

APPLICATION FOR PATENT

TITLE

Wireless Communication Network Employing Beamforming for Improved Network Efficiency

5 TECHNICAL FIELD

The present disclosure relates to communications systems, and more particularly, to wireless communication networks having nodes that perform beamforming to reject interference from other network nodes.

BACKGROUND OF THE INVENTION

10 In wireless communication networks, channel access to network nodes is managed at the media access control (MAC) sub-layer, which is part of the data link layer. Channel access management typically requires preventing mutual interference between nodes of the network when using the same channel. There are generally two types of nodes that can be involved in mutual interference scenarios. One type is the exposed node (or exposed terminal), which can be involved
15 in the exposed node / terminal scenario (also known as the exposed node / terminal problem) in which a network node that is within transmission and/or reception range from an additional network node transmits together (simultaneously) with the additional node thereby creating a collision. This can occur in particular when the network operates in a half-duplex (HDX) regime such that the node has no reception capability when transmitting. The other type of node that can
20 be involved in mutual interference scenarios is the hidden node (or hidden terminal), which can be involved in the hidden node / terminal scenario (also known as the hidden node / terminal problem) in which two network nodes are not coordinated with each other (for example due to being out of transmission and/or reception range from each other) and simultaneously transmit to a common network node thereby creating a collision at the common node. Conventional channel access
25 management provides collision avoidance (to avoid the exposed and hidden node problems) by allocating resources (frequency channels and time slots) to ensure that when a particular set of resources (e.g., a particular channel and particular time slot) is in use by a network node, the network nodes neighboring that node (i.e., “exposed nodes”) and the network nodes neighboring the exposed nodes (i.e., “hidden nodes”) are both in listening mode (i.e., signal reception mode).
30 This compromise in resource allocation reduces the utilization of the channel, and can reduce the overall efficiency of the network.

SUMMARY OF THE INVENTION

The present disclosed subject matter, also referred to herein as the disclosure, includes a wireless communication network and method for communicating in a wireless communication

network. Aspects of the present disclosure provide a wireless communication network with improved (increased) network efficiency by employing beamforming at relay nodes to detect transmissions from source nodes and to reject interference from other nodes that transmit on the same channel and during the same time slot as source nodes. In certain preferred embodiments, the beamforming is performed in conjunction with high data rate (HDR) transmissions from source nodes. According to embodiments of the present disclosure, the beamforming is performed at relay nodes that are part of the routing path from the source node. The routing path is created by the network layer (routing layer), and access to the channel to the nodes (to avoid collisions) is handled by the media access control (MAC) sub-layer. According to embodiments of the present disclosure, the network layer and the MAC sub-layer operate in cooperation with each other, in particular by the MAC sub-layer allocating channel resources to the nodes based on the information (routing path information) received from the network layer, thereby enabling beamforming at the relay nodes to increase the efficiency of the network.

According to the teachings of an embodiment of the present disclosure, there is provided a method for communicating in a wireless communication network having a plurality of nodes. The method comprises: transmitting a signal of interest by a first node of the plurality of nodes, the signal of interest intended for receipt by a second node of the plurality of nodes that is a relay node in a routing path from the first node; and performing beamforming at the second node to detect the signal of interest and to reject an interferer signal that is transmitted by a third node of the plurality of nodes simultaneously with transmission of the signal of interest by the first node, the signal of interest and the interferer signal transmitted on a same frequency channel.

Optionally, the transmitting the signal of interest by the first node is a unicast transmission.

Optionally, the wireless communication network is a half-duplex communication network.

Optionally, the wireless communication network is a mobile ad-hoc network.

Optionally, the signal of interest carries a first message and the interferer signal carries a second message, and the first and second messages belong to different respective message sessions of the wireless communication network.

Optionally, the interferer signal is a signal of interest for an additional node of the wireless communication network.

Optionally, performing the beamforming at the second node rejects an additional interferer signal that is transmitted by an additional node of the plurality of nodes simultaneously with the first node transmitting the signal of interest, the additional node a neighbor to the second node.

Optionally, the signal of interest carries a first synchronization sequence and the interferer signal carries a second synchronization sequence that is orthogonal to the first synchronization sequence.

Optionally, performing the beamforming at the second node includes calculating beam weights for applying to signal received from output of the second node.

Optionally, performing the beamforming at the second node includes calculating beam weights for applying to signal received from output of antenna elements of an antenna array of the
5 second node.

Optionally, the antenna array includes exactly two antenna elements.

Optionally, the antenna array includes more than two antenna elements.

Optionally, calculating the beam weights is based on a synchronization sequence used by the first node and carried in the signal of interest.

10 Optionally, the beamforming performed by the second node is digital beamforming.

There is also provided according to the teachings of an embodiment of the present disclosure a method for communicating in a wireless communication network having a plurality of nodes. The method comprises: for each of one or more message sessions for communicating a message of the message session through the wireless communication network: determining a
15 routing path for routing the message from a source node to a destination node, the routing path at least including a relay node that neighbors the source node, the source node, the relay node, and the destination node are each one of the plurality of nodes, and communication between the source node and the relay node is according to the teachings of any of the above discussed embodiments, the source node and the relay node being the first node and the second node, respectively.

20 There is also provided according to the teachings of an embodiment of the present disclosure a wireless communication network. The wireless communication network comprises: a plurality of nodes including at least a first node, a second node, and a third node, the second node being a relay node in a routing path from the first node, the first node configured to transmit a signal of interest intended for receipt by the second node, and the second node configured to
25 perform beamforming to detect the signal of interest and to reject an interferer signal that is transmitted by the third node simultaneously with transmission of the signal of interest by the first node, the signal of interest and the interferer signal transmitted on a same frequency channel.

Optionally, the first node is configured to transmit the signal of interest as a unicast transmission.

30 Optionally, the wireless communication network is a half-duplex communication network.

Optionally, the wireless communication network is a mobile ad-hoc network.

Optionally, the signal of interest carries a first message and the interferer signal carries a second message, and the first and second messages belong to different respective message sessions of the wireless communication network.

Optionally, the plurality of nodes further includes an additional node, and the interferer signal a signal of interest for the additional node.

Optionally, the second node is configured to perform beamforming to reject an additional interferer signal that is transmitted by an additional node of the plurality of nodes simultaneously
5 with the first node transmitting the signal of interest.

Optionally, the signal of interest carries a first synchronization sequence and the interferer signal carries a second synchronization sequence that is orthogonal to the first synchronization sequence.

Optionally, the second node performs beamforming by calculating beam weights for
10 applying to signal received from output of the second node.

Optionally, the second node includes an antenna array having a plurality of antenna elements, and the second node performs beamforming by calculating beam weights for applying to signal received from output of the antenna elements.

Optionally, the antenna array includes exactly two antenna elements.

Optionally, the antenna array includes more than two antenna elements.
15

Optionally, the third node calculates the beam weights based on a synchronization sequence used by the first node and carried in the signal of interest.

Optionally, the second node is configured to perform digital beamforming.

There is also provided according to the teachings of an embodiment of the present
20 disclosure a method for communicating in a wireless communication network having a plurality of nodes. The method comprises: for each of one or more message sessions for communicating a message of the message session through the wireless communication network: determining a routing path for routing the message from a source node to a destination node, the routing path at least including a relay node that neighbors the source node, the source node, the relay node, and
25 the destination node are each one of the plurality of nodes, transmitting by the source node a first signal carrying the message to the relay node, and transmitting by an additional node a second signal, the first signal and the second signal are transmitted by the source node and the additional node simultaneously and on a same frequency channel, the additional node is one of the plurality of nodes and is a neighbor to the relay node, and the second signal is an interferer signal for the
30 relay node, and performing beamforming at the relay node to reject the second signal and to detect the first signal.

Optionally, the second signal carries a message that is part of a different message session.

Optionally, the additional node is part of the routing path for the message of the message session.

Optionally, the second signal is a signal of interest for an additional node of the wireless communication network.

Optionally, the transmitting the first signal by the source node is a unicast transmission.

Optionally, the wireless communication network is a half-duplex communication network.

5 Optionally, the wireless communication network is a mobile ad-hoc network.

Optionally, the first signal carries a first synchronization sequence and the second signal carries a second synchronization sequence that is orthogonal to the first synchronization sequence.

