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(54) **ISOLATION BETWEEN ANTENNAS USING ELECTROMAGNETIC POLARIZERS**

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H01Q 15/24 (2006.01)

(52) **U.S. Cl.**
CPC ***H01Q 1/525*** (2013.01); ***H01Q 15/242*** (2013.01)

(58) **Field of Classification Search**
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See application file for complete search history.

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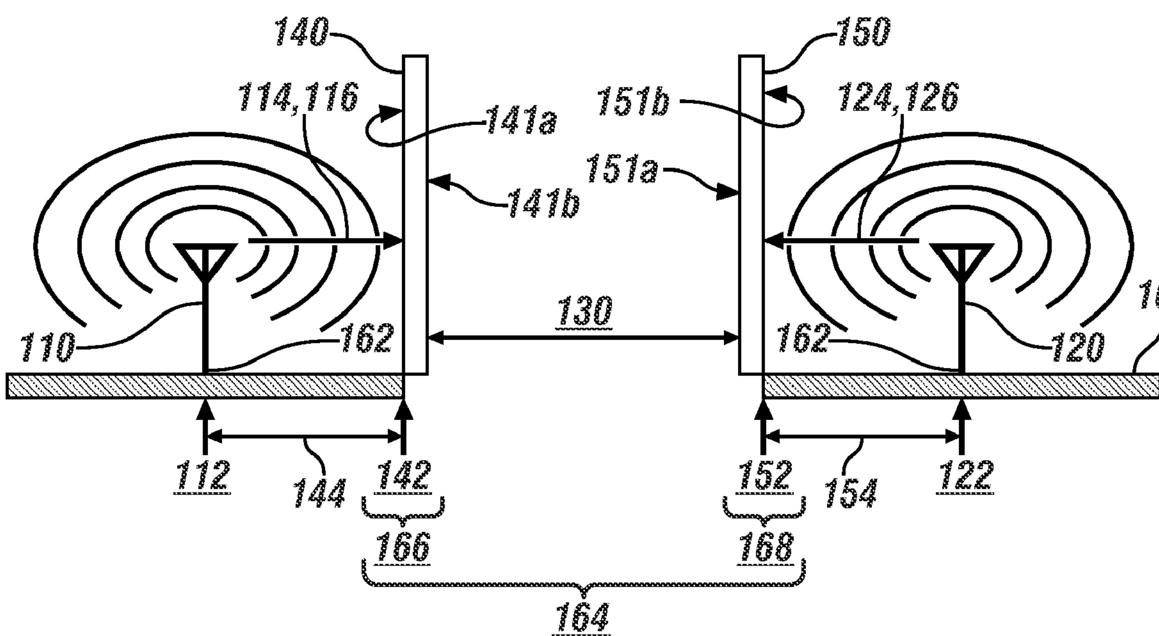
(57) **ABSTRACT**

An antenna system includes a first antenna operational to transmit a first radio-frequency signal, a second antenna operational to receive a second radio-frequency signal and receive the first radio-frequency signal, a first electromagnetic polarizer disposed between the first antenna and the second antenna and operational to change a polarization of the first radio-frequency signal, a second electromagnetic polarizer disposed between the first electromagnetic polarizer and the second antenna and operational to further change the polarization of the first radio-frequency signal, and a conductive ground plane disposed on a ground side of the first antenna and the second antenna. The conductive ground plane defines a gap between the first antenna and the second antenna. The gap extends under the first electromagnetic polarizer. The gap extends under the second electromagnetic polarizer. A horizontal component of the second polarization of the first radio-frequency signal is maintained across the gap.

