An Algebraic Approach to Network Coding

Ralf Koetter, *Member, IEEE,* and Muriel Médard, *Senior Member, IEEE*

***Abstract*—We take a new look at the issue of network capacity. It is shown that network coding is an essential ingredient in achieving the capacity of a network. Building on recent work by Li *et al.*, who examined the network capacity of multicast networks, we extend the network coding framework to arbitrary networks and robust networking. For networks which are restricted to using linear network codes, we find necessary and sufficient conditions for the feasibility of any given set of connections over a given network. We also consider the problem of network recovery for nonergodic link failures. For the multicast setup we prove that there exist coding strategies that provide maximally robust networks and that do not require adaptation of the network interior to the failure pattern in question. The results are derived for both delay-free networks and networks with delays.**

***Index Terms*—Algebraic coding, network information theory, network robustness.**

I. Introduction

THE ISSUE of network capacity has generally been considered in the context of networks of links exhibiting ergodic error processes. Channel coding theorems and capacity regions can be found for certain networks of this type, such as broadcast channels [1]–[3], multiple access channels [4], [5], and relay channels [6]–[8]. Recently, some renewed attention has been paid to the capacity of error-free networks. In particular, coding over error-free networks for the purpose of transmitting multicast connections has been considered [9]–[11]. For a further, recent discussion of network coding, refer to [12, ch. 11, 15].

The work in [9] and [10] examined the network capacity of multicast networks and related capacity to cutsets. Capacity is achieved by coding over a network. We present a new surprisingly simple and effective framework for studying networks and their capacity. The framework is essentially algebraic and makes a straight connection between a given network information flow problem and an algebraic variety over the closure of a finite field. While the results of Li *et al.* [9] and Ahlswede *et al.* [10] contain algebraic elements, (i.e., linear coding [9] and a remark pertaining to convolutional codes [10]) the presented connection to concepts from algebraic geometry opens up the opportunity to employ very powerful theorems in well developed mathematical disciplines. For networks which are restricted to using linear codes (later we make precise the meaning of linear codes, since these codes are not bitwise linear), we find necessary and sufficient conditions for any given set of connections to be achievable over a given network. Using our framework, we show that the case of a multicast connection over a network exhibits a very special structure, which makes its feasibility verifiable in polynomial time. Moreover, similar to results in [9], we show that linear codes over a network are sufficient to implement any feasible multicast connection.

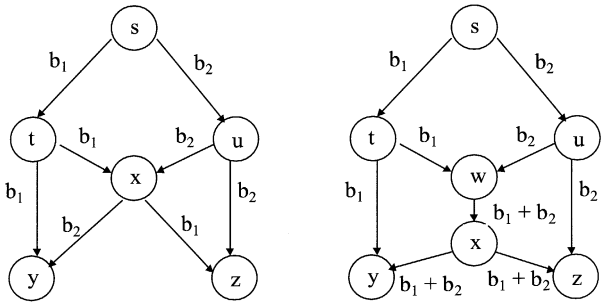


Fig. 1. Networks with multicast from s to y and z.

For networks where connections are not multicast, we show that giving the necessary and sufficient conditions for the connections to be feasible is equivalent to the problem of finding a point in an algebraic variety which, in general, is an NP-complete problem. Moreover, while the cutset conditions are necessary and sufficient to establish the feasibility of a certain set of connections for multicast connections, the cutset conditions are only necessary but provably not sufficient for the case of general connections, i.e., of some arbitrary collection of point-to-point connections.

The usefulness of coding over error-free networks can be easily viewed from an example. Consider Fig. 1 (from [9] and [10]). Each link can transmit a single bit error-free (here,we do not consider delays). On the left-hand side network, the source may easily transmit two bits, b_1 and b_2, to receivers y and z, by using switching at x and broadcasting at t and u. On the right-hand side network, a code is required, where w must code over the arc (w, x). The capacity of such networks is shown to be the maximum flow from the source to each receiver in the network. This approach may be generalized from directed acyclic graphs to general directed graphs as long as we consider delays along the links.

Networks that do not experience ergodic error processes may be reasonable models for networks that in reality are built from links exhibiting ergodic failure processes. Appropriate coding over the links in the network may render those links in effect error-free and network coding can then be used to achieve capacity or recovery over an error-free network, with possible delays due to coding. We do not explicitly consider in this paper the relation between link coding for ergodic failures and network coding. All links are assumed to be error free when they are operational. Links, however, are allowed to fail altogether.

Manuscript received May 14, 2002; revised January 25, 2003; approved by IEEE/ACM TRANSACTIONS ON NETWORKING Editor D. Lee. This work was supported by the National Science Foundation under Awards CCR 99-84515, CCR 03-25673, and CCR-0093349, and by the HP Wireless Center at MIT.

R. Koetter is with the Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, Urbana, IL 61801 USA (e-mail: koetter@uiuc.edu).

M. Médard is with the Laboratory for Information and Decision Systems (LIDS), Massachusetts Institute of Technology, Cambridge, MA 02139 USA (e-mail: medard@mit.edu).

Digital Object Identifier 10.1109/TNET.2003.818197

Indeed, coding is not only applicable to networks in order to achieve capacity, but can also be used to recover from network failures. For an early work pointing into this direction, refer to Ayanoglu *et al.* [14], where coding strategies for simple networks are suggested. Such failures are different from link errors, described by ergodic processes, which would be typically dealt with by using channel coding. The failures we consider entail the permanent removal of an edge, such as would occur in a network if there were a long-term failure due to a link cut or other disconnection. We show that network coding can provide maximal robustness of a network against nonergodic link failures. Moreover, we prove that there exist coding strategies that do not require an adaptation to a specific link failure pattern.

II. Problem Formulation

A communication network is a collection of directed links connecting transmitters, switches, and receivers. It may be represented by a directed graph $\mathcal{G} = (V, E)$ with a vertex set V and an edge set E. We will allow multiple edges between two vertices and hence, E is a subset of $E \subseteq V \times V \times \mathbb{Z}_+$, where the last integer enumerates edges between two vertices. Edges (links) are denoted by round brackets $(v_1, v_2, i) \in E$ and assumed to be directed. If no confusion can arise, we also denote edges simply as (v_1, v_2). The head and tail of an edge $e = (v', v, i)$ is denoted by $v = \mathrm{head}(e)$ and $v' = \mathrm{tail}(e)$.

We define $\Gamma_I(v)$ as the set of edges that end at a vertex $v \in V$ and $\Gamma_O(v)$ as the set of edges originating at v. Formally, we have

$$\Gamma_I(v) = \{e \in E : \mathrm{head}(e) = v\}$$
$$\Gamma_O(v) = \{e \in E : \mathrm{tail}(e) = v\}.$$

The *in-degree* $\delta_I(v)$ of v is defined as $\delta_I(v) = |\Gamma_I(v)|$, while the *out-degree* $\delta_O(v)$ is defined as $\delta_O(v) = |\Gamma_O(v)|$.

A network is called *cyclic* if it contains directed cycles, i.e., if there exists a sequence of edges $(v_0, v_1), (v_1, v_2), \ldots, (v_n, v_0)$ in $\mathcal{G}$. A network is called *acyclic* if it does not contain directed cycles. To each link $e \in E$ we associate a nonnegative number $C(e)$, called the capacity of e.

Let $\mathcal{X}(v) = \{X(v,1), X(v,2), \ldots, X(v,\mu(v))\}$ be a collection of $\mu(v)$ discrete random processes that are observable at node v. We want to allow communication between selected nodes in the network, i.e., we want to replicate, by means of the network, a subset of the random processes in $\mathcal{X}(v)$ at some different node v'. We define a $\mathrm{connection}$ c as a triple $(v, v', \mathcal{X}(v, v')) \in V \times V \times \mathcal{P}_{\mathcal{X}(v)}$, where $\mathcal{P}_{\mathcal{X}}(v)$ denotes the power set of $\mathcal{X}(v)$. The rate $R(c)$ of a connection $c = (v, v', X(v, v'))$ is defined as $R(c) = \sum_{i:X(v,i)\in\mathcal{X}(v,v')} H(X(v,i))$, where $H(X)$ is the entropy rate of a random process X.

Given a connection $c = (v, v', \mathcal{X}(v, v'))$, we call v a source and v' a sink of c, and write $v = \mathrm{source}(c)$ and $v' = \mathrm{sink}(c)$. For notational convenience, we will always assume that $\mathrm{source}(c) \neq \mathrm{sink}(c)$.

A node v can send information through a link $e = (v, u)$ originating at v at a rate of at most $C(e)$ bits per time unit. The random process transmitted through link e is denoted by $Y(e)$. In addition to the random processes in $\mathcal{X}(v)$, node v can observe random processes $Y(e')$ for all e' in $\Gamma_I(v)$. In general, the random process $Y(e)$ transmitted through link $e = (v, u) \in \Gamma_O(v)$ will be a function of both $\mathcal{X}(v)$ and $Y(e')$ if e' is in $\Gamma_I(v)$.

If v is the sink of any connection c, the collection of $\nu(v)$ random processes $\mathcal{Z}(v) = \{Z(v,1), Z(v,2), \ldots, Z(v,\nu(v))\}$ denotes the output at $v = \mathrm{sink}(c)$. A connection $c = (v, v', \mathcal{X}(v, v'))$ is established successfully if a (possibly delayed) copy of $\mathcal{X}(v, v')$ is a subset of $\mathcal{Z}(v')$.

Let a network $\mathcal{G}$ be given together with a set $\mathcal{C}$ of desired connections. We will make a number of simplifying assumptions.

1) *The capacity of any link in $\mathcal{G}$ is a constant, e.g., m bits per time unit.* This is an assumption that can be satisfied to an arbitrary degree of accuracy. If the capacity exceeds m bits per time unit, we model this as parallel edges with unit capacity. Fractional capacities can be well approximated by choosing the time unit large enough.
2) *Each link in the communication network has the same delay*. We will allow for the case of zero delay, in which case we call the network *delay-free*. We will always assume that delay-free networks are acyclic in order to avoid stability problems.
3) *Random processes $X(v,l)$, $l \in \{1, 2, \ldots, \mu(v)\}$ are independent and have a constant and integral entropy rate of, e.g., m bits per unit time*. The unit time is chosen to equal the time unit in the definition of link capacity. This implies that the rate $R(c)$ of any connection $c = (v, v', \mathcal{X}(v, v'))$ is an integer equal to $|\mathcal{X}(v, v')|$. This assumption can be satisfied with arbitrary accuracy by letting the time basis be large enough and by modeling a source of larger entropy rate as a number of parallel sources.
4) *The random processes $X(v,l)$ are independent for different v*. This assumption reflects the nature of a communication network. In particular, information that is injected into the network at different locations is assumed independent.

In addition to the above constraints, we assume that communication in the network is performed by transmission of vectors (symbols) of bits. The length of the vectors is equal in all transmissions and we assume that all links are synchronized with respect to the symbol timing.

Any binary vector of length m can be interpreted as an element in $\mathbb{F}_{2^m}$, the finite field with 2^m elements. The random processes $X(v,l)$, $Y(e)$, and $Z(v,l)$ can, hence, be modeled as discrete processes $X(v,l) = \{X_0(v,l), X_1(v,l), \ldots\}$, $Y(e) = \{Y_0(e), Y_1(e), \ldots\}$, and $Z(v,l) = \{Z_0(v,l), Z_1(v,l), \ldots\}$ that consist of a sequence of symbols from $\mathbb{F}_{2^m}$.

We have the following definition of a delay-free (and hence, by assumption, acyclic) $\mathbb{F}_{2^m}$*-linear* communication network [9].

