Content-Aware Instantly Decodable Network Coding over Wireless Networks

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Abstract—Consider a scenario of broadcasting a common content to a group of cooperating wireless nodes that are within proximity of each other. Nodes in this group may receive partial content from the source due to packet losses over wireless broadcast links. We further consider that packet losses are different for different nodes. The remaining missing content at each node can then be recovered, thanks to cooperation among the nodes. In this context, the minimum amount of time that can guarantee a complete acquisition of the common content at every node is referred to as the “completion time”. It has been shown that instantly decodable network coding (IDNC) reduces the completion time as compared to no network coding in this scenario. Yet, for applications such as video streaming, not all packets have the same importance and not all users are interested in the same quality of content. This problem is even more interesting when additional, but realistic constraints, such as strict deadline, bandwidth, or limited energy are added in the problem formulation. We assert that direct application of IDNC in such a scenario yields poor performance in terms of content quality and completion time. In this paper, we propose a new Content-Aware IDNC scheme that improves content quality and network coding opportunities jointly by taking into account the importance of each packet towards the desired quality of service (QoS). Our proposed Content-Aware IDNC (i) maximizes the quality under the completion time constraint, and (ii) minimizes the completion time under the quality constraint. We demonstrate the benefits of Content-Aware IDNC through simulations.

I. INTRODUCTION

The widely-used and popular applications in today’s wireless devices come with increasing demand for high quality content, bandwidth, and energy [1], [2]. Cooperation among wireless devices, facilitated by improved computational, storage, and connectivity capabilities of these devices, is a promising approach to meet these demands.

In this paper, we consider an increasingly popular application of broadcasting a common content (e.g., video), to a group of cooperating wireless nodes within proximity and transmission range of each other. In such a scenario, the content server may just broadcast the video via cellular links. However, wireless nodes may receive only a partial content due to packet losses over wireless broadcast links. The remaining missing content can then be recovered, thanks to cooperation among the nodes via local area links such as WiFi or Bluetooth.

Network coding (NC) reduces the number of packet exchanges among cooperative wireless nodes [3], [4], [5], [6]. Instantly decodable network coding (IDNC) considers the same

\[ H_A = \{p_2, p_3, p_4\} \]
\[ W_A = \{p_1\} \]

\[ H_B = \{p_1, p_3, p_4\} \]
\[ W_B = \{p_2\} \]

\[ H_C = \{p_1, p_2\} \]
\[ W_C = \{p_3, p_4\} \]

Fig. 1. Nodes: A, B, and C are in close proximity, and are interested in the same video content. As a simple example, let us assume that the video file is composed of four packets: \( p_1, p_2, p_3, p_4 \). Nodes A, B, C want to receive the sets of packets: \( W_A, W_B, W_C \), respectively. They already have the sets of packets: \( H_A, H_B, H_C \), respectively.

In particular, a network coded packet should be decodable by at least one of the nodes. This characteristic of IDNC makes it feasible for real-time multimedia applications in which packets are passed to the application layer immediately after they are decoded. Let us consider the following example to further explain the operation of IDNC.

Example 1: Let us consider Fig. 1 where nodes A, B, and C want to receive the sets of packets, \( W_A, W_B, W_C \), respectively. Without NC, four transmissions are required so that each node receives all the packets. With IDNC, node A broadcasts \( p_2 \oplus p_3 \) to nodes B and C, and node B broadcasts \( p_1 \oplus p_4 \) to nodes A and C. After these transmissions, all nodes have the complete set of packets. This example shows that IDNC has two advantages: (i) it reduces the number of transmissions from four to two, and (ii) packets are instantly decodable at each transmission; e.g., when node A broadcasts \( p_2 \oplus p_3 \), \( p_2 \) is decoded at node B and \( p_3 \) is decoded at node C without waiting for additional network coded packets. These advantages make IDNC feasible for real-time multimedia applications.

