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(54) Title: MULTIPLICATIVE NETWORK CODING

(57) Abstract: Network coding may be performed with encoding and/ or decoding that involves a multiplication operation. In an example embodiment, a communication node is adapted to perform multiplicative network coding. The communication node includes an encoder and a decoder. The encoder is arranged to perform an encoding operation by multiplying two or more signals that bear information to form a composite signal. The decoder is arranged to perform a decoding operation by multiplying a received composite signal with one or more complex- conjugated signals, with the decoder yielding a decoded signal that bears information. With the encoding operation, the communication node is adapted to at least partially perform multiplicative-network-coding encoding for a sending communication mode. With the decoding operation, the communication node is adapted to at least partially perform multiplicative-network-coding decoding for a receiving communication mode.

MULTIPLICATIVE NETWORK CODING

CROSS-REFERENCE(S) TO RELATED APPLICATION(S)

This U.S. Nonprovisional Patent Application claims the benefit of copending U.S. Provisional Patent Application 60/975,552, filed on 27 September 2007 and entitled "Multiplicative En-/Decoding Method for Unitary Signals in Network Coding".

TECHNICAL FIELD

The present invention relates generally to the performance of network coding in communications systems.

BACKGROUND

Many specialized terms and abbreviations are used in the communications arts. At least some of the following are referred to within the text that follows, such as in this background and/or the description sections. Accordingly, the following terms and abbreviations are herewith defined:

4-QAM	4-Quadrature Amplitude Modulation
ARQ	Automatic Repeat Request
AWGN	Additive White Gaussian Noise
BPSK	Binary Phase Shift Keying
CBR	Coded Bi-directional Relaying
CRC	Cyclical Redundancy Checking
CS	Composite Signal
DPC	Dirty Paper Coding
FEC	Forward Error Correction
GF	Galois Field
MRC	Maximum Ratio Combining
MU-ARQ	Multi-User ARQ

NACK	Negative ACKnowledgment
NC	Network Coding
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PAM	Pulse Amplitude Modulated (signal)
PSK	Phase Shift Keying
SINR	Signal-to-Interference Noise Ratio
SNR	Signal-to-Noise Ratio

Data, voice, multimedia, and other communications are the foundation of the modern information-oriented world. Such information is typically communicated over a network or networks. These networks may be public or private, packet-switched or circuit-switched, wireless or wired, some combination thereof, and so forth. Networks may operate under any of many different protocols and standards. Regardless, most networks include multiple nodes that each receive a communication from one node and then forward or otherwise transmit the communication to another node to propagate the information.

The communication of a set of related information pieces over a network is typically termed an information flow. The information flow is transmitted from node to node over the network. An information flow may be propagated over a single network or over multiple networks of the same or different types.

Traditionally, the coding of information for security, redundancy, bandwidth efficiency, or other reasons has been performed at the information flow level. Routing of information over the nodes of a network, on the other hand, has been performed at the network level. Thus, there has traditionally been a separation of coding to the information flow level and routing to the network level.

This separation, however, may be changed in accordance with the concept of network coding.

The concept of network coding is relatively recent—it was first introduced in 2000. Network coding has the potential to improve communication in networks, both fixed networks and wireless networks. Theoretically, fixed/wired networks are free in principle of both noise and errors. (In reality, fixed networks may suffer from either or both of noise and errors.) Wireless networks, on the other hand, are commonly modeled with noise and interference that are individually and jointly capable of inducing errors in communications.

Generally, performing network coding involves mixing different pieces of information from different flows. This means that the notion of coding, which is historically performed on a link or flow level, is being moved up to the network level where multiple links and flows exist. A classical example illustrating network coding is from a seminal network coding paper entitled "Network Information Flow" and published in 2000 by R. Ahlswede, N. Cai, S.-Y. R. Li, and R. W. Yeung in IEEE Transactions on Information Theory (IT-46, pp. 1204-1216, 2000). This classical example is shown in FIG. 1.

FIG. 1 is an example network diagram 100 in which a conventional approach to network coding is implemented among communication nodes. As illustrated, network diagram 100 includes six communication nodes: *a*, *b*, *c*, *d*, *e*, and *f*. There are two information flows: A and B. The two sources of the information flows are nodes *a* and *b*. The two destinations for the information flows are nodes *e* and *f*.

Network diagram 100 illustrates how the two source nodes *a* and *b* initiate the info A and B, respectively, into the network. Both info A and info B are ultimately to be sent to both of the two destination nodes *e* and *f*. Node *a* transmits info A to node *e*. Node *b* transmits info B to node *f*.

The source nodes *a* and *b* also transmit info A and info B, respectively, to an intermediate node *c*. Node *c* creates a modulo sum A+B from info A and info B. The modulo sum may be created, for example, from a modulo-2 operation. A modulo-2 operation is equivalent to a bitwise exclusive OR (XOR) operation. This creation of a modulo sum is an encoding part of a conventional network coding operation.

Intermediate node *c* then forwards the modulo sum A+B to nodes *e* and *f*. As shown, the modulo sum A+B is forwarded to nodes *e* and *f* indirectly via another intermediate node *d*. After receiving the modulo sum A+B from node *c*, node *d* forwards it to both node *e* and node *f*. Because node *e* already knows info A, node *e* can determine info B from the modulo sum A+B. Similarly, node *f* can determine info A from the modulo sum A+B because it already knows info B. The retrieval of info B from the modulo sum A+B by node *e* using info A and the retrieval of info A from the modulo sum A+B by node *f* using info B are decoding parts of a conventional network coding operation.

By sending the packet with the modulo sum A+B, instead of individual packets for info A and info B in turn, it can be shown that the throughput may be increased and that the delay may be decreased. Thus, increasing throughput and/or decreasing delays in a network are benefits that may be attained when implementing network coding generally.

The example above performs conventional network coding using encoding and decoding operations having an XOR functionality, which is a modulo-2 operation. However, network coding has also been extended to addition in larger field sizes, at least in randomized settings.

Other advancements have been developed in network coding since its introduction in 2000. For example, a relationship between dirty paper coding (DPC) and network coding operations has been drawn by Peter Larsson et al. This relationship is explained further in two Published PCT Patent Applications to Peter Larsson, who is the inventor of the instant Patent Application, and two co-inventors Niklas Johansson and Kai-Erik Sunell. These two PCT Patent Applications are: [1] PCT Published Application No. WO 2006/071187, entitled "Method and Arrangement for Bi-Directional Relaying in Wireless Communication Systems" and published on 6 July 2006 by applicant Telefonaktiebolaget LM Ericsson and [2] PCT Published Application No. WO 2007/008123, entitled "Method and Arrangement for Coding and Scheduling in Packet Data Communication Systems" and published on 18 January 2007 by applicant Telefonaktiebolaget LM Ericsson. The former Application addresses ccded bi-directional relaying (CBR), and the latter Application addresses Multi-User ARQ (MU-ARQ).

In these Published PCT Patent Applications, there is description that the encoding and decoding operations need not be based solely on finite fields. Instead, a linear additive modulus operation may be employed for encoding and decoding operations. More precisely, assuming two random variables x_1 and x_2 that are uniformly distributed over [-1/2, 1/2], the encoding operation may be $y=(x_1+x_2) \bmod \Lambda$. The corresponding decoding operation, e.g. for x_1, may be $(y-x_2) \bmod \Lambda = x_1$.

The mod Λ in this instance (e.g., with $\Lambda=1$) means that for any value larger than 1/2 or less than -1/2, a suitable integer number is subtracted or added, respectively, to fold the resulting number into the range [-1/2, 1/2]. Although the linear additive modulus operation is described here in terms of one dimension, it is not limited to a single dimension.

Despite advancements in the field of network coding since its introduction in 2000, a number of deficiencies or weaknesses remain. For example, although existing network coding operations (e.g., finite field summations and the additive modulus operation) work fairly well in certain situations, they are a bit tricky to use in other situations. For instance, existing implementations of network coding can be finicky in noisy channels. Firstly, classical network coding operations with finite fields are intended to be used on forward error correction (FEC) decoded, error-free messages.

Secondly, with the additive modulus operation for encoding and decoding, a network coding implementation may operate on noisy baseband signals prior to FEC decoding. However, the decoding node benefits more from ascertaining precise channel states in order to do a "perfect" cancellation of the undesired, but "known" interfering signal. This precise knowledge and perfect cancellation can be difficult to achieve in real-world implementations.

Thus, deficiencies and weaknesses of conventional network coding include needing FEC-decoded, error-free messages and needing precise knowledge of interfering signals and perfect cancellation thereof in noisy environments to achieve a given level of service. These deficiencies and weaknesses, as well as other drawbacks of conventional network coding, are addressed by one or more of the various embodiments of the present invention.

SUMMARY

It is an object of the present invention to facilitate performance of network coding in different environments. For certain embodiments, different environments may include relatively noisy ones. Network coding may be performed with encoding and/or decoding that involves a (e.g., complex-valued) multiplication operation.

In an example embodiment, a communication node is adapted to perform multiplicative network coding. The communication node includes an encoder and a decoder. The encoder is arranged to perform an encoding operation by multiplying two or more signals that bear information to form a composite signal. The decoder is arranged to perform a decoding operation by multiplying a received composite signal with one or more complex-conjugated signals, with the decoder yielding a decoded signal that bears information. With the encoding operation, the communication node is adapted to at least partially perform multiplicative-network-coding encoding for a sending communication mode. With the decoding operation, the communication node is adapted to at least partially perform multiplicative-network-coding decoding for a receiving communication mode.

In another example embodiment, there is a memory including processor-executable instructions adapted to perform multiplicative network coding that, when executed, direct a communication node to perform a number of acts. The acts include: forming, transmitting, receiving, and yielding. A composite signal is formed by multiplying two

or more information-bearing signals in an encoding operation. The composite signal is transmitted. Another composite signal is received. A decoded signal that bears information is yielded by multiplying the received composite signal with one or more complex-conjugated signals in a decoding operation. With the act of forming, the communication node is adapted to at least partially perform multiplicative-network-coding encoding for a sending communication mode. With the act of yielding, the communication node is adapted to at least partially perform multiplicative-network-coding decoding for a receiving communication mode.