Definition 1: Let $\mathcal{G} = (V, E)$ be a delay-free communication network. We say that $\mathcal{G}$ is a $\mathbb{F}_{2^m}$-linear network, if for all links the random process $Y(e)$ on a link $e = (v, u, i) \in E$ satisfies

$$Y(e) = \sum_{l=1}^{\mu(v)} \alpha_{l,e} X(v,l) + \sum_{e':\mathrm{head}(e')=\mathrm{tail}(e)} \beta_{e',e} Y(e')$$

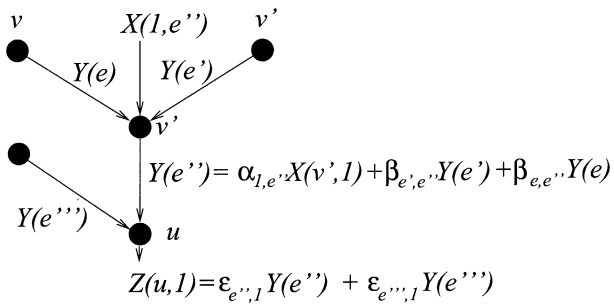
where the coefficients $\alpha_{l,e}$ and $\beta_{e',e}$ are elements of $\mathbb{F}_{2^m}$.

Definition 1 is concerned with the formation of random processes that are transmitted on the links of the network. It is possible to consider time-varying coefficients $\alpha_{l,e}$ and $\beta_{e',e}$ and we call the network *time-invariant* or *time-varying*, depending on this choice.

The output $Z(v,l)$ at any node v is formed from the random processes $Y(e)$ for $e \in \Gamma_I(v)$. It will be sufficient for the purpose of this paper to restrict ourselves to the case that $Z(v,l)$ are also linear combinations of the $Y(e)$, i.e.,

$$Z(v,j) = \sum_{e':\text{head}(e')=v} \varepsilon_{e',j} Y(e') \tag{1}$$

where the coefficients $\varepsilon_{e',j}$ are elements of $\mathbb{F}_{2^m}$. Indeed, we will prove in Section III-A that, for linear networks, it suffices to consider the formation of the $Z(v,j)$ by linear functions of $Y(e)$ for $e \in \Gamma_I(v)$. The concepts of Definition 1 are illustrated in the following example network.



We emphasize that we can freely choose m and the field $\mathbb{F}_{2^m}$ containing the constants $\alpha_{l,e}$, $\beta_{e',e}$, and $\varepsilon_{e',j}$. In particular, we frequently choose to consider the *algebraic closure* $\bar{\mathbb{F}}$ of $\mathbb{F}_2$, which is defined as the union of all possible algebraic extensions of $\mathbb{F}_2$. Once we find suitable coefficients in $\bar{\mathbb{F}}$, it is clear that these coefficients also lie in a finite extension of $\mathbb{F}_2$.

For a given network $\mathcal{G}$ and a given set of connections $\mathcal{C}$, we formally define a network coding problem as a pair $(\mathcal{G},\mathcal{C})$. The problem is to give succinct algebraic conditions under which a set of desired connections is feasible. This is equivalent to finding elements $\alpha_{l,e}$, $\beta_{e',e}$, and $\varepsilon_{e',j}$ in a suitably chosen field $\mathbb{F}_{2^m}$ such that all desired connections can be established successfully by the network. Such a set of numbers $\alpha_{l,e}$, $\beta_{e',e}$, and $\varepsilon_{e',j}$ will be called a *solution* to the network coding problem $(\mathcal{G},\mathcal{C})$. If a solution exists, the network coding problem will be called *solvable*. The solution is time-invariant (time-varying) if the $\alpha_{l,e}, \beta_{e',e}$, and $\varepsilon_{e',j}$ are independent (dependent) of the time.

We also consider the case of networks that suffer from link failure. Link failures are not assumed to be ergodic processes and we assume that a link either is working perfectly or is effectively removed from the network. A link failure pattern can be identified with binary vectors f of length $|E|$ such that each position in f is associated with one edge in $\mathcal{G}$. If a link fails, we assume that the corresponding position in f equals one, otherwise the entry in f corresponding to the link equals zero.

We say that a network is *solvable under link failure pattern* if it is solvable once the links corresponding to the support of f have been removed. While it is straightforward to investigate the solvability for a given failure pattern, finding common solutions for classes of failure patterns is a much more interesting task. We say that a network solution is *static* under a set $\mathcal{F}$ of link failure pattern, if there exists solutions for the network under any link failure pattern $f \in \mathcal{F}$ with the same elements $\alpha_{l,e}, \beta_{e',e}$. Static solutions are particularly desirable because:

1) no new solution has to be found and distributed in the network if a failure pattern $f \in \mathcal{F}$ occurs;
2) the individual nodes in the interior network can be oblivious to the failure pattern, i.e., the basic operation performed at a node in the network is independent of the particular error pattern.

The fundamental questions that we strive to answer in this paper are the following.

1) Under what conditions is a given linear network coding problem solvable?
2) How can we efficiently find a solution to a given linear network coding problem?
3) When does a static solution exist for a network that is subject to link failures?

The main tools we will use for answering the above questions involve concepts from algebraic geometry. In particular, we will relate the network coding problem to the problem of finding points on algebraic varieties, which is one of the central questions of algebraic geometry.

In Section III, we introduce part of the algebraic framework. The goal of the section is to make the reader familiar with some of the employed concepts. The base theorem is an algebraic reformulation of the Min-Cut Max-Flow Theorem. We point out the algebraic interpretation of this theorem in the context of the Ford–Fulkerson algorithm.

In Section IV-A, we apply the algebraic framework to acyclic networks. We rapidly recover and extend the work of Li *et al.* [9] and Ahlswede *et al.* [10]. In particular, we are able to answer some of the problems left open by the authors [9]. In Section IV-B, we address the general network coding problem for cycle-free networks and we derive necessary and sufficient conditions to guarantee the solvability of a network coding problem.

The case of robust networks that are subject to link failure is treated in Section V. The main surprising result is that robust multicast can be achieved with static solutions to the network coding problem. Section VI extends the results to networks with delay and networks with cycles.

III. Algebraic Formulation

In this section, we will develop some of the algebraic concepts used throughout this paper. For the reader's convenience, we will follow a simple example of a point-to-point connection in the communication network given in Fig. 2(a).

Let $\mathcal{G} = (V,E)$ be a communication network. A cut between a node v and v' is a partition of the vertex set of $\mathcal{G}$ into two classes S and $S^{\complement} = V - S$ of vertices such that S contains v and $S^{\complement}$ contains v'. The value $V(S)$ of the cut is defined as

$$V(S) = \sum_{\text{edges from } S \text{ to } S^{\complement}} C(e).$$

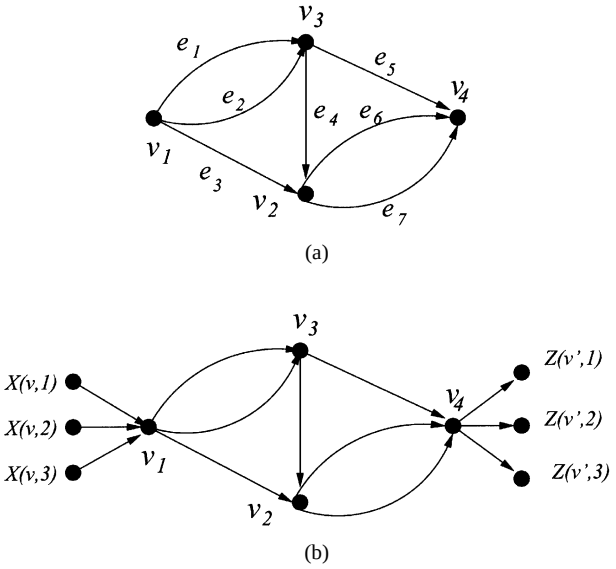


Fig. 2. (a) Point-to-point connection in a simple network. (b) The same network with nodes representing the random processes to be transmitted in the network.

The famous Min-Cut Max-Flow Theorem can be formulated as follows.

Theorem 1 (Min-Cut Max-Flow): Let a network with a single source and a single sink be given, i.e., the only desired connection is $c = (v, v', \mathcal{X}(v, v'))$. The network problem is solvable if and only if the rate of the connection $R(c)$ is less than or equal to the minimum value of all cuts between v and v'.

Proof: See [16] and [17]. ∎

The Ford–Fulkerson labeling algorithm [16] gives a way for finding a solution for point-to-point connections provided a network problem is solvable. The algorithm is graph theoretic by design and finds, under the assumptions made in Section II, a solution such that all parameters $\alpha_{l,e}$ and $\beta_{e',e}$ in Definition 1 are either zero or one.

While the Ford–Fulkerson labeling algorithm provides an elegant solution for point-to-point connections, the technique is not powerful enough to handle a more involved communications scenario. In the remainder of this section, we develop some theory and notation necessary for more complex setups. We first consider a point-to-point setup. Let node v be the only source in the network. We let $\underline{x} = (X(v,1), X(v,2), \ldots, X(v,\mu(v)))$ denote the vector of input processes observed at v. Similarly, let v' be the only sink node in a network. We let $\underline{z} = (Z(v',1), Z(v',2), \ldots, Z(v',\nu(v')))$ be the vector of output processes.

The most important consequence of considering an $\mathbb{F}_{2^m}$-*linear* network is that we can give a *transfer matrix* describing the relationship between an input vector $\underline{x}$ and an output vector $\underline{z}$. Let M be the system transfer matrix of a network with input $\underline{x}$ and output $\underline{z}$, i.e., $\underline{z} = \underline{x}M$. For a fixed set of coefficients $\alpha_{l,e}$, $\beta_{e',e}$, and $\varepsilon_{e',j}$, M is a matrix whose coefficients are elements in the field $\mathbb{F}_{2^m}$ In our case, we go a step further and consider the coefficients as indeterminate variables. Hence, we consider the elements of matrix M as polynomials over the ring $\mathbb{F}_2[\ldots, \alpha_{l,e}, \ldots, \beta_{e',e}, \ldots, \varepsilon_{e',j}, \ldots]$ of polynomials in the variables $\alpha_{l,e}$, $\beta_{e',e}$, and $\varepsilon_{e',j}$.

Example 1: We consider the network of Fig. 2. The following set of equations governs the parameters $\alpha_{l,e}, \beta_{e',e}$, and $\varepsilon_{e,j}$ and the random processes in the network.

$$\begin{aligned}
Y(e_1) &= \alpha_{1,e_1}X(v,1) + \alpha_{2,e_1}X(v,2) + \alpha_{3,e_1}X(v,3)\\
Y(e_2) &= \alpha_{1,e_2}X(v,1) + \alpha_{2,e_2}X(v,2) + \alpha_{3,e_2}X(v,3)\\
Y(e_3) &= \alpha_{1,e_3}X(v,1) + \alpha_{2,e_3}X(v,2) + \alpha_{3,e_3}X(v,3)\\
Y(e_4) &= \beta_{e_1,e_4}Y(e_1) + \beta_{e_2,e_4}Y(e_2)\\
Y(e_5) &= \beta_{e_1,e_5}Y(e_1) + \beta_{e_2,e_5}Y(e_2)\\
Y(e_6) &= \beta_{e_3,e_6}Y(e_3) + \beta_{e_4,e_6}Y(e_4)\\
Y(e_7) &= \beta_{e_3,e_7}Y(e_3) + \beta_{e_4,e_7}Y(e_4)\\
Z(v',1) &= \varepsilon_{e_5,1}Y(e_5) + \varepsilon_{e_6,1}Y(e_6) + \varepsilon_{e_7,1}Y(e_7)\\
Z(v',2) &= \varepsilon_{e_5,2}Y(e_5) + \varepsilon_{e_6,2}Y(e_6) + \varepsilon_{e_7,2}Y(e_7)\\
Z(v',3) &= \varepsilon_{e_5,3}Y(e_5) + \varepsilon_{e_6,3}Y(e_6) + \varepsilon_{e_7,3}Y(e_7).
\end{aligned}$$

It is straightforward to compute the transfer matrix describing the relationship between $\underline{x}$ and $\underline{z}$. In particular, let matrices A and B be defined as

$$A = \begin{pmatrix} \alpha_{1,e_1} & \alpha_{1,e_2} & \alpha_{1,e_3} \\ \alpha_{2,e_1} & \alpha_{2,e_2} & \alpha_{2,e_3} \\ \alpha_{3,e_1} & \alpha_{3,e_2} & \alpha_{3,e_3} \end{pmatrix}$$

$$B = \begin{pmatrix} \varepsilon_{e_5,1} & \varepsilon_{e_5,2} & \varepsilon_{e_5,3} \\ \varepsilon_{e_6,1} & \varepsilon_{e_6,2} & \varepsilon_{e_6,3} \\ \varepsilon_{e_7,1} & \varepsilon_{e_7,2} & \varepsilon_{e_7,3} \end{pmatrix}.$$