In the context of IDNC, the minimum amount of time that can guarantee a complete acquisition of the common content at every node is referred to as the “completion time”. Previous works on IDNC mainly focus on reducing the completion time [9], [10]. However, the interest of each user in receiving the remaining contents may vary depending on the information already received and the overall quality of service (QoS) requirements, such as bandwidth, energy, deadlines, etc. Existing NC or IDNC schemes under such realistic constraints yield poor performance in terms of desired QoS parameters. In the following, we further illustrate on this problem.

Example 1 - continued: Let us consider Fig. 1 again.
Assume that there exists a constraint that nodes should exchange their packets only in one transmission. (Note that IDNC requires two transmissions to deliver complete content to all nodes.) This constraint may be due to (i) deadline or bandwidth; the packets may need to be played after one transmission, or (ii) energy; nodes operating on batteries may put constraints on the number of transmissions. The question in this context is that which network code should be transmitted if there are such constraints, i.e., a decision between \( p_2 \oplus p_4 \) or \( p_1 \oplus p_4 \) in the given transmission opportunity. This decision should be made based on the contents of the packets. The resulting optimization problem is the focus of our work in this paper.

We propose an efficient Content-Aware IDNC which improves content quality and NC opportunities jointly. The following are the key contributions of this work:

- We consider two content-aware optimization problems: (i) completion time minimization under the quality constraint, and (ii) quality maximization under the completion time constraint.

- We characterize the conditions that satisfy the constraints of our completion time minimization and quality maximization problems. We provide analysis of completion time and distortion by taking into account the constraints of these problems as well as the importance of each packet. We develop Content-Aware IDNC algorithms for the quality maximization and completion time minimization problems based on our completion time and distortion analysis.

- We evaluate our proposed Content-Aware IDNC schemes for different number of nodes and packets under the constraints of completion time and quality using real video traces. The simulation results show that Content-Aware IDNC significantly improves completion time and quality as compared to baselines of IDNC and no NC. The cost of solving the optimization problem is relatively low as we assume that the cooperation setup involves small number of users, and each transmission phase consists of small number of packets.

The structure of the rest of the paper is as follows. Section 2 presents related work. Section III gives an overview of the system model and problem setup. Section IV presents our Content-Aware IDNC schemes. Section V presents simulation results. Section VI concludes the paper.

II. RELATED WORK

Broadcasting a common content to a group of cooperating wireless nodes within proximity and transmission range of each other is gaining increasing interest. In this scenario, wireless nodes may receive partial content due to packet losses over wireless broadcast link. The remaining missing content can then be recovered, thanks to cooperation among the nodes via local area links. It has been shown that random NC reduces the number of transmissions necessary to satisfy all nodes in the group. However, this kind of NC, in general, requires that a block of packets be network coded and exchanged among cooperating nodes until all the nodes decode all packets in the block, which makes block based NC not suitable for delay sensitive applications.

Cooperative data exchange problems have considered designing network codes to reduce the number of transmissions in the same setup. The problem of minimizing the number of broadcast transmissions required to satisfy all nodes is considered in [2]. The total number of transmissions needed to satisfy the demands of all nodes, assuming cooperation among nodes and the knowledge of the packet sets available in each node, is minimized in [3]. A deterministic algorithm that computes an optimal solution to the cooperative data exchange problem in polynomial time is proposed in [4]. The cost and fairness issues of the cooperative data exchange problem have been considered in [5]. As compared to previous cooperative data exchange problems, the focus of this paper is on instant decodability and content-awareness.

