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A Delay-Constrained Network Coding Algorithm Based on Power Control in Wireless Networks

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ABSTRACT This paper investigates the problem of delay-constrained encoding by applying transmission power control in wireless networks. First, we formulate the problem using integer nonlinear programming and demonstrate that it is NP-complete. Moreover, a heuristic encoding algorithm based on power self-adaptation (EAPS) is proposed, which includes two sub-algorithms: the power optimal algorithm (POA) and encoding selection algorithm (ESA). The POA determines the initial transmission power for each packet by taking advantage of opportunities in which the transmission power is increased, thereby decreasing the transmission time without extra energy consumption. The ESA constructs two linked lists: the packet delay constraint linked list (*D-List*) and optimal power linked list (*P-List*) based on the POA. Whenever possible, it selects one packet with a tight delay constraint in the D-List and other packets in the same location as the above packet in the *P-List* to code. Furthermore, this paper includes an analysis of the probability of increasing any transmission power level without extra energy consumption in the POA. Lastly, the simulation results show that EAPS can significantly improve the delay satisfaction ratio and reduce transmission time compared to the COPE, TAONC, and heur.VC algorithms.

INDEX TERMS Delay-constrained, delay satisfaction ratio, network coding, power control.

I. INTRODUCTION

Network coding [1], [2] is an effective way to reduce transmission time and improve the network throughput. COPE [3] provides a general scheme that searches coding opportunities and combines packets in a single transmission to improve the network throughput. XOR-Sym [4] includes an optimal scheduling scheme adapted to COPE to obtain similar throughput gains with lower implementation complexity. NBP [5] effectively combines inter-flow network coding with a back-pressure algorithm, aimed at achieving the maximal network coding gain to enhance the achievable network transmission capacity. Transmission algorithm using opportunistic network coding (TAONC) [6] searches coding opportunities that minimize the sum of the communication power consumptions between the sender and receivers in wireless networks. Generalized dynamic- network codes (GDNC) [7] offers a much better rate-diversity trade-off compared with dynamic-network codes. Heur.VC [8] finds the minimal vertex cover of a hypergraph to solve the average packet decoding delay minimization problem (APDD), and provides a lower value of APDD than the random linear network coding while maintaining the same throughput. NC can also be used in cloud computing [9] and big data techniques [10]. For example, Zhou *et al.* [11] introduces a contact-duration-aware offloading scheme that applies the network coding to better utilize the social contact patterns [12].

The current wireless networks support multi-power and multi-rate systems. For example, Cisco Aironet 1250 [13] supports nine transmission power levels ranging from 0.78 to 200mw, and IEEE802.11g/a [14], [15] supports eight transmission rates ranging from 6 to 54Mbps. The significant energy savings for uplink data transmissions is studied by applying transmit power control [16], [17] and PHY rate adaptation [18], [19] in IEEE 802.11a WLANs under the point coordination function. For example, some studies use multi-rate to decrease the transmission delay [20] and reduce the energy consumption [21]. Others use power control to improve transmission performance. AOPC [22] is a dynamic power control algorithm that adapts the outage probability specification to minimize the total energy. TOTPS [23] decreases the transmission power without degrading the link throughput by switching to an optimal transmission mode based on the knowledge of the carrier-to-noise ratio. SMPA [24] combines link adaptation and transmission power control (TPC) in IEEE 802.11a WLANs, and tries to maximize the goodput of the WLAN while minimizing the transmission power.

Few studies investigate power allocation for network coding. Reference [28] considers the outage behavior and power allocation of a two-user network-coded cooperative cognitive radio network. In two-hop wireless networks with two sources and one relay, [29] investigates the performance of limited buffer-aided relaying and non-limited buffer-aided relaying based on decode and forward, and proposes an optimal control method when the transmitters of the two sources have the channel amplitude information. In this paper, we considered the network coding algorithm based on power control in general wireless networks. Thus, in the present study, the problem of delay-constrained encoding algorithm with the application of the transmission power control (DETPC) is investigated by using the transmission power control in wireless networks. The objective is to minimize the total energy consumption under maximizing the delay satisfaction ratio.[1] For example, as shown in Fig. 1, each node has three transmission power levels: $w_1 = 0.78$mw, $w_2 = 1.56$mw, and $w_3 = 3.13$mw. The source node s, wants to send packets p_2 and p_3 to nodes c_1 and c_2; packets p_1 and p_4 to node c_3; and packets p_1 and p_3 to node c_4. Suppose that the delay constraints of packets p_1, p_2, p_3, and p_4 are 0.2, 0.18, 0.4 and 0.12s, respectively. Tab. 1 provides the transmission power and corresponding link transmission rate of each link. Let the packet size be 1Mb. COPE chooses the first packet from the output queue, and then tries to select some packets to code with the first packet. Thus, COPE will broadcast packet $p_1 \oplus p_2$ with transmission power w_1 and a corresponding transmission rate of 6Mbps. Therefore, nodes w_3 and c_4 can decode packet p_1, and nodes c_1 and c_2 can decode packet p_2. COPE then broadcasts packet $p_3 \oplus p_4$ with transmission power w_1 and a corresponding transmission rate of 6Mbps. Thus, nodes c_1, c_2, and c_4 can decode packet p_3, and node c_3 can decode packet p_4. Therefore, the delay satisfaction ratio of COPE is 75% because packet p_4 is beyond the deadline; its total energy consumption and total transmission time are 0.26mJ and 1/3s, respectively.

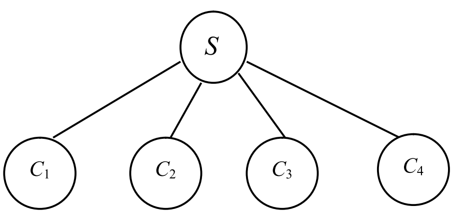

FIGURE 1. Example of encoding algorithm by power control.