The system matrix M is found to equal

$$M = A \begin{pmatrix} \beta_{e_1,e_5} & \beta_{e_1,e_4}\beta_{e_4,e_6} & \beta_{e_1,e_4}\beta_{e_4,e_7} \\ \beta_{e_2,e_5} & \beta_{e_2,e_4}\beta_{e_4,e_6} & \beta_{e_2,e_4}\beta_{e_4,e_7} \\ 0 & \beta_{e_3,e_6} & \beta_{e_3,e_7} \end{pmatrix} B^T.$$

The determinant of matrix M equals $\det(M) = \det(A)(\beta_{e_1,e_5}\beta_{e_2,e_4} - \beta_{e_2,e_5}\beta_{e_1,e_5})(\beta_{e_4,e_6}\beta_{e_3,e_7} - \beta_{e_4,e_7}\beta_{e_3,e_6}) \cdot \det(B)$. We can choose parameters in an extension field $\mathbb{F}_2^m$ so that the determinant of M is nonzero over $\mathbb{F}_{2^m}$. Hence, we can choose A as the identity matrix and B so that the overall matrix M is also an identity matrix. One such solution (found by the Ford–Fulkerson algorithm) would be to let $\beta_{e_1,e_5} = \beta_{e_2,e_4} = \beta_{e_4,e_6} = \beta_{e3,e_7} = 1$ while all other parameters of type $\beta_{e',e}$ are chosen to equal zero. Clearly, a point-to-point communication between v and v' is possible at a rate of three bits per unit time. We note that, over the algebraic closure $\bar{\mathbb{F}}$ there exists an infinite number of solutions to the posed networking problem, namely, all assignments to parameters $\beta_{e',e}$ which render a nonzero determinant of the transfer matrix M. ∎

Inspecting Example 1, we see that the crucial property of the network is that the equation $(\beta_{e_1,e_5}\beta_{e_2,e_4} - \beta_{e_2,e_5}\beta_{e_1,e_5})(\beta_{e_4,e_6}\beta_{e_3,e_7} - \beta_{e_4,e_7}\beta_{e_3,e_6})$ admitted a choice of variables so that the polynomial did *not* evaluate to zero. The following simple lemma will be the foundation of many existence proofs given in this paper.

Lemma 1: Let $\mathbb{F}[X_1, X_2, \ldots, X_n]$ be the ring of polynomials over an infinite field $\mathbb{F}$ in variables $X_1, X_2, \ldots, X_n$. For any nonzero element $f \in \mathbb{F}[X_1, X_2, \ldots, X_n]$ there exists an infinite set of n-tuples $(x_1, x_2, \ldots, x_n) \in \mathbb{F}^n$ such that $f(x_1, x_2, \ldots, x_n) \neq 0$.

Proof: The proof follows by induction over the number of variables and the fact that $\mathbb{F}$ is an infinite field. ∎

The following theorem makes the connection between the network transfer matrix M (an algebraic quantity), and the Min-Cut Max-Flow Theorem (a graph-theoretic tool).

Theorem 2: Let a linear network be given with source node v, sink node v', and a desired connection $c = (v, v', \mathcal{X}(v, v'))$ of rate $R(c)$. The following three statements are equivalent.

1) A point-to-point connection $c = (v, v', \mathcal{X}(v, v'))$ is possible.
2) The Min-Cut Max-Flow bound (Theorem 1) is satisfied between v and v' for a rate $R(c)$.
3) The determinant of the $R(c) \times R(c)$ transfer matrix M is nonzero over the ring $\mathbb{F}_2[\ldots, \alpha_{l,e}, \ldots, \beta_{e',e}, \ldots, \varepsilon_{e',j}, \ldots]$.

Proof: Most of the theorem is a direct consequence of the Min-Cut Max-Flow Theorem. In particular, 1) and 2) are equivalent by Theorem 3. In fact, the theorem only treats the single-source single-sink case for a network with integer flows (by assumption). The Ford–Fulkerson algorithm thus yields $R(c)$ edge-disjoint paths between source and sink nodes. We show the equivalence of 1) and 3). This in turn will show the equivalence of 2) and 3). The Ford–Fulkerson algorithm implies that a solution to the linear network coding problem exists. Choosing this solution for the parameters of the linear network coding problem yields a solution such that M is the identity matrix and, hence, the determinant of M over $\mathbb{F}_2[\ldots, \alpha_{l,e}, \ldots, \beta_{e',e}, \ldots, \varepsilon_{e',j}, \ldots]$ does not vanish identically. Conversely, if the determinant of M is nonzero over $\mathbb{F}_2[\ldots, \alpha_{l,e}, \ldots, \beta_{e',e}, \ldots, \varepsilon_{e',j}, \ldots]$ we can invert matrix M by choosing parameters $\varepsilon_{e',l}$ accordingly. From Lemma 1, we know that we can choose the parameters as to make this determinant nonzero. Hence, 3) implies 1) and the equivalence is shown. ∎

From Example 1, Lemma 1, and Theorem 2, we conclude that studying the feasibility of connections in a linear network scenario is equivalent to studying the properties of solutions to polynomial equations over the field $\bar{\mathbb{F}}$. The third statement of Theorem 3 allows us to translate graph-theoretical properties of a network, like max-flow and connectivity, into an algebraic condition. Powerful algebraic tools can then be employed to arrive at statements concerning the original network. It is worthwhile to point out that it is sufficient in Theorem 3 to consider expressions over fields of fixed characteristic. In other words, if a solution to a point-to-point network problem exists, there also exists a solution restricted to the algebraic closure of the binary field $\mathbb{F}_2$. Hence, there is no need or advantage to consider fields of other characteristic. Nevertheless, it is not clear if *linear* coding strategies are sufficient for a general network problem. In Section III-A, we investigate the structure of general transfer matrices and the polynomial equations to which they give rise.

A. Transfer Matrices

In a linear communication network of Definition 1, any node v_i transmits, on an outgoing edge, a linear combination of the symbols observed on the incoming edges. This relationship between edges in a linear communication network is the natural incidence structure for our problem. We say that any edge $e = (u, v)$ *feeds into* edge $e' = (v, u')$ if $\mathrm{head}(e)$ is equal to $\mathrm{tail}(e')$. We define the *directed labeled line graph* of $\mathcal{G} = (V, E)$ as $\mathfrak{G}(\mathcal{V}, \mathcal{E})$ with vertex set $\mathcal{V} = E$ and edge set $\mathcal{E} = \{(e, e') \in E^2 : \mathrm{head}(e) = \mathrm{tail}(e')\}$. Any edge $e = (e, e') \in \mathcal{E}$ is labeled with the corresponding label $\beta_{e',e}$. Fig. 3 shows the directed labeled line graph of the network in Fig. 2.

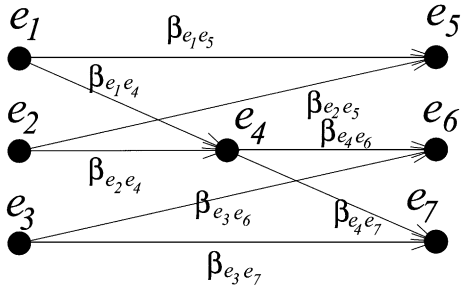


Fig. 3. Directed labeled line graph $\mathcal{G}$ corresponding to the network depicted in Fig. 2(a).

We define the adjacency matrix F of the graph $\mathcal{G}$ with elements $F_{i,j}$ given as

$$F_{i,j} = \begin{cases} \beta_{e_i,e_j} & \mathrm{head}(e_i) = \mathrm{tail}(e_j) \\ 0, & \text{otherwise.} \end{cases}$$

Lemma 2: Let F be the adjacency matrix of the labeled line graph of a cycle-free network $\mathcal{G}$. The matrix I–F has a polynomial inverse with coefficients in $\mathbb{F}_2[\ldots, \beta_{e',e}, \ldots]$.

Proof: Provided the original network $\mathcal{G}$ is acyclic, the graph $\mathfrak{G}$ is acyclic. Hence, we may assume that the vertices in $\mathfrak{G}$ are ordered according to an ancestral ordering. It follows that F is a strict upper-triangular matrix and, hence, I–F is invertible in the field of definition of F. The claim that the I–F is invertible in the ring of polynomials rather than the corresponding quotient field of rational functions follows from a direct back-substitution algorithm. ∎

In order to consider the case that a network contains multiple sources and sinks, we consider $\underline{x} = (x_1, x_2, \ldots, x_\mu) = (X(v_1, 1), X(v_1, 2), \ldots, X(v_1, \mu(v_1)), X(v_2, 1), \ldots, X(v_{|V|}, \mu(v_{|V|})))$ as the vector of input processes on all vertices in V. If a vertex v in a network is not a source node, we set the corresponding parameter $\mu(v)$ equal to zero. $\underline{x} = (x_1, x_2, \ldots, x_\mu)$ is a vector of length $\mu = \sum_i \mu(v_i)$.

Let the entries of a $\mu \times |E|$ matrix A be defined as

$$A_{i,j} = \begin{cases} \alpha_{l,e_j} & x_i = X(\mathrm{tail}(e_j), l) \\ 0, & \text{otherwise.} \end{cases}$$

Similarly, let $\underline{z} = (z_1, z_2, \ldots, z_\mu) = (Z(v_1, 1), Z(v_1, 2), \ldots, Z(v_1, \nu(v_1)), Z(v_2, 1), \ldots, Z(v_{|V|}, \nu(v_{|V|})))$ be the vector of output processes. If v_j is not a sink node of any connection, we let $\nu(v_j)$ be equal to zero. $\underline{z}$ is a vector of length $\nu = \sum_i \nu(v_i)$. Let the entries of a $\nu \times |E|$ matrix B be defined as

$$B_{i,j} = \begin{cases} \varepsilon_{e_j,l} & z_i = Z(\mathrm{head}(e_j), l) \\ 0, & \text{otherwise.} \end{cases}$$

Example 2: We consider the network depicted in Fig. 4(a). The corresponding labeled line graph is depicted in Fig. 4(b).

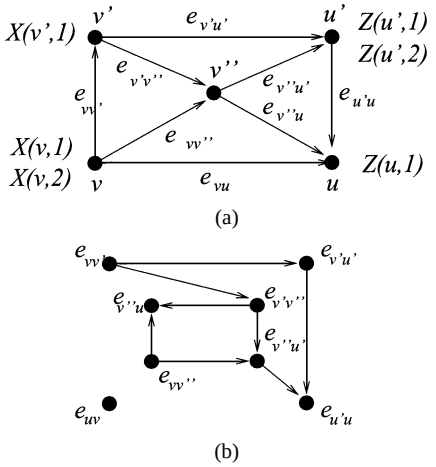


Fig. 4. (a) Network with two source and two sink nodes. (b) Corresponding labeled line graph. Labels in (b) are omitted for clarity. The edge e_{vu} does not feed into any other edge and no edge feeds into e_{vu}, which renders an isolated vertex in the labeled line graph.

We assume that the network is supposed to accommodate two connections $c_1 = (v, u', \{X(v,1),\ X(v,2)\})$ and $c_2 = (v', u, \{X(v',1)\})$. We fix an ordering of edges as $e_{v,v'}, e_{v,v''}, e_{vu}, e_{v',v''}, e_{v',u'},\ e_{v'',u}, e_{v'',u'},\ e_{u',u}$. For this ordering, the adjacency matrix F of the labeled line graph $\mathfrak{G}$ is found to equal (2), shown at the bottom of the page.

Also, matrices A and B are found to equal (3) and (4), respectively, also shown at the bottom of the page. ∎

From the definition of matrices F, A and B, we can easily find the transfer matrix of the overall network.

Theorem 3: Let a network be given with matrices A, B, and F. The transfer matrix of the network is given as

$$M = A(I - F)^{-1}B^T$$

where I is the $|E| \times |E|$ identity matrix.

