Deadline-Aware Adaptive Packet Scheduling and Transmission in Cooperative Wireless Networks

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***Abstract*—We study scheduling and transmission of packets with deadline constraints in cooperative wireless networks. The packets which miss their deadlines become useless and have to be dropped. To minimize packet dropping probability, we consider multiple transmission methods and integrate packet scheduling with adaptive transmission method selection. We first introduce an exhaustive search method to obtain the optimal scheduling sequences and the corresponding transmission methods, under different channel conditions. Through observing the optimal results, we propose a heuristic method based on a dynamic graph. Simulation results show that the proposed heuristic method can obtain results which are similar to those achieved with the exhaustive search method, but with low computational complexity.**

***Index Terms*—Cooperative wireless networks, packet dropping probability, scheduling, transmission method adaptation.**

I. Introduction

With the growth of computational capability and various breakthroughs in wireless technologies, a variety of services with strict delay requirements emerged in commercial wireless networks, such as real-time video communications in mobile cellular systems. In these applications, packets have strict deadline constraints and must arrive at their destinations before their deadlines. Otherwise, they become invalid and will be dropped. The problem becomes more challenging when supporting real-time services in cooperative wireless networks, because the diversity of transmission rates and methods increases the complexity of packet scheduling. Therefore, it is necessary to develop deadline-aware adaptive packet scheduling and transmission schemes in cooperative wireless networks to reduce packet loss.

In the literature, there are many studies focusing on tackling the packet scheduling and transmission problem with deadline constraints in cooperative communications [1]–[7]. One of the promising solutions is the adaptive utilization of conventional network coding (CNC). It is because, on one hand, CNC can reduce transmission time by permitting a relay to encode at least two packets, which are received separately from different source nodes, into one packet and broadcast it to destinations for the decoding of the intended packets; on the other hand, the decoding delay in CNC may become serious if the destination nodes cannot receive sufficient packets for decoding [1]. The authors in [2] proposed an adaptive network coding scheme to optimize the block size of coded packets while scheduling multimedia traffic flows in a time-slotted downlink system in order to maximize the throughput and reduce packets' waiting time. Instead of emphasizing on network throughput, the authors in [3] focused on dealing with the scheduling problem in the single-hop broadcast system to minimize the number of dropped packets, and an encoding algorithm was investigated based on CNC to find a proper transmission order and the number of encoded packets. However, they assumed a fixed transmission rate. Noticing that more network coding opportunities appear through adjusting the transmission rate, an efficient algorithm was proposed to determine the coding strategy and transmission rate of each transmission in [4] based on [3]. An immediately decodable network coding (IDNC) scheme was developed in [5] to reduce packet loss in video streaming. However, another efficient transmission method, analog network coding (ANC), was ignored in these works.

Compared with CNC, ANC can further reduce transmission time by allowing two signals to be transmitted simultaneously from their source nodes and superpose at the relay [8]. However, ANC has more stringent restrictions on channel conditions and network topologies. Therefore, ANC should be applied adaptively and jointly with other transmission methods, such as CNC, plain routing (PR), and direct transmission (non-relaying, NR). In [9], an adaptive relaying method selection scheme was developed for multi-rate wireless networks, but without considering the deadline constraints of packets.

In order to minimize the packet dropping probability in multi-rate cooperative wireless networks, in this paper, we integrate transmission method selection with packet scheduling and propose two deadline-aware methods (exhaustive search and heuristic methods) to decide the optimal transmission methods and sequences of packets. Packet transmissions within two-hop topologies are considered in this paper, and the proposed methods can be easily extended to general multi-hop networks.

The rest of this paper is organized as follows. In section II, we formulate the optimization problem. Section III shows two schemes to resolve the deadline-aware packet scheduling and transmission problem. Simulation results are shown in Section IV and Section V draws conclusions.

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II. Problem Formulation

We consider a network topology consisting of a relay and N source nodes which need to transmit packets with identical length to their corresponding destination nodes. The packets can be relayed or directly transmitted. Each packet has a deadline requirement.

