Novel Joint Network Coding and Scheduling Scheme in Distributed TDMA-based WMNs

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Abstract—Recently, research has been conducted on network coding (NC) scheme as an alternative mechanism to significantly increase the utilization of valuable resources in multihop wireless mesh networks (WMNs). Time division multiple access (TDMA) based medium access control (MAC) protocols also have been proposed for guaranteeing quality of service (QoS). However, if an appropriate link scheduling for NC is not performed in TDMA-based WMNs, end-to-end (ETE) delay may be increased although an NC gain can be obtained. Thus, we propose a novel joint NC and scheduling scheme to increase network throughput with ETE delay guaranteed. The proposed joint NC and scheduling scheme, which is flow-based one, employs a new concept, ‘duplicated allocation followed by resource release: DARR’, so that the slots scheduled on a path are sequentially arranged within a frame even when NC is used. From the performance evaluation results, it can be seen that the proposed DARR scheme can meet delay bound more effectively than the conventional sequential link scheduling with NC.

I. INTRODUCTION

Many works have proposed various network coding (NC) schemes such as linear coding [1] and randomized coding [2]. Compared to these schemes, the practical XOR-based NC scheme, called COPE, first appearing in [3], is very simple and effective. In COPE, opportunistic listening and opportunistic coding are used to encode packets from different unicast sessions. Fig. 1 shows the well-known X constellation for NC, which is composed of two predecessor nodes $P_a$ and $P_b$, an NC coordinator $R$, and two successor nodes $S_a$ and $S_b$. As shown in Fig. 1 (left), $P_a$ has a packet $x_1$ for $S_a$, and $P_b$ has a packet $y_1$ for $S_b$. The two packets from both flows have to be relayed via $R$. In conventional slot scheduling, four transmissions (slots) are necessary for successful delivery of two packets ($x_1$ and $y_1$) as shown in Fig. 1 (left). However, only three transmissions (slots) are necessary if NC is employed. In this case, the fifth slot becomes a common broadcasting slot as shown in Fig. 1 (right). NC also can be used in the case of no opportunistic listening [4], and one of these scenarios is presented in Fig. 2. For more details of baseline NC operation, refer to [3]. In the field of joint NC and scheduling, almost works have been focused on the improvement of the network throughput, which is the fundamental objective of NC [5–8]. To the best of our knowledge, there have been no papers considering the design of joint NC and scheduling (especially XOR-based) with delay bounds. Although these conventional works can get an NC gain, if there is no consideration of delay bound, end-to-end (ETE) delay may be increased according to the increase in the number of hops in TDMA-based WMNs. Therefore, to reduce ETE delay and concurrently get an NC gain, we propose a novel joint NC and scheduling scheme considering wireless channel errors in a distributed TDMA-based WMNs.

![Fig. 1. Example of an X NC constellation.](image1)

![Fig. 2. Example of a string NC constellation.](image2)

![Fig. 3. NC constellations for scheduling](image3)
In the literature, there have been a few studies in the field of a joint NC and scheduling in multihop wireless networks. First, a work proposed by [9] has given important contributions to the field of joint NC and scheduling. It tries to analyze joint routing and NC for wireless unicast traffic. This study is based on the protocol interference model and makes use of an approximated model to compute a broadcast rate. The limitation of this study is that it only computes bounds. Moreover, the joint NC and routing problem is formulated for a given set of predefined routing paths for each source node [8]. Next, the authors of [7] have designed a distributed framework that facilitates the choice of the best rate on each link while considering the need for overhearing and dictates the choice of which decoding recipient will acknowledge the reception of an encoded packet. Their goal is to drive the network towards achieving the best trade-off between the achievable NC gain and the inherent rate gain possible on a link. Recently, the authors of [8] have proposed a study on achievable throughput in wireless multihop networks with unicast flows that use XOR-like NC. A joint routing, scheduling, and NC problem is formulated under a realistic signal to interference plus noise ratio (SINR) interference model. This formulation provides a mathematical framework to study the achievable throughput of a given wireless network for a given utility function.