In yet another example embodiment, there is a method for a communication node adapted to perform multiplicative-network-coding encoding. The method includes acts of: receiving a first signal, receiving a second signal, forming, and transmitting. The first signal bearing first information is received. The second signal bearing second information is received. A composite signal is formed by multiplying the first signal by the second signal in an encoding operation, with the composite signal bearing multiplicatively-network-coded first information and second information. The composite signal is transmitted to another node. Thus, the communication node is adapted to at least partially perform multiplicative-network-coding encoding with the forming of the composite signal.

In yet another example embodiment, there is a method for a communication node adapted to perform multiplicative-network-coding decoding. The method includes acts of receiving a second signal, creating, receiving a composite signal, and retrieving. The second signal bearing second information is received. A complex conjugate of the second signal is created. The composite signal is received, with the composite signal bearing multiplicatively-network-coded information including first information and the second information. A first signal is retrieved by multiplying the composite signal by the complex conjugate of the second signal, with the retrieved first signal bearing the first information. Thus, the communication node is adapted to at least partially perform multiplicative-network-coding decoding with the retrieval of the first signal.

In yet another example embodiment, there is a system that is adapted to perform multiplicative network coding. The system includes a first communication node and a second communication node. The first communication node includes a multiplicative encoder, a transmitter, and a first receiver. The first receiver is adapted to receive a first signal bearing first information and a second signal bearing second information. The multiplicative encoder is adapted to form a composite signal by multiplying the first signal and the second signal, with the composite signal bearing multiplicatively-network-coded information including the first information and the second information. The transmitter is adapted to transmit the composite signal. The second communication node includes a multiplicative decoder and a second receiver. The second receiver is adapted to receive the composite signal from the transmitter of the first communication node. The second receiver is also adapted to receive the second signal bearing the second information. The multiplicative decoder is adapted to create a complex conjugate of the second signal. The multiplicative decoder is also adapted to retrieve the first signal by multiplying the composite signal by the complex conjugate of the second signal, with the retrieved first signal bearing the first information.

An advantage of certain embodiment(s) of the present invention is that the benefit(s) of network coding may be extended to performing encoding and decoding operations for noisy signals and/or channel-affected signals.

Another advantage of certain embodiment(s) of the present invention is that network coding benefit(s) may be obtained without needing to know channel states for the purpose of canceling any interfering signal or signals.

Yet another advantage of certain embodiment(s) of the present invention is that the benefit(s) of network coding may be extended to wireless networks in noisy environments.

Additional aspects of the invention are set forth, in part, in the detailed description, drawings, and claims that follow, and in part may be derived from the detailed description, or can be learned by practice of the invention. It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and are not restrictive of the invention as disclosed or as claimed.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete understanding of the present invention may be obtained by reference to the following detailed description when taken in conjunction with the accompanying drawings wherein:

FIG. 1 is an example network diagram in which a conventional approach to network coding is implemented among communication nodes.

FIG. 2 illustrates an example communication of a composite signal between two communication nodes that are adapted to perform multiplicative network coding.

FIG. 3 is a flow diagram of a method for an example embodiment of multiplicative network coding with one communication node.

FIG. 4 is a diagram illustrating an example multiplicative network coding procedure.

FIG. 5 is a block diagram of an example communication node.

FIG. 6 is a flow diagram of a method for an example embodiment of multiplicative network coding with two communication nodes.

FIG. 7 illustrates a network diagram in which an example approach to multiplicative network coding is performed among communication nodes.

FIG. 8 is a diagram illustrating an example CBR scenario using multiplicative network coding with three communication nodes.

DETAILED DESCRIPTION

In example embodiments, multiplicative network coding involves combining information flows using at least one multiplication operation. In an example encoding operation, a sending node multiplies two or more information-bearing signals to form a composite signal. This composite signal is communicated from the sending node to a receiving node. In an example decoding operation, the receiving node multiplies the received composite signal with one or more complex-conjugated signals. Each complex-conjugated signal may be previously received at the receiving node and/or transmitted from the receiving node, and hence previously stored thereat. Each complex-conjugated signal may bear information and/or may itself be a composite signal. The information-bearing signals, the complex-conjugated signal(s), or both may have a noise component.

More specifically, example embodiments provide encoding and/or decoding operations for multiplicative network coding. Information-bearing signals have a phase domain and carry information in the phase domain. Additionally, each signal may have a constant absolute magnitude, at least from symbol to symbol and possibly across each of the signals.

In an example encoding operation, a sending node multiplies two or more information-bearing signals to form a composite signal. Each of these signals may or may not have a noise component. However, noise components are preferably absent for performance reasons. In an example decoding operation, a receiving node multiplies a received composite signal with one or more complex-conjugated signals, which may be information-bearing signals or composite signals. These complex-conjugated signals may have been previously received or transmitted and thus stored. The signals for the decoding operation may or may not have unknown noise components, but preferably noise components are absent for performance reasons.

These operations enable multiplicative network coding and are suitable for both encoding and decoding. They may be used with unitary signals. For certain embodiments, the decoding does not, in contrast with conventional approaches, need perfect knowledge of channel states for canceling network coded messages, nor does it need to perform FEC decoding prior to network-coding decoding.

Included in the description below are example applications of multiplicative network coding. These example applications include CBR and MU-ARQ. Multiplicative network coding may also be used in DPC, particularly when the interference is multiplicative rather than additive.

FIG. 2 illustrates an example communication of a composite signal 208 between two communication nodes 202 that are adapted to perform multiplicative network coding. As illustrated, a system 200 includes a first communication node 202a and a second communication node 202b. First communication node 202a stores or otherwise has access to two or more signals 210. More specifically, a signal 210(1) bears information A, and a signal 210(2) bears information B.

In an example embodiment, first communication node 202a includes a first multiplicative network coder 204a and a first communication interface 206a. Second communication node 202b includes a second multiplicative network coder 204b and a second communication interface 206b. Second communication node 202b stores or otherwise has access to at least one complex-conjugated signal. For example, second communication node 202b has access to complex-conjugated signal 210*(2), which bears information B.

In an example encoding operation, first multiplicative network coder 204a forms a composite signal 208 by multiplying two or more information bearing signals 210, such as signal 210(1) and signal 210(2). Composite signal 208 therefore comprises multiplicatively-network-coded (MNC) information 212. In other words, signal 210(1) bearing information A and signal 210(2) bearing information B may be multiplied together to form composite signal 208 including or carrying MNC information 212. MNC information 212 may therefore be represented in this instance by $A \otimes B$. First multiplicative network coder 204a provides composite signal 208 to first communication interface 206a.

First communication node 202a transmits via first communication interface 206a composite signal 208 directly or indirectly to second communication node 202b. Second communication node 202b receives composite signal 208 via second communication interface 206b. Second communication interface 206b provides composite signal 208 to second multiplicative network coder 204b.

In an example decoding operation, second multiplicative network coder 204b multiplies composite signal 208 with one or more complex-conjugated signals to yield a desired signal, such as a signal 210(1) or 210(2). In this example, second multiplicative network coder 204b already has access to complex-conjugated signal 210*(2) corresponding to information B. Alternatively, second multiplicative network coder 204b creates complex-conjugated signal 210*(2) from signal 210(2) that bears information B. Thus, second multiplicative network coder 204b multiplies composite signal 208 by complex-conjugated signal 210*(2) to yield signal 210(1) that bears information A.

FIG. 3 is a flow diagram 300 of a method for an example embodiment of multiplicative network coding with one communication node. As illustrated, flow diagram 300 includes five blocks 302, 304, 306, 308, and 310. The method may be performed by a single communication node, such as a communication node 202 (of FIG. 2 or 5). Flow diagram

300 is divided into a sending communication mode 312 and a receiving communication mode 314.

Sending communication mode 312 includes blocks 302-304 and involves an encoding operation. Receiving communication mode 314 includes blocks 306-310 and involves a decoding operation. A single communication node may be in a sending mode for one information flow and multiplicative network coding procedure and may be in a receiving mode for another information flow and multiplicative network coding procedure.

In an example embodiment, at block 302, a composite signal is formed by multiplying two or more information-bearing signals in an encoding operation. Each respective information-bearing signal may be associated with a respective information flow. At block 304, the composite signal is transmitted from the communication node. For a communication node that has a sending communication mode and a receiving communication mode, it may also be receiving a different composite signal and performing a decoding operation on it.

At block 306, another composite signal is received at the communication node. At block 308, the communication node yields a decoded signal that bears information by multiplying the received composite signal with one or more complex-conjugated signals in a decoding operation. Each complex-conjugated signal may be an information-bearing signal or a composite signal. At block 310, the information carried by the decoded signal is extracted by further processing of the decoded signal. Such further processing may include, for example, FEC decoding, demodulation, a combination thereof, and so forth.

FIG. 4 is a diagram illustrating an example multiplicative network coding procedure 400. As illustrated, multiplicative network coding procedure 400 includes a sender 402, a channel 404, and a receiver 406. It also involves information-bearing signals 210(1) and 210(2), as well as complex-conjugated signal 210*(2).

In an example embodiment generally, signal 210(1) and signal 210(2) are multiplied together to form a composite signal. Channel effects from transmitting the composite signal across channel 404 are represented by h_1. At receiver 406, the effects of noise on the signal are represented by w_1. It should be noted that the noise w_1 may originate from a source external to receiver 406 as well as from the receiver itself. Receiver 406 multiplies the resulting channel-affected and noisy signal by complex-conjugated signal 210*(2). This yields a decoded signal corresponding to information-bearing signal 210(1). The decoded signal is forwarded for additional processing, such as FEC decoding and demodulation to extract the desired information that the decoded signal carries.

More specifically, signals 210 are defined to be $s_k(n) = e^{j\varphi_k(n)}$, where *n* is a index for a symbol carrying a piece of information, and *k* is the index for the full information to which the signal belongs (e.g., data word *k*). For the sake of notation simplicity, the symbol index *n* is dropped herein below, and signals are therefore represented by $s_k = e^{j\varphi_k}$.