We use an ordered set partition $C = \{C_1, C_2, \ldots, C_K\}$, where $1 \leq K \leq N$, to represent subsets of N packets $P = \{p_1, p_2, \ldots, p_N\}$ that will be sequentially transmitted during a scheduling round[1]. Each subset contains the packet(s) that is (are) transmitted by invoking a certain method (ANC, CNC, PR, or NR) once. This partition should satisfy three properties: 1) No subset is empty; 2) $C_1 \cap C_2 \cap \ldots \cap C_K = \phi$; 3) $C_1 \cup C_2 \cup \ldots \cup C_K = P$. For one subset C_k, $k \in \{1, 2, \ldots, K\}$, the transmission time that each possible transmission method takes is calculated based on the formulas in [9], and the fastest method is selected. The transmission time of all the subsets is represented as $T = \{T_{C_1}, T_{C_2}, \ldots, T_{C_K}\}$.

We use $D = \{D_1, D_2, \ldots D_N\}$ to denote the transmission deadlines of the N packets. For a packet p_n, $n \in \{1, 2, \ldots, N\}$, no matter which transmission method is used, if it fails to arrive at its destination node before its deadline D_n, it will be dropped. We define packet dropping probability as the ratio of the number of packets missing their deadlines to the total number of packets. In order to minimize the packet dropping probability, we should determine the set partition C with the optimal transmission sequence and corresponding transmission methods of the included subsets.

To formulate this problem, we first introduce two groups of binary variables: $x_{n,k}$ and $z_{n,k}$, where $n \in \{1, 2, \ldots, N\}$ and $k \in \{1, 2, \ldots, K\}$. Let $x_{n,k} = 1$ denote that packet p_n is distributed into subset C_k, otherwise $x_{n,k} = 0$. Let $z_{n,k} = 1$ denote that packet p_n belongs to subset C_k and misses its deadline D_n, and $z_{n,k} = 0$ means that packet p_n does not belong to subset C_k or it belongs to C_k and meets its deadline D_n. Then, the optimization problem can be expressed as follows:

$$\min \quad \sum_{k=1}^{K} \sum_{n=1}^{N} z_{n,k} \tag{1}$$

$$\text{s.t.} \quad \sum_{k=1}^{K} x_{n,k} = 1 \tag{2}$$

$$x_{n,k} \cdot \sum_{i=1}^{k} T_{C_i} \leq D_n + \eta \cdot z_{n,k} \tag{3}$$

$$x_{n,k} \cdot \sum_{i=1}^{k} T_{C_i} > D_n - \eta(1 - z_{n,k}) \tag{4}$$

For a given value of K, the objective function (1) minimizes the number of packets that miss their deadlines. The constraints in (2) ensure that every packet is transmitted once in one scheduling round. A constant η is introduced in constraints (3) and (4), which is set large enough to guarantee that $z_{n,k} = 1$ when packet p_n belongs to subset C_k and misses its deadline D_n, otherwise $z_{n,k} = 0$. The transmission time of each subset T_{C_i} $(1 \leq i \leq k)$ is obtained from the following equation:

$$T_{C_i} = \begin{cases} T_{C_i}^{CNC} & \|C_i\| > 2 \\ \min\{T_{C_i}^{CNC}, T_{C_i}^{ANC}\} & \|C_i\| = 2 \\ \min\{T_{C_i}^{PR}, T_{C_i}^{NR}\} & \|C_i\| = 1 \end{cases} \tag{5}$$

in which $\|C_i\|$ represents the size of subset C_i. For those subsets consisting of more than two packets, CNC is the only choice. ANC and CNC can be selected for two-packet subsets. Packets in single-packet subsets can be transmitted via either NR or PR.

[1]The scheduling round means the time when each source node has transmitted one packet.

III. Adaptive Packet Scheduling and Transmission Schemes

In this section, we introduce two methods to solve the packet scheduling and transmission problem. The straightforward method is to achieve the optimal solution through exhaustive search. However, this method will suffer from high computational complexity when the number of packets increases. Therefore, a heuristic method is proposed to achieve a sub-optimal solution with low computational complexity.