As mentioned before, these works have been focused on improving throughput efficiency in a network, which is the fundamental objective of NC. Almost these conventional studies have mostly been studied based on time division multiple access (TDMA). However, they may suffer from scheduling delay (or also called frame delay) that is determined by the sequence of the slots allocated on a path although they can enhance throughput efficiency. This scheduling delay increases ETE delay, which may result in not guaranteeing QoS of applications [10], [11]. Therefore, we propose a novel joint NC and scheduling scheme that not only gets an NC gain (enhances throughput efficiency) but also considers the aforementioned scheduling delay in order to minimize ETE delay, ultimately guaranteeing QoS of applications in TDMA-based multihop wireless networks.

III. Motivation

According to the result in [12], if considering energy requirements, it is reported that less than 1% of coding operations are related to the combination of more than three packets. Therefore, in this paper, it is assumed that an NC coordinator performing XOR-based NC operation manages only two flows. Consider the NC set of Fig. 3 (right), where an NC operation is possible. A reference NC flow \( f_r \) in an NC set is referred to as the first flow that has finished a scheduling procedure out of two NC flows. Meanwhile, a non-reference NC flow \( f_n \) is referred to as the last flow that has finished a scheduling procedure out of two NC flows. From now onward, in each figure, we use link indexes \( e \) and \( g \) for \( f_r \) and \( f_n \), respectively. We also define \( s(e_i) \) and \( s(g_j) \) as slot indexes of the links \( e_i \) and \( g_j \), respectively, where \( i \geq 1 \) and \( j \geq 1 \) denote link indexes. Consider conventional sequential slot linking (SLS) schemes [10], [11], [13] that have considered the allocation sequence of slots within a frame. The fundamental idea of them is to reduce the secondary queuing delay by sequentially allocating the slots to paths in a flow, where the secondary queuing delay means delay occurring when multiple flows pass through an outbound link of a relay node [11]. It is noted that they can guarantee the sequentiality of slots only for its own flow on a path, while ‘sequentiality’ means a multihop slot allocation (MSA) satisfying the condition \( s(e_k) < s(e_{k+1}) \) \((1 \leq k \leq H)\) in a flow. \( H \) denotes the largest hop value in the network. If the slots scheduled in a flow satisfy the sequentiality, the multihop transmission of a packet from a source node to a destination node is possible within one frame, resulting in reducing ETE delay [10], [11]. However, if considering NC where two flows are mixed, this sequentiality may be broken. For example, Fig. 4 shows an example where the sequentiality is broken in the conventional SLS schemes. Assume that, in the NC set of Fig. 3 (left), the links \( e_1 \) and \( g_2 \) are the ones from previous nodes and the links \( e_2 \) and \( g_3 \) are the ones to the next nodes. If we set a common broadcasting slot to \( s(e_2) \), then the slots for \( f_r \) are arranged in the sequence \( s(e_1), s(e_2), s(e_3) \), and the slots for \( f_n \) are arranged in the sequence \( s(g_1), s(g_2), s(g_3) \). Therefore, the links of \( f_n \) do not satisfy the sequentiality. On the other hand, if we set a common broadcasting slot to \( s(g_3) \), then the slots for \( f_r \) are arranged in the sequence \( s(e_1), s(e_3), s(e_2) \), and the slots for \( f_n \) are arranged in the sequence \( s(g_1), s(g_2), s(g_3) \). In this case, the links of \( f_r \) do not satisfy the sequentiality. Thus, if performing an NC operation without considering the sequentiality in the conventional SLS schemes, one flow of two flows related with the NC operation always experiences extra delay whose value is equal to the frame length. Therefore, in order that NC operation is performed with the sequentiality satisfied, \( s(e_i) \) and \( s(g_j) \) for two predecessor nodes in an NC set must precede \( s(e_{i+1}) \) and \( s(g_{j+1}) \) for two successor nodes (refer to Fig. 3 (right)).