Optionally, performing the beamforming at the relay node includes calculating beam weights for applying to signal received from output of antenna elements of an antenna array of the relay node.

Optionally, the antenna array includes exactly two antenna elements.

Optionally, the antenna array includes more than two antenna elements.

Optionally, calculating the beam weights is based on a synchronization sequence used by the source node and carried in the first signal.

15 Optionally, the beamforming performed by the relay node is digital beamforming.

Unless otherwise defined herein, all technical and/or scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which the disclosure pertains. Although methods and materials similar or equivalent to those described herein may be used in the practice or testing of embodiments of the disclosure, exemplary methods and/or materials are described below. In case of conflict, the patent specification, including definitions, will control. In addition, the materials, methods, and examples are illustrative only and are not intended to be necessarily limiting.

BRIEF DESCRIPTION OF THE DRAWINGS

Some embodiments of the present disclosure are herein described, by way of example only, with reference to the accompanying drawings. With specific reference to the drawings in detail, it is stressed that the particulars shown are by way of example and for purposes of illustrative discussion of embodiments of the disclosure. In this regard, the description taken with the drawings makes apparent to those skilled in the art how embodiments of the disclosure may be practiced.

Attention is now directed to the drawings, where like reference numerals or characters indicate corresponding or like components. In the drawings:

FIG. 1 is a schematic representation of a wireless communication network that has a plurality of nodes that can be configured as relay nodes and perform beamforming processing, according to embodiments of the present disclosure;

FIG. 2 is a schematic block diagram illustrating some of the components of an exemplary node of the wireless communication network of FIG. 1, including a transceiver formed from a combination of a transmitter and a receiver, according to embodiments of the present disclosure;

FIG. 3 is a block diagram of an exemplary transmitter that can be employed by the
5 transceiver of FIG. 2;

FIG. 4 is a block diagram of an exemplary receiver that can be employed by the transceiver of FIG. 2, and that includes or is in signal communication with an antenna array having multiple antenna elements to enable the receiver to perform beamforming processing, according to embodiments of the present disclosure;

10 FIG. 5 is a schematic representation of a communication scenario involving nodes of the wireless communication network of FIG. 1 in which one of the nodes is configured as a relay node and performs beamforming processing to detect a signal of interest and reject an interferer signal transmitted from another node of the wireless communication network, according to embodiments of the present disclosure;

15 FIG. 6 is a flow diagram illustrating a process for communicating in a wireless communication network by employing beamforming processing to detect signals of interest and reject interferer signals transmitted from other nodes of the wireless communication network, according to an embodiment of the present disclosure;

FIG. 7 is a flow diagram illustrating a process for communicating in a wireless
20 communication network by employing beamforming processing to detect signals of interest and reject interferer signals transmitted from other nodes of the wireless communication network, according to another embodiment of the present disclosure; and

FIG. 8 is a schematic representation of some of the nodes of the wireless communication network of FIG. 1, showing a high angular separation between lines of sight of pairs of nodes that
25 simultaneously emit signal transmissions that can be received by a common node.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present disclosure includes a wireless communication network and method for communicating in such a wireless communication network.

The principles and operation of the wireless communication network and communication
30 method according to the present disclosure may be better understood with reference to the drawings accompanying the description.

The communication method according to the present disclosure can be used in many different types of wireless communication networks, including mobile communication networks, and is of particular value when used in a decentralized wireless network such as a mobile ad-hoc
35 network (MANET). The communication method according to the present disclosure is also of

particular value when used in high data rate (HDR) transmission, which is a wideband unicast service that transfers wideband (broadband) information (a “message”) from a source node of the network to a destination node of the network, and is characterized by creating a routing path from the source node to the destination node and using that routing path throughout the duration of the message session.

Before explaining at least one embodiment of the disclosure in detail, it is to be understood that the disclosure is not necessarily limited in its application to the details of construction and the arrangement of the components and/or methods set forth in the following description and/or illustrated in the drawings and/or the examples. The disclosure is capable of other embodiments or of being practiced or carried out in various ways.

Referring now to the drawings, FIG. 1 illustrates a wireless communication network (also referred to interchangeably as “communication network”, “network”, “wireless communication system” or “communication system”), generally designated **10**, according to certain embodiments of the present disclosure. Generally speaking, the wireless communication network **10** is formed from a plurality of nodes, designated **12a** through **12i**. Each of the nodes **12a** through **12i** is in direct or indirect signal communication with every other node of the wireless communication network **10** via one or more communication links, designated **13ab**, **13ac**, **13ah**, **13bf**, **13cd**, **13cg**, **13ch**, **13ci**, **13de**, **13dg**, **13ef**, and **13hi**. Although nine nodes are illustrated in FIG. 1 for simplicity of presentation, embodiments of the present disclosure can be implemented in wireless communication networks having any number of nodes, including several tens of nodes, several hundreds of nodes, or more. In addition, the number of nodes that are part of the wireless communication network **10** may change over time as new nodes join the wireless communication network **10** and/or leave the wireless communication network **10**.

Parenthetically, the letters used as part of a communication link identifier are indicative of the two nodes that are in direct signal communication with each other over that communication link, i.e., nodes that can communicate with each other without needing a relay. Thus, for example, communication link **13ab** is the communication link through which nodes **12a** and **12b** are in direct signal communication with each other. In certain embodiments, some or all of the communication links are bidirectional links that support signal transmission from the first node connected to a communication link to the second node connected to the communication link, and vice versa. Thus, for example, communication link **13ab** may support direct signal transmission from node **12a** to node **12b** and direct signal transmission from node **12b** to node **12a**. As will be discussed, in certain embodiments the network **10** operates as a half-duplex (HDX) network such that the bidirectionality of any link is separated in time.

Within the context of the present disclosure, a pair of nodes that are in direct communication with each other (i.e., without an intervening relay node) and are within communication reach of each other are referred to interchangeably as “neighboring nodes” or “neighbor nodes”. Thus, for example, the pair of nodes **12a, 12b** are neighboring or neighbor nodes, as are, for example, the pair of nodes **12b, 12f**. According to this definition of neighboring nodes, the pair of nodes **12a, 12f** are not neighboring nodes, since the nodes **12a, 12f** are in indirect communication with each other. Furthermore, a neighbor node can operate as a relay node to aid in routing a message from its neighbor to a destination node.

Within the context of the present disclosure, a “network hop” refers to the number of communication links (e.g., **13ab, 13bf**, etc.), and preferably the smallest number of such links, that are traversed in order for a pair of nodes to communicate with each other. Accordingly, within the context of the present disclosure a pair of neighboring nodes are separated by one network hop, whereas a pair of non-neighboring nodes are necessarily separated by more than one network hop. Thus, for example, the nodes **12a, 12b** are separated by one network hop, whereas the nodes **12a, 12f** are separated by two network hops. It is noted that although a pair of nodes may be ideally separated by a certain number of network hops along a particular communication route, other routes may be available through the network which may require more network hops, and may become necessary as one or more of nodes moves or one or more nodes leave or join the network, thereby causing the topology of the wireless communication network **10** to change. For example, although initially the node **12a** may communicate directly with node **12b** (via one network hop), re-deployment or movement of either or both of the nodes **12a, 12b** may result in instances or situations in which the nodes **12a, 12b** are out of communication reach with each other (i.e., in which the link **13ab** is no longer viable or stable), thus resulting in a situation in which the node **12a** communicates with the node **12b** indirectly, for example via the path of nodes **12a-12c-12d-12b** (i.e., three network hops).

One of the main challenges in wireless communication networks, and in particular decentralized networks such as MANETs, is maximizing user (node) throughput for a certain allocated bandwidth. For example, in conventional MANETs, the throughput tends to decrease as the number of nodes increases (resulting in an increase in network hops) due to packet (messages) retransmissions via relay nodes that are necessary to accommodate communication between nodes that are out of direct communication reach of each other. Such throughput challenges can be partially resolved by employing routing algorithms and resource (frequency channel and time slot) allocation algorithms, where the routing algorithms aim to select the minimum number of relays of routing paths that will cover the network, and the resource allocation algorithms aim to schedule when each node is allowed to transmit on what frequency channel while simultaneously avoiding

collisions and utilizing allocated bandwidth efficiently by appropriately allocating the resources of the network to the network nodes. The network layer (routing layer) is responsible for handling the routing of messages, by application of routing algorithms, from source nodes to destination nodes by determining routing paths from sources to destinations that include one or more relay nodes. The media access control (MAC) sub-layer (which is part of the data link layer) is responsible for handling allocation of resources (frequency channels and time slots) to the network nodes for accessing the communication channel. As will be discussed, according to embodiments of the present disclosure the MAC sub-layer allocates channel resources to the nodes of the network based on the routing path information received from the network layer.