The algorithm proposed in the present work first determines the optimal transmission power for each packet by using the power optimal algorithm (POA). The main idea is to increase the transmission power without increasing the energy consumption from the lowest transmission power level for each packet. For example, Tab. 1 shows the transmission power and corresponding maximum transmission rate of each link. To transmit packet p_1 to the intended client c_3, the source s can improve the transmission power from w_1 to w_2 without any extra energy consumption; the corresponding maximum transmission rate then increases from 6 to 12Mbps. Therefore, the optimal transmission power of p_1 is set to w_2. Similarly, the optimal transmission powers are w_2 for packet p_3, and w_3 for packets p_2 and p_4. The packet with a strict delay constraint and some packets with the same optimal transmission power as that packet are then selected for coding together. Therefore, packet p_4 is first chosen, then p_2, with the same optimal transmission power as p_4, is selected for encoding together. Packet $p_2 \oplus p_4$ is sent with transmission power w_3 and a corresponding transmission rate of 24Mbps. By analogy, the source node s broadcasts packet $p_1 \oplus p_3$ with transmission power w_2 and a corresponding transmission rate of 12Mbps. All the nodes can decode their expected packets from the coding packets. The delay satisfaction ratio, total energy consumption, and total transmission time of the algorithm are then determined as 100%, 0.26mJ, and 1/8s, respectively. Compared with COPE, our scheme can improve the delay satisfaction ratio and transmission time by 25% and 62.5%, respectively, without extra energy consumption.

[1]The delay satisfaction ratio is defined as the number of packets successfully received by the clients that are expected to receive them before the deadlines, divided by the number of packets.

TABLE 1. Transmission power and corresponding maximum transmission rate of each link.

	w_1 (Mbps)	w_2 (Mbps)	w_3 (Mbps)
(s,c_1)	6	12	24
(s,c_2)	6	12	24
(s,c_3)	6	12	24
(s,c_4)	6	12	12

The DETPC problem, investigated in this work involves determining a coding packet, the corresponding transmission power, and rate for each transmission, such that the total energy consumption is minimized under maximizing the delay satisfaction ratio. In detail, the contributions of this work are as follows:

- We formulate the DETPC problem with integer nonlinear programming and demonstrate that it is NP-complete.
- We present a heuristic encoding algorithm based on power self-adaptation (EAPS) including the two sub-algorithms: POA and encoding selection algorithm (ESA). The POA sets the optimal transmission power for each packet by using the feature that by increasing the transmission power, the transmission rate increases without extra energy consumption. The ESA constructs the packet delay constraint linked list

(*D_List*) and optimal power linked list (*P_List*), and chooses one packet with tight delay constraint in *D_List* and other packets with the same optimal transmission power for coding together whenever possible, improving the packet delay satisfaction ratio.
- We analyze the probability of increasing any transmission power level in the POA; in the CiscoAironet1250,the probability is close to 20%.
- We carry out simulations to show that the proposed encoding algorithm based on EAPS, which includes the sub-algorithms POA and ESA, could significantly outperform, the existing schemes in terms of the delay satisfaction ratio and transmission time.

The rest of this paper is organized as follows. Section 2 provides the network model and some definitions. Section 3 formulates the problem of DETPC in wireless networks. Section 4 presents the proposed encoding algorithm based on EAPS, which is designed to improve the delay satisfaction ratio and reduce the transmission time. Section 5 provides an analysis of the probability of increasing the transmission power level in the POA. Section 6 discusses the experimental simulation results, demonstrating that our algorithm can apparently improve the delay satisfaction ratio and decrease the transmission time. Lastly, Section 7 presents the conclusions.

II. NETWORK MODEL AND DEFINITION

This section provides the network model and some definitions. The wireless network is modeled as an undirected graph $G_1 = (V_1, E_1)$, where $V_1 = \{c_1, c_2, \ldots, c_n\}$ and $E_1 = \{(c_i, c_j)\}$ are the sets of clients and edges, respectively. Let $W = \{w_1, w_2, \ldots, w_K\}$ and $R = \{r_1, r_2, \ldots, r_J\}$ be the sets of K transmission power levels [13] and J transmission rates [14], respectively, associated with a given network card. The source node s needs to broadcast the set of packets $P = \{p_1, p_2, \ldots, p_m\}$ to its clients C. Due to the wireless broadcast feature, a client may overhear some packets and expects to receive the others. The receive power $W_{rec(i,j)}$ between the sender node i and the receiver node j is calculated by the free space propagation model [25], [26]

$$W_{rec(i,j)} = c\frac{W_{trans(i,j)}}{d^{\alpha}_{i,j}}, \tag{1}$$

where c and α are the path loss parameter and constants, respectively, $W_{trans(i,j)}$ and $W_{rec(i,j)}$ are the transmission and receive powers, respectively, and $d_{i,j}$ is the distance between nodes i and j. In the present work, $c = 1$ and $\alpha = 4$.

As an example, the transmission rate and the corresponding sensitivity of the Cisco Aironet 1250 [13] are shown in Tab. 2. The sets of transmission power levels and transmission rates are $W = \{0.98, 1.56, 3.13, 6.25, 12.5, 25, 50, 100, 200\}$ mw and $R = \{6, 9, 12, 18, 24, 36, 48, 54\}$ Mbps, respectively.

To illustrate the formulation and algorithm, we define the following:

Definition 1: The maximum possible transmission rate (MPTR) of packet p_i under the transmission power w_j, denoted R_i^j, is the maximum transmission rate at which the source transmits packet p_i with the transmission power w_j so that the receive node can decode the packet p_i.

TABLE 2. Transmission rates and sensitivities.