20 Claims, 5 Drawing Sheets



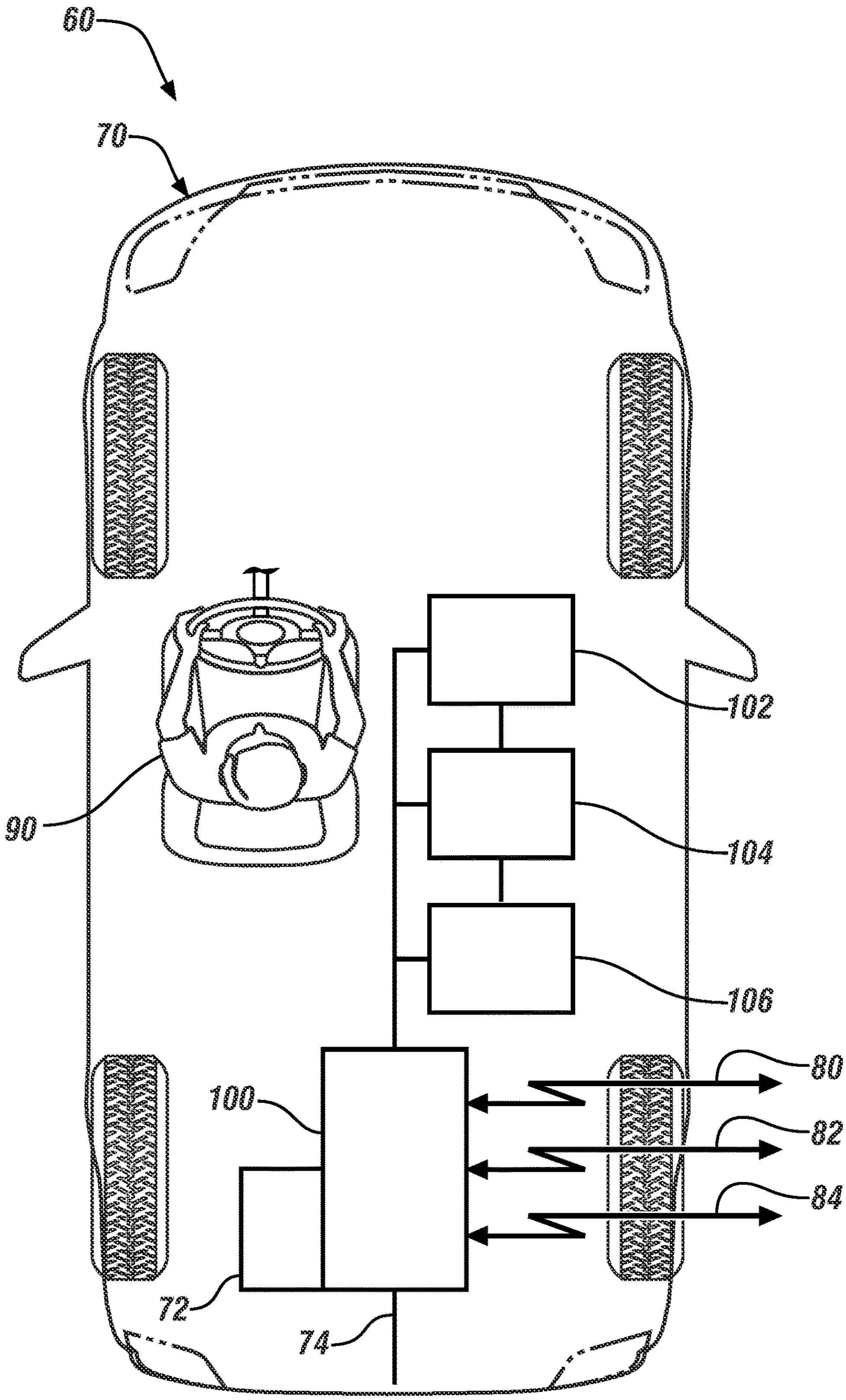
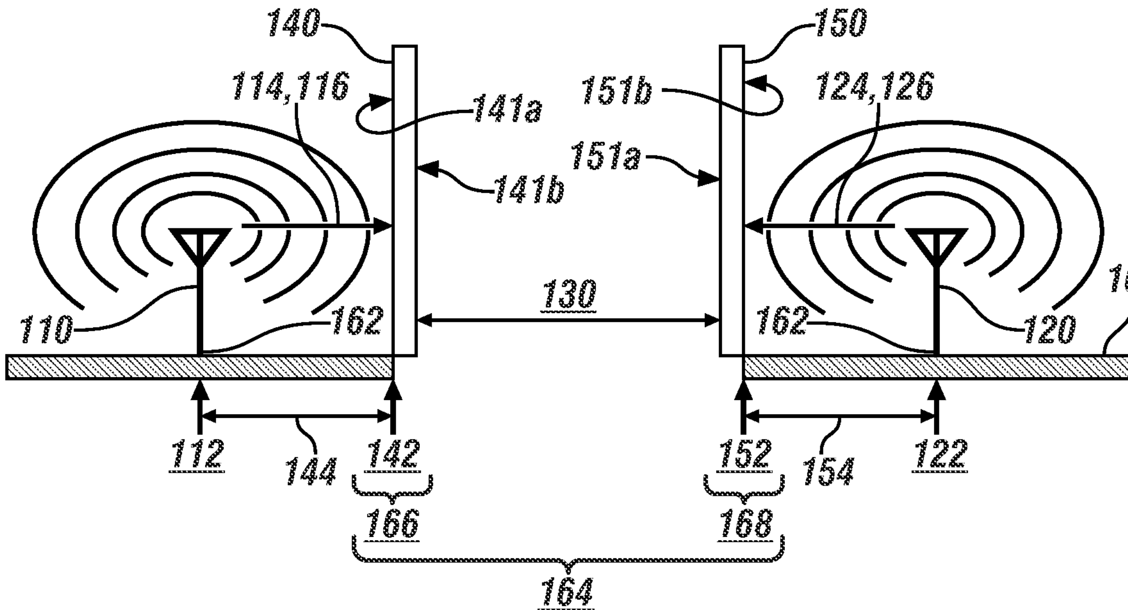


FIG. 1


140
150
114,116
141a
151b
124,126
151a
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144
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152
154
122
166
168
164