Proof: Matrices A and B do not substantially contribute to the overall transfer matrix as they only perform a linear mixing of the input and output random processes. In order to find the *impulse response* of the link between an input random process $X(v,i)$ and an output $Z(v',j)$, we have to add all gains along all paths that the random process $X(v,i)$ can take in order to contribute to $Z(v',j)$. It is straightforward to verify that the path between nodes in the network are accounted for in the series $I + F + F^2 + F^3 + \cdots$. Matrix F is nilpotent and eventually there will be a N such that F^N is the all zero matrix. Hence, we can write $(I - F)^{-1} = (I + F + F^2 + F^3 + \cdots)$. The theorem follows. ∎

The transfer matrix M is considered as a matrix over the ring of polynomials $F_2[\ldots, \alpha_{l,e}, \ldots, \beta_{e',e}, \ldots, \varepsilon(e', j), \ldots]$. In the sequel, we will use a vector $\underline{\xi}$ to denote the set of variables $\ldots, \alpha_{l,e}, \ldots, \beta_{e',e}, \ldots, \varepsilon_{e',j}, \ldots$ and, hence, we consider M as a matrix with elements in $\mathbb{F}_2[\underline{\xi}]$. We will use the explicit form of the vector $\underline{\xi}$ only if we want to make statements about a specific solution of a particular network problem $(\mathcal{G}, \mathcal{C})$.

We conclude this section with a remark that it is sufficient to form the output processes $Z(v,\ell)$ by a linear function of the processes $Y(e), e \in \Gamma_I(v)$. Indeed, provided a network problem is solvable, let the output process $Z(v,\ell)$ be equal to $\psi(Y(e_1), Y(e_2), \ldots, Y(e_{\delta_I(v)}))$ where $\psi(\cdot)$ is an arbitrary function and the edges e_i are in $\Gamma_I(v)$. By Definition 1, the processes $Y(e)$ are a linear function of the input processes $X(w,j)$. Hence, provided that the output $Z(v,\ell)$ equals any particular input, the function $\psi(\cdot)$ describes a vector space homomorphism from $(Y(e_1), Y(e_2), \ldots, Y(e_{\delta_I(v)}))$ to $Z(v,\ell)$ for all ℓ and, hence, $\psi(\cdot)$ must be a linear function. This proves that the form of (1) is no restriction on the solvability of a network coding problem.

IV. Delay-Free Networks

A. Multicast of Information

In its simplest form, the multicast problem consists of the distribution of the information generated at a single source node v to a set of sink nodes $u_1, u_2, \ldots, u_M$ such that all sink nodes get all source bits. In other words, the set of desired connections is given by $\{(v, u_1, \mathcal{X}(v)), (v, u_2, \mathcal{X}(v)), \ldots, (v, u_M, \mathcal{X}(v))\}$. Clearly, each connection $(v, u_i, \mathcal{X}(v))$ must satisfy the cut-set bound between v and u_i. Ahlswede *et al.* [10] showed that this condition is sufficient to guarantee the existence of a coding strategy that ensures the feasibility of the desired connections. Li *et al.* [9] showed that linear coding strategies are sufficient to

$$F = \begin{pmatrix}
0 & \beta_{e_{v,v'},e_{v',v''}} & 0 & 0 & \beta_{e_{v,v'},e_{v',u'}} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \beta_{e_{v,v''},e_{v'',u}} & \beta_{e_{v,v''},e_{v'',u'}} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \beta_{e_{v',v''},e_{v'',u}} & \beta_{e_{v',v''},e_{v'',u'}} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \beta_{e_{v',u'},e_{u',u}} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \beta_{e_{v'',u'},e_{u',u}} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix} \tag{2}$$

$$A = \begin{pmatrix}
\alpha_{1,e_{v,v'}} & \alpha_{1,e_{v,v''}} & \alpha_{1,e_{v,u}} & 0 & 0 & 0 & 0 & 0 \\
\alpha_{2,e_{v,v'}} & \alpha_{2,e_{v,v''}} & \alpha_{2,e_{v,u}} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \alpha_{v',v'',1} & \alpha_{v',u',1} & 0 & 0 & 0
\end{pmatrix} \tag{3}$$

$$B = \begin{pmatrix}
0 & 0 & \varepsilon_{e_{v,u},1} & 0 & 0 & \varepsilon_{e_{v'',u},1} & 0 & \varepsilon_{e_{u',u},1} \\
0 & 0 & 0 & 0 & \varepsilon_{e_{v',u'},1} & 0 & \varepsilon_{e_{v'',u'},1} & 0 \\
0 & 0 & 0 & 0 & \varepsilon_{e_{v',u'},2} & 0 & \varepsilon_{e_{v'',u'},2} & 0
\end{pmatrix} \tag{4}$$

achieve this goal. The following theorem recovers their result in the algebraic framework developed in Section III.

Theorem 4: Let a delay-free network $\mathcal{G}$ and a set of desired connections $\mathcal{C} = \{(v, u_1, \mathcal{X}(v)), (v, u_2, \mathcal{X}(v)), \ldots, (v, u_N, \mathcal{X}(v))\}$ be given. The network problem $(\mathcal{G}, \mathcal{C})$ is solvable if and only if the Min-Cut Max-Flow bound is satisfied for all connections in $\mathcal{C}$.

Proof: We have a single source in the network and, hence, the system matrix M is a matrix with dimension $|\mathcal{X}(v)| \times N|\mathcal{X}(v)|$. Moreover, by assumption and Theorem 2, each $|\mathcal{X}(v)| \times |\mathcal{X}(v)|$ submatrix corresponding to one connection has nonzero determinant over $\mathbb{F}_2[\underline{\xi}]$. We consider the product of the N determinants of the $|\mathcal{X}(v)| \times |\mathcal{X}(v)|$ submatrices. This product is a nonzero polynomial $f \in \mathbb{F}_2(\underline{\xi})$. By Lemma 1, we can find an assignment $\underline{\xi}_0$ for $\underline{\xi}$ such that $f(\underline{\xi}_0) \neq 0$ and, hence, the determinants of all N submatrices are simultaneously nonzero in $\bar{F}$. Matrix B can be chosen as a block diagonal matrix which contains on the main diagonal the inverse of the corresponding $|\mathcal{X}(v)| \times |\mathcal{X}(v)|$ submatrices of M. By choosing matrix B in this way, we can guarantee that M is the N-fold repetition of the $|\mathcal{X}(v)| \times |\mathcal{X}(v)|$ identity matrix, which proves the theorem. ■

The most important ingredient of Theorem 4 is the fact that all sink nodes get the same information. Moreover, all sink nodes receive the entire data that is injected into the network. In other words, provided that the sink nodes know the part of the system matrix that describes their connection, there are no interfering signals in the network. Another interesting aspect of this setup is that the sink nodes do not have to be aware of the topology of the network. Knowledge about the overall effects of all coding occurring in the network is sufficient to resolve their connection.

The construction of special codes for the multicast network coding problem is rather easy. From the proof of Theorem 4, it is clear that we are given a polynomial in $\underline{\xi}$ (the product of the N determinants) and we have to find a point that does not lie on the algebraic variety cut out by this polynomial. A simple greedy algorithm will actually suffice to find such a solution. We formulate this algorithm as follows.

Algorithm 1 Input: A polynomial F in indeterminates $\xi_1, \xi_2, \ldots, \xi_n$; integer: $t = 1$
Iteration:
1) Find the maximal degree δ of ξ_t in F and let i be the smallest number such that $2^i > \delta$.
2) Find an element a_t in $\mathbb{F}_{2^i}$ such that $F(\underline{\xi})|_{\xi_t = a_t} \neq 0$ and let $F \leftarrow F(\underline{\xi})|_{\xi_t = a_t}$.
3) If $t = n$ then halt, else $t \leftarrow t + 1$, goto 2).
Output: $(a_1, a_2, \ldots, a_n)$.

The determination of the coefficients a_i renders a network such that all the transfer matrices between the single source and any sink node are invertible. Choosing the matrix B so that all these matrices are the identity matrix solves the multicast network problem. The following theorem proves the correctness of Algorithm 1 and provides a simple bound on the degree of the extension of $\mathbb{F}_2$ that we will have to consider.

Theorem 5: Let a delay-free communication network $\mathcal{G}$ and a solvable multicast network problem be given with one source and N receivers. Let F be the product of the determinants of the transfer matrices for the individual connections and let δ be the maximal degree of F with respect to any variable ξ_i. There exists a solution to the multicast network problem in F_{2^i}, where i is the smallest number such that $2^i > \delta$. Algorithm 1 finds such a solution.

Proof: We only have to show that Algorithm 1 indeed terminates properly. Also, it suffices to show that we can find ξ_1 in $\mathbb{F}_{2^i}$ as the rest of the proof follows by induction. We consider F as a polynomial in $\xi_2, \xi_3, \ldots, \xi_n$ with coefficients from $\mathbb{F}_2[\xi_1]$. By the definition of δ, the coefficients of F are not divisible by $\xi_1^{2^i} - \xi_1$ and, hence, there exists an element $a_1 \in \mathbb{F}_{2^i}$ such that on substituting a_1 for ξ_1 at least one of the coefficients evaluates to a nonzero element of $\mathbb{F}_{2^i}$. Substituting a_1 for ξ_1 and repeating the procedure yields the desired solution. ■

A simple general upper bound on the necessary degree of the extension field for the multicast problem is given in the following corollary.

Corollary 1: Let a delay-free communication network $\mathcal{G}$ and a solvable multicast network problem be given with one source and N receivers. Let R be the rate at which the source generates information. There exists a solution to the network coding problem in a finite field F_{2^m} with $m \leq \lceil \log_2(NR + 1) \rceil$.

Proof: Each entry in the matrix $(I - F)^{-1}$ has degree at most one in any variable. Hence, the degree of each variable in the determinant of a particular transfer matrix is at most R. It follows that the relevant polynomial has degree at most NR in any variable. ■

B. General Network Coding Problem

The situation is much changed if we consider the general network coding problem, i.e., we are given a network $\mathcal{G}$ and an arbitrary set of connections $\mathcal{C}$. This problem is considerably more difficult than the multicast problem. Some progress on characterizing the achievable set of connections is found in [13] for the case of arbitrary nonlinear coding strategies. The set of achievable connections is there bounded within Yeung's framework of information inequalities [12]. Here, we focus on linear network coding, which allows us to make concise statements for a number of network coding problems. In order to accommodate the desired connections, we have to ensure that: 1) the Min-Cut Max-Flow bound is satisfied for every single connection; and 2) there is no disturbing interference from other connections. The following example outlines the basic requirements for the general case.

Example 3: Let the network $\mathcal{G}$ be given as depicted in Fig. 5(a). The corresponding labeled line graph is given in Fig. 5(b). We assume that we want to accommodate two connections in the network, i.e., $\mathcal{C} = \{(v_1, u_1, \{X(v_1, 1), X(v_1, 2)\}), (v_2, u_2, \{X(v_2, 1), X(v_2, 2)\})\}$. Vectors $\underline{x}$ and $\underline{z}$ are given as $\underline{x} = (X(v_1, 1), X(v_1, 2), X(v_2, 1), X(v_2, 2))$ and $\underline{z} = (Z(u_1, 1), Z(u_1, 2), Z(u_2, 1),$

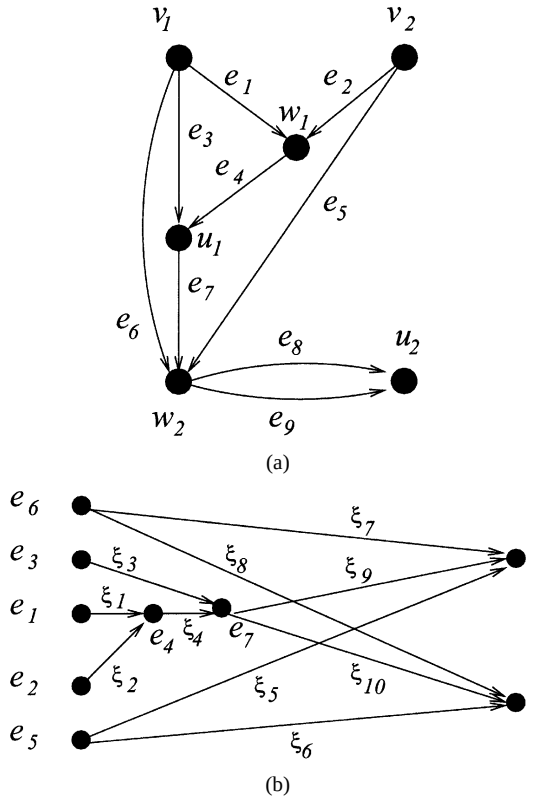


Fig. 5. (a) Network with two source and two sink nodes. (b) Corresponding labeled line graph.