Rate (Mbps)	Sensitivity (dBm)
6	-87
9	-86
12	-83
18	-82
24	-81
36	-80
48	-75
54	-74

Definition 2: For packet p_i, if the transmission power is increased from w_j by k levels (i.e., from w_j to w_{j+k}), the k-power increase metric (k-PIM) $\eta_i^{j,k}$ of packet p_i under transmission power w_j is defined as

$$\eta_i^{j,k} = \frac{w_{j+k} \cdot R_i^j}{w_j \cdot R_i^{j+k}}, \tag{2}$$

where R_i^j and R_i^{j+k} are the MPTRs of packet p_i under the transmission power levels w_j, and w_{j+k}, respectively.

For $\eta_i^{j,k}$, the presence of the inequality

$$\eta_i^{j,k} \leq 1, \tag{3}$$

implies that the transmission power can be increased to obtain a higher transmission rate without extra energy consumption.

Definition 3: Let $P' \subseteq P$ be the set of packets which are successfully received by the clients before the deadlines. The average transmission time and transmission power are calculated by P' instead of P. The energy consumption of the transmission from the source is given by

$$E(w_i, r_j) = \frac{L}{r_j} w_i, \tag{4}$$

where L is the packet length; w_i and r_j are the transmission power and rate, respectively; and $\frac{L}{r_j}$ is the transmission time of the packet.

Definition 4: Let

$$SPR_i = \{(w_j, r_k) \,|\, w_j \in W,\ r_k \in R\}$$

be the sensitivity power-rate set for node i, such that the receive power of node i is not less than the corresponding receiver sensitivity requirement for r_k if the source node transmits a packet with power w_j.

III. PROBLEM FORMULATION

In this section, we formulate the problem of DETPC in wireless networks. Moreover, we show that it is NP-complete.

In order to improve the delay satisfaction ratio, the transmission power can be increased. However, this may lead to a higher energy consumption. Thus, the DETPC problem is as follows. Given the deadline of each packet, the received and required packets of each node, and sensitivity power-rate set for each node, find the coding packet, with the corresponding transmission power, and rate for each transmission is found, such that the total energy consumption is minimized under maximizing the delay satisfaction ratio.

Let H_i and Ex_i be the set of packets which node i has received, and expects to receive, respectively. The deadline of packet p_j is denoted by DL_j $(1 \leq j \leq m)$. Let $G_2 = (V_2, E_2)$ be an undirected graph, where V_2 and E_2 are the vertex and edge sets, respectively. For each packet p_j in Ex_i of node i, there is a corresponding vertex $v_{i,j} \in V_2$. There is an edge $\left(v_{i_1,j_1}, v_{i_2,j_2}\right) \in E_2$ between nodes v_{i_1,j_1} and v_{i_2,j_2} if one of the following conditions is satisfied: (1) $j_1 = j_2$ and (2) $p_{j_1} \in H_{i_2}$ and $p_{j_2} \in H_{i_1}$. Thus, the source node can broadcast the coding packet $p_{j_1} \oplus p_{j_2}$ for the nodes to decode their expected packets. When $j_1 = j_2$, the packet $p_{j_1} \oplus p_{j_2}$ equals p_{j_1} or p_{j_2}. Similarity, for a clique $C = \left\{v_{i_1,j_1}, v_{i_2,j_2}, v_{i_3,j_3}, \ldots\right\}$, in G_2, the source node can broadcast the coding packet $p_{j_1} \oplus p_{j_2} \oplus p_{j_3} \oplus \ldots$ so that all nodes in C can decode their expected packets. Note that if a packet appears more than once in the coding packet, only one copy is kept. Thus, a clique partition of G_2 corresponds to an encoding scheme.

Let $C_k (1 \leq k \leq |V_2|)$ be a clique of G_2, where W_k and R_k are the transmission power and transmission rate of clique C_k, respectively, and WT_j is the earliest time by which all nodes receive packet p_j. To denote whether packet p_j satisfies its deadline, an indicator variable TS_j is defined by

$$TS_j = \begin{cases} 1 & WT_j \leq DL_j \\ 0 & Otherwise. \end{cases} \tag{5}$$

Because each node in V_2 belongs to only one clique in a clique partition, we define an indicator variable as follows:

$$f_{i,j,k} = \begin{cases} 1 & v_{i,j} \in C_k \\ 0 & Otherwise. \end{cases} \tag{6}$$

Now the DETPC problem can be formulated as follows:

$$\text{Minimize} \sum_{\left\{(W_1,R_1),(W_2,R_2),\ldots,\left(W_{|V_2|},R_{|V_2|}\right)\right\} \in S_{WR}} E_{\left\{(W_1,R_1),(W_2,R_2),\ldots,\left(W_{|V_2|},R_{|V_2|}\right)\right\}} \tag{7}$$

$$\text{subject to} \sum_{1 \leq k \leq |V_2|} f_{i,j,k} = 1, \tag{8}$$

$$f_{i_1,j_1,k} + f_{i_2,j_2,k} \leq 1, \tag{9}$$

$$E_{\left\{(W_1,R_1),(W_2,R_2)\ldots\left(W_{|V_2|},R_{|V_2|}\right)\right\}} = \sum_{k=1}^{|V_2|} \frac{W_k \cdot L}{R_k} \tag{10}$$

$$(W_k, R_k) \begin{cases} \in \underset{f_{i,j,k}=1}{I} SPR_i & if \underset{f_{i,j,k}=1}{I} SPR_i \neq \emptyset \\ = (0, +\infty) & otherwise \end{cases} \tag{11}$$

$$WT_j = \sum_{m=1}^{\max_{\exists f_{i,j,k}=1} k} \frac{L}{R_m} \tag{12}$$

$$S_{WR} = \left\{ \left\{(W_1, R_1), (W_2, R_2), \ldots, \left(W_{|V_2|}, R_{|V_2|}\right)\right\} \middle| Maximize \sum_{1 \leq j \leq |P|} TS_j \right\} \tag{13}$$

where

$$\forall v_{i,j} \in V_2,$$
$$\forall \left(v_{i_1,j_1}, v_{i_2,j_2}\right) \notin E_2,$$
$$1 \leq k \leq |V_2|$$