10 In the absence of collision avoidance mechanisms, for example, a relay node that is a neighbor node of a source node and that is part of a routing path from the source node to a destination node can be in a receiver configuration to receive a signal (carrying a message or packet) from the source (on a particular frequency channel during a particular time slot) but may be subjected to interference from a neighbor node of the relay node that is simultaneously
15 transmitting another signal (i.e., during the same time slot) on the same frequency channel but that is intended for a different node because the neighbor node is part of a different route path (i.e., the neighbor node transmits a different message) for a different source-destination node route. One drawback of collision avoidance when using conventional routing and resource allocation algorithms is that the efficiency of the network may decrease. For example, in order to avoid a
20 collision at the relay node, the MAC algorithms may require that the neighbor node delay its transmission to avoid interfering with the relay node's reception of the signal transmitted by the source node, or may require that the source node delay until after the neighbor node completes its transmission to ensure that the signal transmitted by the source node will be received by the relay node without interference from the neighbor node. This compromise in signal transmission timing
25 can result in a reduction of channel utilization to 33%.

Embodiments of the present disclosure provide a solution to the decrease in channel utilization, by employing adaptive beamforming (adaptive null steering) by relay nodes of the network that are subjected to interference from neighbor nodes. As will be discussed, the adaptive beamforming enables a relay node to detect a signal of interest while rejecting an interferer signal
30 that is transmitted simultaneously with the signal of the interest. The adaptive beamforming detects the signal of interest from signals at the output of the antenna array of the relay node by means of optimal spatial filtering and interference rejection.

Bearing the above in mind, and with continued reference to FIG. 1, reference is also made to FIG. 2, which illustrates a schematic block diagram of some of the components of an exemplary
35 node **12** that is part of the wireless communication network **10**. The node **12** includes a transceiver

14 that is operative in a plurality of frequency channels that define the operational RF band assigned to the wireless communication network **10**. The transceiver **14** is formed from a combination of a transmitter **16** and a receiver **38**. Without loss of generality, the node **12** is a representation of each of the nodes **12a** through **12i** of FIG. 1, as well as the nodes illustrated in
 5 FIG. 5. In other words, without loss of generality, each of the nodes illustrated in FIGS. 1 and 5 can be considered as having components represented in the exemplary block diagram of FIG. 2 (and the subcomponents illustrated in FIGS. 3 and 4). Furthermore, any nodes which may join the wireless communication network **10** can each be considered as having components represented in the exemplary block diagram of FIG. 2.

10 The transmitter **16** is capable of dynamically selecting one or more frequency channels (logical channels), selected from the plurality of frequency channels that define the operational RF band assigned to the wireless communication network **10**, and transmitting signals at one or more operational frequencies (for example in one or more sub-channels) in each of the selected one or more frequency channels to one or more neighbor nodes (relay nodes / next hop nodes). FIG. 3
 15 schematically illustrates an exemplary but non-limiting transmitter **16**, which includes a signal processing unit **18**, a digital to analog converter (DAC) **20**, a pair of band filters **22** and **28**, an RF amplifier **24**, gain control circuitry **26**, RF driver **30**, RF power amplifier **32**, and band harmonic filter **34**. The receiver also includes, or can be in signal communication with, an antenna **36**.

The signal processing unit **18** is operative to process (e.g., encode and modulate) and/or
 20 generate digital signals. The DAC **20** is in signal communication with the signal processing unit **18**, and is operative to convert digital signals received from the signal processing unit **18** to analog samples. The band filter **22** is in signal communication with the DAC **20** and is operative to filter the analog samples received from the DAC **20** so complete transformation of the analog samples to analog form. The RF amplifier **24** is in signal communication with the filter **22** and is operative
 25 to provide pre-amplification of the signals received from the filter **22**. The gain control circuitry **26** is in signal communication with the RF amplifier **24** and is operative to adjust the gain of the pre-amplified signals received from the RF amplifier **24**, for example by adjusting the attenuation level applied to the pre-amplified signal. Although not illustrated, the gain control circuitry **26** may be controlled by a control unit (e.g., a digital control unit or an analog control unit) that is linked
 30 to, connected to, or otherwise associated with, the signal processing unit **18**. The second band filter **28** is in signal communication with the gain control circuitry **26** and is operative to further filter the analog signals received from the gain control circuitry **26** in order to clean up any distortion products introduced by the RF amplifier **24**. The RF driver **30** is in signal communication with the band filter **28** and is operative to generate the RF signal to be transmitted, typically by modulating
 35 the signal received from the band filter **28** according to the modulation scheme defined by the

signal processing unit **18** and amplifying the signal to a level sufficient to drive the RF power amplifier **32**. The RF power amplifier **32** is in signal communication with the RF driver **30** and is operative to amplify the typically lower power waveform signal that is generated by the RF driver **30**. The band harmonic filter **34** is in signal communication with the RF power amplifier **32** and is
5 operative to apply harmonic filtering to the amplified signal received from the RF power amplifier **32** in order to reduce harmonic distortion effects resultant from power amplifier products at multiples of the transmit frequency (frequency channel). The antenna **36** (which may include one or more antenna elements, and may include a phased-array) is in signal communication with the band harmonic filter **34** and is operative to emit waves of electromagnetic radiation in frequency
10 channels (designated by the band filters **22** and **28**) corresponding to the signal received from band harmonic filter **34**.

The receiver **38** is preferably a wideband receiver that is, in certain embodiments, capable of simultaneously receiving and processing signals received from other nodes of the wireless communication network **10** in a plurality of different frequency channels (logical channels)
15 selected from the plurality of frequency channels that define the entire operational RF band assigned to the wireless communication network **10**. The receiving frequency channels are among the plurality of frequency channels from which the transmitter **16** selects to transmit (i.e., the transmitter **16** and receiver **38** both operate on frequencies that are selected from the same plurality of frequency channels). In such embodiments, the receiver **38** is referred to as a “multi-channel
20 receiver” or “MCR”. In other embodiments, the receiver **38** is operative to receive and process signals at one selected frequency channel at a time.

FIG. 4 schematically illustrates an exemplary receiver **38**. The receiver includes band preselector **42**, low-noise amplifier (LNA) **44**, gain control circuitry **46**, ADC driver **48**, anti-aliasing filter (AAF) **50**, analog to digital converter (ADC) **52**, and signal processing unit **54**. The
25 receiver also includes, or can be in signal communication with, an antenna array **40**.

The antenna array **40** is operable to receive a plurality of radio signals across the entire operational band of the wireless communication network **10**, and includes at least two antenna elements, designated in FIG. 4 as antenna elements **41a** and **41b**, to enable the node **12** to perform beamforming at the receiver **38**. Each of the antenna elements **41a** and **41b** accommodates an
30 associated antenna channel through which the signal (electromagnetic radiation) captured by the antenna element is propagated to the downstream front-end components of the receiver **38** (e.g., band selector **42**). Although only two antenna elements **41a** and **41b** are illustrated in the drawings, it is noted that the antenna array **40** can include any suitable number of antenna elements that enable beamforming. However, as will be discussed in subsequent sections of the present

disclosure, the beamforming techniques disclosed herein can achieve good performance even when using only two antenna elements.

The antenna elements of the antenna array **40** are preferably implemented and arranged so as to provide the antenna array **40** with a wide-angle aperture to enable the antenna array **40** to capture electromagnetic radiation over a wide spatial area. For example, the antenna elements can be implemented as omnidirectional antennas, and can be arranged in any suitable arrangement or array configuration, including, but not limited to, a linear array configuration, a rectangular array configuration, a square array configuration, a grid configuration, or any suitable polygonal array configuration.

Parenthetically, within the context of the present disclosure, the terms “antenna” and “antenna element” can be used interchangeably.