For the sake of clarity, it is assumed herein below that the communication channel is flat or that OFDM is used such that the channel is flat for the subcarrier under consideration. Similarly, it is given that $|s_k(n)| = 1$. In words, it is given that the power is relatively constant for a signal, at least from symbol to symbol. More specifically, it is given that the magnitudes of each of the signals are substantially equal and approximately identical to unit value. Thus, for such embodiments, information may be carried in the phase domain of such signals, but it need not be carried in their magnitude. Values may be relatively constant, substantially equal, or approximately identical within reasonable tolerances to which the underlying communication technologies are capable of attaining and/or to achieve a targeted level of acceptable error, SNR, SINR, and so forth.

In an example operation, it is given that receiver 406 knows a signal $s_2 = e^{j\varphi_2}$. A composite signal $s_1 s_2 = e^{j\varphi_1} \cdot e^{j\varphi_2} = e^{j(\varphi_1+\varphi_2)}$ is formed from signals 210(1) and 210(2) at sender 402 and sent over channel 404 to receiver 406. Signal 210(1), or s_1, is unknown at receiver 406. Receiver 406 wants to retrieve signal 210(1) from the received noisy and attenuated composite signal $r = h\sqrt{p}s_1 s_2 + w$, where h is the complex channel magnitude, p is the transmit power, and w is the noise. In this case, the noise is modeled as additive white Gaussian noise (AWGN).

Receiver 406 has knowledge of signal 210(2), or s_2. This signal s_2 may be, e.g., reconstructed from a previously received signal and associated decoded data. The reconstruction potentially includes protocol headers, CRC, FEC, modulation, some combination thereof, and so forth. Receiver 406 creates complex-conjugated signal

210*(2), or s_2^*, and calculates rs_2^*. This yields $rs_2^* = (h\sqrt{p}s_1s_2 + w)s_2^* = h\sqrt{p}s_1 + w'$, where w' is AWGN with effectively the same statistics as w.

Thus, for example embodiments, multiplicative-network-coding encoding and decoding operations with unit magnitude and phase modulated signals need not affect the communication performance. Moreover, for the multiplicative-network-coding decoding operation, in contrast with DPC, the receiver does not need to know the value of the channel h. Additionally, the receiver need not do equalization prior to, or even after, a multiplicative-network-coding decoding operation. Example modulation schemes that may be adopted in conjunction with multiplicative network coding include, but are not limited to, PSK, 4-QAM, BPSK, and so forth.

FIG. 5 is a block diagram of an example communication node 202. As illustrated, communication node 202 includes a multiplicative network coder 204 and a communication interface 206. Multiplicative network coder 204 includes a multiplicative encoder 204E and a multiplicative decoder 204D. Communication interface 206 includes a transmitter 502 and a receiver 504.

In an example embodiment, multiplicative network coder 204 is operatively coupled to communication interface 206 for providing or forwarding signals or other information between them. Multiplicative encoder 204E is adapted to perform multiplicative-network-coding encoding operations. Multiplicative decoder 204D is adapted to perform multiplicative-network-coding decoding operations. Although multiplicative network coder 204 is shown as having both a multiplicative encoder 204E and a multiplicative decoder 204D, a communication node 202 may have only one if it is to operate in only a sending communication mode 312 (of FIG. 3) or a receiving communication mode 314, respectively.

Transmitter 502 is capable of transmitting signals from communication node 202 over one or more communication links (not explicitly shown). Receiver 504 is capable of receiving signals at communication node 202 from one or more communication links. Transmitter 502 and receiver 504 may be jointly realized as a transceiver. The links may be wireless links, wired links, both or a combination thereof, and so forth.

Generally, communication node 202 is adapted to perform multiplicative network coding. In an example embodiment, multiplicative encoder 204E is adapted to perform an encoding operation. Multiplicative decoder 204D is adapted to perform a decoding operation. During multiplicative network coding operations, multiplicative encoder 204E is arranged to multiply two or more signals 210 (of FIGS. 2 and 4) that bear information to form a composite signal 208.

Multiplicative decoder 204D is arranged to multiply a received composite signal 208 with one or more complex-conjugated signals 210*. From the decoding operation(s), multiplicative decoder 204D is to yield a decoded signal that bears information. Thus, communication node 202 is adapted to perform multiplicative network encoding for a sending communication mode 312 with the encoding operation and is adapted to perform multiplicative network decoding for a receiving communication mode 314 with the decoding operation.

Communication node 202 may be realized as a device, machine, equipment, module, a combination thereof, and so forth. Although not explicitly illustrated, a communication node 202 may include, for example, one or more processors, at least one memory, and processor-executable instructions. The at least one memory may include the processor-executable instructions. The one or more processors are operatively coupled to the memory. The processor(s) are capable of executing the processor-executable instructions to effectuate performance of functions and/or to perform acts that are described herein. For instance, the acts of flow diagram 300 and 600 (of FIGS. 3 and 6), as well as the other features and procedures described herein, may be realized with processor-executable instructions. Processor-executable instructions may be embodied as hardware, firmware, software, fixed logic circuitry, combinations thereof, and so forth.

Thus, each communication node 202 may be realized as a device, a machine, equipment, a module, some combination thereof, and so forth. Examples include, but are not limited to, a base station controller (BSC), a base transceiver station (BTS), a general packet radio service (GPRS) node, a gateway GPRS service node (GGSN), a mobile station (MS), a mobile telephony application server (MTAS), a media gateway (MGw), a mobile switching center (MSC), a Node B UMTS base station, a packet data serving node (PDSN), a radio base station (RBS), a radio network controller (RNC), a serving GPRS service node (SGSN), a subscriber station (SS), a user equipment (UE), a wired telecommunications network node, an internet node, a mesh network node, a router or switch, an access point, a module coupled to another device, some combination thereof, and so forth.

FIG. 6 is a flow diagram 600 of a method for an example embodiment of multiplicative network coding with two communication nodes 202. A sending node 202a-S is adapted to perform an encoding operation, and a receiving node 202b-R is adapted to perform a decoding operation. Flow diagram 600 includes eight blocks 602-608 and 612-618. Sending node 202a-S is adapted to perform the acts of blocks 602-608. Receiving node 202b-R is adapted to perform the acts of blocks 612-618.

Although not so limited, the description below of flow diagram 600 also references certain elements of other FIGS. (e.g., FIGS. 2, 4, and 5) to facilitate understanding of example embodiments. Also, the acts of the described blocks may be performed in order(s) that differ from the illustrated one. For example, the act(s) of block 612 and/or 614 may be performed after that of block 616. It should also be understood that a communication node may function as a sending node at one time and/or for one communication flow and as a receiving node at another time and/or for another communication flow.

In an example embodiment, at block 602, a first signal bearing first information is received. For example, sending node 202a-S may receive first signal 210(1) bearing first information A via a receiver 504 of a communication interface 206. At block 604, a second signal bearing second information is received. For example, sending node 202a-S may receive second signal 210(2) bearing second information B via receiver 504.

At block 606, a composite signal is formed by multiplying the first signal by the second signal, with the resulting composite signal bearing MNC information. For example, a multiplicative encoder 204E of a multiplicative network coder 204 of sending node 202a-S may multiply first signal 210(1) by second signal 210(2) to form composite signal 208. Composite signal 208 includes MNC information 212. Hence, composite signal 208 carries a product of the first information A and the second information B.

At block 608, the composite signal is transmitted. For example, sending node 202a-S may transmit composite signal 208 via a transmitter 502 of communication interface 206 to (i.e., directly or indirectly to) receiving node 202b-R. The composite signal is received as described below with reference to block 616.

At block 612, the second signal bearing second information is received. For example, receiving node 202b-R may receive second signal 210(2) bearing second information B via a receiver 504 of a communication interface 206. At block 614, a complex conjugate of the second signal is created. For example, receiving node 202b-R may create complex-conjugated signal 210*(2) from second signal 210(2).

At block 616, the receiving node receives the composite signal. For example, receiving node 202b-R may receive via receiver 504 composite signal 208 directly or indirectly from sending node 202a-S.

At block 618, the first signal is retrieved by multiplying the composite signal by the complex-conjugated second signal, with the retrieved first signal bearing the first information. For example, receiving node 202b-R may multiply composite signal 208 by complex-conjugated second signal 210*(2) to retrieve first signal 210(1), which bears first information A.

As noted above, the performance of network coding can increase throughput, reduce delay, and/or enhance the energy efficiency of a network. An example purpose for sending a composite signal may be gleaned from the following scenario. Assume that another receiving node already knows the first signal but also wants the second signal. By transmitting from a sending node the composite signal formed from the product of the first and second signals, both of the receiving nodes may obtain their desired signal with one transmission instead of two. Example scenarios for performing network coding are described in greater detail herein below with particular reference to FIGS. 7 and 8.

FIG. 7 illustrates a network diagram 700 in which an example approach to multiplicative network coding is performed among communication nodes. As illustrated, network diagram 700 includes six nodes: a, b, c, d, e, and f. There are two information flows: A and B. The two sources of the information flows are nodes a and b. The two destinations for the information flows are nodes e and f.

In other words, network diagram 700 is similar to network diagram 100 (of FIG. 1). However, for an example embodiment, multiplicative network coding with phase-modulated signals and complex multiplication is performed in network diagram 700. As noted above, multiplicative network coding can provide improved performance in certain situations, such as noisy environments.

Node *a* initiates information A into the network and transmits it to intermediate node *c*. Node *b* initiates information B into the network and transmits it to node *c*. Node *c* performs multiplicative-network-coding encoding on information A and information B by multiplying them to form a composite signal that carries MNC information $A \otimes B$. Thus, phase-modulated signals are multiplied together to produce MNC information $A \otimes B$. This multiplication may be performed below FEC.

Node *a* transmits information A to node *e*. Node *b* transmits information B to node *f*. Node *c* transmits MNC information $A \otimes B$ to nodes *e* and *f*. More specifically, node *c* transmits MNC information $A \otimes B$ to another intermediate node *d*, and node *d* transmits MNC information $A \otimes B$ to node *e* and node *f*. Alternatively, node *c* may transit MNC information $A \otimes B$ directly to nodes *e* and *f*.

Both nodes *e* and *f* perform multiplicative-network-coding decoding operations. Node *e* multiplies the composite signal having MNC information $A \otimes B$ with the complex conjugate of information A to retrieve information B. Node *f* multiplies the composite signal having MNC information $A \otimes B$ with the complex conjugate of information B to retrieve information A. These complex-conjugate multiplication operations to recover the desired signal may be performed below FEC. With multiplicative network coding, the signal of information A, the signal of information B, and/or the signal of MNC information $A \otimes B$ may have a noise component.