Instantly decodable network coding (IDNC) which requires instant decodability of the transmitted packets is introduced by [6] and [7]. Minimization of the completion delay in IDNC has been considered in [8] and [9]. Generalized IDNC which relaxes instant decodability constraint of IDNC to target more receivers is introduced in [10]. The problem of minimizing the decoding delay of generalized IDNC in persistent erasure channels is considered in [11]. Minimization of the broadcast completion delay for IDNC with limited feedback is considered in [12]. Lossy feedback scenario is considered in [13]. IDNC is exploited in cooperative data exchange problem by making coding and scheduling decisions to generate IDNC packets in [14]. Capacity of immediately-decodable coding schemes for applications with hard deadline constraints is analyzed in [15]. IDNC is further relaxed in [16], where the nodes are satisfied if they receive any one message that they do not have, and in [17], where the authors are interested in finding a code that is instantly decodable by the maximum number of users. As compared to previous works on IDNC, our goal in this paper is to develop Content-Aware IDNC.

NC and content-awareness have met in several previous works. Multimedia video quality improvement has been considered in [18], and multimedia-aware NC scheme is developed for a broadcast and unicast scenarios for one-hop downlink topologies. One-hop opportunistic NC scheme is improved for video streaming over wireless networks in [19]. As compared to [20] and [21], in this paper, we consider the packet recovery problem among cooperative nodes using IDNC. Packet prioritization is considered in IDNC [22], where packet prioritization is determined based on the number of requests for a packet, whereas in this paper content-based information is used for packet prioritization.

III. SYSTEM MODEL & PROBLEM SETUP

We consider a wireless network model, which consists of cooperating wireless nodes. Let \( \mathcal{N} \) be the set of cooperating nodes in our system where \( \mathcal{N} = |\mathcal{N}| \). These nodes are within close proximity of each other, so they are in the same transmission range. Note that we do not consider any malicious
or strategic activity in our setup. We rely on possible social ties in close proximity setup for cooperation incentive and to eliminate any malicious or strategic behavior.

The cooperating wireless nodes in $\mathcal{N}$ are interested in receiving the packets $p_{m,n}$, $m = 1, 2, \ldots, M$ from the set $\mathcal{M}$ where $M = |\mathcal{M}|$. Packets are transmitted in two stages. In the first stage, an access point or a base station broadcasts the packets in $\mathcal{M}$ to the cooperating wireless nodes $\mathcal{N}$. In this stage, the cooperating nodes may receive partial content due to packet losses over wireless broadcast link. We consider that there is no error correction mechanism in the first stage, which is dealt with in the second stage. After the first stage, the set of packets that node $n$ has is $\mathcal{H}_n$, and is referred to as Has set of node $n$. The set of packets that are missing at node $n$ is, $\mathcal{L}_n (\mathcal{L}_n = \mathcal{M} \setminus \mathcal{H}_n)$, and is referred to as Lacks set of node $n$. Each node $n$ wants all or a subset of its Lacks set, which is referred to as Wants set of node $n$ and denoted by $\mathcal{W}_n$.

In the second stage, the nodes cooperate to recover the missing contents via their local area links such as WiFi or Bluetooth. Each node $n$ is satisfied after receiving the packets in its Wants set; $\mathcal{W}_n$. In this stage, at each transmission opportunity the best network coded packet is selected according to our Content-Aware IDNC algorithms which we present in the next sections. If there exists a node that has all packets in the selected coded packet, it will be chosen as the sender. Otherwise, the coded packet is broadcast from the base station or access point to all nodes. The minimum amount of time that can guarantee the satisfaction of all nodes $n \in \mathcal{N}$ is referred to as the "completion time"; $T$. For the simplicity of the analysis, we assume that the link transmissions in the second stage are error free. Note that it is straightforward to extend our analysis to include packet loss considerations, however, we ignore this part in this paper to focus on content-awareness.