In certain embodiments, the transmitter **16** and the receiver **38** can share antenna elements. For example, the antenna array **40** can, in certain embodiments, include the antenna elements of the transmitter antenna **36**. In other embodiments, the transmitter **16** and the receiver **38** use different (i.e., separate) respective antenna elements.

The band selector **42** is in signal communication with the antenna array **40** and is operative to filter the beam weight multiplied analog signals received from the antenna elements of the antenna array **40** so as to select a frequency band (preferably a wideband range of frequencies) that includes a plurality of frequency channels. The LNA **44** is in signal communication with the band selector **42**, and is configured to increase the signal strength of the signals in the selected frequency band and to prevent noise in subsequent stages from contributing materially to signal sensitivity. The gain control circuitry **46** is in signal communication with the LNA **44** and provides gain control functionality, typically in the form of automatic gain control (AGC) functionality, by amplifying and/or attenuating, as necessary, the received signals from the LNA **44**. The ADC driver **48** is in signal communication with the gain control circuitry **46** and is operative to operate on the signals received from the gain control circuitry **46** by performing one or more of amplitude scaling, buffering, offset adjustment, and filtering. The AAF **50** is in signal communication with the ADC driver **48** and is operative to pass frequencies that are below the Nyquist bandwidth associated with the sampling rate of the ADC **52** and reject frequencies above the Nyquist bandwidth. The AAF **50** can be implemented as a low-pass filter having the associated Nyquist frequency as the filter cutoff frequency, or in cases where the ADC **52** may perform undersampling or downsampling the AAF **50** may be implemented as a band-pass filter. The ADC **52** is in signal communication with the AAF **50** and is operative to convert the signals from the AAF **50** to digital signals, i.e., to digitize the signals from the AAF **50**. Preferably, the ADC **52** is a high-speed high-dynamic-range ADC, such as those used in direct RF sampling receivers that can be, for example,

implemented as software defined radio receivers. Most direct RF sampling ADCs achieve a high clock rate using interleaving techniques. The signal processing unit **54** is in signal communication with the ADC **52** and is operative to process the digital signals from the ADC **52**. The signal processing unit **54** may include a digital filter bank for dividing the frequency band to a selected frequency channel (or multiple selected frequency channels if operating as a multi-channel receiver) so as to perform signal channelization, and a modem, for example in the form of one or more digital signal processors (DSPs), for demodulating, decoding, and generating digitized baseband signals at the selected frequency channel (the channelized signal) according to the modulation and coding scheme employed by the corresponding transmitter. The signal processing unit **54** may further employ one or more processors, for example in the form of one or more DSPs, for processing the digitized baseband signals to recover desired signals in each of the selected frequency channels. The signal processing unit **54** can, in certain embodiments, be implemented in suitably configured hardware, including, but not limited to, one or more application-specific integrated circuit (ASIC), one or more field-programmable gate array (FPGA), one or more field-programmable logic array (FPLA), and the like.

It is noted that the processing unit **18** of the transmitter **16** and the signal processing unit **54** of the receiver **38** may be part of a common processing arrangement or hardware arrangement having one or more signal processors. For example, the processing unit **18** and the signal processing unit **54** can be implemented in a single FPGA having one or more DSP cores that perform both transmitter and receiver functions. Alternatively, each of the processing unit **18** and the signal processing unit **54** can have its own dedicated processing arrangement having one or more DSP cores. For example, each of the processing unit **18** and the signal processing unit **54** can be implemented in a dedicated FPGA each having its own DSP core.

In certain preferred embodiments, the signal processing unit **54**, or the processing arrangement formed from the processing unit **18** and the signal processing unit **54**, is configured to calculate beam weights for performing beamforming at the receiver **38**. In other embodiments, a dedicated beamformer processor having one or more computer processors, such one or more DSPs, can be configured to calculate the beam weights for performing beamforming at the receiver **38**.

In certain embodiments, the network **10** is a decentralized network, such as a mobile ad-hoc network (MANET) that operates as a half-duplex (HDX) network. The HDX operation of the network means that during a given time slot, the network nodes can either transmit or receive, but not both. In other words, a network node cannot simultaneously transmit signals and receive signals, i.e., each node cannot receive during transmission and cannot transmit during reception.

In preferred embodiments, the receiver **38** is configured to perform digital beamforming, where the beamforming process is performed on the digitized and channelized outputs from the ADC **52**. In some embodiments, the signal derived from each of the antenna elements of the antenna array **40** is digitized and channelized by the ADC **52**, and these digitized signals are
5 digitally combined and then scaled and/or phase shifted via beam weight application (for example as applied by the signal processing unit **54**). In certain embodiments, the antenna elements of the antenna array **40** may share analog / RF front-end components (i.e., the antenna elements may commonly share the band selector **42**, LNA **44**, gain control circuitry **46**, ADC driver **48**, and AAF **50**) and may share a common ADC. In other digital beamforming embodiments, each antenna
10 element of the antenna array **40** may have its own set of analog / RF front end components (i.e., own band selector **42**, LNA **44**, gain control circuitry **46**, ADC driver **48**, and AAF **50**) that provides filtered and gain adjusted analog signal input from the antenna element to the ADC **52**. In other embodiments, each antenna element may be associated with its own ADC **52** for outputting a digitized signal for that antenna element, and the outputs from the ADCs may be
15 digitally combined and then scaled and/or phase shifted via beam weight application (for example as applied by the signal processing unit **54**).

It is noted that in certain embodiments the receiver **38** may operate as a multi-channel receiver but only perform digital beamforming for one selected channel at a time as needed, for example if that selected channel supports unicast transmission for example as part of an HDR
20 service. Alternatively, the receiver **38** may operate as a multi-channel receiver and perform digital beamforming for more than one channel of the multiple channels. Further still, the receiver **38** may operate as a single-channel receiver and perform digital beamforming for one selected channel at a time. Details of the digital beamforming process for both single-channel and multi-channel will be provided in subsequent sections of the present disclosure.

With continued reference to FIGS. 1 – 4, refer now to FIG. 5 which schematically illustrates an example communication scenario involving four nodes, all of which can be nodes of the network **10**, in which the communication method according to embodiments of the present disclosure can be performed. It is noted that the use of a relatively small number of nodes in FIG.
25 5 is solely for the purposes of illustrating the communication method, including beamforming processing, according to embodiments of the present disclosure. As should be apparent, the communication method, including the beamforming processing, performed by the nodes illustrated in FIG. 5 can be extrapolated to any number of the nodes of the network **10**.

Bearing the above in mind, in FIG. 5, a relay node **R₁** of the network **10** performs adaptive beamforming according to embodiments of the present disclosure. In the illustrated example, the
35 relay node **R₁** performs adaptive beamforming to detect a signal of interest **S₁** (also referred to as

a “desired signal”) by means of optimal spatial filtering and interference rejection to reject an interferer signal S_2 . The signal S_1 is transmitted by the node $\mathbf{T_x}$ of the network **10**, and is intended for receipt by the relay node $\mathbf{R_1}$ which is in (i.e., is a part of) the routing path for the message session associated with a message carried by the signal S_1 . The relay node $\mathbf{R_1}$ is a neighbor to the node $\mathbf{T_x}$. Simultaneously with the transmission of the signal S_1 by the node $\mathbf{T_x}$, another node $\mathbf{R_2}$ of the network **10**, which is a neighbor to the relay node $\mathbf{R_1}$, transmits signal S_2 . The signal S_2 can carry a message that can be different from the message carried by the signal S_1 , for example as part of a different message session than the session associated with the message carried by the signal S_1 . In the illustrated example, the signal S_2 is intended for receipt by node $\mathbf{R_3}$, which can be part of a routing path for the message session associated with the message carried by the signal S_2 . Due to the wide-angle aperture of the antenna elements of the antenna array **40** of the relay node $\mathbf{R_1}$, and due to the relay node $\mathbf{R_1}$ being within range of the node $\mathbf{R_2}$, the signal S_2 can be received at the relay node $\mathbf{R_1}$.