FIG. 2

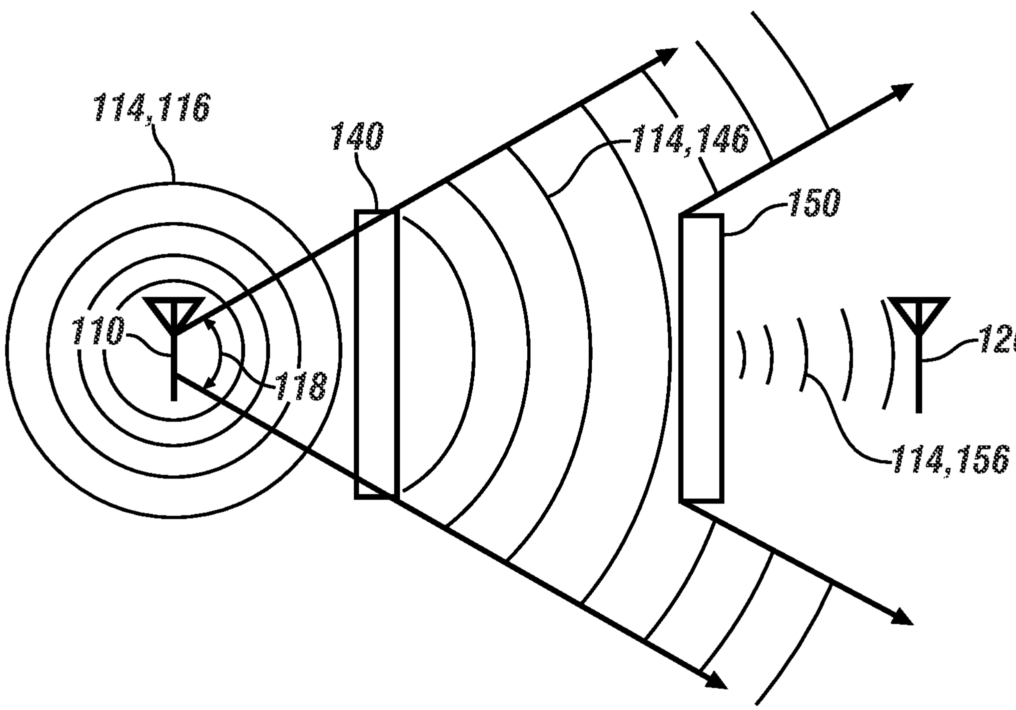
114,116
140
114,146
150
110
118
120
114,156

FIG. 3

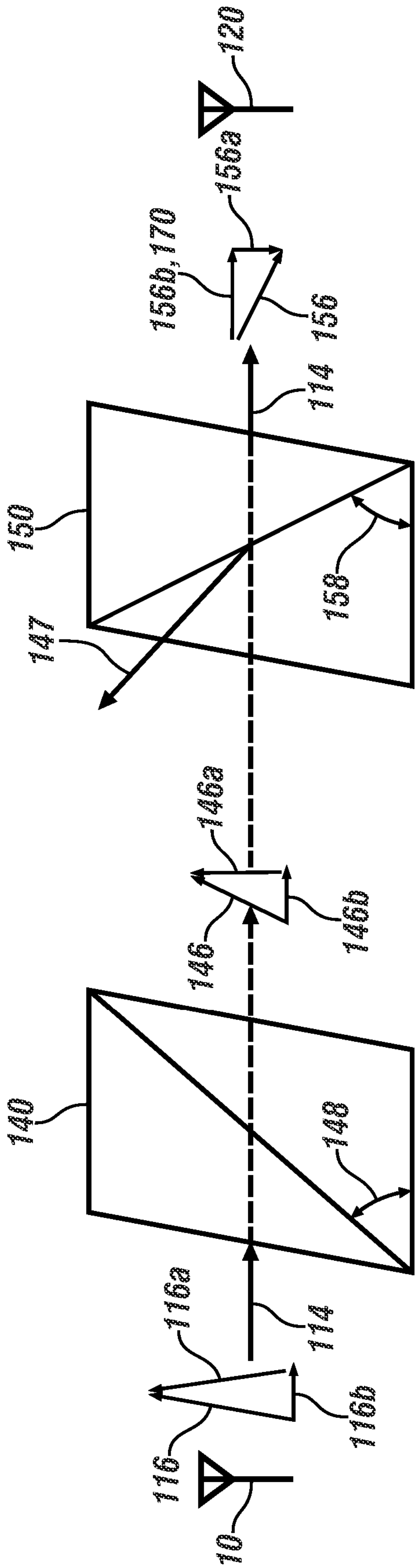
110
116
116a
116b
114
140
148
146
146a
146b
147
150
158
114
156
156a
156b,170
120