In our content-aware setup, each packet $p_{m,n} \in \mathcal{M}$ has a contribution to the quality of the overall content. We refer to this contribution as the importance of packet $p_{m,n}$. The importance of packet $p_{m,n}$ for node $n$ is denoted by $r_{m,n} \geq 0$. The larger the $r_{m,n}$, the more important packet $p_{m,n}$ is for node $n$. For example, in applications that the content is video or image, $r_{m,n}$ is calculated as the distortion of the content that node $n$ experiences from lacking packet $p_{m,n}$. Therefore, the distortion value for node $n$ is calculated as:

$$D_n = \sum_{m | p_{m,n} \in \mathcal{M}} r_{m,n} - \sum_{m | p_{m,n} \in \mathcal{H}_n} r_{m,n}. \quad (1)$$

The goal of traditional IDNC is "to minimize $T$". On the other hand, Content-Aware IDNC takes into account packet importances and distortion value $D_n$ formulated in Eq. (1). In particular, we consider the following two problems:

- **Content-Aware IDNC-P1**: Our first problem minimizes the completion time $T$ under the quality constraint.

$$\text{minimize } T$$

subject to $D_n \leq D^\text{cons}_n, \forall n \in \mathcal{N} \quad (3)$$

where $D^\text{cons}_n$ is the maximum tolerable distortion for node $n$. This problem is relevant if there are limitations on the number of transmissions due to available bandwidth or energy. E.g., if nodes are conservative in terms of their energy consumption, then the correct problem is to minimize the number of transmissions, which is equivalent to minimizing the completion time $T$, while satisfying a quality constraint; Eq. (3).

- **Content-Aware IDNC-P2**: Our second problem maximizes quality under the completion time constraint.

$$\text{minimize } f(D)$$

subject to $T \leq T^\text{cons}$, \quad (4)

where $T^\text{cons}$ is the maximum allowed completion time, $D$ is the vector of per node distortions; $D = [D_1, D_2, \ldots, D_N]$, and $f(D)$ is the function of the distortion vector; $D$. $f(D)$ should be a convex function, and depending on the application, it can take different values. For example, in some applications the goal may be to minimize the sum distortion over all nodes; i.e., $f(D) = \sum_{n \in \mathcal{N}} D_n$, while in some other applications the goal may be to minimize the sum distortion over all nodes; $f(D) = \max_{n \in \mathcal{N}} D_n$. We further explain our approach to select $f(D)$ in Section IV. The problem of minimizing $f(D)$ is relevant if there are constraints on delay. E.g., if packets should be played out before a hard-deadline constraint; $T^\text{cons}$, then the goal is to improve the content quality as much as possible; Eq. (4), before the deadline; Eq. (5).

In the next section, we provide our solutions to **Content-Aware IDNC-P1** and **Content-Aware IDNC-P2**.

**IV. CONTENT-AWARE IDNC**

**A. Minimizing Completion Time under Quality Constraint**

In this section, we present our approach to solve the problem; Content-Aware IDNC-P1 in Eqs. (2), (3).

**Stochastic Shortest Path (SSP):** The main difficulty of this problem (i.e., solving Eq. (2) subject to Eq. (3)) is that it is not straightforward to find analytically closed form formulation for the completion time; $T$. One possible approach, as also considered in [3], is to formulate the problem as a stochastic shortest path (SSP) problem. We consider a similar approach.

Let state $s$ be the set of Has sets of all nodes, $\mathcal{S}$ be the set of all states, action $a$ be the selection and transmission of an IDNC packet, and the terminating state is any state, for which the constraint on the distortion values; Eq. (3) is satisfied. By taking an action $a$, the system moves to state $s'$ from state $s$. Noting that there are no losses over the links in the second stage, the optimal network coding policy at state $s$ is $\pi^*(s)$.
where \( P_a(s, s') \) is the probability of moving from state \( s \) to state \( s' \) by taking action \( a \). \( V_a(s') \) is the cumulative cost, which is equal to the completion time, defined as the number of packets required to be transmitted to reach the terminating state (any state for which Eq. (4) is satisfied) from state \( s' \). Eq. (4) shows that the best action at each state, i.e., network code selection and transmission, is the one that results in a state \( s' \) with the minimum \( V_a(s') \), which is defined as the completion time at state \( s' \). In other words, considering that \( T \) is the completion time at the current state \( s \), Eq. (5) shows that the best action, i.e., network code, taken at state \( s \) should be one that results to the next state \( s' \) with the minimum completion time \( T' \). Motivated by this fact, next we analyze the completion time at the current state; \( T \) as well as at the next state; \( T' \).