As mentioned, the signals S_1 and S_2 are transmitted simultaneously, i.e., they are transmitted in the same time slot, and in addition are transmitted on the same frequency channel, as allocated by the MAC sub-layer. This simultaneous transmission of signals S_1 and S_2 , coupled with the capability of the relay node $\mathbf{R_1}$ to contemporaneously receive both of the signals S_1 and S_2 , results in the signal S_2 being presented to the relay node $\mathbf{R_1}$ as an interferer signal that interferes with the ability of the relay node $\mathbf{R_1}$ to cleanly receive (i.e., detect, demodulate, process, etc.) the signal S_1 (which is the signal of interest for the relay node $\mathbf{R_1}$). In the example illustrated in FIG. 5, the node $\mathbf{R_2}$ presents as a hidden terminal for the node $\mathbf{T_x}$, and the relay node $\mathbf{R_1}$ presents as an exposed terminal.

In general, signal received at any node can include multiple signal components. Those signal components can include a signal of interest, and noise and interference. In the example illustrated in FIG. 5, the signal components of signal received at the relay node $\mathbf{R_1}$ include the signal of interest transmitted from the node $\mathbf{T_x}$, the interferer signal transmitted from the neighbor of the node $\mathbf{R_1}$ (i.e., node $\mathbf{R_2}$), and noise and other interference.

The relay node $\mathbf{R_1}$ performs adaptive beamforming to detect the signal of interest S_1 by taking advantage of the angular separation between the lines of sight (LOSs) of the node $\mathbf{T_x}$ and the interfering node $\mathbf{R_2}$. This angular separation between the LOSs of the node $\mathbf{T_x}$ and the interfering node $\mathbf{R_2}$ is composed of the angular separation between the LOSs of the relay node $\mathbf{R_1}$ and the node $\mathbf{T_x}$ (designated α_1) and the angular separation between the LOSs of the relay node $\mathbf{R_1}$ and the interfering node $\mathbf{R_2}$ (designated α_2). This angular separation is exploited in order to spatially suppress the interfering signal component (signal S_2) in the total signal received at the

relay node $\mathbf{R}_1$. Thus, the total angular separation between the LOSs of the node $\mathbf{T}_x$ and the interfering node $\mathbf{R}_2$ can be designated as $|\alpha_1| + |\alpha_2|$.

As part of the digital beamforming processing, the relay node $\mathbf{R}_1$, for example using the signal processing unit **54**, calculates a vector of optimal beam weights that can be applied to the received signal derived from the output of the antenna elements of the antenna array **40** for beamforming. In embodiments in which the receiver **38** performs digital beamforming, the beam weights are calculated as part of the signal receiving process, which as will be discussed below includes correlation processing using synchronization sequences.

In general, when using an antenna array of N elements (where N is greater than or equal to two), the received signal for the vector of N elements at a relay node can be expressed as follows:

$\mathbf{y}(t) = \mathbf{h}(\alpha_1) \cdot x(t) + \sqrt{ISR} \cdot \mathbf{h}(\alpha_2) \cdot d(t) + 1/\sqrt{SNR} \cdot \mathbf{v}(t)$, where $\mathbf{y}$ is the received signal vector on the N antenna elements of the antenna array **40** of the relay node, x is the desired signal (i.e., the signal of interest, e.g., signal S_1 in FIG. 5) arriving from the corresponding transmitter (e.g., node $\mathbf{T}_x$ in FIG. 5) at an angle of arrival (e.g., α_1 in FIG. 5) and at a received power P_x , d is the interferer signal (e.g., signal S_2 in FIG. 5) arriving from the node that neighbors the relay node (i.e., the node $\mathbf{R}_2$ in FIG. 5) at an angle of arrival (e.g., α_2 in FIG. 5) and at a received power P_d , $\mathbf{v}$ is the thermal noise vector in the N antenna channels having noise power P_v , $\mathbf{h}(\alpha)$ is the spatial-channel vector of a signal arriving at the relay node receiver at angle of arrival α , SNR is the ratio of the desired signal power to the noise power at the antenna array of the relay node (i.e., $SNR = \frac{P_x}{P_v}$), and ISR is the ratio of the interferer signal power to the desired signal power at the antenna array of the relay node (i.e., $ISR = \frac{P_d}{P_x}$).

Since the node transmitting the desired signal x (e.g., node $\mathbf{T}_x$ in FIG. 5) and the node transmitting the interferer signal d (e.g., the node $\mathbf{R}_2$ in FIG. 5) are part of the same network **10** which maintains approximately constant transmit power across the nodes, it can be generally assumed that the signal powers of the two signals are approximately equal. Therefore, $ISR = \frac{P_d}{P_x} \approx 1$.

Multiplication of the signal $\mathbf{y}(t)$ above by a vector of calculated beam weights $\mathbf{w}$ produces a desired received signal $\mathbf{y}_{eq}(t)$ (also referred to as an equalized signal), which can be expressed as follows:

$\mathbf{y}_{eq}(t) = \mathbf{w}^H \cdot \mathbf{y}(t) \cong x(t) + \frac{1}{\sqrt{SNR_{pp}}} \cdot v_{eq}(t)$, where $\mathbf{w}$ is the vector of optimal beam weights (calculated, for example, by the signal processing unit **54**), $\mathbf{y}_{eq}$ is the signal output after multiplication of $\mathbf{y}$ by the beam weight vector $\mathbf{w}$, v_{eq} is the noise signal plus residual signal

components from the interferer signal d and having power P_{veq} , and $SINR_{pp}$ is the ratio of the desired signal power to the noise plus residual interferer power, where $SINR_{pp} = \frac{P_x}{P_{veq}}$. As can be seen, by performing the beamforming processing, the equalized signal in-effect is comprised of signal components that includes the desired signal (x) and noise (v_{eq}), which can be easily
 5 processed (e.g., demodulated, decoded, etc.) to extract the message carried by the signal of interest from the equalized signal.

According to certain embodiments of the present disclosure, the calculation of optimal beam weights is performed as part of the overall receiver processing and is based on synchronization sequences, in particular the synchronization sequence that is utilized by the node
 10 transmitting the desired signal and is carried in the desired signal as part of a message preamble. In general, each transmitting node of the network **10** may utilize a (binary) synchronization sequence as part of a message preamble (for example as a pilot sequence). The preamble sequence can be used by the node receivers, for which the transmitted desired signal is intended, for example, in a receiving process similar to as is performed in orthogonal frequency division multiplexing
 15 (OFDM) communication systems. According to certain embodiments of the present disclosure, the node transmitting the desired signal and the node transmitting the interferer signal use different respective synchronization sequences of the same length which are orthogonal to each other. In certain embodiments, the synchronization sequences can be orthonormal sequences. The relay node, for which the desired signal is intended, calculates the optimal beam weights using an
 20 optimization criterion which minimizes the MSE (Mean Squared Error) based on the synchronization sequences used by the node transmitting the desired signal, and using the fact that the synchronization sequence used by the node transmitting the desired signal and the synchronization sequence used by the node transmitting the interferer signal are orthogonal. In particular, the relay node, for which the desired signal is intended, performs correlation processing
 25 of the received signal by correlating the received signal with the synchronization sequence used by the node transmitting the desired signal. Since the synchronization sequences used by the node transmitting the desired signal and the node transmitting the interferer signal are orthogonal, the correlation will be maximum when the relay node uses the synchronization sequence used by the node transmitting the desired signal, and will be minimum when the relay node uses the
 30 synchronization sequence used by the node transmitting the interferer signal.

The synchronization sequences can be allocated by the network layer (i.e., the routing layer), and can be generated using any suitable algorithm that generates one or more set of orthogonal binary sequences of the same length and power. In certain embodiments, the set of binary sequences can be a set of orthonormal sequences. The network layer can, as part of its

routing algorithms for handling routing of messages from source nodes to destination nodes, determine which nodes of the network **10** will use which synchronization sequence according to the routing path determined from the source to the destination. For example, each routing path for a message session may be associated with a particular synchronization sequence. In certain
5 embodiments, the synchronization sequences can be stored in a look-up table or a routing table distributed amongst the nodes of the network **10** and for example stored in a memory of the nodes of the network **10**. A particular node can then select (look-up) a synchronization sequence from the look-up or routing table according to the network layer algorithms. Accordingly, a signal of interest transmitted by a transmitting node includes (carries) a selected synchronization sequence
10 (for example looked-up by the transmitting node from a routing table), and the relay node for which the signal of interest is intended knows that it is part of the relay path (from the routing algorithms) and uses the selected synchronization sequence associated with that routing path (for example as identified in the look-up table or the routing algorithm) that is embedded in the signal of interest to perform a correlation on the received signal. The relay node can then, while using
15 the correct synchronization sequence, calculate the optimal beam weight vector, where the optimization criterion can minimize MSE.