$Z(u_2,2)$). It is straightforward to check that the system matrix M is given as

$$M = \begin{pmatrix} \xi_{11} & \xi_{12} & \xi_{13} & 0 & 0 \\ \xi_{14} & \xi_{15} & \xi_{16} & 0 & 0 \\ 0 & 0 & 0 & \xi_{17} & \xi_{18} \\ 0 & 0 & 0 & \xi_{19} & \xi_{20} \end{pmatrix} \times \begin{pmatrix} 0 & \xi_1 & \xi_1\xi_4\xi_9 & \xi_1\xi_4\xi_{10} \\ 1 & 0 & \xi_3\xi_9 & \xi_3\xi_{10} \\ 0 & 0 & \xi_7 & \xi_8 \\ 0 & \xi_2 & \xi_2\xi_4\xi_9 & \xi_2\xi_4\xi_{10} \\ 0 & 0 & \xi_5 & \xi_6 \end{pmatrix} \begin{pmatrix} \xi_{21} & \xi_{22} & 0 & 0 \\ \xi_{23} & \xi_{24} & 0 & 0 \\ 0 & 0 & \xi_{25} & \xi_{26} \\ 0 & 0 & \xi_{27} & \xi_{28} \end{pmatrix}.$$

We can write M as a block matrix

$$M = \begin{bmatrix} M_{1,1} & M_{1,2} \\ M_{2,1} & M_{2,2} \end{bmatrix}$$

where $M_{1,1}$ denotes the transfer matrix between $(X(v_1,1), X(v_1,2))$ and $(Z(u_1,1), Z(u_1,2))$, $M_{1,2}$ denotes the transfer matrix between $(X(v_1,1), X(v_1,2))$ and $(Z(u_2,1), Z(u_2,2))$, etc. It is easy to see that the network problem $(\mathcal{G},\mathcal{C})$ is solvable if and only if the determinants of $M_{1,1}$ and $M_{2,2}$ are unequal to zero, while the matrices $M_{1,2}$ and $M_{2,1}$ are zero matrices. Note that the determinant of $M_{1,1}$ and $M_{2,2}$ is nonzero over $\mathbb{F}_2[\underline{\xi}]$ if and only if the Min-Cut Max-Flow bound is satisfied. Indeed, we have

$$\det(M_{1,1}) = (\xi_{11}\xi_{15} - \xi_{12}\xi_{14})\xi_1(\xi_{21}\xi_{24} - \xi_{22}\xi_{23})$$

and

$$\det(M_{2,2}) = \xi_2\xi_4(\xi_{17}\xi_{20} - \xi_{18}\xi_{19})(\xi_9\xi_6 - \xi_5\xi_{10})(\xi_{25}\xi_{28} - \xi_{26}\xi_{27}).$$

It is interesting to note that the Min-Cut Max-Flow condition is satisfied for each connection individually and also for any cut between both sources and both sinks. This condition is guaranteed by edge e_6. If edge e_6 is removed the determinant of the transfer matrix would vanish identically, which indicates a violation of the Min-Cut Max-Flow condition applied to cuts separating v_1 and v_2 from u_1 and u_2. In order to satisfy $M_{2,1} = \mathbf{0}$, we have to choose $\xi_2 = 0$ which implies that $\det(M_{2,2})$ equals zero. However, then, we cannot satisfy the requirements that $\det(M_{2,2}) \neq 0$ and $M_{2,1} = \mathbf{0}$ simultaneously and, hence, the network problem $(\mathcal{G},\mathcal{C})$ is not solvable. It is worthwhile to point out that it can be verified that this nonsolvability of the network coding problem is pertinent to any coding strategy and is not a shortcoming of linear network coding. ■

As before, let $\underline{x}$ denote the vector of input processes and let $\underline{z}$ denote a vector of output processes. Following Example 3, we consider the transfer matrix in a block form as $M = \{M_{i,j}\}$ such that $M_{i,j}$ is the submatrix of M describing the transfer matrix between the input processes at v_i and the output processes at v_j. The following theorem states a succinct condition under which a network problem $(\mathcal{G},\mathcal{C})$ is solvable.

Theorem 6 (Generalized Min-Cut Max-Flow Condition): Let an acyclic delay-free linear network problem $(\mathcal{G},\mathcal{C})$ be given and let $M = \{M_{i,j}\}$ be the corresponding transfer matrix relating the set of input nodes to the set of output nodes. The network problem is solvable if and only if there exists an assignment of numbers to variables $\underline{\xi}$ such that:

1) $M_{i,j} = \mathbf{0}$ for all pairs (v_i, v_j) of vertices such that $(v_i, v_j, \mathcal{X}(v_i, v_j)) \notin \mathcal{C}$;
2) if $\mathcal{C}$ contains the connections $(v_{i_1}, v_j, \mathcal{X}(v_{i_1}, v_j))$, $(v_{i_2}, v_j, \mathcal{X}(v_{i_2}, v_j)), \ldots, (v_{i_\ell}, v_j, \mathcal{X}(v_{i_\ell}, v_j))$, the submatrix $\left[M_{i_1,j}^T M_{i_2,j}^T, \ldots, M_{i_\ell,j}^T\right]$ is a nonsingular $\nu(v_j) \times \nu(v_j)$ matrix.

Proof: Assume the conditions of the theorem are met and assume the network operates with the corresponding assignment of numbers to $\underline{\xi}$. Condition 1) ensures that there is no disturbing interference at the sink nodes. Also, any sink node v_j can invert the transfer matrix $\left[M_{i_1,j}^T M_{i_2,j}^T, \ldots, M_{i_\ell,j}^T\right]$ and, hence, recover the sent information.

Conversely, assume that either of the conditions is not satisfied. If Condition 1) is not satisfied, then the collection of random processes observed on the incoming edges of v_j is a superposition of desired information and interference. Moreover, the sink node v_j has no possibility of distinguishing interference from desired information and, hence, the desired processes cannot be reliably reproduced at v_j.

Condition 2) is equivalent to a Min-Cut Max-Flow condition, which clearly has to be satisfied if the network problem is solvable. ■

Theorem 6 gives a succinct condition for the satisfiability of a network problem. However, checking the two conditions is a tedious task as we have to find a solution, i.e., an assignment to number $\underline{\xi}$ that exhibits the desired properties. We will sketch an algebraic approach to this problem in the remainder of this section.

Let $f_1(\underline{\xi}), f_2(\underline{\xi}), \ldots, f_K(\underline{\xi})$ denote all the entries in M that have to evaluate to zero in order to satisfy the first

condition of Theorem 6. We consider the ideal generated by $f_1(\underline{\xi}), f_2(\underline{\xi}), \ldots, f_K(\underline{\xi})$ and denote this ideal by $I(f_1, f_2, \ldots, f_K)$. From the Hilbert Nullstellensatz [18], we know that this ideal is a proper ideal of $\mathbb{F}_2[\underline{\xi}]$ if and only if we can find an assignment of numbers for $\underline{\xi}$ such that we can satisfy the first condition of Theorem 6. In order to satisfy the second condition of the theorem, we let $g_1(\underline{\xi}), g_2(\underline{\xi}), \ldots, g_L(\underline{\xi})$ denote the determinants of the $\nu(v_j) \times \nu(v_j)$ matrices that have to be nonzero. Next, we introduce a new variable ξ_0 and consider the function $\xi_0 \prod_{i=1}^{L} g_i(\underline{\xi}) - 1$. We call the ideal $I(f_1(\underline{\xi}), f_2(\underline{\xi}), \ldots, f_K(\underline{\xi}), 1 - \xi_0 \prod_{i=1}^{L} g(\underline{\xi}))$ the *ideal of the linear network problem* denoted by $\mathrm{Ideal}((\mathcal{G}, \mathcal{C}))$. The algebraic variety associated with $\mathrm{Ideal}((\mathcal{G}, \mathcal{C}))$ is denoted $\mathrm{Var}((\mathcal{G}, \mathcal{C}))$, given by

$$\mathrm{Var}((\mathcal{G}, \mathcal{C})) = \{(a_1, a_2, \ldots, a_n) \in \mathbb{F}^n : f(a_1, a_2, \ldots, a_n) = 0 \quad \forall\, f \in \mathrm{Ideal}((\mathcal{G}, \mathcal{C}))\}.$$

Theorem 7: Let a linear network problem $(\mathcal{G}, \mathcal{C})$ be given. The network problem is solvable if and only if $\mathrm{Var}((\mathcal{G}, \mathcal{C}))$ is nonempty and, hence, the ideal $\mathrm{Ideal}((\mathcal{G}, \mathcal{C}))$ is a proper ideal of $\bar{\mathbb{F}}[\xi_0, \underline{\xi}]$, i.e, $\mathrm{Ideal}((\mathcal{G}, \mathcal{C})) \subsetneq \mathbb{F}_2[\xi_0, \underline{\xi}]$.

Proof: Assume first that the ideal $\mathrm{Ideal}((\mathcal{G}, \mathcal{C}))$ is a proper ideal of $\mathbb{F}_2[\xi_0, \underline{\xi}]$. The Hilbert Nullstellensatz implies that the variety $\mathrm{Var}((\mathcal{G}, \mathcal{C}))$ of points where all elements of $\mathrm{Ideal}((\mathcal{G}, \mathcal{C}))$ vanish is nonempty. Hence, there exists an assignment to ξ_0 and $\underline{\xi}$ such that Condition 1 of Theorem 6 is satisfied. Moreover, for all solutions in the variety $\mathrm{Var}((\mathcal{G}, \mathcal{C}))$ we have $\xi_0 \neq 0$ and $\prod_{i=1}^{L} g(\underline{\xi}) \neq 0$ as otherwise 1 is in the generating set of the ideal and, hence, $\mathrm{Ideal}((\mathcal{G}, \mathcal{C}))$ would be identified with $\mathbb{F}_2[\xi_0, \underline{\xi}]$. Hence, Condition 2) of Theorem 6 is satisfied and any element of V is a solution of the linear network problem. Conversely, assume that $\mathrm{Ideal}((\mathcal{G}, \mathcal{C})) = \mathbb{F}_2[\xi_0, \underline{\xi}]$. It follows that the variety $\mathrm{Var}((\mathcal{G}, \mathcal{C}))$ is empty and there is no solution which satisfies the required conditions. Indeed, by choosing a proper value for ξ_0 any solution to the network coding problem would immediately give rise to a nonempty variety $\mathrm{Var}((\mathcal{G}, \mathcal{C}))$. ∎

Using Theorem 7, we have reduced the problem of deciding the solvability of a linear network problem to the problem of deciding if a variety is empty or not. We can decide this problem using Buchberger's algorithm [19] to compute a Gröbner basis for the ideal $\mathrm{Ideal}((\mathcal{G}, \mathcal{C}))$. It is well known [19] that the Gröbner basis of an ideal equals 1 if and only if the corresponding variety is nonempty. The techniques involving Gröbner bases exceed the scope of the paper, and we refer the reader to Cox *et al.* [19] for a thorough treatment of this material. We only note that it is well known that, in general, the complexity of Gröbner basis computations is not polynomially bounded in the number of variables. Nevertheless, mathematics software routinely solves large Gröbner basis computations. A careful study of the structure of $\mathrm{Ideal}((\mathcal{G}, \mathcal{C})) \subset \mathbb{F}_2[\xi_0, \underline{\xi}]$ as obtained from network problems, as well as optimizing the computation of a Gröbner basis for the ideal of a linear network problem, are important future tasks for deriving efficient algorithms deciding a network problem.

C. Some Special Network Problems

In a few cases, it is relatively straightforward to satisfy the conditions of Theorems 6 and 7. These approaches can be subsumed under the principle that the conditions of Theorem 6 can be satisfied by means of linear algebra alone. The multicast scenario of Section IV-A is the simplest example of this situation.