FIG. 4

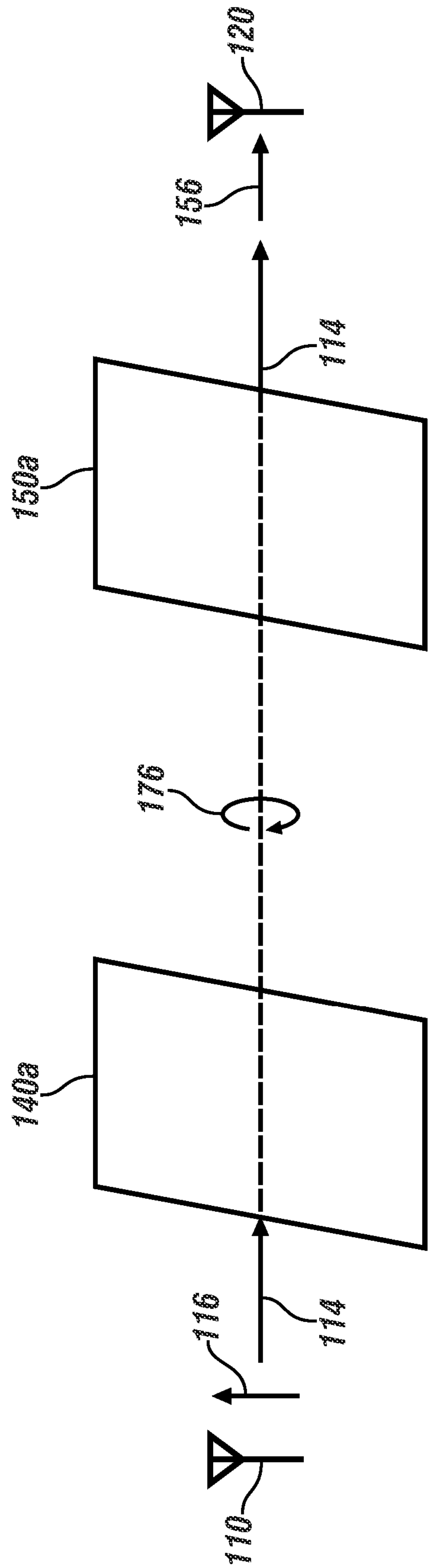
110
116
114
140a
176
150a
114
156
120

FIG. 5

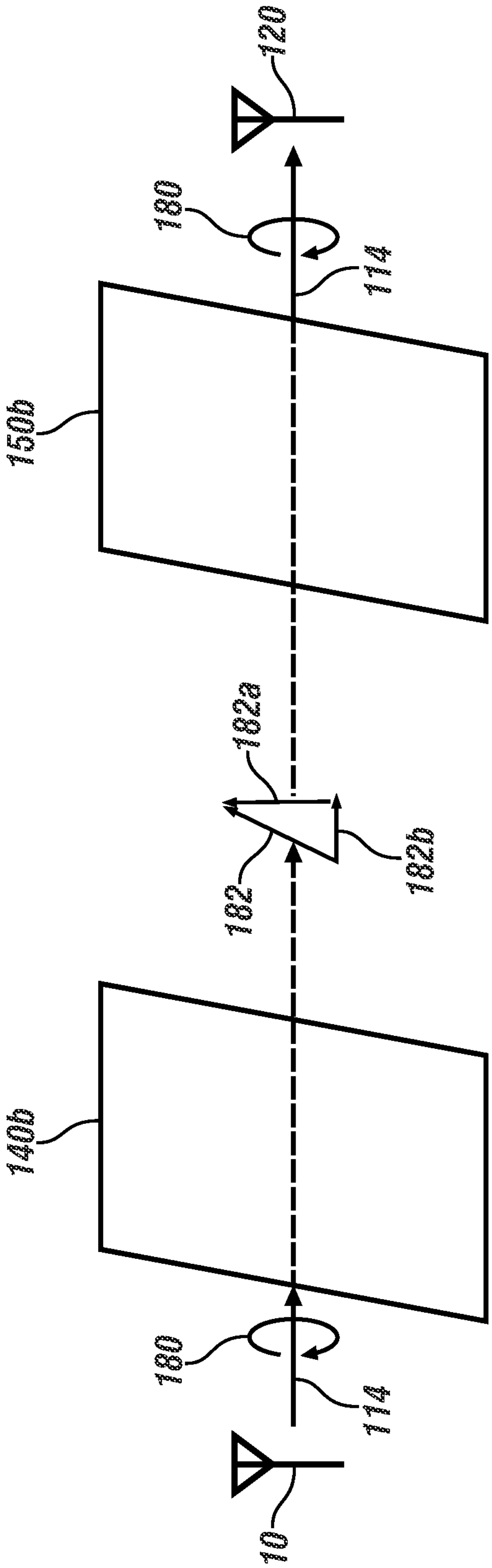

FIG. 6

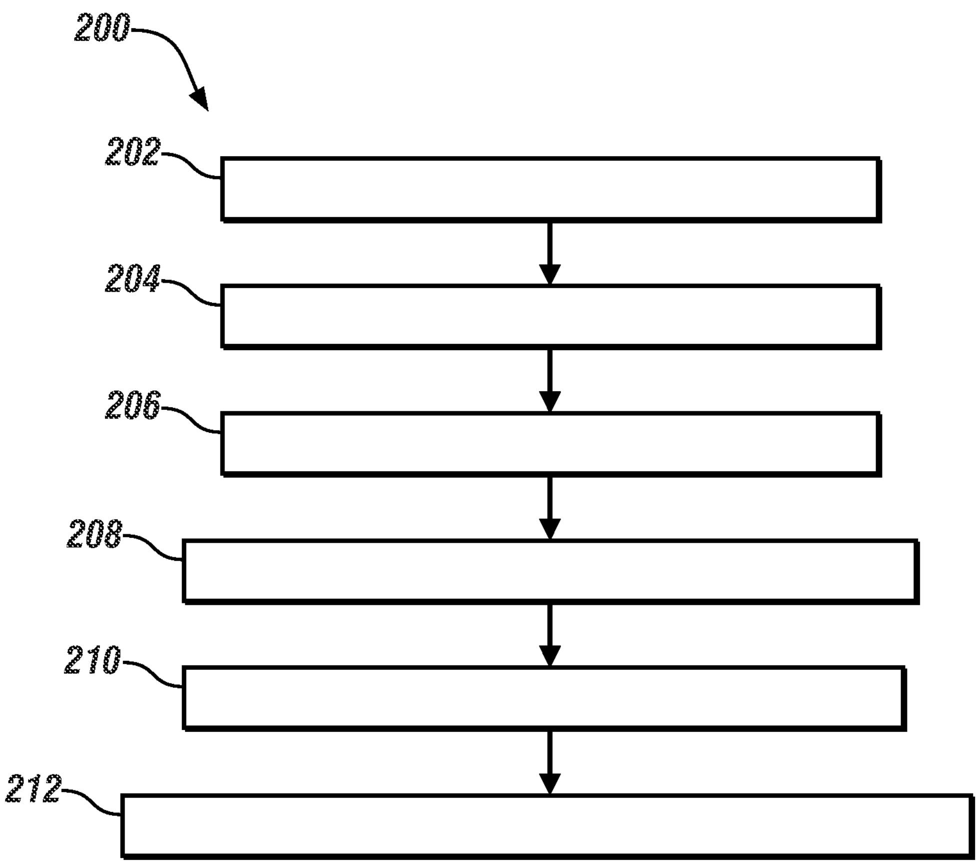

FIG. 7

ISOLATION BETWEEN ANTENNAS USING ELECTROMAGNETIC POLARIZERS

INTRODUCTION

The present disclosure relates to a system and a method for isolation between antennas using electromagnetic polarizers.

Absorbing materials or conducting structures are sometimes used between neighboring antennas to achieve better inter-antenna isolation. Both techniques act as a barrier that disturbs radio signals flowing between the antennas. The barriers either reduce the signal strengths or shift radiation patterns away from the other antenna. Both techniques disrupt antenna radiation patterns.

Accordingly, those skilled in the art continue with research and development efforts in the field of reducing interference between commonly located antennas that transmit and receive at similar frequencies.

SUMMARY

An antenna system is provided herein. The antenna system includes a first antenna, a second antenna, a first electromagnetic polarizer, a second electromagnetic polarizer, and a conductive ground plane. The first antenna is operational to transmit a first radio-frequency signal with a first polarization. The second antenna is operational to receive a second radio-frequency signal with the first polarization and receive the first radio-frequency signal. The first radio-frequency signal would disrupt conversion of the second radio-frequency signal to a useable form if the first radio-frequency signal is received unattenuated at the second antenna. The first electromagnetic polarizer is disposed between the first antenna and the second antenna and operational change the first polarization of the first radio-frequency signal to a second polarization. The second polarization is offset relative to the first polarization by a first predetermined angle. The second electromagnetic polarizer is disposed between the first electromagnetic polarizer and the second antenna and operational change the second polarization of the first radio-frequency signal to a third polarization. The third polarization is offset relative to the first polarization by a second predetermined angle. The first electromagnetic polarizer and the second electromagnetic polarizer attenuate the first radio-frequency signal at the second antenna so that the second radio-frequency signal is convertible to the useable form. The conductive ground plane is disposed on a ground side of the first antenna and the second antenna. The conductive ground plane defines a gap between the first antenna and the second antenna. The gap extends under the first electromagnetic polarizer. The gap extends under the second electromagnetic polarizer. A horizontal component of the second polarization of the first radio-frequency signal is maintained across the gap.

In one or more embodiments of the antenna system, the first electromagnetic polarizer is operational to pass a first component of the first radio-frequency signal, and reject a second component of the first radio-frequency signal.

In one or more embodiments of the antenna system, the second electromagnetic polarizer is operational to pass a third component of the first radio-frequency signal, and reject a fourth component of the first radio-frequency signal.