A. Exhaustive Search

In the exhaustive search method, we first obtain all partitions of packet set P (the number of partitions is equal to a Bell number [10]). The number of subsets in a partition ranges from 1 to N, and the optimal transmission method of each subset is the least time-consuming one. Then, for each partition, we check through all the possible transmission sequences of its subsets to calculate the number of dropped packets. Finally, the ordered partition with minimum packet dropping probability is selected as the optimal packet scheduling and transmission solution. The complexity of this method is $O(N^N)$.

Based on the optimal solutions achieved through exhaustive search under different channel conditions, we can observe the following facts:

- Observation 1: Among all the optimal ordered set partitions, the chance that more than two packets are cooperatively transmitted via CNC is rare.
- Observation 2: In optimal ordered set partitions, once a packet in one subset misses its deadline, the packet(s) in its subsequent subset(s) will also miss its/their deadline(s), if any.

B. Heuristic Strategy

According to the above observations, we define three rules on packet scheduling and transmission.

- Rule 1: The number of packets within one subset is no more than two.
- Rule 2: All the packet(s) in any scheduled subset should be transmitted successfully.
- Rule 3: The transmission of one subset may cause some other packets miss their deadlines. Therefore, in this paper, the efficiency of one-subset transmission is regarded as the

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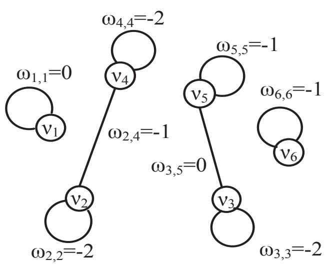
difference between the number of packets in the subset and the number of dropped packets caused by this transmission. The subset with the highest transmission efficiency should be scheduled with the highest priority.

$T_{i,j}$ \ $p_i(D_i)$ / $p_j(D_j)$	1(0.1)	2(1)	3(1)	4(1)	5(0.4)	6(0.4)
1(0.1)	0.0973	0.4384	0.3141	0.2778	0.3373	0.6482
2(1)	–	0.3166	0.5579	0.4925	0.5724	0.4019
3(1)	–	–	0.2168	0.3973	0.3196	0.7076
4(1)	–	–	–	0.1805	0.4206	0.6065
5(0.4)	–	–	–	–	0.2401	0.5919
6(0.4)	–	–	–	–	–	0.371

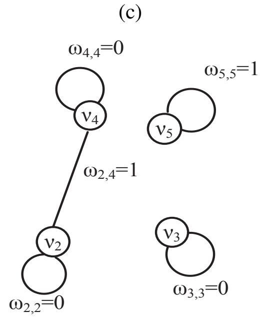
(a)



(b)

$T_{i,j}$ \ $p_i(D_i)$ / $p_j(D_j)$	1(0.1)	2(1)	3(1)	4(1)	5(0.4)	6(0.4)
1(0.1)	0.0973	0.4384	0.3141	0.2778	0.3373	0.6482
2(1)	–	0.3166	0.5579	0.4925	0.5724	0.4019
3(1)	–	–	0.2168	0.3973	0.3196	0.7076
4(1)	–	–	–	0.1805	0.4206	0.6065
5(0.4)	–	–	–	–	0.2401	0.5919
6(0.4)	–	–	–	–	–	0.371

(c)



(d)

Fig. 1. Example of graph updating process in heuristic strategy for 6 packets: (a) initial minimum transmission time of all the possible subsets, (b) initial graph before the first one-subset transmission, (c) first updated minimum transmission time of all the possible subsets, (d) first updated graph before the second one-subset transmission.

