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Systematic Network Coding for Time-Division Duplexing

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Abstract—We present a systematic network coding approach for time-division duplexing channels. In particular, we study the case of a node transmitting to a single receiver. We show that the use of systematic network coding using XORs can provide the same or close to the same performance in terms of completion time as a random linear network coding scheme that uses a large field size, with the added advantage of requiring fewer and simpler operations during the decoding process. We show that the average computation required to decode using systematic network coding in an erasure channel grows as $O(M^3Pe^3)$, where M is the number of original packets being coded together, and Pe is the packet erasure probability. This means that systematic network coding requires Pe^{-3} times fewer operations on average than random linear network coding with the same field size.

I. INTRODUCTION

Proposed in [2], network coding allows and encourages mixing of data at both the source and intermediate nodes in a network. Network coding considers the nodes to have a set of functions that operate upon received or generated data packets. Classical networks, which transport packets provided by the source nodes without modifications, constitute a subset of the coded packet networks, where each node performs two main functions: forwarding and replicating a packet. In contrast, network coding considers information as an algebraic entity, on which one can operate.

Systematic network coding consist of sending the original packets initially, and transmitting random linear combinations of the packets in subsequent transmissions. Reference [11] considers the implementation of systematic and random linear network coding on battery constrained mobile devices with low computational capabilities using a field size of 2. Reference [7] uses systematic network coding as a MAC layer mechanism for WiMAX, called MAC layer Systematic Network Coding (MSNC), which transmits the packets once uncoded, and employs random network coding for retransmissions. The authors showed that it achieves the optimum performance for delay sensitive applications while achieving the same overhead level as an equivalent MAC layer random network coding scheme [8]. Reference [9] proposes variants of the systematic network coding idea for online applications, showing that they are both throughput optimal and have better decoding delay performance than other online network coding approaches.

Reference [1] proposed the use of network coding in time division duplexing (TDD) channels, i.e., when a node can transmit and receive, but not both at the same time, with the objective to reduce the mean time to complete the transmission of a block of M data packets. The main insight provided by reference [1] is that the transmitter should vary the amount of time allocated to transmit data and receive acknowledgements (ACK), based on the propagation time of the packets, the transmission time of the data and ACK packets, and the probability of erasures of the packets.

In particular, reference [1] studied the case of a node that has to transmit a block of M data packets through a link to another node using random linear network coding. This reference showed that there is an optimal number of coded data packets to be transmitted back-to-back before stopping to wait for an ACK, in terms of the mean time to complete transmission of the block of packets. Reference [4] provides an extension to the case of broadcasting M data packets reliably to N receivers. Reference [10] studied the effect of field size in this scheme, showing that the degradation of performance when using XORs is mild.

This work considers the use of systematic network coding in TDD channels as a means to preserve the performance in completion time obtained in [1] for large field sizes while reducing complexity of the operations by using XORs. We also show that the use of systematic network coding considerably reduces decoding complexity. On average, the computation complexity is $O(M^3Pe^3)$, where M is the number of data packets to be transmitted and Pe is the packet erasure probability.

The paper is organized as follows. In Sections II and III, we discuss the system model and the effect of field size in random linear network coding. Section IV presents and studies our systematic network coding scheme for TDD channels. In Section V, we discuss the decoding complexity advantage of using a systematic network coding approach. Section V provides numerical results. Conclusions are summarized in Section VI.

II. SYSTEM MODEL

We consider that a sender wants to transmit M data packets at a given data rate R [bps] to a receiver. Since we have a TDD constraint, nodes can transmit and receive, but not both at the same time. We assume that the sender transmits the first

M packets uncoded, i.e., it transmits the original data packets, while any additional packet to be transmitted is encoded using random linear network coding [5], and is referred to as a coded data packet. Each coded data packet has three parts: 1) an information header of size h bits, 2) a data section which contains a random linear combination of the M data packets of n bits each, and 3) the random coding coefficients used in the linear combination of the data packets. If we are encoding over a field size q , then each coefficient is represented by g bits, where $g = \log_2 q$. Thus, the total number of bits per coded packet is $h+n+gM$ [1]. The uncoded packets have the same structure with the only difference that the data section undergoes no linear combination and the coefficients are not random, and are used to indicate to which original packet it corresponds. We consider that the transmitted packets and ACK packets can undergo erasures that are IID Bernoulli with parameters Pe and Pe_{ack} , respectively.