The constraint in (8) indicates that each vertex $v_{i,j}$ is only included in a unique clique. Constraint (9) guarantees that, for two nodes $v_{i_1,j_1}, v_{i_2,j_2} \in V_2$, they can not be included in a clique if edge $(v_{i_1,j_1}, v_{i_2,j_2}) \notin E_2$. Constraint (10) describes the total energy consumption of all cliques. As shown in constraint (11), if clique C_k is not empty, (W_k, R_k) belongs to the intersection of SPR_i. Otherwise, (W_k, R_k) equals $(0, +\infty)$ to ensure the energy consumption of the clique is zero, which is used in constraint (10). Constraints (12) expresses the WT_j of packet p_j. The last constraint for each element $\left\{(W_1, R_1), (W_2, R_2) \ldots \left(W_{|V_2|}, R_{|V_2|}\right)\right\}$ in S_{WR} corresponds to a clique partition of G_2 with the corresponding transmission power and rate of the clique; and this partition maximizes the delay satisfaction ratio. The above integer nonlinear programming can yield the optimal solution. However, it is computationally expensive and impractical. The complexity of the DETPC problem is shown in lemma 1.

Lemma 1: The DETPC problem is NP-complete.

Proof: When the sets of transmission power of a specified network card both only include one element, i.e. $|W| = 1$ and the deadline of packet is set infinity, our problem is reduced to the minimum transmission time encoding problem [27], which has been proven to be NP-complete. Thus, the DETPC problem is NP-complete.

IV. POWER SELF-ADAPTIVE ALGORITHM

An encoding algorithm based on EAPS according to network coding is proposed to improve the delay satisfaction ratio by applying, whenever possible, the power control without extra energy consumption in wireless networks. The EAPS includes two sub-algorithms: POA and ESA. First, the POA takes advantage of PIM to determine the transmission power for each packet. Then, the ESA systematically determines the coded packets by using two constructed linked lists: *D-List* and *P-List*. The ESA chooses for coding, whenever possible, one packet with tight delay constraint in the *D-List*and other packets in the same location as that packet in the *P-List*.

A. POWER OPTIMAL ALGORITHM

The POA is used to initialize the transmission power of each packet. To increase the delay satisfaction ratio, the transmission rate can be improved by increasing the transmission power. However, based on Eq. (4), this may lead to a higher energy consumption. Fortunately, there are some cases in

TABLE 3. Combinations of the transmission power (mw), transmission rate (Mbps), and energy consumption (mJ).

Rate \ Power	0.78	1.56	3.13	6.25	12.5	25	50	100	200
6	0.13	0.26	0.52	1.04	2.08	4.16	8.32	16.64	33.28
9	0.09	0.18	0.36	0.72	1.44	2.88	5.76	11.52	23.04
12	0.065	0.13	0.26	0.52	1.04	2.08	4.16	8.32	16.64
18	0.043	0.086	0.172	0.344	0.688	1.376	2.752	5.504	11.008
24	0.0325	0.065	0.13	0.26	0.52	1.04	2.08	4.16	8.32
36	0.021	0.042	0.084	0.168	0.336	0.672	1.344	2.688	5.376
48	0.0163	0.0325	0.065	0.13	0.26	0.52	1.04	2.08	4.16
54	0.0144	0.0289	0.0578	0.1156	0.2312	0.4624	0.9248	1.8496	3.6992

TABLE 4. MPTR of p1 (Mbps) under different transmission powers levels (mw).

Transmission power	0.78	1.56	3.13	6.25	12.5	25	50	100	200
MPTR	6	12	24	24	36	36	48	54	54

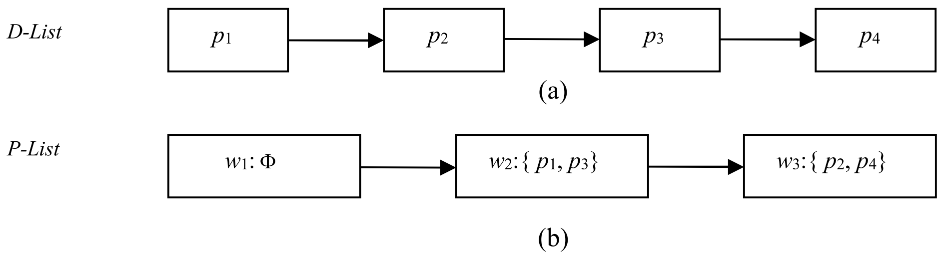

FIGURE 2. The two linked lists of the ESA.

which the transmission rate is increased when the transmission power is increased but without increasing the energy consumption, e.g. the Cisco Aironet 1250. Tab. 3 shows all the combinations of the transmission power, transmission rate, and energy consumption with a packet length of 1Mb. A good rule in this case is: if the transmission power is increased by k levels and transmission rate is increased by no more than $2k$ levels, then the energy consumption will barely increase. For example, when the transmission power and rate vary from 0.78mw and 6Mbps to 1.56mw and 12Mbps, respectively, the energy consumption does not increase. Therefore, if Eq. (4) holds, then it may be possible to increase the transmission power level to obtain a high transmission rate without additional energy consumption. The proposed POA is described in algorithm 1. In Lines 3-8, the above-mentioned possibility, of increasing the transmission power without increasing the energy consumption, is searched for by $\eta_i^j \leq 1$. Line 9 sets the initial transmission power of p_i as *current_power*.