In order for relay nodes to know which synchronization sequence to use and when to use that synchronization sequence (i.e., when to correlate the received signal with the correct synchronization sequence), synchronization sequence information and message session timing
20 information are provided to the relay nodes of the routing path, for example by the MAC sub-layer as part of network configuration steps for message session initialization. Accordingly, when a communication service for a message session is initialized, the MAC sub-layer can, in certain embodiments, provide the relay nodes in the routing path (determined by the network layer) for that message session with the appropriate synchronization sequence (i.e., the synchronization
25 sequence that will produce a maximum correlation), and timing information which provides an indication of when to use the appropriate synchronization sequence (i.e., at which point during the receiving time interval the relay node should perform the correlation processing).

According to embodiments of the present disclosure, the MAC sub-layer allocates channel resources to a node based on the routing path information received from the network layer. In other
30 words, channel access information is provided to a given node by the MAC sub-layer once the MAC sub-layer knows that given node is a relay node in a routing path from a source node. This channel access information includes the synchronization sequence information that the relay node is to use in order to perform optimal beam weight calculation. Without this routing information, the MAC sub-layer may not be able to properly sense availability of channel resources and thus
35 may not be able provide matching against the synchronization sequence in the relays (i.e., may not

be able to provide appropriate synchronization sequence information to enable optimal beam weight calculation).

It is noted that in certain embodiments, the beam weights may be calculated according to other criteria, which may, in certain cases, be sub-optimal criteria. For example, the beam weights may be calculated according to criteria that do not minimize MSE. As one particular example, the beam weights may be calculated using minimum variance distortionless response (MVDR) beamforming algorithm, which may, in certain cases, produce sub-optimal beam weight calculation.

The interferer rejection techniques afforded by the beamforming methods described herein are particularly suitable for use with unicast transmissions, whereby a routing path from a source node to a destination node is created – by the network layer routing algorithms – and that routing path is used throughout the duration of the message session. In unicast service transmission, once the routing path is known and fixed, each relay node in the routing path can spatially direct its antenna array to receive the signal of interest from the single node transmitting that signal, and can simultaneously performing nulling to reject a potential interferer signal transmitted from a neighboring node.

In general, more synchronization sequences can be added to accommodate rejection of interferer signals from multiple neighboring nodes. However, when the signal of interest is transmitted according to a unicast service, two orthogonal synchronization sequences may be sufficient to perform interference rejection from a single neighbor node. For example, in the non-limiting example configuration illustrated in FIG. 5, the nodes **T_x** and **R₂** use respectively different (and orthogonal) synchronization sequences during transmission of their respective messages. Once node **T_x** completes its transmission, the synchronization sequence used by node **T_x** can be re-used by a different node of the network **10** that may be a relay node of a routing path for a different message session that is spatially separated (i.e., out of signal range) of any relay node that is concurrently (simultaneously) transmitting the message from node **T_x**.

Although the interferer rejection techniques afforded by the beamforming methods described herein are particularly suitable for use with unicast transmissions, interferer rejection according to certain embodiments of the present disclosure can be implemented for non-unicast services, for example multi-cast services or broadcast services. In multi-cast services, for example, more than one hidden terminal may be transmitting in the presence of a relay node that is attempting to receive a signal of interest from a source node. In such scenarios, each hidden terminal has its own synchronization sequence, and the relay node can perform selective beamforming to selectively reject interferer signals from those transmitting hidden terminals.

The beamforming process for interferer rejection performed by relay nodes has been described thus far in the context of a relay node operating as a single channel receiver. However, as mentioned above, relay nodes may operate according to a multi-channel receiver configuration and perform digital beamforming for more than one channel of the multiple channels. In such
5 embodiments, a relay node may simultaneously be part of a plurality of routing paths on different channels such that the relay node simultaneously receives a plurality of signals of interest from a corresponding plurality of source nodes on a corresponding plurality of channels. For example, a given relay node may simultaneously receive a first signal of interest from a first source node on a first logical channel, a second signal of interest from a second source node on a second logical
10 channel, and so on. Multiple neighbor nodes of the relay node may be simultaneously transmitting with the source nodes on the same channels as those source nodes, and the transmissions from the neighbor nodes present as interferer signals to the relay node. For example, a first neighbor node may be simultaneously transmitting with the first source node on the first logical channel, a second neighbor node may be simultaneously transmitting with the second source node on the second
15 logical channel, and so on. The relay node may perform beamforming to detect the different source node signals and reject the interferer signals from the multiple neighbor nodes that are simultaneously transmitting with the source nodes on the same channels as those source nodes. The relay node may perform the beamforming per channel where there is an interferer signal.

Each relay node that performs a relay function to route a message to a next node along a
20 routing path can generally perform processing steps to receive messages and then processing steps to transmit (route) the message to the next node. According to certain embodiments, the processing performed at each receiving (relay) node may generally include the steps of: i) performing optimal spatial filtering and interference rejection using antenna weighting and combining (performing adaptive beamforming), ii) message decoding, which can include demodulation and decoding, and
25 iii) encoding of the decoded message and transmission of the encoded message to the next node in the routing path. Steps i) and ii) can be generally thought of as part of receiving processing, whereas step iii) can be generally thought of as transmission processing.

It is noted that following paragraphs describe, with reference to FIGS. 6 and 7, methods (processes), according to certain embodiments of the present disclosure, that include multiple
30 steps, including various sub-steps that encompass and relate to step i) (i.e., the performance of adaptive beamforming). It should be apparent that the methods of FIGS. 6 and 7 can also include sub-steps that encompass and/or relate to steps ii) and iii), as well as additional sub-steps.

Attention is now directed to FIG. 6, which shows a flow diagram detailing a process **600**
in accordance with embodiments of the disclosed subject matter. The process **600** includes an
35 algorithm for communicating in a wireless communication network, such as the network **10**, where

each node of the wireless communication network is provided with a transceiver architecture, some (and in some cases) all of which are capable of perform beamforming function according to the embodiments of the present disclosure. Reference is also made to the elements of FIGS. 1 – 5. The process and sub-processes of FIG. 6 include computerized (i.e., computer-implemented) processes performed by the various nodes of the network and their associated components, including the node transceivers **14**, including the transmitter **16** and the receiver **38** and their associated sub-components. The aforementioned process and sub-processes are for example, performed automatically, and are performed, for example, in real time.

The process **600** begins at step **602**, which can be considered as a network configuration step whereby nodes are initialized or configured to support a communication service initiated for a message session (or sessions) for a source node (or nodes). For example, as part of step **602**, a source node can initiate a unicast service or other transmission service to propagate a message as part of a message session to a destination node, and the network layer can generate a routing path from the source node to the destination node. As part of step **602**, the synchronization sequence or sequences for each message session can also be allocated (or distributed) amongst the relevant nodes for the routing path, and each relay node in the routing path can be provided with instructions (for example by the MAC sub-layer) as to which synchronization sequence to use and when to use that synchronization sequence.

At step **604**, which can also be considered as a node configuration step, a relay node that neighbors the source node and that is in (i.e., is part of) the routing path, and that is to receive a signal of interest from the source node, determines which synchronization sequence to use and when to use that synchronization sequence (for example from instructions provided by the MAC sub-layer) in order to perform optimal reception of the signal of interested that is transmitted from the source node.

At step **606**, the source node transmits a signal of interest that is intended for receipt by the relay node that neighbors the source node and that is in (i.e., is a part of) the routing path. The signal of interest carries the message and a synchronization sequence, and is part of a message session. The source node transmits the signal of interest during a time slot and on a frequency channel, as allocated by the MAC sub-layer.

The signal transmission associated with step **606** occurs simultaneously with a signal transmission by another node of the wireless communication network that neighbors the relay node. In other words, the signal transmitted by the other node occurs during the same time slot as the transmission of the signal of interest by the source node. In addition, the other node transmits its signal on the same frequency channel as the transmission of the signal of interest. This transmission during the same time slot and on the same frequency channel presents the signal

transmitted by the other node as an interferer signal to the relay node. In other words, the signal transmitted by the other node acts as an interferer signal for the relay node. The transmission of the interferer signal during the same time slot as the signal of interest is designated as step **608**.