III. EFFECT OF FIELD SIZE

Reference [10] shows that we can model the process of decoding M packets at a receiver from the random linear coded packets received at a node, regardless of the channel, as a Markov chain. The main factor of interest is the arrival of a new coded packet to the receiver. A transition occurs when a new coded packet is successfully received.

The transition probability matrix for the field size effect problem is

$$P_q = \begin{bmatrix} q^{-M} & 1-q^{-M} & 0 & \dots & 0 & 0 \\ 0 & q^{-M+1} & 1-q^{-M+1} & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & q^{-1} & 1-q^{-1} \\ 0 & 0 & 0 & \dots & 0 & 1 \end{bmatrix}.$$

Reference [10] provides a detailed analysis of this problem, including a full characterization via the moment generating function of the number of coded packets required at the receiver in order to completely decode the information. We use this analysis to study our systematic network coding scheme.

IV. SYSTEMATIC NETWORK CODING IN TDD CHANNELS

We study the case of one node transmitting information to a receiver. We can extend these ideas to the case of broadcast by using the techniques discussed in [4], [10]. Our main contribution is to include the effect of systematic network coding and the effect of the field size into the transition probabilities. We present an overview of the scheme before starting our study of the transition probabilities.

Similarly as in [1], the sender can transmit packets back-to-back before stopping to wait for an ACK packet from each receiver. However, in this work we consider that in the first transmission the system will transmit back-to-back all M original packets first without coding followed by random linear coded packets. Every ACK packet returns the number of degrees of freedom (dof) that a particular receiver still requires to decode successfully the M original data packets. Note that the uncoded packets represent a dof with a particular structure.

The transmission process starts with M data packets being encoded into $N_s \geq M$ packets, M original data packets followed by $N_s - M$ random linear coded packets, and transmitted to the receiver. If all M packets are decoded successfully by the receiver, the process is completed. Otherwise, the receiver sends an ACK packet that informs the transmitter how many dofs are missing, say i . At this point, the transmitter sends N_i coded packets. The process is repeated until the M data packets are successfully decoded. As in previous work, we are interested in the optimal number N_i of coded packets to be transmitted back-to-back in order to minimize a specific metric, e.g., mean completion time.

The process can be modelled as a Markov Chain where we have an initial 'systematic' state (State S in Figure 1) which is the starting point of the system. This state is only visited once to represent the fact that uncoded packets are only sent during the first transmission. The remaining states represent the knowledge of the sender in terms of the number of dofs that the receiver needs in order to decode.

A. Transition Probabilities

Let us compute the transition probabilities of the Markov chain in Figure 1. The transition probabilities from state i to state i' of the Markov chain in Figure 1 are given by $P_{i \rightarrow i'} = P(X(n)=i' | X(n-1)=i)$ where $X(n)$ is the number of dof required at the receiver at the end of transmission n .

The previous state i determines N_i , the number of coded data packets sent by the transmitter given that i dofs are required at the receiver. Let us study in detail the probabilities $P_{i \rightarrow i'}$. First, we consider the transitions from the systematic state S to all other states. Note that there is no self-transition to S . The transition probability to go from state S to state i is given by the probability of receiving $M-i$ dofs given that N_s coded packets were sent and the first M packets are uncoded, i.e.,

$$P_{S \rightarrow i} = P(M-i|S) = \sum_{j=0}^{M-i} P(M-i-j \text{ uncoded}, S) P(j \text{ uncoded}|S) \quad (1)$$

where $P(M-i|S)$ indicates the probability that $M-i$ dofs are correctly received, given that the system was in state S ,