As an example, Tab. 4 shows the MPTR of p_1 under different powers levels: the optimal power of packet p_1 is 0.78mw. According to Lines 4-6 of the POA, the transmission power is systematically increased to 1.56mw with $\eta_1^{1,1} = 1$, and to 3.13mw with $\eta_1^{2,1} = 1$. Finally, the optimal transmission power of packet p_1 is set to 3.13mw.

B. ENCODING SELECTION ALGORITHM

Having identified the optimal transmission power for each packet by using the POA, we now systematically determine the coded combination to improve the delay satisfaction ratio according to the packet delay constraint and optimal transmission power. Two linked lists are designed: *D-List* and *P-List*. The *D-List* is a linked list of packets, sorted in ascending order of the packet delay constraint. In the *P-List*, each item includes one transmission power level and an associated set of packets whose optimal transmission power is equal that power level, and the items are sorted in ascending order of the power level. Fig. 2 shows the corresponding linked lists for Fig. 1. The ESA is described in Algorithm 2. The main idea of which is to combine, whenever possible, the packet with tight delay constraint and the packets in the *D-List* with the same optimal transmission power in the *P-List* to be an encoded packet improving the delay satisfaction ratio and reducing the energy consumption. First, one packet, called p_i, with the

Algorithm 1 Power Optimal Algorithm

1 for packet p_i do
2 $k \leftarrow 1$, $current\_power \leftarrow 1$
3 while $k \leq K - 1$ do
4 if $\eta_i^{1,k} \leq 1$ then
5 $current\_power \leftarrow k + 1$
6 $k++$
7 end if
8 end while
9 Initialize the transmission power of packet p_i as *current_power*
10 end for

Algorithm 2 Encoding Selection Algorithm

```
1  while D-List is not empty do
2    Choose the first packet, called p_i, in the D-List, with
     the optimal transmission power w_j
3    code_packet ← {p_i}
4    for all packets in the j^th item P-List then
5      Choose a packet called p_j
6      if all the clients that expect to receive packet p_i can
       decode that packet from the coding packet obtained
       by ⊕p_j and the packets in code_packet then
7        code_packet ← code_packet ∪ {p_j}
8      end if
9    end for
10   Transmit the code packet obtained by ⊕ all packets in
     code_packet
11   for ∀p_k in code_packet
12     if all clients expected to receive packet p_k can
       decode it from the encoded packet then
13       Delete p_k from D-List and P-List
14     end if
15   end for
16   Delete ∀p_l whose delay constraint could not be
     satisfied even be transmitted at the MPTR R_l^K under
     the highest transmission power in the next
     transmission from D-List and P-List
17 end while
```

smallest delay constraint is chosen, as shown in Line 2. Then, some packets that are coding with p_i, as shown in Lines 4-9, are selected. Finally, the coding packet is transmitted, and the two linked lists are updated, as shown in Lines 11-16.

V. ANALYSIS OF THE POA

The POA determines the optimal transmission power by applying the k-power increase metric. In this section, the probability of increasing the transmission power in the POA is discussed.

Lemma 2: For packet p_i, assume that the current transmission power has power level w_l, called w^l_{trans}. The MPTR is denoted as R^l_i, corresponding to a certain transmission rate, r_k (i.e., $R^l_i = r_k$). The probability of $\eta^{l,1}_i \leq 1$ can be written as

$$P\{\eta^{l,1}_i \leq 1 | R^l_i = r_k\} = \frac{Sen_{k+1} - \frac{Sen_j \cdot w^l_{trans}}{w^{l+1}_{trans}}}{Sen_{k+1} - Sen_k},$$

where Sen_k and Sen_{k+1} are the sensitivities of the transmission rates r_k and r_{k+1}, respectively, and $R^{l+1}_i = r_j$.

Proof: All packets are assumed to be transmitted at the MPTR. According to Eq. (1), we obtain

$$\frac{w^{l+1}_{rec}}{w^l_{rec}} = \frac{w^{l+1}_{trans}}{w^l_{trans}}$$
$$w^l_{rec} = \frac{w^l_{trans} \cdot w^{l+1}_{rec}}{w^{l+1}_{trans}}, \tag{14}$$

where w^l_{rec} and w^{l+1}_{rec} are the receive power levels corresponding to the transmission powers levels w^l_{trans} and w^{l+1}_{trans}, respectively. For packet p_i, when the transmission power is increased from w^l_{trans} to w^{l+1}_{trans}, if $\eta^{l,1}_i \leq 1$, based on Eq. (3), we obtain:

$$\frac{R^{l+1}_i}{R^l_i} \geq \frac{w^{l+1}_{trans}}{w^l_{trans}}. \tag{15}$$

Suppose that $R^l_i = r_k$ and $R^{l+1}_i = r_j$. By substituting r_k and r_j into Eq. (15), we obtain $r_j \geq \frac{r_k \cdot w^{l+1}_{trans}}{w^l_{trans}}$. Let Sen_k be the sensitivity of the transmission rate r_k, as shown in Tab. 2. To correctly receive the packet, the receive power levels should satisfy the following inequalities for transmission rates r_k and r_j, respectively:

$$Sen_k \leq w^l_{rec} < Sen_{k+1} \tag{16}$$
$$Sen_j \leq w^{l+1}_{rec}. \tag{17}$$

Based on Eqs. (14) and (17), we obtain

$$w^l_{rec} \geq \frac{Sen_j \cdot w^l_{trans}}{w^{l+1}_{trans}}. \tag{18}$$

According to the value range of w^l_{rec} as shown in Eqs. (16-18) and the geometric probability model, we obtain the probability of

$$\eta^{l,1}_i \leq 1 P\{\eta^{l,1}_i \leq 1 | R^l_i = r_k\} = \frac{Sen_{k+1} - \frac{Sen_j \cdot w^l_{trans}}{w^{l+1}_{trans}}}{Sen_{k+1} - Sen_k}. \tag{19}$$

