0, 1, 2, 3\}$ (noted that $r_{i,j} = r_i$) with the size of (9 $\times$ 430,569). Inputs are a set of $\{r_{i,j}\}$ (noted that $r_{i,j} = r_i$), a set of $\{q_{i,j}\}$ (noted that $q_{i,j} = q_j$). And outputs are a set of 9 optimal $\{C_{i,j}\}$ (called $C_o$). Each set has 9 elements based on this paper's 4-4 Model.

## IV. Simulation Results

### A. Simulation setup

Simulation and performance assessment are conducted within the 4-4 Model topology, shown in Fig. 4. Eight nodes are located between two GWs. The selected configuration has a $T$ of 120 time-slots, a wireless link bandwidth of $10\,Kbps$, a packet size of $100\,Byte$, and a inter-packet gap of 0.003 seconds. Therefore, in one cycle of 60 seconds, the complete transmission of $T$ is 10 seconds, and the following sleeping period is 50 seconds (for power-saving). The simulation iteration is 1,000,000 to ensure accurate analysis.

The evaluation considers three scenarios with average packet generation counts at individual nodes of 3, 4, and 5 packets. Time-slot allocation for each node is optimized using both the RT scheme (explained in Sect. II-C) and the NC scheme (outlined in Sect. III-C). Besides, the simulations also cover the packet fluctuation with minor ($\pm1$ packet), moderate ($\pm2$ packets), and substantial ($\pm3$ packets) deviations.

### B. Successful delivery probability evaluation

Figure 6 shows the successful delivery rates of all packets from various nodes to server S correspond to average generated packet counts of 3, 4, and 5, respectively. The label "RT in Theory" in these plots represents the theoretically calculated value for the RT scheme without packet fluctuation in the real number domain. "RT" and "NC" denote experimental values obtained through Repeat Transmission and Network Coding simulations. Additionally, variations including "var=$\pm0$", "var=$\pm1$," "var=$\pm2$," and "var=$\pm3$" represent scenarios of no packet fluctuation, minor packet variation, moderate packet variation, and substantial packet variation, respectively.

For an average generated packet count of 3 or 4, the "RT in Theory" and "RT (var=$\pm0$)" results are closely aligned, indicating a similarity between theoretical and simulation-based calculations. However, when the average generated packet count rises to 5, a slight discrepancy arises, attributed to the integer-based nature of "RT (var=$\pm0$)" calculations as opposed to the real-number "RT in Theory" calculations. With larger average generated packet counts, rounding errors in integer computations become more pronounced.

A notable observation is the inverse relationship between packet fluctuation magnitude and successful delivery rate. As fluctuations widen, they significantly influence time-slot allocations, leading to decreased success rates, particularly in scenarios involving many upstream nodes where fluctuations impact transmission counts per packet. The NC scheme consistently outperforms the RT scheme across all cases. This discrepancy is more pronounced with higher average generated packet counts. The inherent advantage of NC lies in its ability to amalgamate packets into interconnected combinations, in contrast to the discrete packet repetition characteristic of the RT scheme. Consequently, the NC scheme proves less sensitive to loss order, ensuring superior recovery of original packets even under identical packet loss conditions. Refer to Table II for a comprehensive presentation of these results; with the same conditions, the NC scheme always performs better than the RT scheme. For example, with the link loss rate of 0.3 and the average generated packet of 4, the successful delivery rate of the NC scheme is 2.1865, 2.6424, and 3.7992 times higher than that of the RT scheme corresponding to no packet fluctuation ("var=$\pm0$"), with the packet fluctuation of "var=$\pm1$" and the "var=$\pm3$" cases.

TABLE II
SUCCESSFUL DELIVERY RATE COMPARISON IN CASE THAT AVERAGE GENERATED PACKET EQUALS 4.

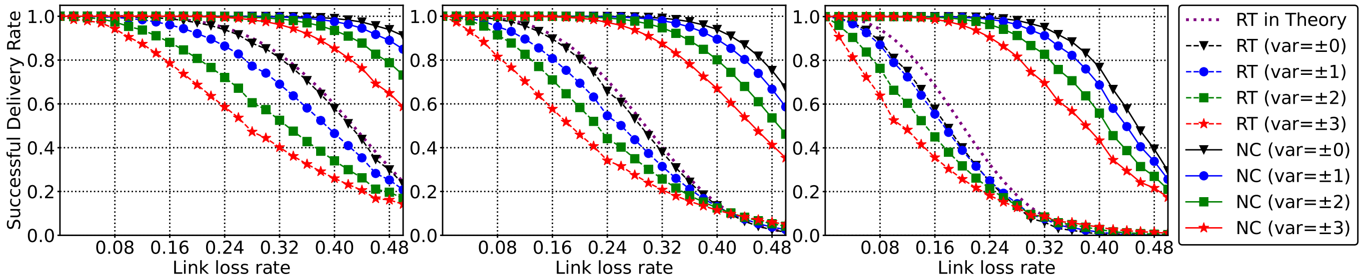
| Scheme / $q$ | RT | NC | Difference $(NC-RT)$ | Improvement $\left(\frac{NC}{RT}\right)$ |
|---|---|---|---|---|
| **No packet fluctuation ("var=$\pm$0")** | | | | |
| 0.1 | 0.974699 | 1.0 | 0.025301 | 1.0260 |
| 0.3 | 0.455107 | 0.995084 | 0.539977 | 2.1865 |
| 0.5 | 0.014457 | 0.673158 | 0.658701 | 46.563 |
| **Packet fluctuation with minor packet variation ("var=$\pm$1")** | | | | |
| 0.1 | 0.930503 | 0.999999 | 0.069496 | 1.0747 |
| 0.3 | 0.373797 | 0.988082 | 0.614285 | 2.6434 |
| 0.5 | 0.025813 | 0.586319 | 0.560506 | 22.714 |
| **Packet fluctuation with substantial packet variation ("var=$\pm$3")** | | | | |
| 0.1 | 0.765744 | 0.999892 | 0.234148 | 1.3058 |
| 0.3 | 0.239478 | 0.909832 | 0.670354 | 3.7992 |
| 0.5 | 0.050261 | 0.353194 | 0.302933 | 7.0273 |