$$P(j \text{ uncoded}|S) = \binom{M}{j} (1-Pe)^j Pe^{M-j} \quad (2)$$

indicates the probability of j uncoded data packets have been received given that the system was in state S , and

$$P(M-i-j \text{ uncoded}, S) = P(M-i-j \text{ coded}|S) = \sum_{l=M-i-j}^{N_s-M} P[M-i-j \text{ coded}|S, l \text{ received}] P[l|S]$$

constitutes the probability that $M-i$ dofs are correctly received, given that the system was in state S and j uncoded packets have been received, and it is equivalent to the probability of $M-i-j$ coded packets being received given that the system was in state S , $P(M-i-j \text{ coded}|S)$. Note that $P[l|S] = \binom{N_s-M}{l} (1-Pe)^l Pe^{N_s-M-l}$ constitutes the probability of l coded packets being received, but with some probability of

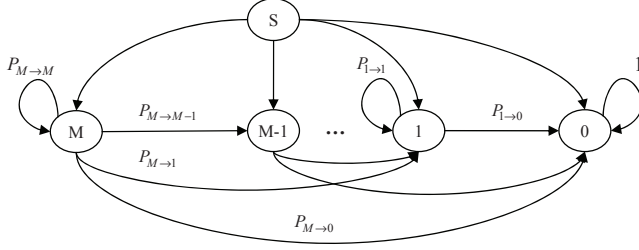


Fig. 1. Markov chain representation of our network coding TDD scheme for a link.

being linearly dependent of the information at the receiver due to the effect of the field size. Then, $P[M-i-j \text{ coded} | S, l \text{ received}]$ can be found by computing P_q^l , using the transition probability matrix P_q computed in Section III, and searching in the appropriate column and row corresponding to starting state S and end state $M-i-j$.

Let us now consider the transition probabilities starting from states other than the systematic state S . We assume that $N_i \geq i$, which means that there is some probability of transitioning from any i to $i' = 0$. For $i > i'$ we have that

$$P_{i \rightarrow i'} = (1 - P_{e_{ack}}) \sum_{k=\max\{1, i-i'\}}^{N_i} P[i'|i, k] P[k|i]$$

where k represents the number of coded packets that have been received, i.e., that have not been erased when going through the channel.

Note that $P[i'|i, k]$ represents the probability of starting at state i in the field size Markov Chain and transitioning to state i' in k transitions or hops. This can be found by computing P_q^k , and searching in the appropriate column and row corresponding to starting state i and end state i' . For the case of $i = i' > 0$,

$$P_{i \rightarrow i} = (1 - P_{e_{ack}}) \left[\sum_{k=0}^{N_i} P[i|i, k] P[k|i] \right] + P_{e_{ack}}$$

and that $P_{0 \rightarrow 0} = 1$. Finally, note that $P[k|i] = \binom{N_i}{k} (1 - P_e)^k P_e^{N_i-k}$ which completes the characterization of the problem.

B. Mean Completion Time

The mean time for completing the transmission of the M data packets to the receiver constitutes the expected time of absorption, i.e., the time to reach state 0 for the first time, given that the initial state is S . If we define T_i as the mean completion time when the system is in state i , then we are interested in determining T_S . Reference [1] studies a similar problem in more detail.

We can define T^i as the time it takes to transmit N_i coded data packets and receive the ACK packets from the receiver. It is easy to show that $T^i = N_i T_p + T_w$, where T_w combines the effect of the propagation delay and the duration of the ACK packet.

The mean completion time when the system is in state i is given by

$$T_i = T^i + \sum_{j \leq i} P_{i \rightarrow j} T_j$$

by exploiting the structure of the Markov Chain.

Our objective is to minimize the value of the expected transmission time T_S , that is,

$$\min_{N_s, N_M, \dots, N_1} T_M = \min_{N_s} \left(T^S + \sum_{i=1}^M P_{S \rightarrow i} \min_{N_i, \dots, N_1} T_i \right)$$

where $T^i = N_i T_p + T_w$. Similarly to the result in [1], regardless of the assumption on N_i , the problem of minimizing T_M in terms of the variables N_s, N_M, \dots, N_1 can be solved iteratively [1]. First, we compute $\min_{N_1} T_1$, then use this results in the computation of $\min_{N_2, N_1} T_2$, and so on. Also, note that if the values of N_M, \dots, N_1 were previously computed for the case of purely random linear network coding, e.g., as in [4], we could use this values and only focus on computing N_s .