IV. System Model

In this paper, we model WMNs with a topology graph connecting the nodes that are present in each other’s wireless

![Frame structure in DCH](Fig. 5)
Algorithm 1 Slot allocation (SA) in a source node

1: if $k = 1$ then
2: \hspace{1em} $p_1$ first runs the TSA algorithm.
3: \hspace{1em} $p_1$ sets $s_{index}$ to the slot index of the obtained slot.
4: \hspace{1em} $p_1$ marks the obtained slot as a TN.
5: \hspace{1em} $p_1$ transfers the SA packet with $s_{index}$ to $p_2$.
6: end if

Algorithm 2 SA in an intermediate/destination node

1: if $1 < k < q$ then
2: \hspace{1em} if ($p_k = \text{NC coordinator}$) & (current flow = $f_n$) then
3: \hspace{2em} Based on received $s_{index}$, $p_k$ allocates the slot(s) for both $p_{k-1}$ and $p_k$ as an RN.
4: \hspace{2em} $p_k$ runs the TSA algorithm.
5: \hspace{2em} $p_k$ sets $s_{index}$ to the slot index of the obtained slot.
6: \hspace{2em} $p_k$ transfers an SA packet with $s_{index}$ twice to two $p_{k-1}$ nodes of $f_r$ and $f_n$.
7: \hspace{1em} else if ($p_k = \text{NC coordinator}$) & (current flow = $f_n$) then
8: \hspace{3em} Based on received $s_{index}$, $p_k$ allocates the slot(s) for both $p_{k-1}$ and $p_k$ as an RN.
9: \hspace{3em} $p_k$ runs the TSA algorithm.
10: \hspace{3em} $p_k$ sets $s_{index}$ to the slot index of the obtained slot.
11: \hspace{3em} $p_k$ marks the obtained slot as a TN.
12: \hspace{3em} $p_k$ transfers an SA packet with $s_{index}$ to $p_{k+1}$.
13: \hspace{1em} else if $k = q$ then
14: \hspace{2em} Based on received $s_{index}$, $p_q$ allocates the slot(s) for both $p_{q-1}$ and $p_q$ as an RN.
15: \hspace{2em} $p_q$ transfers an SA completion message to the source node $p_1$.
16: end if
17: end if

V. PROPOSED JOINT NC AND SCHEDULING SCHEME

The proposed joint NC and scheduling scheme, which is flow-based one, employs a new concept, ‘duplicated allocation’ followed by resource release: DARR’, so that the slots scheduled on a path are sequentially arranged within a frame even when NC is used. Prior to the slot scheduling, every node selects interference-free slots that it can use for the communication with a neighbor node. To select interference-free slots, we adopt the channel locking algorithm proposed by [14], which consists of four states: idle, request, release, and grant states. For the convenience, in this paper, we call it a time slot acquisition (TSA) algorithm. We define an NC set as five nodes constructing X constellation of Fig. 1 or as three nodes constructing string constellation of Fig. 2. Algorithm 1 and 2 show the MSAs process of the proposed DARR scheme. In Algorithm 1 and 2, $s_{index}$ denotes an allocated slot index in a frame. In Algorithm 2, when an intermediate node allocates the slot(s) as a TN, it is very important for the intermediate node to reserve the right-hand side slot for comparison with the value of $s_{index}$ of the SA packet received, such that the sequentiality can be guaranteed on a path. The basic idea of the proposed DARR scheme is that, when the MSA algorithm has been initiated from $f_n$, an NC coordinator not only transfers an SA packet to the next node of $f_n$ but also again transfers another SA packet to the next node of $f_r$. Thus, from the links $e_i+1$ to $e_h$ of $f_r$, additional slots are allocated; i.e., existing slots that have been used and newly allocated slots for $f_r$. At this time, the NC coordinator releases the existing slots and, in the next frame, uses the newly allocated slots for the sequentiality. The released slots may be used for other flows. The extra transmissions for the slot release are an overhead of the proposed DARR scheme. However, it is shown that they are not big burden in the network. If considering the time difference between the slot allocations of $f_r$ and $f_n$, there exist the following three cases.

- **Case 1:** Before allocating the slot for link $e_{i+1}$, when NC coordinator $R$ receives the SA packet that includes the SA information for $g_{ij}$ in the current frame.
- **Case 2:** After allocating the slot for $e_{i+1}$, when NC coordinator $R$ receives the SA packet that includes the SA information for $g_{ij}$ in the current frame.
- **Case 3:** After the slot allocation for $f_r$ has been already completed in a frame, when NC coordinator $R$ receives the SA packet that includes the SA information for $g_{ij}$ in another frame.