### C. Fairness between nodes

Figure 7 shows the advantages of the NC scheme through achieving higher successful delivery rates for all nodes. Notably, the successful delivery rate is enhanced as the number of upstream nodes grows. The packets generated by upstream nodes are more susceptible to loss than the other nodes, resulting in a decrease in the overall successful delivery rate when the number of generated packets increases. However, the NC scheme introduces a beneficial effect on the success rate of upstream-generated packets; thus, overall improvement in success rate. Furthermore, a noteworthy finding when observed in the successful delivery rates across nodes when applying the NC scheme, in contrast to the RT scheme. The NC scheme achieves more fairness than the RT scheme through the uniform distribution of successful delivery rates among nodes (small deviations of success rates probability among nodes).

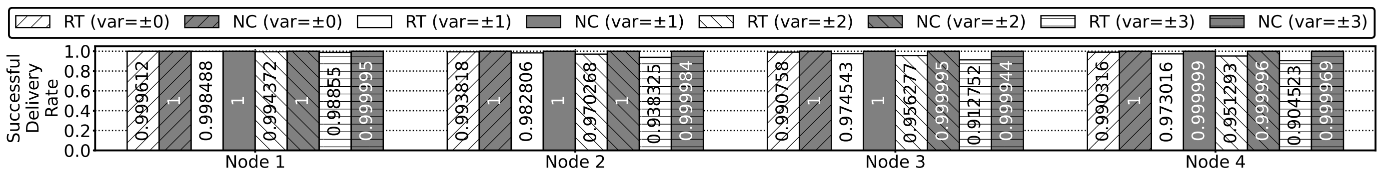
## V. Conclusion

This paper has proposed applying the Network Coding scheme to improve the reliability of TDMA-based optimally scheduled data transmission within linear multi-hop wireless sensor networks. This approach has shown an outperformance in the cases of packet fluctuations, high link loss rates, and many generated packets at each sensor node compared to previous studies. The simulation outcomes underscore the potency of this approach, showcasing an impressive enhancement of the successful delivery rate by more than 2 times in both no and fluctuation packet cases, the link loss rate of 0.3, and

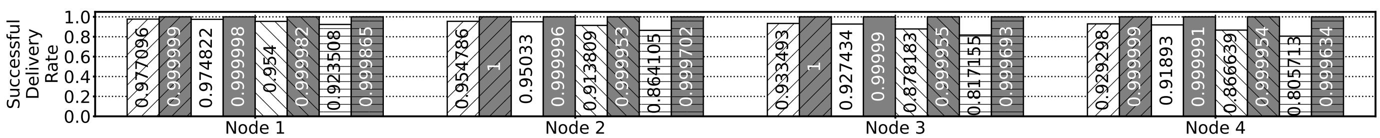



(a) (b) (c)

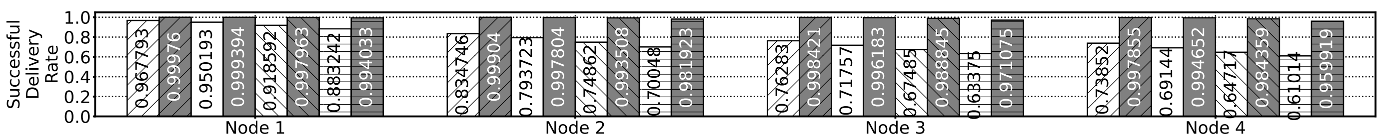
Fig. 6. Successful delivery rate vs. Link loss rate with in case of average generated packets equal to 3 (a), 4 (b), 5 (c).



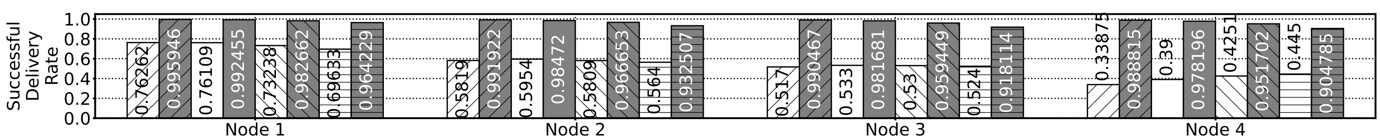

(a) Successful delivery rate of each node in case of Link loss rate equal to 0.1 and Average generated packets equal to 4.




(b) Successful delivery rate of each node in case of Link loss rate equal to 0.1 and Average generated packets equal to 5.




(c) Successful delivery rate of each node in case of Link loss rate equal to 0.3 and Average generated packets equal to 4.




(d) Successful delivery rate of each node in case of Link loss rate equal to 0.3 and Average generated packets equal to 5.

Fig. 7. Successful delivery rate at each node vs. packet variations.

an average generated packet of 4 compared to the previous scheme.

Moving forward, our research encompasses a comprehensive evaluation of the system under more practical conditions while considering factors such as network delays, coding delays, and coding buffer size.

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