We start with the case of multiple sources and multiple sinks in a network coding problem where all sources want to communicate all their information to all sinks. In other words, the set of desired connections between N sources and K sinks is given as $\mathcal{C} = \{(v_i, u_j, \mathcal{X}(v_i)) : i = 0, 1, \ldots N, j = 1, 2, \ldots K\}$. One characterization of this setup is, again, that it is interference free due to the fact that all sinks are supposed to receive all the information. This interference-free situation was also exploited in [15], where a similar theorem was stated in the context of general, potentially nonlinear, coding strategies.

Theorem 8: Let a linear acyclic delay-free network $\mathcal{G}$ be given with a set of desired connections $\mathcal{C} = \{(v_i, u_j, \mathcal{X}(v_i)) : i = 0, 1, \ldots N, j = 1, 2, \ldots K\}$. The network problem $(\mathcal{G}, \mathcal{C})$ is solvable if and only if the Min-Cut Max-Flow bound is satisfied for any cut between all source nodes $\{v_i : i = 0, 1, \ldots N\}$ and any sink node u_j.

Proof: We consider the transfer matrices between the N source nodes and any of the K sink nodes individually. Each matrix, considered as matrix over $\mathbb{F}_2[\underline{\xi}]$, is nonsingular by assumption. Hence, we can find an assignment of numbers to the variables $\underline{\xi}$ such that the matrix evaluated at these points is nonsingular over $\mathbb{F}$. This holds for each relevant $\sum_{i=1}^{N} \mu(v_i)$ by $\sum_{i=1}^{N} \mu(v_i)$ matrix. The sink nodes can obtain the desired information by choosing matrix B appropriately. ∎

We note that Theorem 8 contains Theorem 4 as a special case for $N = 1$. The situations are relatively similar and Theorem 8 can be reduced to Theorem 4 by introducing a super node having access to the entire information feeding information to the nodes v_i.

A surprising fact in solving a given set of connections in the setup of Theorem 8 is that there is no encoding necessary at the source nodes. This is also clear from the observation that this case is "interference free." However, allowing for proper encoding at the source node is crucial for the general networking problem. In a number of special cases, we can make use of the encoding opportunity at the sources to guarantee the existence of a solution to a network coding problem. In the remaining theorems of this section, we specialize to the case of one source, which gives us complete control over the encoding matrix A. The specific type of network coding problem that is covered in each of the subsequent theorems is specified in the set of desired connections.

We say that the Min-Cut Max-Flow is satisfied between a source node v and a set of sink nodes $\{u_1, u_2, \ldots, u_K\}$ at rates $|\mathcal{X}(v, u_i)|$ if it is satisfied for any cut seperating a set $\mathcal{U} \subseteq \{u_1, u_2, \ldots, u_K\}$ from v at a rate $\sum_{u \in \mathcal{U}} |\mathcal{X}(v, u)|$.

Theorem 9: Let a linear acyclic delay-free network $\mathcal{G}$ be given with a set of desired connections $\mathcal{C} = \{(v, u_j, \mathcal{X}(v, u_j)) : j = 1, 2, \ldots K\}$ such that all collections of random processes are mutually disjoint, i.e., $\mathcal{X}(v, u_j) \cap \mathcal{X}(v, u_i) = \emptyset$ for $i \neq j$. The network problem is solvable if and only if the Min-Cut Max-Flow bound is satisfied

between v and the set of sink nodes $\{u_1, u_2, \ldots, u_K\}$ at rates $|\mathcal{X}(v, u_i)|$.

Proof: We can assume, without loss of generality, that the mutually disjoint random processes $\mathcal{X}(v, u_j)$ partition the set $\mathcal{X}(v)$. Hence, the overall transfer matrix is a $|\mathcal{X}(v)|$ by $|\mathcal{X}(v)|$ square matrix that is nonsingular by assumption. Choosing matrix A at the source node properly, we can guarantee that the overall transfer matrix realizes the identity matrix and each sink node receives the data stream intended for it. Conversely, assume that the Min-Cut Max-Flow is not satisfied for any subset of the sink nodes. It follows that the corresponding submatrix of the transfer matrix contains linearly dependent columns and, hence, the overall transfer matrix cannot be nonsingular. ∎

We note that the setup of Theorem 9 breaks down if we allow more than one source node because this imposes a restriction on the particular form of matrix A. However, we can loosen the restrictions on the disjointness of the information to be distributed to different nodes. In particular, we can augment the set of connections $\mathcal{C}$ of Theorem 9 by a number of connections $\{(v, u_\ell, \mathcal{X}(v)) : \ell = 1, 2, \ldots N\}$ that should receive the entire information injected into the network at node v.

Theorem 10: Let a linear acyclic delay-free network $\mathcal{G}$ be given with a set of desired connections $\mathcal{C} = \{(v, u_j, \mathcal{X}(v, u_j)) : j = 1, 2, \ldots K\} \cup \{(v, u_\ell, \mathcal{X}(v)) : \ell = K+1, K+2, \ldots K+N\}$ such that the collections of random processes $\mathcal{X}(v, u_i)$, $\mathcal{X}(v, u_j)$ are mutually disjoint for $i, j < K$, i.e., $\mathcal{X}(v, u_j) \cap \mathcal{X}(v, u_i) = \emptyset$ for $i \neq j$, $i, j < K$. The network problem is solvable if and only if the Min-Cut Max-Flow bound is satisfied between v and the set of sink nodes $\{u_1, u_2, \ldots, u_K\}$ at rates $|\mathcal{X}(v, u_i)|$ and between v and u_ℓ, $\ell > K$ at a rate $|\mathcal{X}(v)|$.

Proof: The proof is an extension of the proof of Theorem 9. The transfer matrix of this proof is augmented by a number of $|\mathcal{X}(v)|$ by $|\mathcal{X}(v)|$ square matrices corresponding to the connections $(v, u_\ell, \mathcal{X}(v))$. The matrix A that we chose in the proof of Theorem 9 is nonsingular and, hence, the product of A and the square matrices corresponding to the connections $(v, u_\ell, \mathcal{X}(v))$ is nonsingular, too. These matrices can be inverted by a proper choice of matrix B. ∎

Theorem 10 has an interesting corollary for the case of two sink nodes, which might be best described as *two-level* multicast. The setup assumes two sinks such that one sink should receive all the information $\mathcal{X}(v)$, while a second sink receives only a subset of $\mathcal{X}(v)$.

Corollary 2: Let a linear acyclic delay-free network $\mathcal{G}$ be given with a set of desired connections $\mathcal{C} = \{(v, u_1, \mathcal{X}(v, u_1)), (v, u_2, \mathcal{X}(v))\}$. The network problem is solvable if and only if the Min-Cut Max-Flow bound is satisfied between v and u_1 at a rate $|\mathcal{X}(v, u_1)|$ and between v and u_2 at a rate $|\mathcal{X}(v)|$. ∎

There are a large number of special cases which can be treated similarly to the results given in this section. The proofs of the above theorems should be adaptable to these situations with only minor modifications.

We now turn our attention to the problem of robust networks.

V. Robust Networks

An interesting challenge is added to the problem of network coding if we assume that links in a network may fail. The question then becomes, under which failure pattern a successful network usage is still guaranteed. Let $e = (v, u, i)$ be a failing link. We assume that any downstream sink node, i.e., any node that can be reached from u via a directed path, can be notified of the failure of link e. However, no other nodes are being notified of the link failure. Given a network $\mathcal{G}$ and a link failure pattern f, it is straightforward to consider the network $\mathcal{G}_f$ that is obtained by deleting the failing links and applying the results of Sections II–IV to this setup. We are interested in static solutions where the network is oblivious to the particular failure pattern. The idea is that each node transmits on outgoing edges a function of the observed random processes, such that the functions are independent of the current failure pattern. Here, we use the convention that the constant 0 is observed on failing links. We can achieve the effect of a failing link e by setting parameters $\beta_{e',e}, \beta_{e,e''}$ and $\alpha_{\ell,e}$ to zero for all e', e'' and ℓ, which effectively anihilates the influence of any random process transmitted on edge e. Let $M[\underline{\xi}]$ be the system matrix for a particular linear network coding problem. Moreover, let the set of parameters ξ_i that are affected by a failing link e, i.e., that correspond to $\beta_{e',e}, \beta_{e,e''}$ and $\alpha_{\ell,e}$ for all e', e'' and ℓ, be denoted as B_e

$$B_e = \{\xi_i : \xi_i \text{ is identified with } \beta_{e',e},\ \beta_{e,e''} \text{ or } \alpha_{\ell,e} \text{ for any } e',\ e'' \text{ and } \ell\}.$$

For any particular link failure pattern f, we define $B(f)$ as

$$B(f) = \bigcup_{e: f_e = 1} B_e.$$

The following lemma makes the connection between the network problem without and with a link failure pattern f.

Lemma 2: Let $M[\underline{\xi}]$ be the system matrix of a linear network coding problem with system matrix $M[\underline{\xi}]$. Let f be a particular link failure pattern and let $M_f[\underline{\xi}]$ be the system matrix for the network $\mathcal{G}_f$ obtained by deleting the failing links. We have the following relation between $M[\underline{\xi}]$ and $M_f[\underline{\xi}]$.

$$M_f[\underline{\xi}] = M[\underline{\xi}]|_{\xi_i = 0\ \forall\ \xi_i \in B(f)}.$$

Proof: The effect of a failed link can be modeled by the fact that no information about a random process is either fed into a failed link or is fed from the failed link into another link. Setting the coefficients $\xi_i \in B(f)$ to zero is compliant with the assumption that a constant 0 is observed on failed nodes. ∎

Let $\bar{\mathcal{F}}$ be the set of failure patterns f such that the network coding problem $(\mathcal{G}_f, \mathcal{C})$ is solvable. For the multicast scenario, i.e., the case $\mathcal{C} = \{(v, u_1, \mathcal{X}(v)), (v, u_2, \mathcal{X}(v)), \ldots, (v, u_N, \mathcal{X}(v))\}$, we have the following surprising result.

Theorem 11: Let a linear network $\mathcal{G}$ and a set of connections $\mathcal{C} = \{(v, u_1, \mathcal{X}(v)), (v, u_2, \mathcal{X}(v)), \ldots, (v, u_N, \mathcal{X}(v))\}$ be given. There exists a common static solution to the network problems $(\mathcal{G}_f, \mathcal{C})$ for all $f \in \bar{\mathcal{F}}$.

Proof: Let f be any particular failure pattern that renders a solvable network. Let $g_{f,i}(\underline{\xi})$ be the determinant of the transfer matrix corresponding to connection $(v, u_i, \mathcal{X}(v))$. We consider the product $g(\underline{\xi}) = \prod_{i=1}^{N} \prod_{f \in \bar{\mathcal{F}}} g_{f,i}(\underline{\xi})$. By Lemma 1, we can find an assignment of numbers to $\underline{\xi}$ such that $g(\underline{\xi})$ and, hence, every single determinant $g_{f,i}(\underline{\xi})$ evaluates to a nonzero value simultaneously. It follows that regardless of error pattern in $\bar{F}$, the basic multicast requirements are satisfied. ∎

Theorem 11 makes very robust multicast scenarios possible—in a sense, the multicast can be organized as robustly as possible. It is also interesting to note that choosing the value of the variables $\underline{\xi}$ at random from a large enough field yields a solution, which with high probability achieves maximum robustness of the network. We can give an equivalent to Theorem 5 and Corollary 1. In formulating the following theorem, the price we have to pay for this exceptional robustness becomes apparent.

Theorem 12: Let a delay-free communication network $\mathcal{G}$ and a solvable multicast network problem be given with one source and N receivers. Moreover, let $\mathcal{F} \subseteq \bar{\mathcal{F}}$ be a set of failure patterns from which we want to recover. Let R be the rate at which the source generates information. There exists a solution to the network coding problem in a finite field F_{2^m} with $m \leq \lceil \log_2(|\mathcal{F}|NR+1) \rceil$.

Proof: Let F be the product of the determinants of the transfer matrices for the individual connections and let δ be the maximal degree of F with respect to any variable ξ_i. Following the proof of Corollary 1, we know that δ is bounded by R. Altogether, we have to consider the product of $N|F|$ determinants. The theorem follows. ■

The question arises if statements like Theorem 11 can be derived for a general network problem. The following example shows that simple network coding problems exist that do not allow a static solution for different failure patterns in $\mathcal{F}$.