### Relating Completion Time to “Wants Sets”:
In our setup, as different from previous work [9], each node does not have a fixed initial Wants set. Instead, each node is interested in receiving any set of packets so that Eq. (4) is satisfied. Indeed, for node \( n \), \( L_n \) different Wants sets; \( W_n = \{l_1, l_2, \ldots, l_n\} \) could satisfy Eq. (4) as long as the following conditions are met.

- **C1**: \( W_n \subseteq L_n \).
- **C2**: \( \sum_{m|p_m \in M} r_{m,n} - \sum_{m|p_m \in (W_n \cup H_n)} r_{m,n} \leq D_n^{\text{cons}} \).
- **C3**: If \( W_n \supset W_{n'}, l_1, l_2 = 1, 2, \ldots, L_n \) then delete \( W_{n'} \).

It is obvious that a Wants set should be one of the subsets of the Lacks set (the first condition; C1). The second condition; C2 is required to satisfy the constraint of our problem, i.e., Eq. (4). The third condition; C3 picks the set with the minimum cardinality between each pair of sets that are supersetsubset of each other and deletes the other one. This condition is required to reach our objective of minimizing the number of packets to be transmitted.

**Example 2**: Let us explain the conditions; C1, C2, C3 via an example. Assume that node \( n \in N \) is interested in receiving \( M = 4 \) packets with the importance values of: \( r_{1, n} = 4, r_{2, n} = 5, r_{3, n} = 3, r_{4, n} = 1 \), node \( n \)'s Has set is \( H_n = \{p_1\} \), and its maximum tolerable distortion is equal to \( D_n^{\text{cons}} = 5 \). By applying the first and the second conditions, the potential Wants sets are: \( W_n^1 = \{p_2\}, W_n^2 = \{p_3, p_4\}, W_n^3 = \{p_2, p_4\}, W_n^4 = \{p_2, p_3, p_4\} \). According to the third condition, \( (W_n^1 \cap W_n^2 \cap W_n^3 \cap W_n^4) = \emptyset \), only the first two sets are kept as potential Wants sets: \( W_n = \{p_2\}, W_n = \{p_3, p_4\} \).

Now that we defined Wants sets for our problem, we can formulate the completion time in terms of Wants sets as follows. The completion time for node \( n \), denoted by \( T_n \), is equal to the minimum number of packets that it should receive so that its distortion is equal to or less than its maximum tolerable distortion:

\[
T_n = \min_{t=1,\ldots,L_n} |W_n^t|, \quad \text{(7)}
\]

Note that node \( n \) can benefit from a transmitted IDNC packet, if it is instantly decodable for node \( n \) and the decoded packet is a member of the set \( \bigcup_{t=1}^{L_n} W_n^t \). Assume that node \( n \) decodes packet \( p_m \) and the system moves from state \( s \) to state \( s' \). The completion time and the potential Wants sets for node \( n \) at state \( s' \) are expressed as:

\[
T_n' = \begin{cases} 
T_n - 1, & \text{if } \exists l \leq L_n : p_m \in W_n^l \text{ and } |W_n^l| = T_n \\
T_n, & \text{otherwise}
\end{cases}
\]

\[
W_n^l = (W_n^l \setminus p_m), l = 1, 2, \ldots, L_n. \quad \text{(8)}
\]

**Lower and Upper Bounds of \( T \)**: The completion time \( T \), which is the minimum number of packets required to be transmitted to reach the terminating state, has the lower and upper bounds of:

\[
\max_{n \in N} T_n \leq T \leq \sum_{n \in N} T_n. \quad \text{(10)}
\]

These bounds (i.e., Eq. (10)) are explained via the next example.