In one or more embodiments of the antenna system, a portion of the first radio-frequency signal transmitted by the first antenna toward the second antenna is attenuated approximately 20 decibels after passing through the first electromagnetic polarizer and the second electromagnetic polarizer, relative to free space attenuation between the first antenna and the second antenna.

In one or more embodiments of the antenna system, the second predetermined angle is approximately perpendicular to the first predetermined angle.

In one or more embodiments of the antenna system, the first predetermined angle is slanted approximately 45 degrees relative to the conductive ground plane, and the second predetermined angle is slanted approximately −45 degrees relative to the conductive ground plane.

In one or more embodiments of the antenna system, the first electromagnetic polarizer is operational to change the first radio-frequency signal from a circular polarization to a linear polarization at the first predetermined angle.

In one or more embodiments of the antenna system, the second electromagnetic polarizer is operational to change the first radio-frequency signal from the linear polarization to the circular polarization, and reject a component of the first radio-frequency signal.

In one or more embodiments of the antenna system, the first antenna and the second antenna are mounted on a vehicle.

A method for establishing isolation between antennas is provided herein. The method includes transmitting a first radio-frequency signal with a first polarization from a first antenna, receiving a second radio-frequency signal with the first polarization at a second antenna, and receiving the first radio-frequency signal at the second antenna. The first radio-frequency signal would disrupt conversion of the second radio-frequency signal to a useable form if the first radio-frequency signal is received unattenuated at the second antenna. The method further includes changing the first polarization of the first radio-frequency signal to a second polarization with a first electromagnetic polarizer. The first electromagnetic polarizer is disposed between the first antenna and the second antenna. The second polarization is offset relative to the first polarization by a first predetermined angle. The method includes changing the second polarization of the first radio-frequency signal to a third polarization with a second electromagnetic polarizer. The second electromagnetic polarizer is disposed between the first electromagnetic polarizer and the second antenna. The third polarization is offset relative to the first polarization by a second predetermined angle. The first electromagnetic polarizer and the second electromagnetic polarizer attenuate the first radio-frequency signal at the second antenna so that the second radio-frequency signal is convertible to the useable form. The method further includes maintaining a horizontal component of the second polarization of the first radio-frequency signal across a gap in a conductive ground plane. The conductive ground plane is disposed on a ground side of the first antenna and the second antenna. The conductive ground plane defines the gap between the first antenna and the second antenna. The gap extends under the first electromagnetic polarizer. The gap extends under the second electromagnetic polarizer.

In one or more embodiments of the method, the changing of the first polarization of the first radio-frequency signal includes passing a first component of the first radio-frequency signal through the first electromagnetic polarizer, and rejecting a second component of the first radio-frequency signal with the first electromagnetic polarizer.

In one or more embodiments of the method, the changing of the second polarization of the first radio-frequency signal includes passing a third component of the first radio-frequency signal through the second electromagnetic polarizer, and rejecting a fourth component of the first radio-frequency signal with the second electromagnetic polarizer.

In one or more embodiments, the method further includes attenuating a portion of the first radio-frequency signal transmitted by the first antenna toward the second antenna by approximately 20 decibels with the first electromagnetic polarizer and the second electromagnetic polarizer, relative to free space attenuation between the first antenna and the second antenna.

In one or more embodiments of the method, the second predetermined angle is approximately perpendicular to the first predetermined angle.

In one or more embodiments of the method, the first predetermined angle is slanted approximately 45 degrees relative to the conductive ground plane, and the second predetermined angle is slanted approximately −45 degrees relative to the conductive ground plane.

In one or more embodiments of the method, the changing of the first polarization of the first radio-frequency signal includes changing the first radio-frequency signal from a circular polarization to a linear polarization at the first predetermined angle with the first electromagnetic polarizer.

In one or more embodiments of the method, the changing of the second polarization of the first radio-frequency signal includes changing the first radio-frequency signal from the linear polarization to the circular polarization with the second electromagnetic polarizer, and rejecting a component of the first radio-frequency signal with the second electromagnetic polarizer.

A vehicle is provided herein. The vehicle includes an exterior surface, a first antenna, a second antenna, a first electromagnetic polarizer, a second electromagnetic polarizer and a conductive ground plane. The first antenna is disposed on the exterior surface and operational to transmit a first radio-frequency signal with a first polarization. The second antenna is disposed on the exterior surface and operational to receive a second radio-frequency signal with the first polarization and receive the first radio-frequency signal. The first radio-frequency signal would disrupt conversion of the second radio-frequency signal to a useable form if the first radio-frequency signal is received unattenuated at the second antenna. The first electromagnetic polarizer is disposed between the first antenna and the second antenna and operational change the first polarization of the first radio-frequency signal to a second polarization, wherein the second polarization is offset relative to the first polarization by a first predetermined angle. The second electromagnetic polarizer is disposed between the first electromagnetic polarizer and the second antenna and operational change the second polarization of the first radio-frequency signal to a third polarization. The third polarization is offset relative to the first polarization by a second predetermined angle. The first electromagnetic polarizer and the second electromagnetic polarizer attenuate the first radio-frequency signal at the second antenna so that the second radio-frequency signal is convertible to the useable form. The conductive ground plane is disposed on a ground side of the first antenna and the second antenna. The conductive ground plane defines a gap between the first antenna and the second antenna. The gap extends under the first electromagnetic polarizer. The gap extends under the second electromagnetic polarizer. A horizontal component of the second polarization of the first radio-frequency signal is maintained across the gap.