Example 4: We consider the network $\mathcal{G}$ depicted in Fig. 6. Let the capacity of all edges be one bit per time unit and let the set of desired connections be given as $\mathcal{C} = \{(v_1, u_1, \mathcal{X}(v_1)), (v_2, u_2, \mathcal{X}(v_2))\}$ with $|\mathcal{X}(v_1)| = |\mathcal{X}(v_2)| = 1$.

The example is small enough that it is possible to verify directly that: 1) the network coding problem is solvable for any single failure involving a single link; and 2) there does not exist a static solution for any (linear or nonlinear) coding strategy.

We show how this observation is reflected in the algebraic setup of our approach. Let the input vector $\underline{x}$ and the output vector $\underline{z}$ be given as $\underline{x} = (X(v_1,1), X(v_2,1))$ and $\underline{z} = (Z(u_1,1), Z(u_2,1))$. The transfer matrix M is found to equal

$$M = \begin{pmatrix} \xi_5 & \xi_6 & 0 & 0 & 0 & 0 \\ 0 & 0 & \xi_7 & \xi_8 & 0 & 0 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & \xi_1 \\ 0 & 1 & 0 & 0 & \xi_2 & \xi_2\xi_4 \\ 0 & 0 & 1 & 0 & \xi_3 & \xi_3\xi_4 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & \xi_4 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \xi_9 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \xi_{11} \\ \xi_{10} & 0 \\ 0 & \xi_{12} \end{pmatrix} = \begin{pmatrix} \xi_5\xi_9 + \xi_6\xi_2\xi_{10} & (\xi_5\xi_1 + \xi_6\xi_2\xi_4)\xi_{12} \\ \xi_7\xi_3\xi_{10} & \xi_8\xi_{11} + \xi_7\xi_3\xi_4\xi_{12} \end{pmatrix}$$

where $\xi_5, \xi_6, \xi_7, \xi_8$ account for the way the elements of $\underline{x}$ are fed into the network, while $\xi_9, \xi_{10}, \xi_{11}, \xi_{12}$ account for the linear mixing being performed at the sink nodes.

The ideal of the network coding problem $\mathrm{Ideal}((\mathcal{G}, \mathcal{C}))$ is generated by the polynomials $\{\xi_7\xi_3\xi_{10},\ (\xi_5\xi_1 + \xi_6\xi_2\xi_4)\xi_{12}, \xi_0(\xi_5\xi_9 + \xi_6\xi_2\xi_{10})(\xi_8\xi_{11} + \xi_7\xi_3\xi_4\xi_{12}) - 1\}$ and we can easily find a point in the corresponding variety.

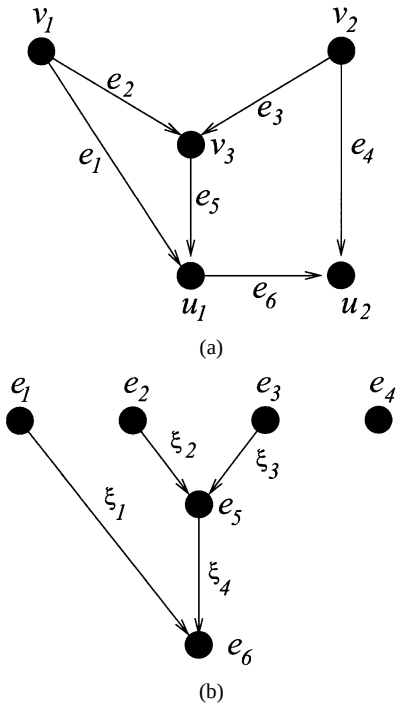


Fig. 6. (a) Communication network with two source nodes (v_1, v_2) and two sink nodes (u_1, u_2). (b) Corresponding labeled line graph.

Next, we consider the case that link e_4 fails. According to Lemma 2, we find the corresponding transfer matrix M_{e_4} by letting all variables $\xi_i \in B_{e_4} = \{\xi_8, \xi_{11}\}$ be zero. Hence, the ideal $\mathrm{Ideal}((\mathcal{G}_{e_4}, \mathcal{C}))$ is generated by $\{\xi_7\xi_3\xi_{10}, (\xi_5\xi_1 + \xi_6\xi_2\xi_4)\xi_{12}, \xi_0'(\xi_5\xi_9 + \xi_6\xi_2\xi_{10})\xi_7\xi_3\xi_4\xi_{12} - 1\}$. Similarly, we consider the case that link e_1 fails in which case we find that $B_{e_1} = \{\xi_5, \xi_1, \xi_9\}$ and $\mathrm{Ideal}((\mathcal{G}_{e_1}, \mathcal{C}))$ is generated by $\{\xi_7\xi_3\xi_{10}, \xi_6\xi_2\xi_4\xi_{12}, \xi_0''(\xi_6\xi_2\xi_{10})(\xi_8\xi_{11} + \xi_7\xi_3\xi_4\xi_{12}) - 1\}$.

A necessary condition for the existence of a common solution to the network problems obtained if either e_4 or e_1 fails is that the smallest ideal J containing $\mathrm{Ideal}((\mathcal{G}_{e_1}, \mathcal{C}))$ and $\mathrm{Ideal}((\mathcal{G}_{e_4}, \mathcal{C}))$ is a proper ideal of $\mathbb{F}_2[\xi_0', \xi_0'', \underline{\xi}]$ or, in other words, the intersection of the corresponding varieties is not empty.

The ideal J is generated by $\{\xi_{12}\xi_5\xi_1, \xi_0'\xi_7\xi_3\xi_4\xi_{12}\xi_5\xi_9 - 1, \xi_7\xi_3\xi_{10}, \xi_0''\xi_6\xi_2\xi_{10}\xi_8\xi_{11} - 1, \xi_6\xi_2\xi_4\xi_{12}\}$ and it can be seen that the condition that either of ξ_3, ξ_7, or ξ_{10} has to be equal to zero leads to a situation in which either the equation $\xi_0''\xi_6\xi_2\xi_{10}\xi_8\xi_{11} - 1 = 0$ or $\xi_0'\xi_7\xi_3\xi_4\xi_{12}\xi_5\xi_9 - 1$ cannot be satisfied. Hence, $1 \in J$ and $J = \mathbb{F}_2[\underline{\xi}]$ and there does not exist a static solution which allows for failure of the link e_1 or e_8. ■

VI. Networks With Delay

So far, we have dealt with delay-free (and hence, by assumption, cycle-free) networks. The extension to networks with delays is relatively straightforward (while technical) for the multicast scenario. The general scenario requires considerably more technical tools. The main problem in the treatment of the general setup is that the system matrix is a matrix over the polynomial ring $\mathbb{F}_2(D)[\underline{\xi}]$ whose coefficients are rational functions in a delay variable D. Hence, the natural field of consideration is the algebraic closure of the field of rational functions in D.

Given an acyclic network with delay, we can either operate the network in a continuous mode where information is continuously injected into the network or we can operate the network in a burst-oriented mode. In the latter mode, each vertex transmits information on an outgoing node only if an input has been observed on all incoming links. This approach, taken by Li *et al.* [9], leads to a situation where a network with delay can be thought of as instantaneous and the results of Section IV-A apply. The time fraction during which a particular link is idle can be controlled by choosing the frame length large enough.

Here, we treat the case of continuous operation of a network with delay. The problem arises that the same injected information can take different routes causing different delays through the network. This delay necessitates memory at the sink nodes.

We now consider input random processes $X(v,i)$, output random processes $Z(u,j)$, and random processes $Y(e)$ transmitted on a link e as power series in a delay parameter D, i.e., $X(v,j)(D) = \sum_{\ell=0}^{\infty} X_\ell(v,j)D^\ell$, $Z(v,j)(D) = \sum_{\ell=0}^{\infty} Z_\ell(v,j)D^\ell$, and $Y(e)(D) = \sum_{\ell=0}^{\infty} Y_\ell(e)D^\ell$.

Also, as before, given a particular ordering of sources and sinks we use the the notation $\underline{x}(D) = (X(v,1)(D), X(v,2)(D), \ldots, X(v,\mu(v))(D))$ and $\underline{z}(D) = (Z(v',1)(D), Z(v',2)(D), \ldots, Z(v',\nu(v'))(D))$ to denote the vectors of random processes that are input and output of the system.

In this paper, we restrict ourselves to interior network nodes that operate in a memoryless fashion, which means that any internal node of the network can take linear combinations of the symbols observed simultaneously on its incoming edges. However, this turns out to be too restrictive for the general linear network problem. Still, memoryless operation of the nodes is sufficient to treat a robust multicast scenario. Nevertheless, even for this case, we will see that we have to allow for memory at the sink (or source) nodes. Formally, we have the following definition.

Definition 2 (Networks With Delay): Let $\mathcal{G} = (V,E)$ be a communication network with delay. We say that $\mathcal{G}$ is a $\mathbb{F}_{2^m}$-linear network if for all edges in E the random process $Y(e) = \sum_{t=0}^{\infty} Y_t(e)D^t$ on a link $e = (v,u)$ satisfies

$$Y_{t+1}(e) = \sum_{l=1}^{\mu(v)} \alpha_{l,e} X_t(v,l) + \sum_{e':\mathrm{head}(e')=\mathrm{tail}(e)} \beta_{e',e} Y_t(e')$$

where the coefficients $\alpha_{l,e}$ and $\beta_{e',e}$ are elements of $\mathbb{F}$. ∎

The output $Z(v,l)$ at any node v can be formed from the observed random processes at v in any suitable fashion. However, it turns out that it is sufficient to consider linear operation at the output, i.e., we have

$$Z_{t+1}(v,j) = \sum_{\ell=t-m(v)}^{t} \varepsilon'_{j,t-\ell} Z_\ell(v,j) + \sum_{\ell=t-m(v)}^{t} \sum_{e':\mathrm{head}(e')=v} \varepsilon''_{e',j,t-\ell} Y_\ell(e')$$

where the coefficients $\varepsilon'_{e',j,\ell}$ and $\varepsilon''_{e',j,\ell}$ are elements of $\mathbb{F}$ and $m(v)$ accounts for the memory required at sink node v.

The process of encoding information at the network nodes and feeding it into outgoing edges can again be captured in the adjacency matrix F of the corresponding directed line graph. We distinguish the case of acyclic networks with delay from the case of a network that contains cycles.

Lemma 3: Let F be the adjacency matrix of the labeled line graph of a cycle-free network $\mathcal{G}$. The matrix $I - DF$ has a polynomial inverse in the ring $\mathbb{F}_2[D, \ldots, \beta_{e_i,e_j}, \ldots]$.

Proof: Using an ancestral ordering of the edges in the network, we see that $I - DF$ can be written as an upper triangular matrix with entries from the ring $\mathbb{F}_2[D, \ldots, \beta_{e_i,e_j}, \ldots]$. The claim follows by using a back-substitution algorithm to give an explicit form of the inverse $(I - DF)^{-1}$. ∎

Lemma 4: Let F be the adjacency matrix of labeled line graph of a network G. The matrix $I - DF$ has a inverse in the field of rational functions $\mathbb{F}_2(D, \ldots, \beta_{e_i,e_j}, \ldots)$.

Proof: The determinant of $I - DF$ is nonzero, which can be seen from letting D be equal to zero. Hence, the matrix is invertible over its field of definition which can be taken to be $\mathbb{F}_2(D, \ldots, \beta_{e_i,e_j}, \ldots)$. ∎

As in the case of delay-free networks, we consider the system matrix M. The entries of M are defined as the rational functions $M_{i,j}(D) = \underline{z}_j(D)/\underline{x}_i(D)$, where $\underline{z}_j(D)$ is the response of the system to an excitation $\underline{x}_i(D)$. The system matrix is again composed of the multiplication of three matrices $A(D)$, $B(D)$, and a matrix $(I - DF)^{-1}$ defined as in Section III-A. However, now matrices $A(D)$ and $B(D)$ in general also contain rational functions in D.