To utilize these rules to guide packet scheduling and transmission, we build a dynamic graph $G(V, E, W)$, where V is a set of vertices representing packets that are waiting for being transmitted before their deadlines, E is a set of edges representing possible subsets, and W is a set of weights of edges. If any two packets have a chance of performing ANC or CNC, an edge is drawn between their corresponding vertices. Therefore, for edge $e_{i,j} \in E$, if $i = j$, the corresponding packet represented by $\nu_i \in V$ is from a single-packet subset to be transmitted by PR or NR; if $i \neq j$, the corresponding two packets belong to a subset to be transmitted by ANC or CNC. Based on Rule 3, the weight of edge $e_{i,j}$ is equal to the transmission efficiency of the subset containing packets represented by ν_i and ν_j, as follows:

$$\omega_{i,j} = U_{i,j} - A_{i,j}, \tag{6}$$

where $U_{i,j}$ is the number of packets in the subset, and $A_{i,j}$ is the number of the packets that will be dropped if the subset associated to $e_{i,j}$ is scheduled in the next transmission. We always choose the edge with the maximum weight in the graph and schedule the corresponding subset in the next transmission. If there exist two or more than two edges with the maximum weight, we schedule the subset that has the earliest deadline first. If there are more than one edge with both the maximum weight and the earliest deadline, the subset that has the shortest transmission time is scheduled first.

Every time when one subset of packet(s) is transmitted, the graph is updated. The vertex (vertices) and edge(s) associated with both the transmitted packet(s) and the dropped packet(s) due to missing their deadlines are deleted. Additionally, if the remaining time before some waiting packets' deadlines is not long enough for completing their transmissions regardless of which transmission method is used, the packets are removed from the queue and the associated vertices and edges are deleted correspondingly. The weights of the remaining edges are recalculated based on the time left for each packet.

Now we use an example (shown in Fig. 1) to illustrate the graph updating process. We assume 6 packets need to be scheduled in a scheduling round, and their respective deadlines are $D = \{D_1, D_2, \ldots, D_6\}$. Initially, we calculate the minimum transmission time of all the possible subsets: $T_{i,j} = \min\{T_{p_i}^{PR}, T_{p_i}^{NR}\}$ when $i = j$, and $T_{i,j} = \min\{T_{p_i,p_j}^{ANC}, T_{p_i,p_j}^{CNC}\}$ when $i \neq j$, $i, j \in \{1, 2, \ldots, 6\}$. The results are shown in Fig. 1(a), where the underlined numbers represent that their corresponding transmissions are infeasible, and the ones without underlines are feasible. When $T_{i,j} > (T_{i,i} + T_{j,j})$ $(i \neq j)$, which means transmitting the corresponding two packets separately by PR or NR takes less time than transmitting them cooperatively via ANC or CNC, the transmission associated with $T_{i,j}$ is infeasible. We use t to denote the accumulative transmission time which is initially set to 0. When $t+T_{i,j} > \min\{D_i, D_j\}$ (i and j may be the same), which means the packet(s) in the subset will miss its (their) deadlines even with the most efficient transmission method, the transmission of the subset is also regarded as infeasible. These values of $T_{i,j}$ are also shown with underlines in Fig. 1(a). After ignoring the infeasible transmissions shown with underlines in Fig. 1(a), we construct an initial graph based on

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feasible transmissions, as shown in Fig. 1(b), where the weight of each edge is calculated according to equation (6). We can observe that $e_{1,1}$ and $e_{3,5}$ have the same maximum weight 0, but $D_1 < \min\{D_3, D_5\}$. Therefore, a single-packet subset associated to $e_{1,1}$ is scheduled for transmission, meanwhile, t is updated by adding $T_{1,1} = 0.0973$ and the value $T_{1,1}$ is underlined in Fig. 1(c). After the first transmission, the transmissions of the packets in the subsets associated to $e_{6,6}$ and $e_{3,5}$ become infeasible since $t+T_{6,6} > D_6$, $t+T_{3,5} > D_5$. Therefore, the values $T_{6,6}$ and $T_{3,5}$ are also underlined in Fig. 1(c). Then, ν_1, ν_6, $e_{1,1}$, $e_{6,6}$ and $e_{3,5}$ are removed from the initial graph and the weights of remaining edges are recalculated, as shown in Fig. 1(d). According to the new graph, the subset with the maximum transmission efficiency $\omega_{5,5}$ is scheduled. We repeat the graph updating and scheduling process until there is no vertex left. The whole process of achieving the sub-optimal solution is shown in details in Algorithm 1.