Fig. 6 shows the examples of these three cases mentioned above. First, for Case 1, because NC coordinator R received the SA packet for $g_2$ before allocating the slot for link $e_2$, NC coordinator R can allocate the common broadcasting slot to the sixth slot without the extra SA packet transmission. Therefore, there is no burden for this case. In the case of Case 2 and Case 3, because NC coordinator R received the SA packet for $g_2$ after having allocated the slot for link $e_2$, NC coordinator R must transfer the same SA packet twice to the nodes $S_a$ and $S_b$ respectively after the completion of the MSA process of...
$f_n$. In this case, the extra release process for the third and fourth slot is necessary.

VI. PERFORMANCE EVALUATION

A. Simulation Scenario

To evaluate the overhead and delay performance of the proposed scheme, we have simulated a grid network with 49 nodes. The vertical and horizontal distances between two adjacent nodes are 100-meter, and the communication range of each node is set to 100-meter. During the simulation, each node creates one flow for realtime applications. As soon as all source nodes complete an MSA algorithm, they generate one packet per $T_M$ before transmitting them in the allocated slot. As performance metrics, we consider average ETE delay and average coding gain. The average ETE delay means the time taken for each source node to transfer a packet to a destination. And, the coding gain is defined by

$$
coding\ gain = \frac{h \cdot \eta_{total} \cdot N}{h \cdot \eta_{total} \cdot N - \eta_{NC}}, \tag{1}
$$

where $h$ denotes the number of hops; $\eta_{total}$ denotes the total number of packets transferred per node; $N$ denotes the total number of nodes in the network; and $\eta_{NC}$ denotes the number of transmissions reduced by NC. We additionally employ the power consumed for scheduling by all the nodes in the network as a performance metric.

B. Performance Analysis Results

Fig. 7 shows the ETE delay of the conventional and the proposed scheme with an increase in the value of $\omega$, where packets arrive deterministically. The packet interarrival time is set to $(unit\ slot\ time \times L/\omega)$, where $\omega$ increases from 0.1 to 1 in steps of 0.1. If the value of $\omega$ is 0.5, each node generates one packet per two-frame. On the other hand, if the value of $\omega$ is 1, then each node generates one packet per one frame. Therefore, increasing the value of $\omega$ is the same as the increase in packet interarrival rate. When there is no error in wireless channel, all schemes show the stable performance regardless of the increase in the value of $\omega$. This is because each node generates at most one-packet arrival per frame, resulting in no primary queuing delay in the network. However, as TX power is decreased (0 → -1 → -2 dBm), ETE delay is increased. Especially, in the high traffic load (e.g. when $\omega \geq 0.9$), the ETE delay is sharply increased. This is because the packets experience large delay owing to the packet retransmission caused by wireless channel errors, not the primary queuing delay. Meanwhile, in the conventional SLS-NC scheme, half of NC flows experience extra delay whose value is $T_M$. Therefore, the conventional SLS-NC scheme experiences the lowest delay performance. Different from the conventional SLS-NC scheme, the proposed DARR
scheme can guarantee the sequentiality while the network gets the whole NC gain. Therefore, the slots can be saved as much as the number of the NC points, resulting in the decrease in the ETE delay. Fig. 8 shows the ETE delay of the conventional and the proposed scheme with an increase in the value of $\omega$, where packets arrive exponentially (non-deterministically). In the case of non-deterministic packet arrival, each node may experience the primary queuing delay. Each node may also experience additional delay owing to the packet retransmission caused by wireless channel errors. Therefore, even in the low traffic load, each packet goes through relatively high ETE delay compared with the deterministic packet arrival. In the case of average coding gain, the conventional and proposed scheme have the same NC gain whose value is 1.11 because they all performs the NC operation for all NC points.

VII. CONCLUSION

In this paper, we proposed a novel joint NC and scheduling scheme so that the slots scheduled on a path are sequentially arranged within a frame even when NC is used. The proposed scheme can not only get the same NC gain as the conventional scheme but also guarantee the sequentiality with small overhead, thereby resulting in decreasing ETE delay in multihop WMNs. In conclusion, by applying the conventional XOR-based NC to the link scheduling, the proposed DARR scheme gives the more delay-efficient slot assignment while at the same time using less network resources and energy. The important contributions of this study are as follows:

- Novel joint NC and scheduling scheme called DARR was proposed.
- End-to-end delay evaluation of the proposed DARR scheme was performed.

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