FIG. 8 is a diagram illustrating an example CBR scenario 800 using multiplicative network coding with three communication nodes 202. As illustrated, CBR scenario 800 includes communication node v_1 202(v_1), communication node v_2 202(v_2), and communication node v_3 202(v_3). These three communication nodes are wireless nodes, but CBR may also be applied to wired nodes of a wired network. Three transmissions are made at three times T1, T2, and T3. Transmit powers for communication nodes v_1, v_2, and v_3 are P_1, P_2, and P_3, respectively. The channel effects between node v_1 and v_3 are modeled with h_1, and the channel effects between node v_2 and v_3 are modeled with h_2.

The following example scenario is presented for CBR scenario 800. Communication node v_1 wants to send a message to communication node v_2 and vice versa. A 3-phase protocol is employed here. This means that node v_1 sends its message to the relay station, node v_3. Node v_2 also sends its message to the relay station node v_3. Subsequently, the relay station node v_3 sends an encoded composite signal that is created by multiplying the two messages from nodes v_1 and v_2.

For the sake of descriptive simplicity, it is assumed that the channels are reciprocal. In other words, it is assumed that the complex channel gain to noise variance is approximately identical independent of direction. However, it should be understood that such reciprocity is not required to successfully perform multiplicative network coding.

Also, as described in PCT Published Application No. WO 2006/071187, soft combining for CBR may be performed. Soft combining involves one or more network-coded data packets and regular data packets. With multiplicative network coding, the versions of the signals that are directly received in the first and second phases may be used for MRC with the network-coded decoded signals at each respective node. Consequently, when employing MRC with multiplicative network coding, the directly-received version of the signal's SNR and the network-coded decoded signal's SNR are added. For notational simplicity, the presence of the direct signal and application of MRC are omitted from the mathematical description below of CBR scenario 800.

Four different cases are described with regard to CBR scenario 800. Each case can be distinguished depending on whether the relay node v_3 can decode a received message. These four cases are: [1] relay node v_3 can decode both v_1 message and v_2 message, [2] relay node v_3 can decode v_1 message but not v_2 message, [3] relay node v_3 can decode v_2 message but not v_1 message, and [4] relay node v_3 can not decode either v_1 message or v_2 message.

Case [1] is that relay node v_3 can decode both the v_1 message and the v_2 message. The relay node v_3 sends $\alpha s_1 s_2$, where α is a scaling factor that in this case is equal to the square root of the transmit power $\sqrt{P_3}$. The two receiving nodes v_1 and v_2 receive the composite signals $r_1 = h_1 \alpha s_1 s_2 + w_1$ and $r_2 = h_2 \alpha s_1 s_2 + w_2$, respectively. Each node having knowledge of what it had previously sent, it can undo the impact of its own signal such that $r_1 s_1^* = h_1 \alpha s_2 + w_1'$ and $r_2 s_2^* = h_2 \alpha s_1 + w_2'$, respectively. The resulting SNR is $\Gamma_{31} = P_3 G_1 / \sigma^2$ and $\Gamma_{32} = P_3 G_2 / \sigma^2$ at nodes v_1 and v_2, respectively. (For simplicity in the above SNR equations, it has been assumed without limitation that the noise variances are the same.)

Case [2] is that relay node v_3 can decode the v_1 message but not the v_2 message. The relay node v_3 sends $\alpha s_1 r_{3(2)} = \alpha s_1 \left(h_2 \sqrt{P_2} s_2 + w_{3(2)} \right)$, where α is a scaling factor that normalizes the transmit power to P_3. In other words,

$\alpha = \sqrt{P_3} / \sqrt{G_2 P_2 + \sigma^2}$. The variable $r_{3(2)}$ is the received noisy signal in relay node v_3 from node v_2, whereas $w_{3(2)}$ is the noise left on top of the undecoded message from node v_2 in relay node v_3.

The receiving nodes v_1 and v_2 receive the composite signals $r_1 = h_1 \alpha s_1 r_{3(2)} + w_1$ and $r_2 = h_2 \alpha s_1 r_{3(2)} + w_2$. Each node having knowledge of what it had previously sent, it can undo the impact of its own signal such that $r_1 s_1^* = h_1 \alpha r_{3(2)} + w_1' = h_1 \alpha (h_2 \sqrt{P_2} s_2 + w_{3(2)}) + w_1'$ and $r_2 s_2^* = h_2 \alpha r_{3(2)} + w_2' = h_2 \alpha (h_2 \sqrt{P_2} s_2 + w_{3(2)}) + w_2'$ for node v_1 and node v_2, respectively. The resulting SNR is $\Gamma_1 = \Gamma_{23}\Gamma_{31}/(1+\Gamma_{23}+\Gamma_{31})$ and $\Gamma_2 = \Gamma_{23}\Gamma_{32}/(1+\Gamma_{23}+\Gamma_{32})$, where $\Gamma_{23} = P_2 G_2 / \sigma^2$.

Case [3] is that relay node v_3 can decode the v_2 message but not the v_1 message. This permutation is analogous to that of case [2], but the signal from v_2 is decoded and the one from v_1 remains noisy. Hence, in this case the noisy signal from v_1 is multiplied with s_2 and forwarded from the relay node v_3. This results in the following SNRs for nodes v_1 and v_2, respectively: $\Gamma_1 = \Gamma_{13}\Gamma_{31}/(1+\Gamma_{13}+\Gamma_{31})$ and $\Gamma_2 = \Gamma_{13}\Gamma_{32}/(1+\Gamma_{13}+\Gamma_{32})$, where $\Gamma_{13} = P_1 G_1 / \sigma^2$.

Case [4] is that relay node v_3 can not decode either the v_1 message or the v_2 message. Even if neither of the messages can be decoded in the relay node, they may still be multiplied to form a composite signal, but the noisiness increases. The relay node v_3 transmits

$\alpha r_{3(1)} r_{3(2)} = \alpha\left(h_1\sqrt{P_1}s_1 + w_{3(1)}\right)\left(h_2\sqrt{P_2}s_2 + w_{3(2)}\right)$ as the composite signal.

The composite signal is expanded in its components, and the noise is replaced with a statistically-equivalent noise term:

$$\alpha r_{3(1)} r_{3(2)} = \alpha\left(h_1\sqrt{P_1}s_1 h_2\sqrt{P_2}s_2 + h_2\sqrt{P_2}w'_{3(1)} + h_1\sqrt{P_1}w'_{3(2)} + w_{3(1)}w_{3(2)}\right) .$$

As is apparent from the composite signal, the two noise terms are multiplied with each other. This term can be neglected in the following analysis so as to provide an upper SNR bound because this term is small for the medium-to-high SNR ranges (for which the analysis is particularly applicable), and the statistics of two complex Gaussian random variables is non-complex Gaussian after multiplication of them. Even though the multiplicative terms of the noise are neglected in the analysis, the proper power normalization is utilized:

$$\alpha = \sqrt{P_3} \Big/ \sqrt{(G_1P_1 + \sigma^2)(G_2P_2 + \sigma^2)} .$$

After noise is added upon reception, the receivers operate as before. They multiply the received composite signal with the complex conjugate of their respective known signals. More specifically, the receiving nodes v_1 and v_2 receive the composite signals $r_1 = h_1\alpha r_{3(1)} r_{3(2)} + w_1$ and $r_2 = h_2\alpha r_{3(1)} r_{3(2)} + w_2$. Each node having knowledge of what it had previously sent, it can undo the impact of its own signal such that $r_1 s_1^* = \alpha h_1 h_2 \sqrt{P_1}\sqrt{P_2}s_2 + w'_1$ and $r_2 s_2^* = \alpha h_1 h_2 \sqrt{P_1}\sqrt{P_2}s_1 + w'_2$. After some calculation, the SNRs can be derived. The inverse SNR upper bounds are $\Gamma_1^{-1} = \Gamma_{13}^{-1} + \Gamma_{23}^{-1} + \Gamma_{31}^{-1}(1 + \Gamma_{13}^{-1})(1 + \Gamma_{23}^{-1})$ and

$\Gamma_2^{-1} = \Gamma_{13}^{-1} + \Gamma_{23}^{-1} + \Gamma_{32}^{-1}(1+\Gamma_{13}^{-1})(1+\Gamma_{23}^{-1})$ for nodes v_1 and v_2, respectively.

An example embodiment of CBR with multiplicative network coding can offer performance improvements. The performance generally depends on PSK constellation size in combination with which FEC method is employed. The performance for case [1] in which the relay node decodes both signals can provide, assuming $P_1G_1 = P_2G_2$ for simplicity, a 33% throughput increase relative to a classical 4-phase scheme. The reason for this increase is that the same amount of information is transferred in only 3/4 of the time consumed as compared to the 4-phase scheme.

When one of the messages is not decoded in the relay node v_3, both nodes v_1 and v_2 likely suffer somewhat from the noise that remains in the composite signal that is sent out. In contrast, for the 4-phase scheme, because the relay node transmits twice, only the receiver node that is actually receiving the noisy message is harmed. Hence, a performance comparison between the 3-phase CBR scheme and the classical 4-phase scheme for such permutations depends, at least partially, on a selected FEC code and PSK constellation size. In general, however, there will likely be some gain because of the 4/3 throughput increase.

Different embodiment(s) of the invention can offer one or more advantages. Generally, multiplicative network coding provides an alternative network-coding encoding and decoding approach as compared to traditional network coding. For example, certain embodiment(s) of multiplicative network coding provide a relatively low complexity method for the network-coding encoding of a noisy signal and a non-noisy signal into a composite signal.

Also, certain embodiment(s) provide a relatively low complexity method for the network-coding decoding of a composite signal without precise knowledge of channel state information. The prior decoding signals may also be noisy. Furthermore, certain embodiment(s) of multiplicative network coding may involve network-coding encoding and/or decoding with a fixed absolute magnitude of the signals and non-coherent detection of the network-coded decoded signal.