At step **610**, beamforming is performed at the relay node, by calculating optimal beam weights based on the synchronization sequence in the signal transmitted by the source node, to reject the interferer signal and to detect the signal of interest.

It is noted that step **604** can be repeated for each relay node in the routing path for a message session as needed. In addition, step **602** can be repeated (or executed in parallel with other executions of step **602**) throughout the operation of the wireless communication network for other nodes propagating other messages for other message sessions. Furthermore, steps **606 – 610** can be repeated for each of one or more message session. For example, step **608** can be used by each of one or more relay node in each of one or more message session, where each message session has an associated routing path from a source node to a destination node.

FIG. 7 shows a flow diagram detailing a process **700** in accordance with embodiments of the disclosed subject matter that is generally similar to the process of FIG. 6, but is more explicit in terms of steps that can be performed for each message session.

The process **700** begins at step **702**, which similar to step **602** can be considered as a network configuration step whereby nodes are initialized or configured to support communication services initiated for one or more source node. For example, as part of step **702**, one or more message sessions that support communication (propagation) of respective messages through the network from respective source nodes to respective destination nodes can be initiated.

Steps **704 – 712** are performed for each of one or more of the message sessions initiated at step **702**.

At step **704**, for each message session, the network layer can determine (generate) a routing path from a source node for that message session to an associated destination node for that message session (for example, using a unicast service) in order to support routing of a message for the message session from the source to the destination. The routing path for each message session includes one or more relay node, where the first relay node neighbors the source node and each subsequent relay node neighbors the previous relay node in the routing path.

At step **706**, which can also be considered as a node configuration step, a relay node in the routing path (that is to receive a desired signal from a source node) determines which synchronization sequence to use (for example as directed by the MAC sub-layer) and when to use that synchronization sequence in order to perform optimal reception of the desired signal from the source node.

At step **708**, for each routing path, the source node transmits a signal of interest that is intended for receipt by the relay node that neighbors the source node and that is part of the routing path. The signal of interest carries a synchronization sequence (e.g., preamble) and a message which are part of the message session. The source node transmits the signal of interest during a
5 time slot and on a frequency channel, as allocated by the MAC sub-layer.

For each routing path (i.e., each message session), the signal transmission associated with step **708** occurs simultaneously with a signal transmission by another node of the wireless communication network that neighbors the relay node. In other words, the signal transmitted by the other node occurs during the same time slot as the transmission of the signal of interest by the
10 source node. In addition, the other node transmits its signal on the same frequency channel as the transmission of the signal of interest. This transmission during the same time slot and on the same frequency channel presents the signal transmitted by the other node as an interferer signal to the relay node. The transmission of the interferer signal during the same time slot as the signal of interest is designated as step **710**.

At step **712**, beamforming is performed at the relay node, by calculating optimal beam weights based on the synchronization sequence in the signal transmitted by the source node, to reject the interferer signal and to detect the signal of interest.

It is noted that step **702** can be repeated periodically as new message sessions are initiated, and step **706** can be repeated for each relay node in the routing path as needed. The remaining
20 steps **704**, **708**, **710**, and **712** can also be repeated as needed.

In the context of the present disclosure, a “message”, that is carried by a signal that is transmitted from one node of the network **10** to a destination (such as another node of the network **10**) includes operative information which can include various types of data and information that is to be propagated by the network **10** from one node to another node, including, but not limited to,
25 voice data, image data, video data, command and control data (for example for controlling remote devices deployed on or implemented as other nodes of the network, for example surveillance drone), and the like. A “message” can include synchronization information, for example in the form of preamble data (i.e., a synchronization sequence), for indicating the start of the message transmission, as well as a postamble for indicating the end of the message transmission. The
30 operative information in the “message” can also be referred to as a “payload”.

As should be apparent from the foregoing description, the communication method, using beamforming techniques, and the wireless communication network, according to embodiments of the present disclosure provide several advantages over conventional methods and networks. One clear advantage is the increase in channel utilization. In fact, by using the beamforming techniques
35 disclosed herein, the ratio of source node required time slots to relay node required time slots is

increased from 1 to 2 (as in conventional methods and networks) to 1 to 1, increasing channel utilization in some cases by 33%. This increase in channel utilization leads to another advantage in the form of increased network efficiency.

It should be noted that the communication method using the disclosed beamforming techniques may not guarantee with certainty complete rejection of interferer signals originating from other nodes of the network **10**. However, the beamforming techniques are typically used under the assumption that all of the nodes in a routing path are known whereby each progressive relay node is closer to the destination node than is the preceding node in the routing path, resulting in both lower interference level and a high angular separation between LOSs of pairs of nodes (a source node and interfering node) that simultaneously emit signal transmissions that can be received by a common node. This is schematically illustrated in FIG. 8, which shows nodes labeled '1', '2', '3', and '8'. Node 8 is the destination node in a routing path (that includes at least node 2) from node 1. Node 8 is the destination node in a routing path (that includes at least nodes 2 and 3 which act as relay nodes) from node 1, whereby the relay node 3 is closer to the destination node 8 than is the relay node 2. Parenthetically, it can be assumed that there may be additional relay nodes between relay node 3 and the destination node 8, each additional relay node being closer to the destination node 8 than the preceding relay node. Due to this decreasing distance between relay nodes and destination node when progressing along the routing path, the angular separation between the LOSs of the node transmitting the signal of interest (e.g., node 1) and a potential interfering node (i.e., a hidden terminal, e.g., node 3) of the network increases, such that beam directivity enabled by the beamforming techniques according to embodiments of the disclosure can, with high probability (and in many cases, if not most cases, with near certainty), successfully reject interferer signals from those interfering nodes.

In fact, once a minimum angular separation between the LOSs of the nodes is achieved, the beamforming techniques disclosed herein all but guarantee successful interferer rejection. Moreover, increasing the number of antenna elements of the antenna array reduces the minimum angular separation that is needed to achieve successful interferer rejection. As mentioned, the communication method, utilizing beamforming processing, according to certain embodiments of the present disclosure is of particular value when used in HDR transmission, for example in situations where transmission of wideband / broadband data from a source to destination is necessary. This can be particularly advantageous, for example, in embodiments where the network **10** is implemented as a tactical MANET, where high bandwidth data, such sets of one or more images or videos, is captured by a surveillance drone (which can itself be a node of the network **10**) and requires priority routing to a destination node, for example implemented as a ground station terminal.

Although the beamforming techniques discussed thus far have been described in the context of digital beamforming, embodiments are contemplated herein in which the receiver of the nodes can be configured to perform analog beamforming. In some analog beamforming embodiments, the signal at each antenna channel is scaled and/or phase-shifted by multiplying the signal with an appropriate beam weight that corresponds to a scaling factor (imparted, for example, by an amplitude adjustor circuit such as a digitally controlled attenuator) and/or phase shift (imparted, for example, by a phase adjustor circuit), and then these weighted signals are combined prior to input to the band selector 42. In other analog beamforming embodiments, the antenna elements of the antenna array 40 may be mechanically coupled to mechanical steering arrangements, such as multi-axis gimbal mounts, that can individually steer the beams of each antenna element via mechanical control, for example gimbal control. In such embodiments, the beam weight for each antenna element can be applied via appropriate control of the steering arrangement for that antenna element. It is noted that analog beamforming embodiments may be less preferred to digital beamforming embodiments, as analog embodiments, in addition to requiring additional components in hardware (e.g., phase adjustors, attenuators, gimbals, etc.), may also require iterative beam weight calculation algorithms according to the synchronization sequence-based correlation.

Implementation of the systems and/or methods of embodiments of the disclosure can involve performing or completing selected tasks implemented by hardware, by software or by firmware or by a combination thereof. For example, hardware for performing selected tasks according to embodiments of the disclosure could be implemented as a chip or a circuit. As software, selected tasks according to embodiments of the disclosure could be implemented as a plurality of software instructions being executed by a computer using any suitable operating system. In certain embodiments of the disclosure, one or more tasks according to exemplary embodiments of systems and/or methods as described herein are performed by a computerized data processor that can execute a plurality of instructions. Optionally, the data processor includes a volatile memory for storing instructions and/or data and/or a non-volatile storage, for example, non-transitory storage media such as a magnetic hard-disk and/or removable media, for storing instructions and/or data.