Algorithm 1 Process of Heuristic Strategy

Construct a complete graph $G(V, E, W)$, the $V = \{\nu_1, \nu_2, \ldots, \nu_N\}$ corresponds to a set of packets $P = \{p_1, p_2, \ldots, p_N\}$
Define an empty partition C
Define a variable $t = 0$ to record current cumulative transmission time
Calculate minimum transmission time of all the possible subsets: $T_{i,j},\ i \leq j,\ i, j \in \{1, 2, \ldots, N\}$
Delete those edges having $T_{i,j} > (T_{i,i} + T_{j,j})$ when $i \neq j$
while $V \neq \phi$ **do**
  for all $\nu_i \in V$ **do**
    Delete vertex ν_i if $(t + T_{i,i}) > D_i$
  end for
  for all $e_{i,j} \in E$ **do**
    Delete edge $e_{i,j}$ if $(t + T_{i,j}) > \min\{D_i, D_j\}$
  end for
  for all $e_{i,j} \in E$ **do**
    $\omega_{i,j} \leftarrow U_{i,j} - A_{i,j}$
  end for
  Choose the edge with maximum transmission efficiency, denoted by ω_{i^*,j^*}, from W
  $t \leftarrow t + T_{i^*,j^*}$
  Add the subset associated to e_{i^*,j^*} into C
  Delete vertices ν_{i^*} and ν_{j^*} and the edges that connect to these two nodes
  $W \leftarrow \phi$
end while
return C

Our heuristic strategy emphasizes on maximizing the efficiency of one-subset transmission. In each transmission, we consider all the possible single-packet and two-packet subsets to make the best scheduling choice. The complexity of this heuristic strategy is $O(N^5)$, which is polynomial.

IV. Simulation Results

We evaluate the performance of the proposed adaptive packet scheduling and transmission schemes via simulations. We assume that one relay node is placed in the center of a region which covers 500×500 m^2 square, and 16 end nodes are distributed in the region uniformly. The source nodes and their corresponding destination nodes are randomly selected, and packets are generated by the source nodes. We consider a Rician flat-fading channel with Rician factor $\gamma = 5$ dB. The noise power density is -174 dBm/Hz, the bandwidth is set to 1 MHz, and the noise figure is 6 dB. We evaluate the performance in different scenarios with different maximum transmission power or different number of packets, and each setting is run $10,000$ times with $10,000$ different random seeds (which correspond to $10,000$ different network topologies). The deadlines of the packets is set to three classes (100ms, 400ms and 1s) which meet the ITU-T QoS standard for IP-based networks [11].

We compare the average packet dropping probability of the proposed heuristic strategy with several other schemes, which include the optimal scheme (i.e. exhaustive search), optimal scheme without ANC, and optimal scheme without network coding (including both ANC and CNC) in Figs. 2 and 3. We first consider scenarios with different numbers of packets in each scheduling round in Fig. 2, and the maximum transmission power is set to 5 dBm. We can observe that the performance of the heuristic scheme is close to the exhaustive search method which returns the optimal results. With the increase of the total number of packets, the heuristic scheme slightly underperforms the optimal scheme because the heuristic scheme focuses on the local optimum (i.e. only considering the current and next transmissions) instead of the global optimum. The limitation of the heuristic scheme becomes obvious when the network load increases. The results also confirm that network coding has great advantage on reducing packet dropping probability, especially ANC. In Fig. 3, we fix the number of packets to 6, and vary the maximum transmission power from -15 dBm to 15 dBm. The results show that four schemes have similar performance when the transmission power is low. This is because the network coding opportunities are rare when channel status is bad. When the transmission power is large enough, packets can be successfully delivered via PR or even NR, the advantage of network coding is overshadowed and the performance of the four schemes becomes similar again.