Different embodiment(s) of the invention can offer one or more of the following further advantages. For example, throughput may be increased by enabling full transmit times per data stream and by enabling use on different links with dissimilar SNRs. Also, embodiments can enable direct operation on baseband signals, or even radio frequency signals, if the hardware so permits. Additionally, the baseband or radio frequency layer in a multiplicative-network-coding-enabled relay/repeater may be utilized. This may provide reduced hardware complexity and/or cost. Moreover, embodiments may be relatively latency-free, cellular HARQ friendly, and network-coding enabled in a FDD repeater when network-coding noisy non-decoded signals. Furthermore, the SNR, or signal and noise statistics, is conserved under network decoding with noise-free signals. A noisy signal may, however, be used if desired when encoding and/or as the a priori known information when decoding.

Although multiple embodiments of the present invention have been illustrated in the accompanying Drawings and described in the foregoing Detailed Description, it should be understood that the invention is not limited to the disclosed embodiments, for it is also capable of numerous rearrangements, modifications and substitutions without departing from the scope of the invention as set forth and defined by the following claims.

CLAIMS

1. A communication node (202) adapted to perform multiplicative network coding, the communication node comprising:

an encoder (204E) adapted to perform an encoding operation;

a decoder (204D) adapted to perform a decoding operation;

c h a r a c t e r i z e d in that:

said encoder is arranged to multiply two or more signals (210) that bear information to form a composite signal (208); and

said decoder is arranged to multiply a received composite signal with one or more complex-conjugated signals (210*), and said decoder is further arranged to yield a decoded signal that bears information;

the communication node adapted to at least partially perform multiplicative-network-coding encoding for a sending communication mode (312) with the encoding operation; and the communication node adapted to at least partially perform multiplicative-network-coding decoding for a receiving communication mode (314) with the decoding operation.

2. The communication node as recited in claim 1, wherein the one or more complex-conjugated signals comprise at least one information bearing signal that has been complex conjugated.

3. The communication node as recited in claim 1 or 2, wherein the one or more complex-conjugated signals comprise at least one composite signal that has been complex conjugated.

4. The communication node as recited in any one of claims 1-3, wherein the two or more signals that bear information have a phase domain and carry information in the phase domain of the signals.

5. The communication node as recited in claim 4, wherein the two or more signals that bear information carry information in the phase domain of the signals but not in a magnitude of the signals.

6. The communication node as recited in any one of claims 1-5, wherein the two or more signals that bear information each have a substantially constant absolute magnitude at least from symbol to symbol.

7. The communication node as recited in any one of claims 1-6, wherein the two or more signals that bear information are each capable of being defined by a respective equation having a form of $s_k(n) = e^{j\varphi_k(n)}$ that has a variable *n* and a variable *k*; and wherein the variable *n* is an index for a symbol carrying a piece of information and the variable *k* is an index for a full set of information to which the signal is associated.

8. The communication node as recited in any one of claims 1-7, wherein the communication node is adapted to perform multiplicative-network-coding encoding or multiplicative-network-coding decoding to participate in a coded bi-directional relaying, CBR, scenario (800).

9. A method for a communication node (202) adapted to perform multiplicative network coding, the method comprising acts of:

forming a composite signal;

transmitting (304) the composite signal;

receiving (306) another composite signal; and

yielding a decoded signal that bears information from the received composite signal;

c h a r a c t e r i z e d in that:

said act of forming comprises forming (302) the composite signal (208) by multiplying two or more information-bearing signals (210) in an encoding operation; and

said act of yielding comprises yielding (308) the decoded signal that bears information by multiplying the received composite signal with one or more complex-conjugated signals (210*) in a decoding operation;

the communication node adapted to at least partially perform multiplicative-network-coding encoding for a sending communication mode (312) with said act of forming; and the communication node adapted to at least partially perform multiplicative-network-coding decoding for a receiving communication mode (314) with said act yielding.

10. The method for a communication node adapted to perform multiplicative network coding as recited in claim 9, wherein said act of forming comprises:

multiplying the two or more information-bearing signals in which at least one of the two or more information-bearing signals includes a noise component.

11. The method for a communication node adapted to perform multiplicative network coding as recited in claim 9 or 10, wherein said act of yielding comprises:

multiplying the received composite signal with one or more complex-conjugated signals in which at least one of the one or more complex-conjugated signals includes a noise component.

12. The method for a communication node adapted to perform multiplicative network coding as recited in any one of claims 9-11, wherein said act of yielding comprises:

multiplying the received composite signal with one or more complex-conjugated signals in which the received composite signal includes a noise component.

13. The method for a communication node adapted to perform multiplicative network coding as recited in any one of claims 9-12, wherein said act of yielding comprises:

multiplying the received composite signal with one or more complex-conjugated signals in which the received composite signal is attenuated.

14. The method for a communication node adapted to perform multiplicative network coding as recited in any one of claims 9-13, wherein said act of yielding is performed on the received composite signal while it is forward error correction, FEC, encoded; the method further comprising an act of:

after said act of yielding, performing FEC decoding on the decoded signal that bears information.

15. The method for a communication node adapted to perform multiplicative network coding as recited in any one of claims 9-14, wherein the received composite signal includes a complex channel magnitude component having a value; and wherein said act of yielding comprises:

yielding the decoded signal that bears information by multiplying the received composite signal without knowing the value of the complex channel magnitude component of the received composite signal.

16. The method for a communication node adapted to perform multiplicative network coding as recited in any one of claims 9-15, the method further comprising an act of:

extracting (310) the information from the decoded signal that bears information by further processing the decoded signal.

17. The method for a communication node adapted to perform multiplicative network coding as recited in claim 16, wherein said act of extracting comprises:

extracting the information from the decoded signal that bears information without performing equalization on the received composite signal or on the decoded signal that bears information.

18. The method for a communication node adapted to perform multiplicative network coding as recited in claim 16, wherein said act of extracting comprises:

performing forward error correction, FEC, decoding on the decoded signal that bears information; and

demodulating the decoded signal to extract the information.

19. The method for a communication node adapted to perform multiplicative network coding as recited in claim 16, wherein said act of extracting comprises:

performing maximum ratio combining, MRC, on the decoded signal that bears information and a directly-received version of the signal that bears information.

20. A system (200) that is adapted to perform multiplicative network coding, the system comprising:

a first communication node (202a); and

a second communication node (202b);

c h a r a c t e r i z e d by:

the first communication node includes a multiplicative encoder (204E), a transmitter (502), and a first receiver (504);

the first receiver adapted to receive a first signal (210(1)) bearing first information and a second signal (210(2)) bearing second information;

the multiplicative encoder adapted to form a composite signal (208) by multiplying the first signal and the second signal, the composite signal bearing multiplicatively-network-coded information (212) including the first information and the second information; and

the transmitter adapted to transmit the composite signal; and

the second communication node includes a multiplicative decoder (204D) and a second receiver (504);

the second receiver adapted to receive the composite signal from the transmitter of said first communication node, the second receiver further adapted to receive the second signal bearing the second information; and

the multiplicative decoder adapted to create a complex conjugate (210*(2)) of the second signal, the multiplicative decoder further adapted to retrieve the first signal by multiplying the composite signal by the complex conjugate of the second signal, the retrieved first signal bearing the first information.

21. A memory comprising processor-executable instructions adapted to perform multiplicative-network-coding encoding that, when executed, direct a communication node (202a-S) to perform acts comprising:

receiving (602) a first signal (210(1)) bearing first information;

receiving (604) a second signal (210(2)) bearing second information;

c h a r a c t e r i z e d by:

forming (606) a composite signal (208) by multiplying the first signal by the second signal in an encoding operation, the composite signal bearing multiplicatively-network-coded first information and second information (212); and

transmitting (608) the composite signal to another node;

the communication node adapted to at least partially perform multiplicative-network-coding encoding with said act of forming.

22. A memory comprising processor-executable instructions adapted to perform multiplicative-network-coding decoding that, when executed, direct a communication node (202b-R) to perform acts comprising:

receiving (612) a second signal (210(2)) bearing second information;

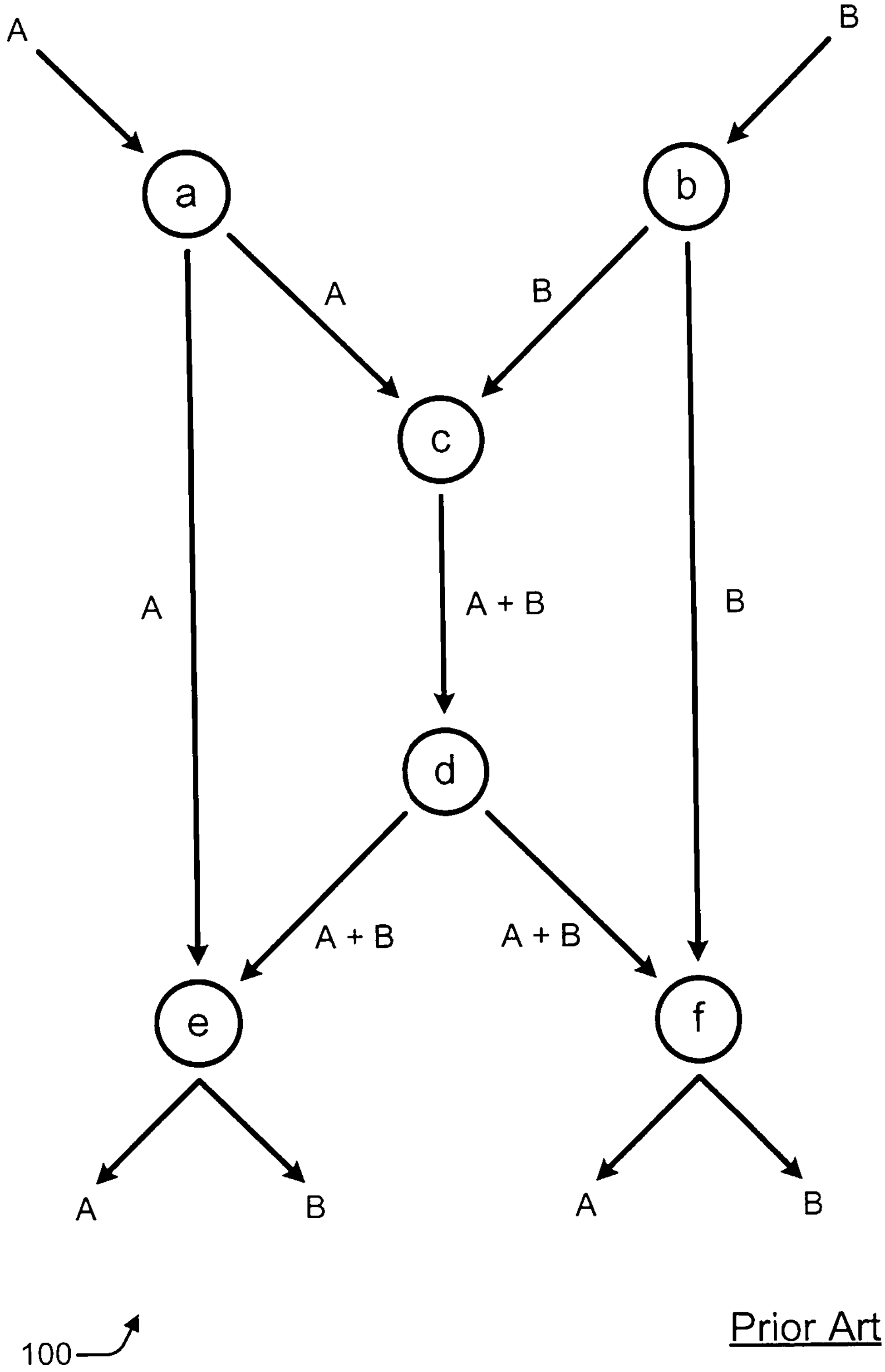
c h a r a c t e r i z e d by:

creating (614) a complex conjugate (210*(2)) of the second signal;

receiving (616) a composite signal, the composite signal (208) bearing multiplicatively-network-coded information (212) including first information and the second information; and

retrieving (618) a first signal (210(1)) by multiplying the composite signal by the complex conjugate of the second signal, the retrieved first signal bearing the first information;

the communication node adapted to at least partially perform multiplicative-network-coding decoding with said act of retrieving.



Prior Art

FIG. 1

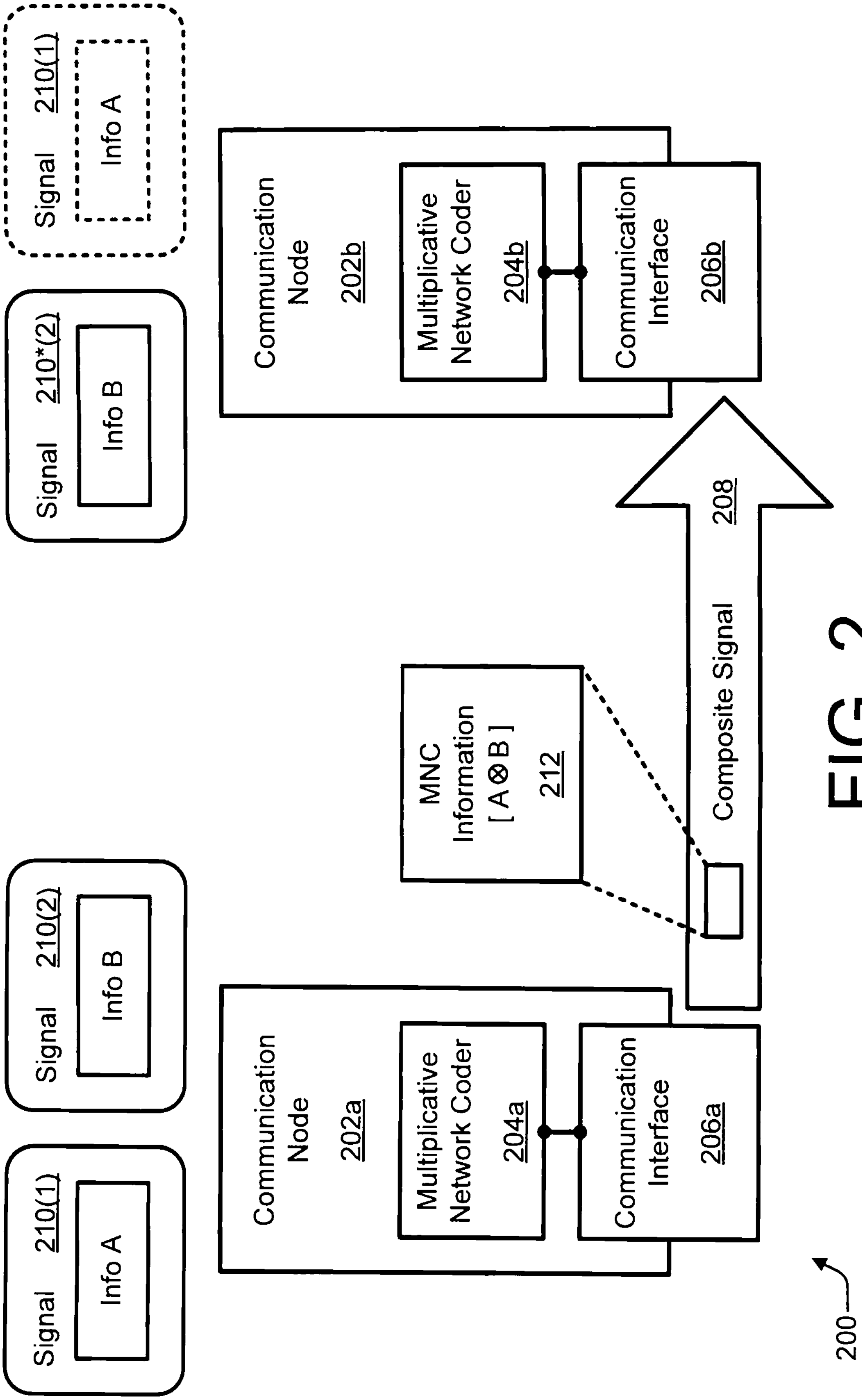

Signal 210(1)
Info A
Signal 210(2)
Info B
Communication Node 202a
Multiplicative Network Coder 204a
Communication Interface 206a
MNC Information [A⊗B] 212
Composite Signal 208
Communication Node 202b
Multiplicative Network Coder 204b
Communication Interface 206b
Signal 210*(2)
Info B
Signal 210(1)
Info A
200

FIG. 2

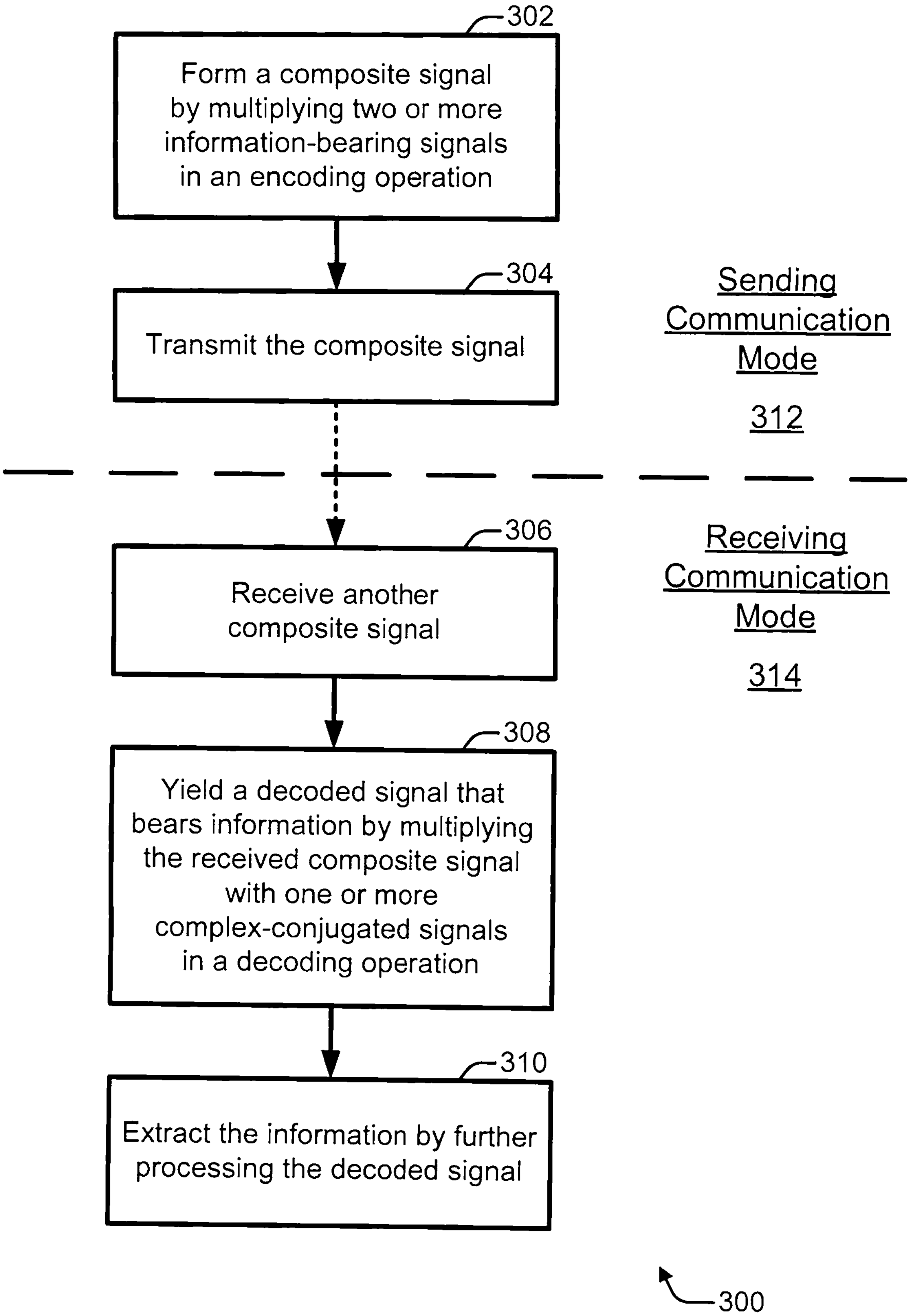

302
Form a composite signal by multiplying two or more information-bearing signals in an encoding operation
304
Transmit the composite signal
Sending Communication Mode
312
306
Receive another composite signal
Receiving Communication Mode
314
308
Yield a decoded signal that bears information by multiplying the received composite signal with one or more complex-conjugated signals in a decoding operation
310
Extract the information by further processing the decoded signal
300