**Example 3**: Let us consider three nodes with the completion times of \( T_1 = 1, T_2 = 2, T_3 = 3 \) Obviously node 3 needs at least three transmission, \( T_3 = 3, \) to be satisfied, i.e., to receive all the packets in its Wants set with the minimum size, \( \min_{n=1,\ldots,L_3} |W_3^l| \) (Eq. (7)). In the worst case scenario, these three transmissions can also satisfy the other two nodes. In other words, according to Eq. (8), the completion time is decreased by one for node 3 in all three transmissions, the completion time is decreased by one for node 2 in two of the transmissions and the completion time is decreased by one for node 1 in just one of the transmissions. Therefore, the upper bound for the completion time is (Eq. (10)) \( T = \max_{n \in N} T_n = 3 \). On the other hand, in the worst case scenario, at each transmission, just one of the nodes is satisfied. Therefore, 3 transmissions are required to satisfy node 3, 2 transmissions are required to satisfy node 2, and 1 transmission is required to satisfy node 1. Therefore, the upper bound for the completion time is \( T = \sum_{n \in N} T_n = 1 + 2 + 3 = 6 \). In general, the completion time varies between the lower and upper bounds in Eq. (10).

**Expressing \( T' \) as a \( p - \text{norm} \)**: As we mentioned in our SSP discussion, Eq. (5) shows that the best action, i.e., network code, is the one that results in the next state with the minimum completion time \( T' \). Although we do not have analytically closed form formulation for the completion time; \( T \), hence \( T' \), we have lower and upper bounds on \( T \); Eq. (10), which
also applies to $T'$:
\[
\max_{n \in N} T'_n \leq T' \leq \sum_{n \in N} T'_n,
\]
(11)
where $T'_n$ is characterized by Eq. (8).

Our goal is to find the best network code that minimizes $T'$, so let us examine its lower and upper bounds closely. The lower bound of $T'$ is $\max_{n \in N} T'_n$, which is actually the maximum norm (infinity norm or $L_{\infty}$ norm) of the vector $T' = [T'_1, T'_2, \ldots, T'_N]$, i.e., the maximum norm of $T'$ is $\|T'\|_{\infty} = \max_{n \in N} T'_n$. On the other hand, the upper bound of $T'$ is $\sum_{n \in N} T'_n$, which is the $L_1$ norm of the vector $T' = [T'_1, T'_2, \ldots, T'_N]$, i.e., the $L_1$ norm of $T'$ is expressed as $\|T'\|_1 = \sum_{n \in N} T'_n$. Thus, $\|T'\|_{\infty} \leq T' \leq \|T'\|_1$. Since the following inequality holds; $\|T'\|_{\infty} \leq \|T'\|_p \leq \|T'\|_1$, we can conclude that $T' = \|T'\|_p$ for some $p$ such that $1 < p < \infty$. Now that we know $T' = \|T'\|_p$, we can select a network code which minimizes $\|T'\|_p$.

**Taking Action:** Since our goal is to select a network code which minimizes $\|T'\|_p$, we should determine all possible instantly decodable network coding candidates. Then, we should select the best network code which minimizes $\|T'\|_p$. A trivial approach would be exhaustively listing all possible network coding candidates, and calculating $\|T'\|_p$ for each of them to determine the best one. More efficient approach is to use a graph: IDNC graph [9]. IDNC graph is constructed so that each clique in the graph corresponds to a network code. Thus, we can find the best clique to determine the best network code which minimizes $\|T'\|_p$. The IDNC graph $G$ for our problem is constructed as follows.

For node $n$, $|\bigcup_{l=1,\ldots,L} \mathcal{W}_n^l|$ vertices, each shown by $v_{n,m}$ such that $p_m \in (\bigcup_{l=1,\ldots,L} \mathcal{W}_n^l)$ are added to the graph. A pair of vertices, $v_{n,m_1}$ and $v_{n,m_2}$, are connected if one of the following conditions; $C_1$ or $C_2$ is satisfied:
- $C_1$: $p_{m_1} = p_{m_2}$
- $C_2$: $p_{m_1} \in \mathcal{H}_{m_2}$ & $p_{m_2} \in \mathcal{H}_{n_1}$.