In one or more embodiments of the vehicle, the first antenna and the second antenna are aligned parallel to a longitudinal axis of the vehicle.

In one or more embodiments of the vehicle, the first radio-frequency signal is a vehicle-to-vehicle signal and the second radio-frequency signal is a Wi-Fi signal.

The above features and advantages and other features and advantages of the present disclosure are readily apparent from the following detailed description of the best modes for carrying out the disclosure when taken in connection with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic plan diagram of a context of an environment around a vehicle in accordance with one or more exemplary embodiments.

FIG. **2** is a schematic diagram of an antenna system in accordance with one or more exemplary embodiments.

FIG. **3** is a schematic plan view of the antenna system in accordance with one or more exemplary embodiments.

FIG. **4** is a schematic diagram of linear-to-linear electromagnetic polarizers in accordance with one or more exemplary embodiments.

FIG. **5** is a schematic diagram of linear-to-circular and circular-to-linear electromagnetic polarizers in accordance with one or more exemplary embodiments.

FIG. **6** is a schematic diagram of circular-to-linear and linear-to-circular electromagnetic polarizers in accordance with one or more exemplary embodiments.

FIG. **7** is a flow diagram of a method for increasing isolation between antennas in accordance with one or more exemplary embodiments.

DETAILED DESCRIPTION

Embodiments of the disclosure provide an antenna system and/or isolation method that reduces a probability that a signal being transmitted from one antenna corrupts another signal being simultaneously received by a neighboring (or co-existing) antenna. In a vehicle, different antennas that operate in the same bands or near-by bands (such as Wi-Fi, vehicle-to-vehicle and vehicle-to-everything) are provided with a significant degree of inter-antenna isolation for proper operation. The antenna system increases an electromagnetic isolation between two antennas by mounting a +45 degree electromagnetic polarizer adjacent to one antenna and mounting a −45 degree electromagnetic polarizer adjacent to the other antenna. The electromagnetic polarizers may be limited to a small range between the antennas, therefor effecting a certain angle of the radiation patterns. The electromagnetic polarizers generally reduce the vertical polarization of the original signals in the angle by approximately 3 decibels. Mounting the polarizations facing each may increase the isolation between the antennas by approximately 20 decibels.

Referring to FIG. **1**, a schematic plan diagram of an example context of an environment **60** around a vehicle **70** is shown in accordance with one or more exemplary embodiments. The vehicle **70** resides on the ground (e.g., a roadway) at a current location. The vehicle **70** generally includes an exterior surface **72** and may define a longitudinal axis **74**. A driver **90** and one or more passengers (not shown) may reside inside the vehicle **70**.

The vehicle **70** includes an antenna system **100**, a first transceiver **102**, a second transceiver **104** and a controller **106**. Vehicle-to-vehicle (V2V) bidirectional communication **80** may be established between the antenna system **100** and the neighboring vehicles. Vehicle-to-everything (V2X) bidirectional communication **82** may be established between the antenna system **100** and other equipment, such as computers, networks, relay stations, and the like. Wi-Fi bidirectional communications **84** may be established between the antenna system **100** and other Wi-Fi nodes. Oher types of radio-frequency communications may be established between the antenna system **100** and other radio-frequency receivers, transmitters and/or transceivers to meet the design criteria of a particular application.

The vehicle **70** implements a gas-powered vehicle, an electric vehicle, a hybrid vehicle, or a plug-in hybrid vehicle. In various embodiments, the vehicle **70** may include, but is not limited to, a passenger vehicle, a truck, an autonomous vehicle, a motorcycle, a boat, and/or an aircraft. Other types of vehicles **70** may be implemented to meet the design criteria of a particular application.