FIG. 3

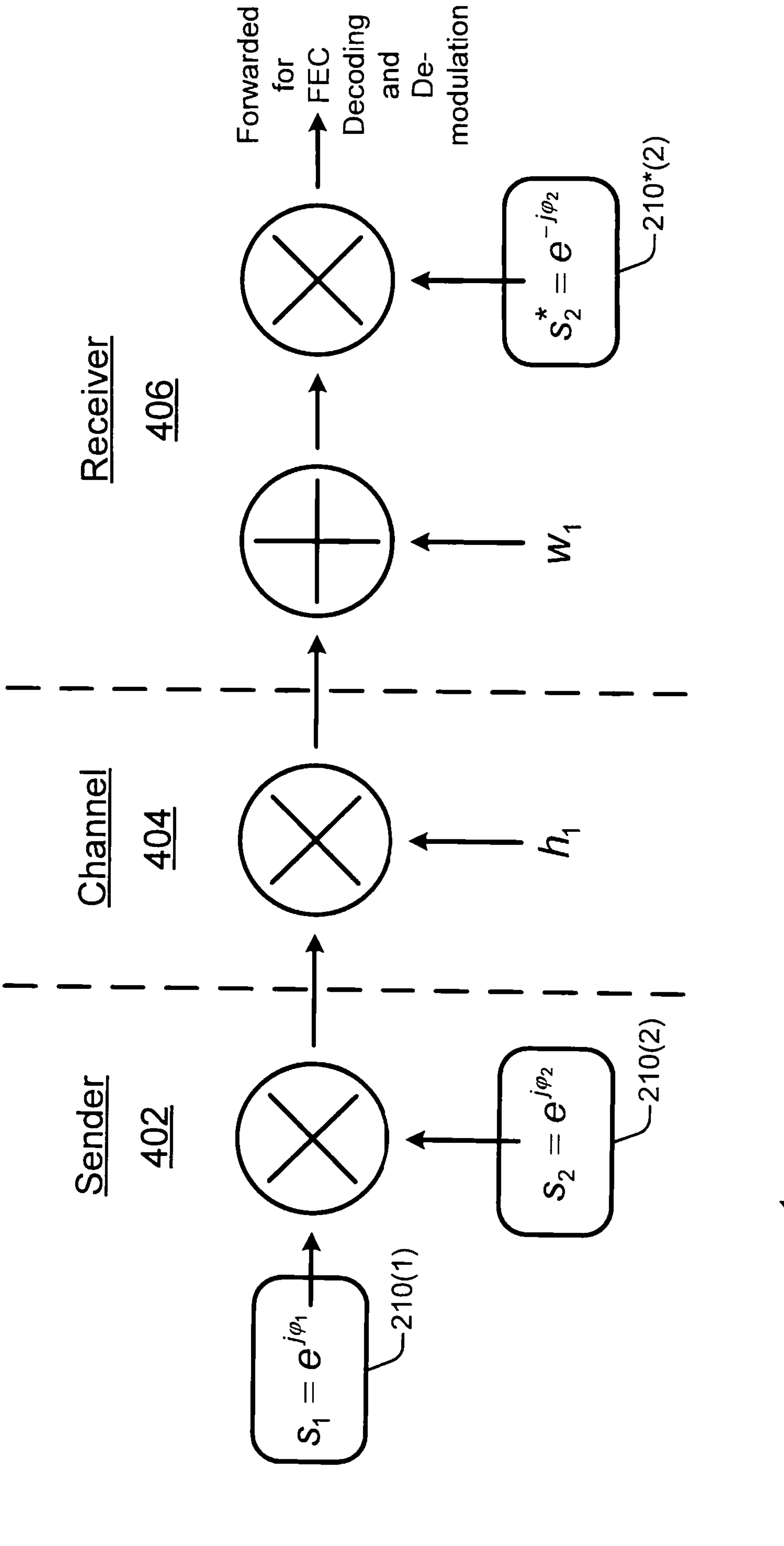

Sender
402
Channel
404
Receiver
406
$s_1 = e^{j\varphi_1}$
210(1)
$s_2 = e^{j\varphi_2}$
210(2)
h_1
w_1
$s_2^* = e^{-j\varphi_2}$
210*(2)
Forwarded for FEC Decoding and De-modulation
400

FIG. 4

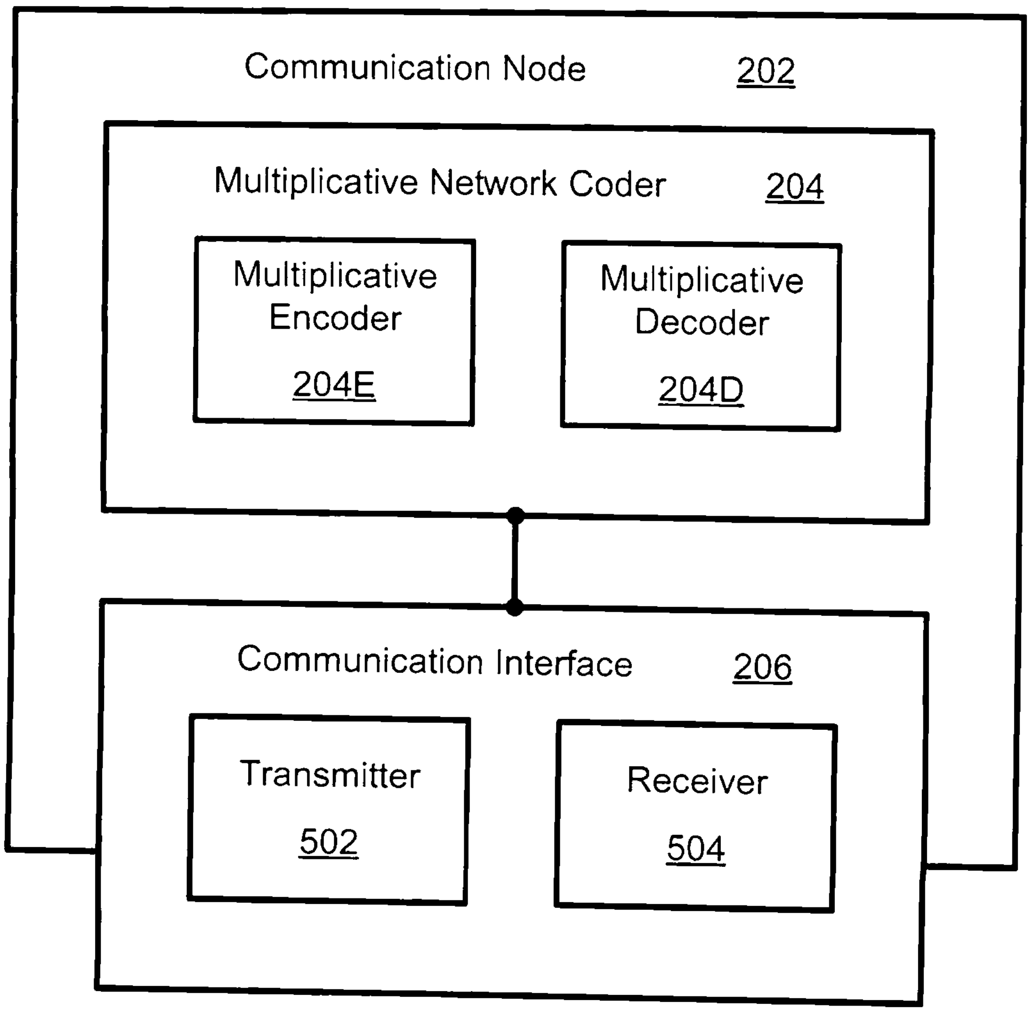

Communication Node 202
Multiplicative Network Coder 204
Multiplicative Encoder 204E
Multiplicative Decoder 204D
Communication Interface 206
Transmitter 502
Receiver 504