In particular, the entries of a $\mu \times |E|$ matrix $A(D)$ are now defined as

$$A_{i,j} = \begin{cases} \alpha_{l,e_j}(D) & x_i = X(\mathrm{tail}(e_j), l) \\ 0, & \text{otherwise.} \end{cases}$$

Similarly, the entries of a $\nu \times |E|$ matrix $B(D)$ are defined as

$$B_{i,j} = \begin{cases} \varepsilon_{e_j,l}(D) & z_i = Z(\mathrm{head}(e_j), l) \\ 0, & \text{otherwise.} \end{cases}$$

We will call matrices *constant*, *polynomial*, and *rational*, depending on their domain of definition. Also, we call a rational matrix A *realizable* if all entries in A are realizable rational functions, i.e., any entry in A is defined when evaluated at $D = 0$.

The following theorem gives the equivalent of Theorem 5 for the case of networks with delay.

Theorem 13: Let a communication network $\mathcal{G}$ with delay be given with rational matrices $A(D)$, $B(D)$. Let F be the adjacency matrix of the corresponding labeled line graph G. The transfer matrix of the network is given as

$$M = A(D)(I - DF)^{-1}B(D)^T$$

where I is the $|E| \times |E|$ identity matrix.

Proof: The proof is essentially identical to the proof of Theorem 3 and is, therefore, omitted.

The base theorem underlying the development in Section IV is Theorem 2. The following reformulation applies to networks with cycles.

Theorem 14: Let a communication network $\mathcal{G}$ be given. The following three statements are equivalent.

1) A point-to-point connection $c = (v, v', \mathcal{X}(v, v'))$ is possible.
2) The Min-Cut Max-Flow bound is satisfied for a rate $R(c)$.
3) The determinant of the $R(c) \times R(c)$ transfer matrix M is nonzero over the field

$$\mathbb{F}_2(D \ldots, \alpha_{l,e}, \ldots, \beta_{e',e}, \ldots, \varepsilon'_{j,l}, \ldots, \varepsilon''_{e,j,l}, \ldots).$$

Proof: Again, most of the theorem is a direct consequence of the Min-Cut Max-Flow Theorem, which also is true in the case of cyclic networks. Statements 1) and 2) are equivalent by this theorem. The Ford–Fulkerson algorithm yields a solution to the network problem that satisfies the requirements of a linear solution. Hence, we can associate a system transfer matrix with this solution which, consequently, has to have a nonzero determinant.

Conversely, if the determinant of M is nonzero, we can invert matrix M by choosing parameters $\varepsilon'_{j,l}$ and $\varepsilon''_{e,j,l}$ accordingly. From Lemma 1, we know that we can choose the parameters so as to make this determinant nonzero. Hence, 3) implies 1) and the equivalence is shown. ■

We are now in a position to state the main results concerning networks with cycles in a multicast and robust multicast setup. We start with a formulation of the multicast scenario.

Theorem 15: Let a communication network $\mathcal{G}$ and a set of connections $\mathcal{C} = \{(v, u_1, \mathcal{X}(v)), (v, u_2, \mathcal{X}(v)), \ldots, (v, u_N, \mathcal{X}(v))\}$ be given. The network problem $(\mathcal{G}, \mathcal{C})$ is solvable if and only if the Min-Cut Max-Flow bound is satisfied for all connections in $\mathcal{C}$.

Proof: After changing the field of constants from $\mathbb{F}_2$ to $\mathbb{F}_2(D)$, the field of rational functions in D, the proof is essentially the same as the proof of Theorem 4. The determinants of the N relevant transfer matrices can be considered as the ratio of polynomials from the ring $\mathbb{F}_2(D)[\underline{\xi}]$. By Lemma 1, we can find an assignment of $\underline{\xi}$ such that all N determinants are nonzero in $\mathbb{F}(D)$ and, hence, that all N submatrices are invertible. Again, we can choose a realizable matrix $B(D)$, as a matrix with elements from $\mathbb{F}(D)$ such that M is the N-fold repetition of $D^\ell I$ where ℓ is a large enough integer and I is the $|\mathcal{X}(v)| \times |\mathcal{X}(v)|$ unit matrix. ■

Corollary 3: Let a linear network $\mathcal{G}$ be given with a set of desired connections $\mathcal{C} = \{(v_i, u_j, \mathcal{X}(v_i)) : i = 0, 1, \ldots N, j = 1, 2, \ldots K\}$. The network problem $\mathcal{G}$ is solvable if and only if the Min-Cut Max-Flow bound is satisfied for any cut between all source nodes $\{v_i : i = 0, 1, \ldots N\}$ and any sink node u_j. ■

Li *et al.* give a result for the multicast problem that concerns the achievability of the Min-Cut Max-Flow bound in networks with cycles. The codes employed in their setup are time-varying and the question is raised if a time-invariant multicast network exists that satisfies the simultaneous Min-Cut Max-Flow bound. An important consequence of the proof of Theorem 15 is the following corollary, which answers this question affirmatively.

Corollary 4: Let a communications network $\mathcal{G}$ and a set of connections $\mathcal{C} = \{(v, u_1, \mathcal{X}(v)), (v, u_2, \mathcal{X}(v)), \ldots, (v, u_N, \mathcal{X}(v))\}$ be given. The network problem $(\mathcal{G}, \mathcal{C})$ has a time-invariant solution if and only if the Min-Cut Max-Flow bound is satisfied for all connections in $\mathcal{C}$.

Proof: The proof follows from the proof of Theorem 15. In particular, the individual determinants can be made nonzero by choosing the assignment of $\underline{\xi}$ over $\bar{F}$ rather than $\bar{F}(D)$. It should be noted that while the operations performed at the interior nodes of the network are time-invariant, the individual sink nodes have to implement rational functions (involving memory) in order to output the (possibly delayed) input $\mathcal{X}(v)$. ■

The same arguments that lead to the derivation of robust networks and Theorem 11 can be extended to the case of networks with delays allowing the sink nodes to implement rational functions in D. In particular, following Corollary 4, such a robust solution can be made time-invariant.

By now, it should be clear that all the particular network problems treated in Section IV-C have an equivalent formulation for networks with cycles. For brevity, we will not reformulate these theorems.

VII. Conclusion

We have presented an algebraic framework for investigating capacity issues in networks using linear codes. The introduced technique makes a connection between certain systems of polynomial equations and the solutions to network problems. The use of algebra in this context is a significant and enabling tool, since it is possible to capitalize on powerful theorems in this well-established field of mathematics.

We see many roads opening up for further research. The investigation of network behavior under randomly chosen codes is an intriguing question in the context of self-organizing networks. Other avenues are a structured investigation of network management requirements for robust networks. In particular, relating a change in a network to the change in receiver function can give insight into the minimum number of bits required to respond to failure scenarios.

Other issues involve the development of protocols that capitalize on the insights from network coding. More theoretical issues address questions about the sufficiency of network coding as well as a general separability of network coding and coding for ergodic link failures.

References

[1] T. M. Cover, "Comments on broadcast channels," *IEEE Trans. Inform. Theory*, vol. 44, pp. 2524–2530, Oct. 1998.
[2] ——, "Broadcast channels," *IEEE Trans. Inform. Theory*, vol. IT-18, pp. 2–14, Jan. 1972.
[3] ——, "An achievable rate region for the broadcast channel," *IEEE Trans. Inform. Theory*, vol. IT-21, pp. 300–404, July 1975.
[4] R. Ahlswede, "Multi-way communication channels," in *Proc. 1971 IEEE Int. Symp. Information Theory*, pp. 23–52.
[5] H. Liao, "Multiple-access channels," Ph.D. dissertation, Univ. Hawaii, 1972.
[6] E. Van der Meulen, "Three-terminal communication channels," *Adv. Appl. Probabil.*, vol. 3, pp. 120–154, 1971.
[7] T. Cover and A. El Gamal, "Capacity theorems for the relay channel," *IEEE Trans. Inform. Theory*, vol. IT-25, pp. 572–584, Sept. 1979.
[8] B. Schein and R. Gallager, "The Gaussian parallel relay network," in *Proc. 2000 IEEE Int. Symp. Information Theory*, p. 22.
[9] S. Y. R. Li, R. W. Yeung, and N. Cai, "Linear network coding," *IEEE Trans. Inform. Theory*, vol. 49, p. 371, Feb. 2003.
[10] R. Ahlswede, N. Cai, S.-Y. R. Li, and R. W. Yeung, "Network information flow," *IEEE Trans. Inform. Theory*, vol. 46, pp. 1204–1216, July 2000.
[11] S.-Y. R. Li and R. W. Yeung, "Network multicast flow via linear coding," in *Proc. Int. Symp. Operations Research and its Applications*, 1998, pp. 197–211.

[12] R. W. Yeung, *A First Course in Information Theory*. Norwood, MA: Kluwer, 2002.
[13] R. W. Yeung and Z. Zhang, "Distributed source coding for satellite communications," *IEEE Trans. Inform. Theory*, vol. 45, pp. 1111–1120, May 1999.
[14] E. Ayanoglu, I. Chih-Lin, R. D. Gitlin, and J. D. Mazo, "Diversity coding: Using error control for self-healing in communication networks," in *Proc. IEEE INFOCOM*, vol. 1, 1990, pp. 95–104.
[15] S.-Y. R. Li and R. W. Yeung, "Network information flow—multiple sources," in *Proc. 2001 IEEE Int. Symp. Information Theory*, p. 102.
[16] D. P. Bertsekas, *Network Optimization: Continuous and Discrete Models*. Belmont, MA: Athena Scientific, 1998.
[17] P. Elias, A. Feinstein, and C. E. Shannon, "A note on the maximum flow through a network," *IEEE Trans. Info. Theory*, vol. IT-2, pp. 117–119, Dec. 1956.
[18] W. Fulton, *Algebraic Curves*. New York: Benjamin, 1969.
[19] D. Cox, J. Little, and D. O'Shea, *Ideals, Varieties, and Algorithms: An Introduction to Computational Algebraic Geometry and Commutative Algebra*. New York: Springer, 1992.

Ralf Koetter (S'92–M'95) received the Diploma degree in electrical engineering from the Technical University Darmstadt, Darmstadt, Germany, in 1990 and the Ph.D. degree from the Department of Electrical Engineering, Linköping University, Sweden.

From 1996 to 1997, he was a Visiting Scientist at the IBM Almaden Research Laboratory, San Jose, CA. He was a Visiting Assistant Professor at the University of Illinois at Urbana-Champaign, and a Visiting Scientist at CNRS, Sophia Antipolis, France, from 1997 to 1998. He joined the faculty of the University of Illinois at Urbana/Champaign in 1999, where he is currently an Assistant Professor with the Coordinated Science Laboratory. His research interests include coding and information theory and their application to communication systems.

Dr. Koetter received an IBM Invention Achievement Award in 1997, a National Science Foundation CAREER Award in 2000, and an IBM Partnership Award in 2001. He served as Associate Editor for coding theory and techniques for the IEEE TRANSACTIONS ON COMMUNICATIONS from 1999 to 2001. In 2000, he started a term as Associate Editor for coding theory of the IEEE TRANSACTIONS ON INFORMATION THEORY.

Muriel Médard (S'91–M'95–SM'00) received B.S. degrees in electrical engineering and computer science and in mathematics in 1989, the B.S. degree in humanities in 1990, the M.S. degree in electrical engineering in 1991, and the Sc.D. degree in electrical engineering in 1995, all from the Massachusetts Institute of Technology (MIT), Cambridge.

She is an Esther and Harold E. Edgerton Associate Professor in the Department of Electrical Engineering and Computer Science, MIT, and a member of the Laboratory for Information and Decision Systems. She was previously an Assistant Professor in the Department of Electrical and Computer Engineering and a member of the Coordinated Science Laboratory of the University of Illinois at Urbana-Champaign. From 1995 to 1998, she was a Staff Member of the MIT Lincoln Laboratory in the Optical Communications and the Advanced Networking Groups. Her research interests are in the areas of reliable communications, particularly for optical and wireless networks.

Dr. Médard received the IEEE Leon K. Kirchmayer Prize Paper Award in 2002. She is an Associate Editor for the Optical Communications and Networking Series of the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, and has been a Guest Editor for the JOURNAL OF LIGHTWAVE TECHNOLOGY and an Associate Editor for the OSA *Journal of Optical Networking.*