V. DECODING COMPLEXITY

Let us compute the average decoding complexity of using systematic network coding. We assume that the decoder can recognize uncoded packets and use this knowledge to speed up the decoding process. Note that, in vector form, each packet CP_j , coded or not, can be expressed as a linear combination of the original packets as $CP_j = [a_{j1} a_{j2} \dots a_{jM}] [P_1 \dots P_M]^T$ where a_{ji} 's are the random linear coefficients and P_i 's are the original data packets. Clearly an original packet P_j can be represented as $[0 \dots 0 1 0 \dots 0] [P_1 \dots P_{j-1} P_j P_{j+1} \dots P_M]^T$.

It can be shown that if a receiver has $D \leq M$ uncoded packets, it can decode the remaining $M-D$ coded packets in $O((M-D)^3)$ operations if it uses Gaussian elimination. The decoding procedure requires performing Gaussian elimination in a matrix that can be reordered as

$$[CP_j] = \begin{bmatrix} 1 & 0 & \dots & 0 & \dots & 0 \\ 0 & 1 & \dots & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \dots & 1 & \dots & 0 \\ a_{(D+1)1} & a_{(D+1)2} & \dots & a_{(D+1)D} & \dots & a_{(D+1)M} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{M1} & a_{M2} & \dots & a_{MD} & \dots & a_{MM} \end{bmatrix} P'$$

where $[CP_j]$ constitutes the vector of (coded) packets received, P' is the vector of original packets in the appropriate order to have the adequate matrix structure.

Note that the uncoded packets will be used to perform a forward elimination only in the coded packets that are received and not in the other uncoded packets. Furthermore, the operation will be restricted to a single column in the matrix corresponding to the equivalent uncoded packet, i.e., no operations have to be performed for the columns that are known to be zero in the uncoded packet. Finally, no backward substitution step is needed for the uncoded packets. Then, considering the characteristics of the channel, we can formulate the following Lemma.

Lemma 1: The average number of operations required to decode using Gaussian elimination on a full rank matrix when systematic network coding is used to transmit M original

data packets where each transmitted coded packet undergoes erasures that are IID Bernoulli with parameter Pe , grows as $O(M^3 Pe^3)$.

Proof: Note that the number of uncoded packets D that are received depends only on the channel and the number of original data packets M that are transmitted, and it is given by a binomial distribution with probability Pe of a packet being erased. Thus, $E[D] = M(1 - Pe)$, $E[D^2] = (1 - Pe)M + (1 - Pe)^2 M(M - 1)$, and $E[D^3] = (1 - Pe)M + 3(1 - Pe)^2 M(M - 1) + (1 - Pe)^3 M(M - 1)(M - 2)$ which are necessary for the computation of the average number of operations.

Assuming that the matrix of coefficients is full rank, and that the total number of operations of Gaussian elimination is given by $An^3 + Bn^2 + Cn$, for some constants A, B, C , for a procedure on an $n \times n$ matrix. The number of operations required to decode the M original data packets is given by two effects: 1) elimination of contribution of uncoded packets in the linear combinations of coded packets, which requires $A_1(M - D)D$ operations, where A_1 is a constant, and 2) a full Gaussian elimination in the remaining $(M - D) \times (M - D)$ matrix, which requires $A(M - D)^3 + B(M - D)^2 + C(M - D)$ operations. Then, $E[A_1(M - D)D] = (A_1 Pe(1 - Pe))(M^2 - M)$ and $E[A(M - D)^3 + B(M - D)^2 + C(M - D)] = A(MPe)^3 + (3A + B - 3APe)(MPe)^2 + (A - 3APe + 2APe^2 + B - BPe + C)(MPe)$. The average number of operations comes from adding these two terms, which is $O(Pe^3 M^3)$. ■

This result shows that systematic network coding allows us to reduce computational complexity by a factor of Pe^3 on average with respect to pure random linear network coding. Note that decoding random linear network coded packets using Gaussian elimination on a full rank matrix takes $O(M^3)$ operations. This can be a considerably large value, e.g., in a channel with $Pe = 0.1$ on average we will require 1000 times fewer operations in order to decode.