FIG. 5

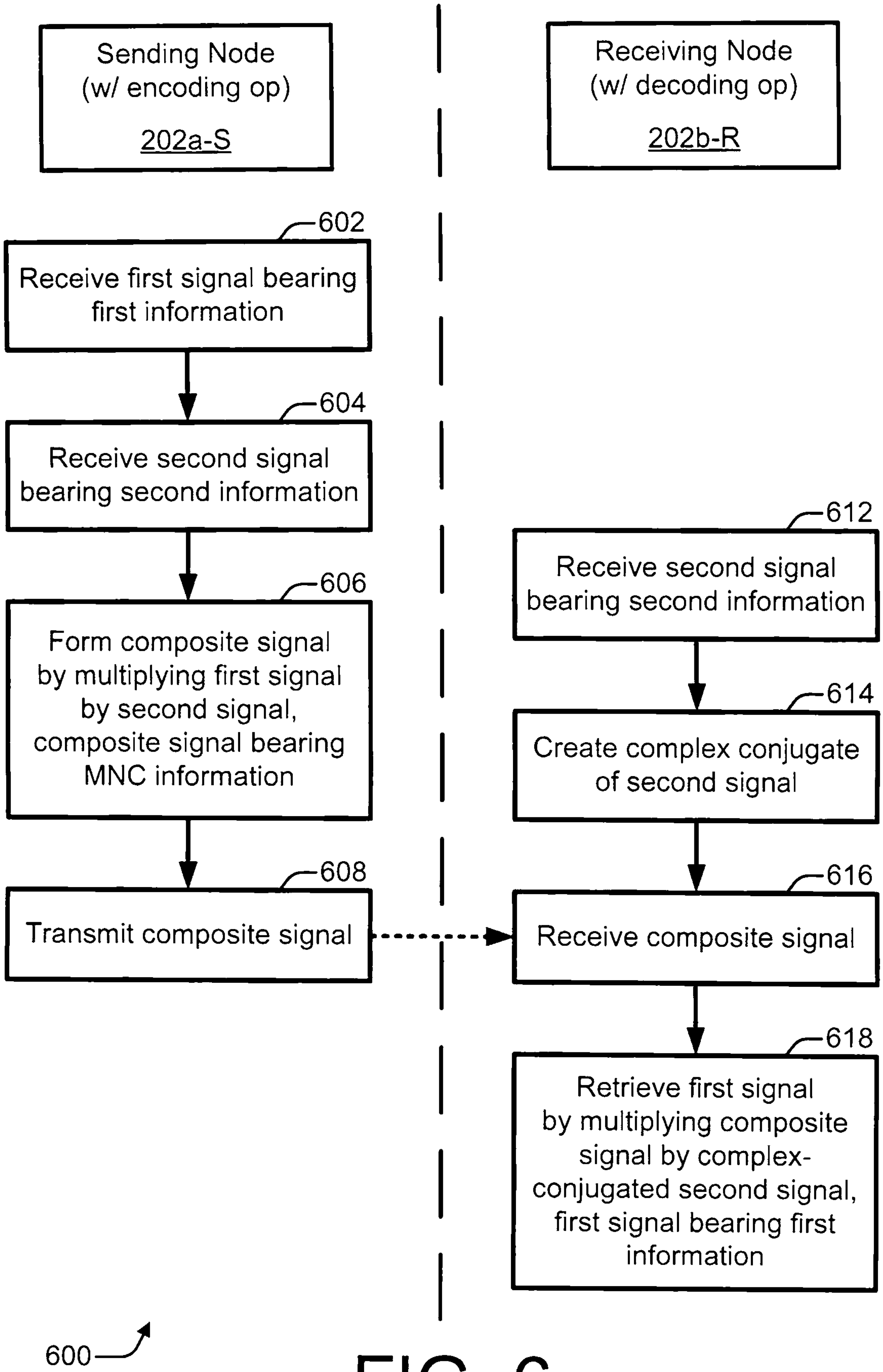

Sending Node
(w/ encoding op)
202a-S
Receiving Node
(w/ decoding op)
202b-R
602
Receive first signal bearing first information
604
Receive second signal bearing second information
606
Form composite signal by multiplying first signal by second signal, composite signal bearing MNC information
608
Transmit composite signal
612
Receive second signal bearing second information
614
Create complex conjugate of second signal
616
Receive composite signal
618
Retrieve first signal by multiplying composite signal by complex-conjugated second signal, first signal bearing first information
600

FIG. 6

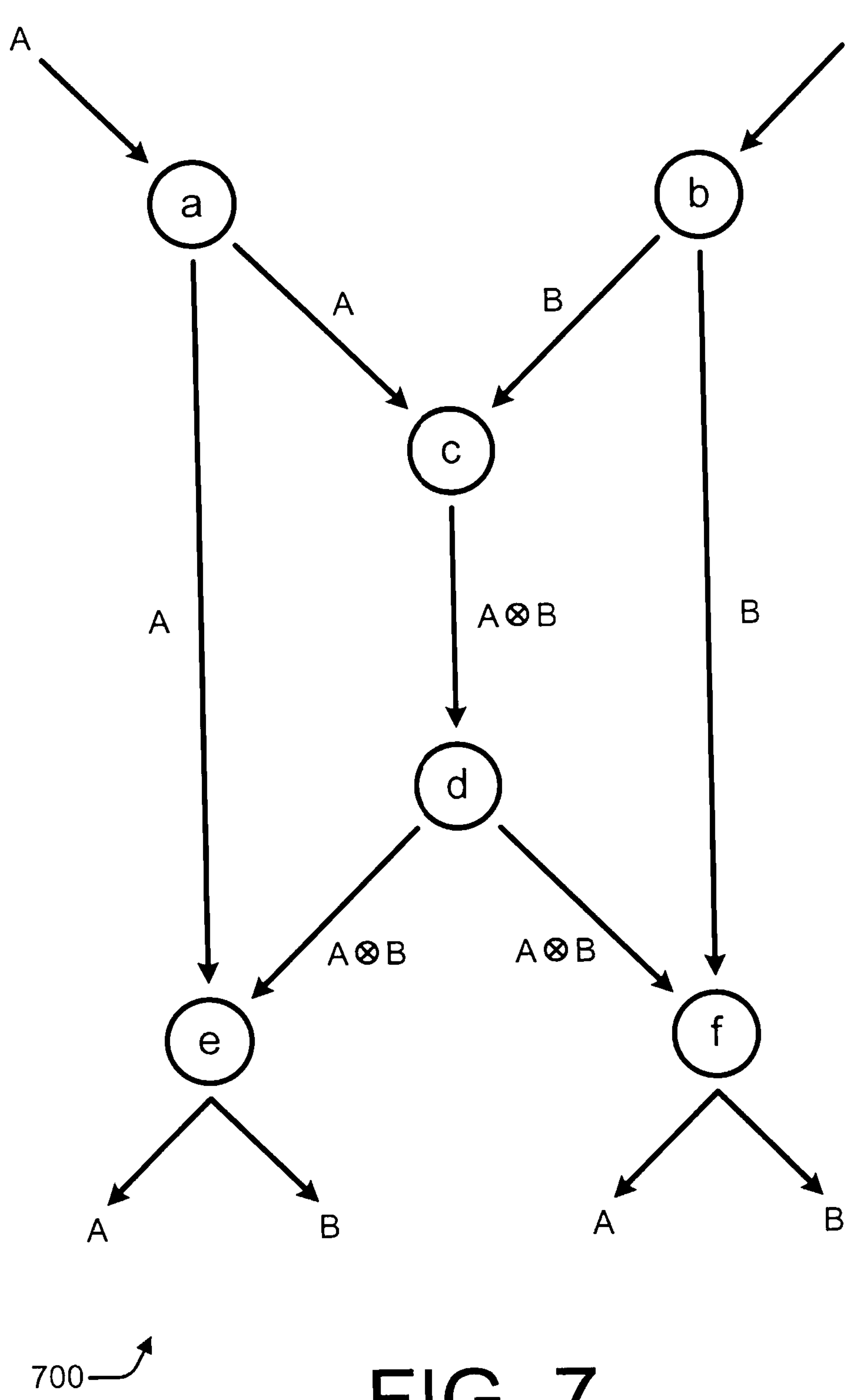


FIG. 7

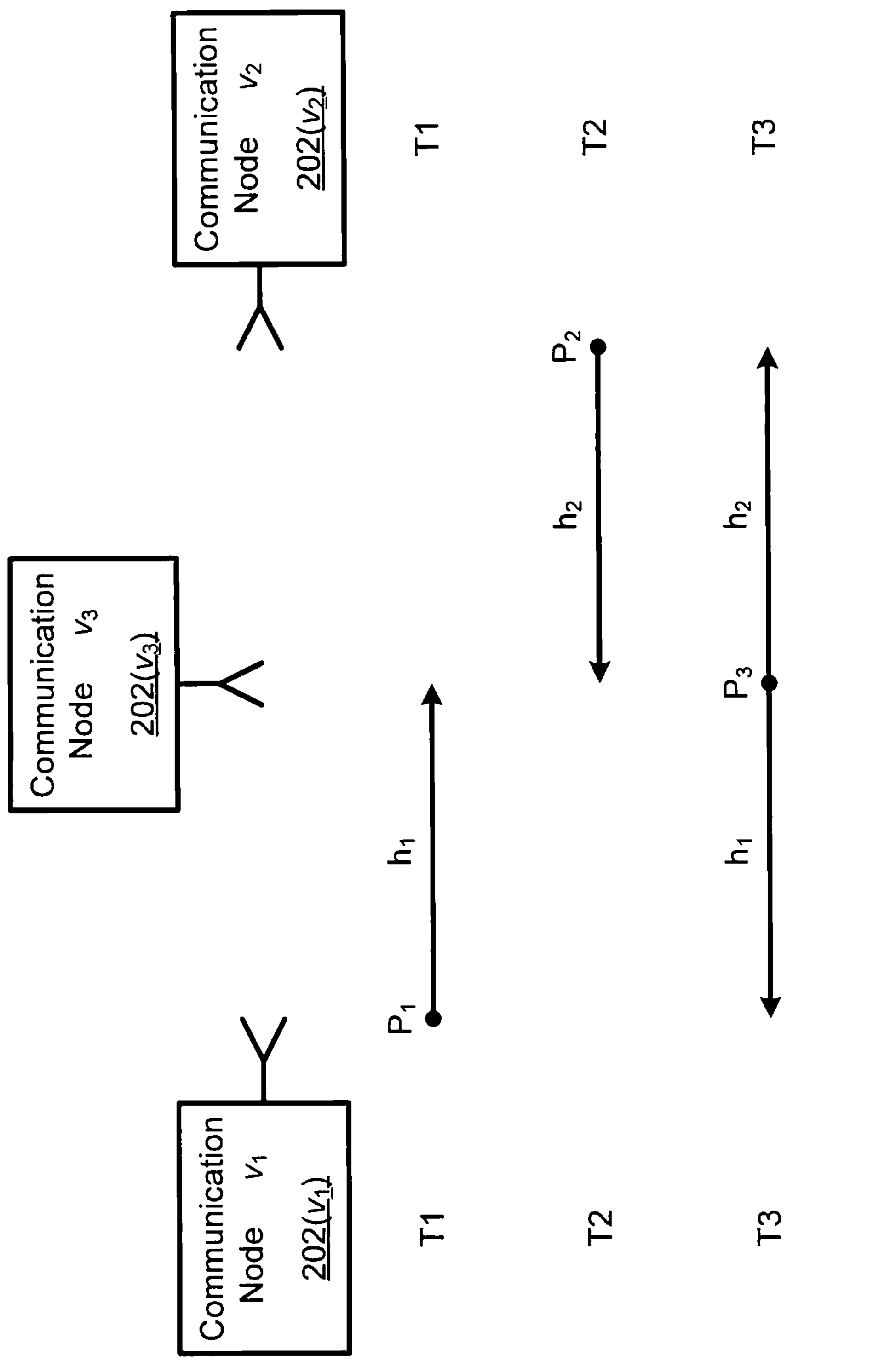

Communication Node v1
202(v1)
Communication Node v3
202(v3)
Communication Node v2
202(v2)
T1
T2
T3
P1
h1
P2
h2
P3
h1
h2
T1
T2
T3

FIG. 8

800