The total number of possible actions, i.e., the number of network codes, is equal to the number of cliques in the graph $G$. The action associated with clique $q$ corresponds to transmitting the network coded packet generated by XORing all the packets associated with the clique, i.e., XORing $\forall p_m$ such that $v_{n,m} \in q$. Since the best network code, hence the best clique in $G$ is the one that minimizes $\|T'\|_p$, we assign weights to each vertex in the graph so that the sum weight of all the vertices in clique $q$ corresponds to the $p-$norm of the network code represented by the clique $q$. Then, we search for the clique that has the largest total weight summed over its vertices. Next, we determine the weight of vertex $v_{n,m}$ in clique $q$: $w_{n,m}$.

If a network code corresponding to clique $q$ is selected, the resulting $T'$ will have $p-$norm; $\|T'\|_p$, which is equal to:
\[
\|T'\|_p = \left( \sum_{n}(T'_n)^p + \sum_{m}(T'_m)^p \right)^{1/p}
\]
(12)
Note that the completion time for node $n$ changes from $T_n$ to $T'_n$ (Eq. (8)) if the selected clique covers node $n$, i.e., it includes a vertex that represents a packet from Wants set of node $n$. The term $\sum_{n}(\exists m|v_{n,m} \in q)(T'_n)^p$ in Eq. (12) corresponds to this fact. On the other hand, the completion time for the nodes that are not covered by the selected clique does not change. The term $\sum_{m}(\exists n|v_{n,m} \in q)(T'_n)^p$ in Eq. (12) corresponds to this fact. Eq. (12) is expressed as:
\[
\|T'\|_p = \left( \sum_{n}(T'_n)^p + \sum_{m}(T'_m)^p - (T'_n)^p \right)^{1/p}
\]
(13)
Note that the first term in Eq. (13) is the same and fixed for all cliques in the graph. Therefore, in order to minimize $\|T'\|_p$, the second term should be minimized, which corresponds to:
\[
q^* = \arg \max_q \sum_{n}(\exists m|v_{n,m} \in q)(T'_n)^p - (T'_n)^p,
\]
(14)
where $q^*$ is the best clique and the corresponding network code is the best network code. By substituting $T'_n$ from Eq. (8) into Eq. (13), the following weight assignment to vertex $v_{n,m} \in G$ is obtained:
\[
w_{n,m} = \begin{cases} (T'_n)^p - (T_n - 1)^p, & \text{if } \exists L : p_m \in \mathcal{W}_n^l \\ 0, & \text{otherwise} \end{cases}
\]
(15)
Using the weight assignments in Eq. (15), Content-Aware IDNC-P$_1$ finds the network code that corresponds to the maximum weighted clique in graph $G$ at each transmission opportunity until Eq. (8) is satisfied.

**B. Maximizing Quality under Completion Time Constraint**

In this section, we present our approach to solve the problem; Content-Aware IDNC-P$_2$ presented in Eqs. (4), (5).

**Expressing $f(D)$ as a $p-$norm:** As we mentioned earlier, depending on the application, the distortion function $f(D)$ can take different values. If the goal is to minimize the sum distortion over all nodes, then $f(D) = \sum_{n \in N} D_n$ which is actually the $L_1$ norm of the distortion vector: $D = [D_1, D_2, \ldots, D_N]$, i.e., $\|D\|_1 = \sum_{n \in N} D_n$. On the other hand, if the goal is to minimize the maximum distortion over all nodes, then $f(D) = \max_{n \in N} D_n$, which is actually the maximum (infinity) norm of the distortion vector: $D = [D_1, D_2, \ldots, D_N]$, i.e., $\|D\|_{\infty} = \max_{n \in N} D_n$. For the sake of generality, we consider the objective function as a $p-$norm; $f(D) = \|D\|_p$, $\forall p \geq 1$.