Let us consider the case in which Gaussian elimination is used not just to decode the information but also to determine if a newly received coded packet is useful, i.e., linearly independent of the information already at a receiver. As before, we assume that no decoding operations are performed when uncoded packets are received. If only D out of M uncoded packets are received, all the remaining packets will be linear combinations of the original packets. Let us consider the particular case of multiplication operations, although only small adjustments are necessary to consider the case of additions. The number of multiplication operations to determine if a coded packet is linearly independent (and stored) or if it should be discarded is given by $D(1 + K) + \mathbf{1}_{\{\beta > D\}} \sum_{u=1}^{\beta-D} (M - D - u + 1 + K)$, where β indicates the number of independent linear combinations previously received, K represents the size of the data in the packet in number of symbols of size $\log_2 q$ bits, and $\mathbf{1}_{\{s \in S\}}$ is 1 when $s \in S$ and zero otherwise. Lemma 2 shows that our previous result holds even when this Gaussian elimination procedure is performed regardless of q .

Lemma 2: The average number of operations required to

decode, when systematic network coding is used and Gaussian elimination is performed on every new packet to determine linear independence, is upper bounded by a function that is $O(M^3 Pe^3)$, regardless of the field size q .

Proof: We shall prove for the case of multiplication operations (# Mult). Only small changes are necessary for the case of addition operations. We can use the Markov Chain model that considers the effect of field size to solve this problem. The number of operations required to process a newly received packet depends on whether the packet is uncoded (no operations) or not, and how many uncoded packets were received, say D , and how many coded packets were previously received, say $\beta - D$. This number of operations could be thought of as the time or penalty for a transition when the system is in a particular state. We have developed techniques in previous work to characterize this type of problems, e.g., [6]. In order to upper bound the average number of operations, let us first consider the case in which D uncoded packets are received, i.e.,

$$E[\# \text{ Mult} | D] = \sum_{m=1}^{M-D} \frac{D+DK}{1-q^{-m}} + \kappa \sum_{m=1}^{M-D-1} \frac{1}{1-q^{-m}} + (-K-1/2) \sum_{m=1}^{M-D-1} \frac{m}{1-q^{-m}} + (-1/2) \sum_{m=1}^{M-D-1} \frac{m^2}{1-q^{-m}} \quad (3)$$

where $\kappa = \frac{-D}{2}(2M - D + 2K + 1) + M^2/2 + MK + M/2$, and the q^{-m} factors come from a random linear network coding argument.

We have shown in [10] that $\sum_{m=1}^X \frac{1}{1-q^{-m}} \leq X + 2$ for any integer $X > 0$ and $q \geq 2$. Using similar manipulations, we can show that $\sum_{m=1}^{M-D-1} \frac{m}{1-q^{-m}} \leq (M - D - 1)(M - D)/2 + 4$. Finally, $\sum_{m=1}^{M-D-1} \frac{m^2}{1-q^{-m}} \geq \sum_{m=1}^{M-D-1} m^2$, which is a well known series.

Let us compute $E[\# \text{ Mult}] = \sum_d E[\# \text{ Mult} | d] P(D = d)$, using the fact that $P(D = d)$ is characterized by a binomial distribution. After some manipulations, it can be shown that $E[\# \text{ Mult}] = M^3 Pe^3 / 3 + o(M^3)$. The proof concludes by noting that the operations related to the backward substitution step in Gaussian elimination grow as $O(M^2 Pe^2)$ and are performed only once after enough dofs have been received, regardless of the field size q . ■

VI. NUMERICAL RESULTS

This section provides numerical results that compare the performance of our network coding scheme in TDD channels for different field size. We consider a GEO satellite setting with a propagation time $T_{prop} = 125$ ms [1], and data packets of size $n = 10,000$ bits.