For example, any combination of one or more non-transitory computer readable (storage) medium(s) may be utilized in accordance with the above-listed embodiments of the present disclosure. The non-transitory computer readable (storage) medium may be, for example, but not limited to, an electronic, magnetic, optical, electromagnetic, infrared, or semiconductor system, apparatus, or device, or any suitable combination of the foregoing. More specific examples (a non-exhaustive list) of the computer readable storage medium would include the following: a portable

computer diskette, a hard disk, a random-access memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM or Flash memory), a portable compact disc read-only memory (CD-ROM), an optical storage device, a magnetic storage device, or any suitable combination of the foregoing. In the context of this document, a computer readable storage
5 medium may be any tangible medium that can contain, or store a program for use by or in connection with an instruction execution system, apparatus, or device.

As will be understood with reference to the paragraphs and the referenced drawings, provided above, various embodiments of machine-implemented methods are provided herein, some of which can be performed by various embodiments of systems described herein and some
10 of which can be performed according to instructions stored in non-transitory computer-readable storage media described herein. Still, some embodiments of machine-implemented methods provided herein can be performed by other systems and can be performed according to instructions stored in computer-readable storage media other than that described herein, as will become apparent to those having skill in the art with reference to the embodiments described herein. Any
15 reference to systems and computer-readable storage media with respect to machine-implemented methods is provided for explanatory purposes, and is not intended to limit any of such systems and any of such non-transitory computer-readable storage media with regard to embodiments of computer-implemented methods described above. Likewise, any reference to machine-implemented methods with respect to systems and computer-readable storage media is provided
20 for explanatory purposes, and is not intended to limit any of such computer-implemented methods disclosed herein.

The block diagrams and flowcharts in the drawings illustrate the architecture, functionality, and operation of possible implementations of systems and/or methods according to various embodiments of the present disclosure. In this regard, each block in the block diagrams or
25 flowcharts may represent a module, segment, or portion of code, which comprises one or more executable instructions for implementing the specified logical function(s). It should also be noted that, in some alternative implementations, the functions noted in the block may occur out of the order noted in the figures. For example, two blocks shown in succession may, in fact, be executed substantially concurrently, or the blocks may sometimes be executed in the reverse order, depending upon the functionality involved. It will also be noted that each block of the block
30 diagrams and/or flowchart illustration, and combinations of blocks in the block diagrams and/or flowchart illustration, can be implemented by special purpose hardware-based systems that perform the specified functions or acts, or combinations of special purpose hardware and computer instructions.

The descriptions of the various embodiments of the present disclosure have been presented for purposes of illustration, but are not intended to be exhaustive or limited to the embodiments disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art without departing from the scope and spirit of the described embodiments. The terminology used
5 herein was chosen to best explain the principles of the embodiments, the practical application or technical improvement over technologies found in the marketplace, or to enable others of ordinary skill in the art to understand the embodiments disclosed herein.

As used herein, the singular form, “a”, “an” and “the” include plural references unless the context clearly dictates otherwise.

10 The word “exemplary” is used herein to mean “serving as an example, instance or illustration”. Any embodiment described as “exemplary” is not necessarily to be construed as preferred or advantageous over other embodiments and/or to exclude the incorporation of features from other embodiments.

It is appreciated that certain features of the disclosure, which are, for clarity, described in
15 the context of separate embodiments, may also be provided in combination in a single embodiment. Conversely, various features of the disclosure, which are, for brevity, described in the context of a single embodiment, may also be provided separately or in any suitable subcombination or as suitable in any other described embodiment of the disclosure. Certain features described in the context of various embodiments are not to be considered essential features
20 of those embodiments, unless the embodiment is inoperative without those elements.

To the extent that the appended claims have been drafted without multiple dependencies, this has been done only to accommodate formal requirements in jurisdictions which do not allow such multiple dependencies. It should be noted that all possible combinations of features which would be implied by rendering the claims multiply dependent are explicitly envisaged and should
25 be considered part of the disclosure.

Although the disclosure has been described in conjunction with specific embodiments thereof, it is evident that many alternatives, modifications, and variations will be apparent to those skilled in the art. Accordingly, it is intended to embrace all such alternatives, modifications and variations that fall within the spirit and broad scope of the appended claims.

WHAT IS CLAIMED IS:

1. A method for communicating in a wireless communication network having a plurality of nodes, the method comprising:
transmitting a signal of interest by a first node of the plurality of nodes, the signal of interest intended for receipt by a second node of the plurality of nodes that is a relay node in a routing path from the first node; and
performing beamforming at the second node to detect the signal of interest and to reject an interferer signal that is transmitted by a third node of the plurality of nodes simultaneously with transmission of the signal of interest by the first node, wherein the signal of interest and the interferer signal are transmitted on a same frequency channel.
2. The method of claim 1, wherein the transmitting the signal of interest by the first node is a unicast transmission.
3. The method of claim 1, wherein the wireless communication network is a half-duplex communication network.
4. The method of claim 1, wherein the wireless communication network is a mobile ad-hoc network.
5. The method of claim 1, wherein the signal of interest carries a first message and the interferer signal carries a second message, and wherein the first and second messages belong to different respective message sessions of the wireless communication network.
6. The method of claim 1, wherein the interferer signal is a signal of interest for an additional node of the wireless communication network.
7. The method of claim 1, wherein performing the beamforming at the second node rejects an additional interferer signal that is transmitted by an additional node of the plurality of nodes simultaneously with the first node transmitting the signal of interest, wherein the additional node is a neighbor to the second node.

8. The method of claim 1, wherein the signal of interest carries a first synchronization sequence and the interferer signal carries a second synchronization sequence that is orthogonal to the first synchronization sequence.

9. The method of claim 1, wherein performing the beamforming at the second node includes calculating beam weights for applying to signal received from output of the second node.

10. The method of claim 9, wherein calculating the beam weights is based on a synchronization sequence used by the first node and carried in the signal of interest.

11. The method of claim 1, wherein the beamforming performed by the second node is digital beamforming.

12. A wireless communication network comprising:

a plurality of nodes including at least a first node, a second node, and a third node, the second node being a relay node in a routing path from the first node,
the first node configured to transmit a signal of interest intended for receipt by the second node, and
the second node configured to perform beamforming to detect the signal of interest and to reject an interferer signal that is transmitted by the third node simultaneously with transmission of the signal of interest by the first node, wherein the signal of interest and the interferer signal are transmitted on a same frequency channel.

13. The wireless communication network of claim 12, wherein the first node is configured to transmit the signal of interest as a unicast transmission.

14. The wireless communication network of claim 12, wherein the wireless communication network is a half-duplex communication network.

15. The wireless communication network of claim 12, wherein the wireless communication network is a mobile ad-hoc network.

16. The wireless communication network of claim 12, wherein the signal of interest carries a first message and the interferer signal carries a second message, and wherein the first and second messages belong to different respective message sessions of the wireless communication network.

17. The wireless communication network of claim 12, wherein the plurality of nodes further includes an additional node, and wherein the interferer signal is a signal of interest for the additional node.

18. The wireless communication network of claim 12, wherein the second node is configured to perform beamforming to reject an additional interferer signal that is transmitted by an additional node of the plurality of nodes simultaneously with the first node transmitting the signal of interest.

19. The wireless communication network of claim 12, wherein the signal of interest carries a first synchronization sequence and the interferer signal carries a second synchronization sequence that is orthogonal to the first synchronization sequence.

20. The wireless communication network of claim 12, wherein the second node performs beamforming by calculating beam weights for applying to signal received from output of the second node.

21. The wireless communication network of claim 20, wherein the third node calculates the beam weights based on a synchronization sequence used by the first node and carried in the signal of interest.

22. The wireless communication network of claim 12, wherein the second node is configured to perform digital beamforming.

23. A method for communicating in a wireless communication network having a plurality of nodes, the method comprising:

for each of one or more message sessions for communicating a message of the message session through the wireless communication network:

determining a routing path for routing the message from a source node to a destination node, the routing path at least including a relay node that neighbors the source node, wherein the source node, the relay node, and the destination node are each one of the plurality of nodes, wherein communication between the source node and the relay node is performed according to any one of claims 1 to 11, the source node and the relay node being the first node and the second node, respectively.