■ Consider, for example, the Cisco Aironet 1250; given $w^{l+1}_{trans} = 2w^l_{trans}$, Eq. (19) is reduced to

$$P\{\eta^{l,1}_i \leq 1 | R^l_i = r_k\} = \frac{Sen_{k+1} - Sen_j/2}{Sen_{k+1} - Sen_k}. \tag{20}$$

Suppose $R^l_i = r_2 = 9$Mbps. When the transmission power is increased from w^l_{trans} to w^{l+1}_{trans}, $R^{l+1}_i = r_4 = 18$Mbps, and therefore, the probability of $\eta^{l,1}_i \leq 1$ is

$$P\left\{\eta^{l,1}_i \leq 1 | R^l_i = 9\right\} = \frac{5.012 \times 10^{-9} - \frac{6.31 \times 10^{-9}}{2}}{5.012 \times 10^{-9} - 2.512 \times 10^{-9}} = 75\%.$$

Similarly, we have $P\left\{\eta^{l,1}_i \leq 1 | R^l_i = 12\right\} = 100\%$, $P\left\{\eta^{l,1}_i \leq 1 | R^l_i = 18\right\} = 100\%$.

Lemma 3: For packet p_i, suppose that the current transmission power has power level w_l, denoted as w^l_{trans}. Then, the probability of $R^l_i = r_k$ is

$$P\{R^l_i = r_k\} = \frac{\left(\sqrt[\alpha]{\frac{1}{Sen_k}}\right)^2 - \left(\sqrt[\alpha]{\frac{1}{Sen_{k+1}}}\right)^2}{\left(\sqrt[\alpha]{\frac{1}{Sen_1}}\right)^2},$$

where c and α are constants.

Proof: If $R_i^l = r_k$ is under the transmission power w_{trans}^l, then the receive power w_{rec}^l should satisfy the following inequality:

$$Sen_k \le w_{rec}^l < Sen_{k+1}. \tag{21}$$

Therefore, based on Eq. (1), the distance between the source and client d is given by:

$$\sqrt[\alpha]{\frac{c \cdot w_{trans}^l}{Sen_{k+1}}} < d \le \sqrt[\alpha]{\frac{c \cdot w_{trans}^l}{Sen_k}}, \tag{22}$$

where c and α are constants as in Eq. (1).

To ensure that the transmit packet is at least at the lowest rate r_1, the maximum distance D between the sender and receiver is obtained as:

$$D = \sqrt[\alpha]{\frac{c \cdot w_{trans}^l}{Sen_1}}. \tag{23}$$

Therefore, according to the value range of d as shown in Eqs. (22-23) and the geometric probability model, the probability of $R_i^l = r_k$can be expressed as

$$P\{R_i^l = r_k\} = \frac{\pi\left(\left(\sqrt[\alpha]{\frac{c \cdot w_{trans}^l}{Sen_k}}\right)^2 - \left(\sqrt[\alpha]{\frac{c \cdot w_{trans}^l}{Sen_{k+1}}}\right)^2\right)}{\pi D^2} = \frac{\left(\sqrt[\alpha]{\frac{1}{Sen_k}}\right)^2 - \left(\sqrt[\alpha]{\frac{1}{Sen_{k+1}}}\right)^2}{\left(\sqrt[\alpha]{\frac{1}{Sen_1}}\right)^2}. \tag{24}$$

■

If $c = 1$ and $\alpha = 4$, then Eq. (24) becomes

$$P\{R_i^l = r_k\} = \frac{\sqrt{\frac{1}{Sen_k}} - \sqrt{\frac{1}{Sen_{k+1}}}}{\sqrt{\frac{1}{Sen_1}}}. \tag{25}$$

Based on Eq. (25), if the maximum distance between the sender and receiver can ensure that the sender transmits packets at the lowest rate, then the probability of the transmission rate reaching r_k is unrelated to the initial transmission power.

In the Cisco Aironet 1250, the MPTR is calculated as 9Mbps (i.e., r_k = 9Mbps), and the transmission power is assumed to be 0.78mw. Then, according to Eq. (24), the probability that r_k = 9Mbps under the transmission power is

$$P\{R_i^l = 9\} = \frac{132.745^2 - 111.69^2}{140^2} = 26\%$$

Similarly, we obtain $P\{R_i^l = 12\} = 7\%$ and $P\{R_i^l = 18\} = 5\%$.

Given an initial transmission power w_{trans}^l, we can obtain the probability of improving the initial power with a specific transmission rate according to Lemma 2 in the POA, and the probability of the specific transmission rate in Lemma 3. Thus, we can deduce the following theorem:

Theorem 1: For each packet, the initial transmission power is w_{trans}^l, and the probability of the POA improving the initial power is

$$P = \sum_{1\le k\le J} P\{\eta_i^{l,1} \le 1 | R_i^l = r_k\} \cdot P\{R_i^l = r_k\}$$
$$= \sum_{1\le k\le J} \left(\frac{Sen_{k+1} - \frac{Sen_j \cdot w_{trans}^l}{w_{trans}^{l+1}}}{Sen_{k+1} - Sen_k} \cdot \frac{\left(\sqrt[\alpha]{\frac{1}{Sen_k}}\right)^2 - \left(\sqrt[\alpha]{\frac{1}{Sen_{k+1}}}\right)^2}{\left(\sqrt[\alpha]{\frac{1}{Sen_1}}\right)^2} \right), \tag{26}$$

where J means that the network card supports J levels of transmission rate and $R_i^{l+1} = r_j$.

$P\{\eta_i^{l,1} \le 1 | R_i^l = r_k\}$ in Th. 1 is the probability of improving the initial power with a specific transmission rate r_k as shown in Lemma 2. $P\{R_i^l = r_k\}$ in Th. 1 is the probability of the specific transmission rate r_k in Lemma 3.