We compare performance of our systematic network coding scheme to that of random linear network coding (RLNC) schemes presented in [1] and [10] in terms of mean completion time under different packet erasure probabilities. Figure 2 shows that using the proposed systematic network coding approach with field size $q = 2$, i.e., XORs for the coded packets, has very little or no degradation in performance with respect to RLNC with high field size ($q = 2^{20}$). This means

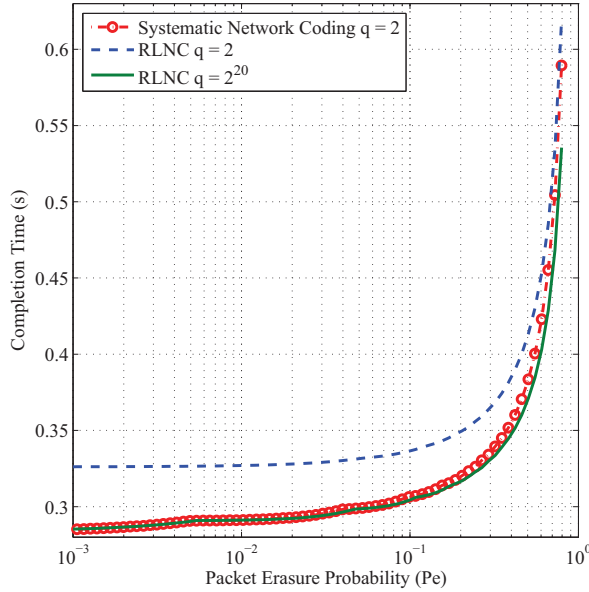


Fig. 2. Mean completion time for the TDD scheme with $M = 5$. We use the following parameters $R = 1.5$ Mbps, $h = 80$ bits, $n_{ack} = 100$ bits, $M = 5$ packets

that using systematic network coding allows us to reduce the complexity of the operations (only performing XORs) and reducing the total number of operations, in average by a factor of Pe^3 , while maintaining close to the same performance to the high field size RLNC proposed in previous work.

Figure 2 shows that the performance of systematic network coding is essentially the same as RLNC with a high field size for moderate values of Pe and the difference in performance at high Pe is very small. Figure 2 also shows the performance of RLNC with field size $q = 2$. The performance in terms of mean completion time for RLNC with $q = 2$ constitutes an upper bound to the mean completion time of the systematic network coding scheme with the same field size $q = 2$. Since Reference [10] showed that as M increases, we should expect the gap between RLNC with $q = 2$ and RLNC with large field sizes to close. For this reason, the difference in performance between our systematic approach and RLNC with high field sizes should also decrease as the number of original packets M increases.

VII. CONCLUSIONS

This paper considers a systematic network coding approach over time division duplexing channels. We show that we can maintain the Markov chain models proposed in previous work, e.g., [1], to study the problem. The only relevant change is to include an additional state to capture the first transmission, which includes M uncoded packets. We also showed that, with small modifications, the search algorithm proposed in Reference [1] for a link is still valid when used with systematic network coding.

We present numerical results that illustrate that systematic

network coding using XORs can provide almost the same performance as the random linear network coding procedure presented in [1] that uses large field sizes. This fact implies that the complexity of the operations at both encoder and decoder can be considerably reduced.

Finally, we have shown that there is a considerable reduction in computational complexity by using systematic network coding. The average number of operations required to decode using systematic network coding in an erasure channel is reduced by a factor of Pe^3 with respect to using a random linear network coding approach with the same field size. These results apply not only to the case of a point-to-point link or broadcast system, but also to any network that uses systematic network coding. The key problem there will be to identify the equivalent Pe of such a system. As an example, a daisy chain that preserves the systematic structure of the code and that shows an erasure probability of Pe_i in link i , will have an equivalent $Pe = 1 - \prod_i (1 - Pe_i)$.

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