**Taking Action:** Since our goal is to select a network code which minimizes $f(D) = \|D\|_p$, we should determine all possible instantly decodable network coding candidates. Then,
we should select the best network code which minimizes $\|D\|_p$. As we discussed in the solution of Content-Aware IDNC-P_1, a trivial approach would be exhaustively listing all possible network coding candidates, and calculating $\|D\|_p$ for each of them to determine the best one. However, constructing IDNC graph is more efficient. In Content-Aware IDNC-P_2, the IDNC graph $\mathcal{G}$ is constructed as follows. For node $n$, $|\mathcal{L}_n|$ vertices, each shown by $v_{n,m}$ such that $p_m \in \mathcal{L}_n$ are added to the graph. The vertex $v_{n,m}$ represents the missing packet $p_m$ (with priority of $r_{m,n}$) in node $n$. The vertices in the graph are connected according to the rules $C_1$ and $C_2$ presented in the previous section. Each clique in the graph represents a network coded packet. The $p$-norm of the distortion when a network coded packet corresponding to clique $q$ is selected is equal to:

$$
\|D\|_p = \left( \sum_{n \in V} (D_n - r_{m,n})^p + \sum_{n \in V} (D_n)^{p/2} \right) \\
\quad + \sum_{n \in V} (D_n)^{p/2} - (D_n)^{p/2}.
$$

Note that the first term in the above equation is the same and fixed for all cliques in the graph. In order to minimize $W_q$ in Eq. (16), the second term should be minimized. Therefore, the weight assigned to vertex $v_{n,m} \in \mathcal{G}$ is equal to:

$$
w_{n,m} = (D_n)^p - (D_n - r_{m,n})^p.
$$

Our algorithm Content-Aware IDNC-P_2 selects the clique with the maximum weight summed over its vertices. A network code corresponding to the maximum weighted clique is selected and transmitted to all nodes.

V. SIMULATION RESULTS

We implemented the proposed Content-Aware IDNC scheme, and compared it with two baselines: (i) IDNC (proposed in [10]), and (ii) No-NC (No Network Coding). We consider a topology shown in Fig. 1 for different number of nodes.

Completion Time & Distortion: Fig. 2(a) and 2(b) show the completion time required by Content-Aware IDNC-P_1, IDNC, and No-NC under the constraint of $D_{cons} = 0.2 \sum_{m|p_m \in \mathcal{M}} r_{m,n}$ for node $n$. In this setup, $r_{m,n}$ is generated according to a gamma distribution with mean 1 and variance 50. Each node selects its loss probability uniformly from the region $[0.3, 0.5]$, and misses packets according to the selected loss probability. Fig. 2(a) shows the results for transmitting 5 packets to different number of nodes. Fig. 2(b) shows the results for transmitting different number of packets to 5 nodes. In both graphs, the required completion time increases with increasing number of nodes/packets. As seen, the completion time using Content-Aware IDNC-P_1, is smaller than the other two methods.

Fig. 2(c) shows the required completion time for sending 5 packets to 10 nodes, under the constraint of 0, 20%, and 40% distortion for each node. As expected, under the constraint of

![Fig. 2. The performance of Content-Aware IDNC-P_2, IDNC, and No-NC.](image)

![Fig. 3(a) and 3(b) show total distortion of Content-Aware IDNC-P_2, IDNC, and No-NC under the constraint that $T_{cons} = 3$.](image)

![Real Video Traces: Table 1 shows the results of the total distortion improvement of Content-Aware IDNC-P_2 over IDNC and No-NC for real video traces (Akiyo and Grandma) under completion time constraint.](image)
IDNC that delivers a high quality content to each user by taking advantage of the contributions different parts have to the content. Simulation results showed significant improvement over IDNC and No-NC.

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