Therefore, in the Cisco Aironet 1250, under the condition of a packet being able to be transmitted at least at the lowest rate, the probability of increasing the transmission power in the POA is $0.75 \times 0.26 + 0.07 + 0.05 = 20.7\%$.

VI. SIMULATION

In this section, the performance of the proposed EAPS is compared with that of COPE [3], TAONC [6], and heur.VC [8]. A simulator is developed in Java language, with nodes randomly placed in a square area and the packet delay constraint is uniformly chosen from the interval [200ms, 1000ms]. The IEEE 802.11g and Cisco Aironet 1250 are used in all simulations. Tab. 3 lists the sets of transmission powers and rates. The packet length is 1Mb. The performance metrics are the delay satisfaction ratio as well as the energy consumption and transmission time of each packet. COPE, TAONC and heur.VC are assumed to transmit the packets at the MPTR.

The number of clients is varied from 3 to 10 to sufficiently investigate the impact of this variable on the three algorithms. In this simulation, we set 20 packets, and the network size is 140 m. Fig. 3 shows the simulation results. As indicated in Fig. 3(a), with the increasing of number of clients, the delay satisfaction ratios of all algorithms decrease because the coding opportunities decrease. The delay satisfaction ratio of the proposed EAPS is always higher than that of COPE, TAONC, and heur.VC. Moreover, the EAPS is able to improve the delay satisfaction ratio by up to 32%, 54%, and 12%, compared with COPE, TAONC, and heur.VC, respectively. Fig. 3(b) shows that the EAPS can decrease the transmission time by an average of 28%, 27%, and 20% compared with COPE, TAONC, and heur.VC, respectively. As shown in Fig. 3(c), the EAPS increases the energy consumptions by only 32%, 28%, and 35% over COPE, TAONC, and heur.VC, respectively. The reason may be that, compared with COPE, TAONC, and heur.VC, the proposed EAPS

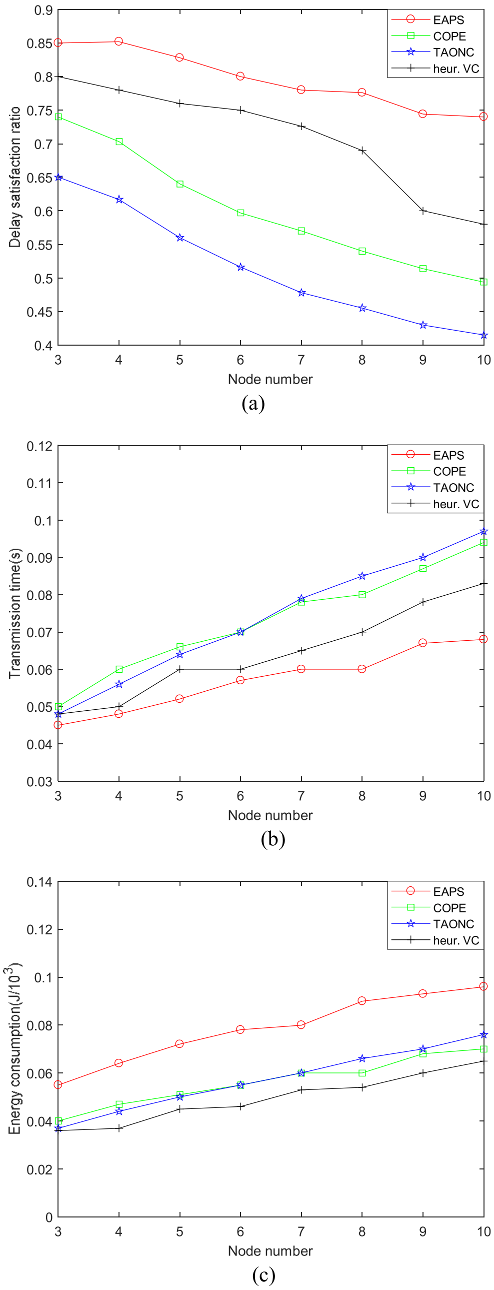

FIGURE 3. Performance comparison under different number of nodes. (a) Delay satisfaction ratio. (b) Transmission time. (c) Energy consumption.

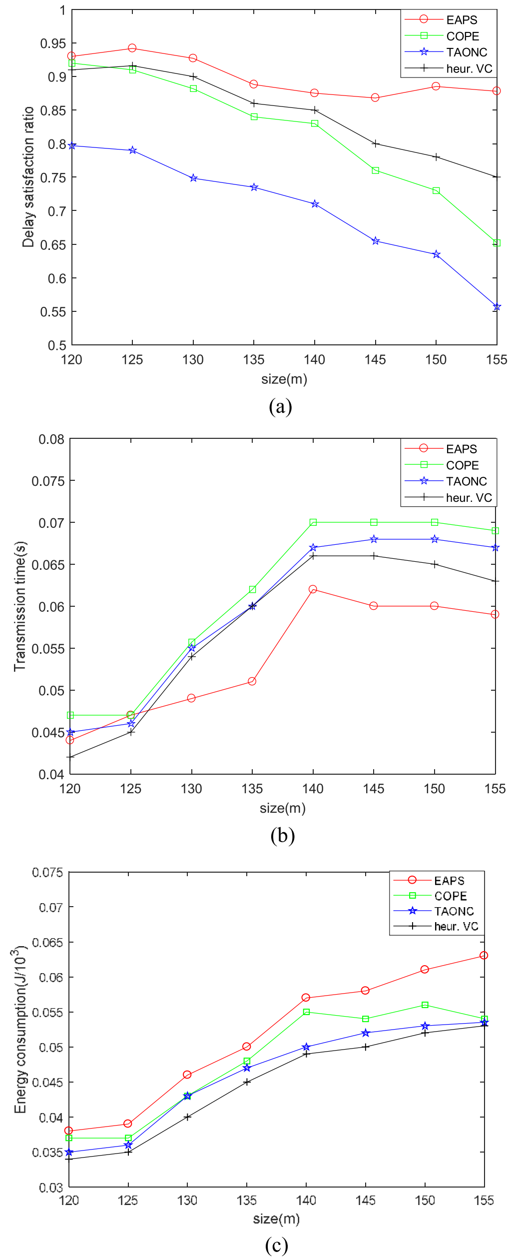

FIGURE 4. Performance comparison under different network sizes. (a) Delay satisfaction ratio. (b) Transmission time. (c) Energy consumption.

successfully transmits a higher number of packets, leading to higher energy consumption.