To further investigate the contribution of network coding, we record the times that ANC and CNC are executed in the heuristic scheme, optimal scheme, and optimal scheme without ANC, respectively. The results are plotted in Figs. 4 and 5. We can observe that ANC is used more often than CNC both in heuristic and optimal schemes due to its superiority on saving transmission time. Especially in the heuristic scheme where the number of encoded packets in CNC is limited to two, when channel conditions are suitable for both ANC and CNC, ANC is normally selected. However, with the improvement of transmission power, the more-than-two-packet CNC is preferred in the optimal method and NR is preferred

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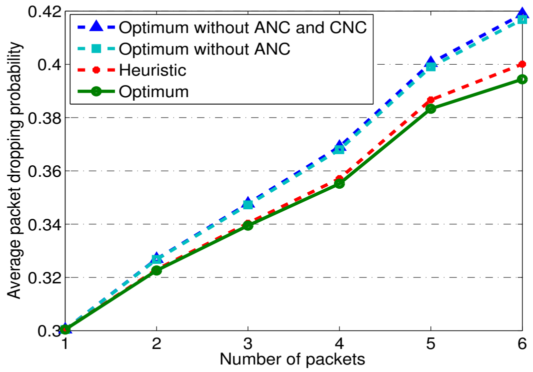

Fig. 2. Average packet dropping probability vs. number of packets.

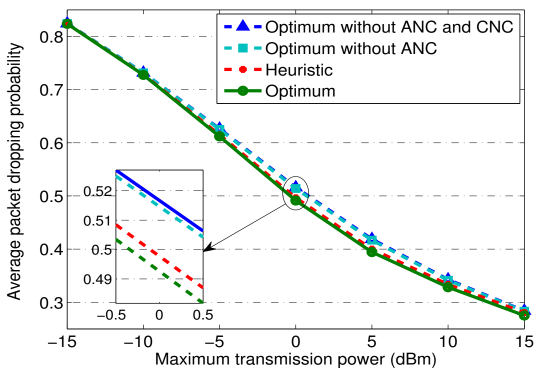

Fig. 3. Average packet dropping probability vs. max. transmission power.

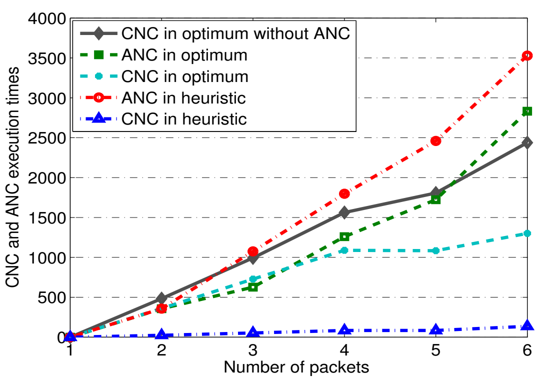

Fig. 4. ANC and CNC execution times vs. number of packets.

in the heuristic method, resulting in fewer execution times of ANC, as shown in Fig. 5.

V. Conclusions

In this paper, we have focused on packet scheduling and transmission with deadline constraints in multi-rate cooperative wireless networks. Four transmission methods, which include ANC, CNC, PR, and NR, are supported. Through exploring the packet transmission sequences and their corresponding transmission methods of optimal solutions achieved by exhaustive search, we have proposed a heuristic strategy based on a dynamic graph. In each transmission, we make

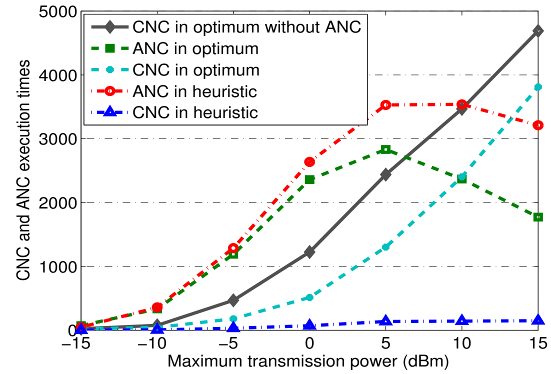

Fig. 5. ANC and CNC execution times vs. maximum transmission power.

the most efficient choice to transmit more packets with fewer packets that will be dropped due to this transmission. Simulation results reveal that the adaptive packet scheduling and transmission methods can reduce average packet dropping probability, and the proposed heuristic strategy has close performance to the optimum.

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