The network size is further varied from 120 to 155m. Fig. 4 presents the experimental results. In this simulation, we set 20 packets and 5 clients. As shown in Fig. 4(a), the EAPS improves the delay satisfaction ratio by approximately 15%, 25%, and 10% compared with COPE, TAONC, and heur.VC, respectively. The results indicate that the performances of COPE and TAONC decline dramatically as the network size increases, whereas our algorithm achieves a high performance under the same condition. As shown in Fig. 4(b), our algorithm saves the transmission time by approximately 15%, 12%, and 8% respectively, compared with COPE, TAONC, and heur.VC. Fig. 4(c) shows that the EAPS uses 10%, 13%, and 15% additional energy compared with COPE, TAONC, and heur.VC, respectively.

Lastly, to study its impact on the proposed algorithm, the number of packets is varied from 10 to 24. In this simulation, we set 5 clients, and the network size is 140m. The simulation results are plotted in Fig. 5. As shown in Fig. 5(a), with the increased network load caused by the increasing number of packets, the delay satisfaction ratios of the three algorithms decrease rapidly. However, the delay satisfaction

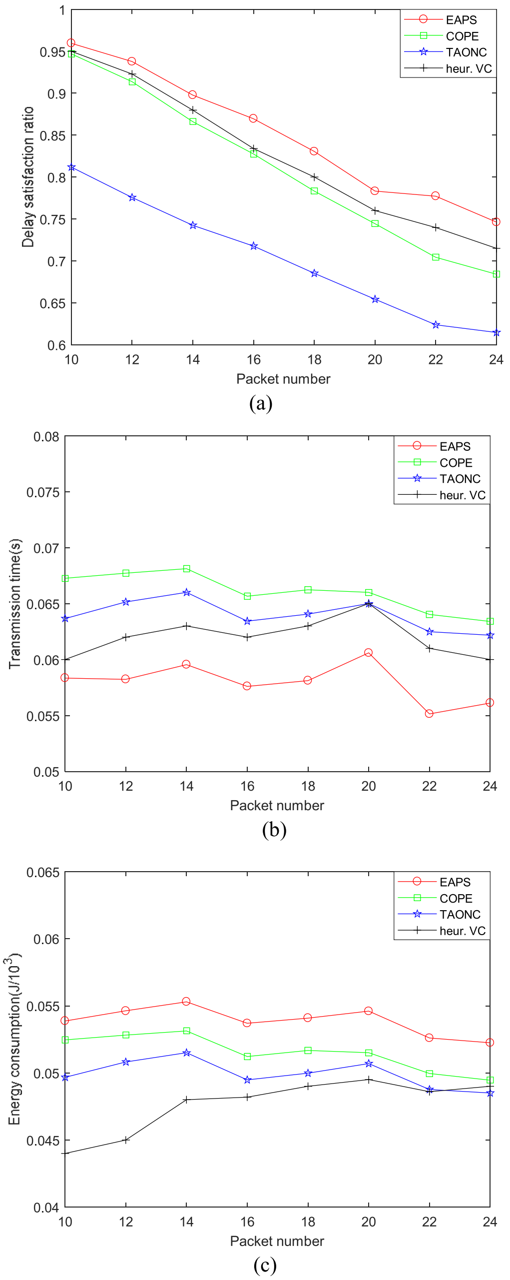

FIGURE 5. **Performance comparison under different packet numbers. (a) Delay satisfaction ratio. (b) Transmission time. (c) Energy consumption.**

ratio of the proposed algorithm is higher than that of COPE, TAONC, and heur.VC. As indicated in Fig.5 (b), the EAPS saves the transmission time by 17%, 12% and 10% compared with COPE, TAONC and heur.VC, respectively. Nonetheless, compared with COPE, TAONC, and heur.VC, the EAPS consumes less than 5%, 7%, and 9% energy, respectively, as shown in Fig. 5(c).

VII. CONCLUSION

This study has studied the problem of delay-constrained encoding by applying the transmission power control in wireless networks. We formulate the problem as an integer nonlinear programming optimization and demonstrate it is NP-complete. Additionally, we present a heuristic encoding algorithm based on EAPS that includes two sub-algorithms: POA and ESA. The POA finds opportunities to increase the transmission power without extra energy consumption. To improve the delay satisfaction ratio and decrease the transmission time, the ESA chooses for encoding the packet with a high delay constraint and other packets with the same initial transmission power. This study also analyses the probability of increasing any transmission power levels in the POA; using the Cisco Aironet 1250 as an example, this probability is close to 20%. Simulation results further show that the EAPS can improve the delay satisfaction ratio by up to 32%, 54%, and 12% compared with COPE, TAONC, and heur. VC, respectively. Future works will focus on increasing the coding opportunities to improve the performance of our algorithm.

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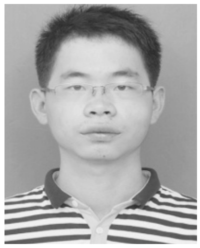

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