The antenna system **100** implements a multi-antenna array that enables simultaneous communications on multiple radio frequencies. The antenna system includes at least a first antenna, a second antenna, a first electromagnetic polarizer, a second electromagnetic polarizer and an optional conductive ground plane mounted on and/or inside the vehicle **70**. The first antenna is operational to transmit and receive a first radio-frequency signal (e.g., a V2V signal, a V2X signal or a Wi-Fi signal) with a first polarization. The second antenna is operational to transmit and receive a second radio-frequency signal (e.g., a V2V signal, a V2X signal or a Wi-Fi signal) with the first polarization. The first electromagnetic polarizer is disposed between the first antenna and the second antenna. The first electromagnetic polarizer is operational change the first polarization of the first radio-frequency signal heading toward the second electromagnetic polarizer to a second polarization. The second electromagnetic polarizer is disposed between the first electromagnetic polarizer and the second antenna. The second electromagnetic polarizer is operational change the second polarization of the first radio-frequency signal heading toward the second antenna to a third polarization. The first radio-frequency signal with the third polarization may be received by the second antenna. Where implemented, the conductive ground plane is disposed on a ground side of the first antenna and the second antenna. The conductive ground plane may define a gap between the first antenna and the second antenna. The gap extends under the first electromagnetic polarizer, and the gap extends under the second electromagnetic polarizer. The conductive ground plane is operational to maintain a horizontal component of the first radio-frequency signal across the gap. A combination of the electromagnetic polarizers and the conductive ground plane with the gap generally attenuate the first radio-frequency signal at the second antenna by at least 20 decibels, relative to the same antenna system without the electromagnetic polarizers. In a similar fashion, the combination of the electromagnetic polarizers and the conductive ground plane with the gap generally attenuate the second radio-frequency signal at the first antenna by at least 20 decibels, relative to the same antenna system without the electromagnetic polarizers.

The first transceiver **102** implements a radio-frequency transmitter and receiver. The first transceiver **102** is electrically coupled to the first antenna in the antenna system **100**, and is operational to alternatively transmit and receive the first radio-frequency signal via the first antenna. In various embodiments, the first radio-frequency signal may implement the V2V bidirectional communications **80**, the V2X bidirectional communications **82**, the Wi-Fi bidirectional communications **84**, or other radio-frequency bidirectional communications with nodes external to the vehicle **70**.

The second transceiver **104** implements another radio-frequency transmitter and receiver. The second transceiver **104** is electrically coupled to the second antenna in the antenna system **100**, and is operational to alternatively transmit and receive the second radio-frequency signal via the second antenna. In various embodiments, the second radio-frequency signal may implement the V2V bidirectional communications **80**, the V2X bidirectional communications **82**, the Wi-Fi bidirectional communications **84**, or other radio-frequency bidirectional communications with nodes external to the vehicle **70**.

The controller **106** implements one or more electronic control units. The controller **106** is in electrical communication with the first transceiver **102** and the second transceiver **104**. In various embodiments, the controller **106** may be implemented in a body controller of the vehicle **70**. The controller **106** is operational to relay digital signals to and from the first transceiver **102** and the second transceiver **104** for the V2V bidirectional communications **80**, the V2X bidirectional communications **82**, and/or the Wi-Fi bidirectional communications **84**.

In various embodiments, the controller **106** generally comprises at least one microcontroller. The at least one microcontroller may include one or more processors, each of which may be embodied as a separate processor, an application specific integrated circuit (ASIC), a field programmable gate array (FPGA), or a dedicated electronic control unit. The at least one microcontroller may be an electronic processor (implemented in hardware, software executing on hardware, or a combination of both). The at least one microcontroller may also include tangible, non-transitory memory (e.g., read-only memory in the form of optical, magnetic, and/or flash memory). For example, the at least one microcontroller may include application-suitable amounts of random-access memory, read-only memory, flash memory and other types of electrically-erasable programmable read-only memory, as well as accompanying hardware in the form of a high-speed clock or timer, analog-to-digital and digital-to-analog circuitry, and input/output circuitry and devices, as well as appropriate signal conditioning and buffer circuitry.

Computer-readable and executable instructions embodying the present method may be recorded (or stored) in the memory and executed as set forth herein. The executable instructions may be a series of instructions employed to run applications on the at least one microcontroller (either in the foreground or background). The at least one microcontroller may receive commands and information, in the form of one or more input signals from various controls or components in the vehicle **70** and communicate instructions to the other electronic components.

Referring to FIG. **2**, a schematic diagram of an example implementation of the antenna system **100** is shown in accordance with one or more exemplary embodiments. Referring to FIG. **3** a schematic plan view of the antenna system **100** is shown in accordance with one or more exemplary embodiments. Referring to FIG. **4**, a schematic diagram of an example linear-to-linear electromagnetic polarizers is shown in accordance with one or more exemplary embodiments. The antenna system **100** includes at least the first antenna **110**, the second antenna **120** and the conductive ground plane **160** (where implemented). Additional antennas may be implemented to meet the design criteria of a particular application.

The first antenna **110** is located at a first antenna position **112** near the conductive ground plane **160**. The first antenna position **112** may be inside or outside the vehicle **70**. The first antenna **110** transmits and receives a first radio-frequency signal **114** at a first frequency with a first polarization **116**. The first antenna **110** may define a ground side **162**. In various embodiments, the first polarization **116** may be a vertical polarization. In some embodiments, the first polarization **116** may be circular (e.g., left-handed or right-handed) or elliptical. In still other embodiments, the first polarization **116** may be horizontal. Other directions of the first polarization **116** may be implemented to meet the design criteria of a particular application. As illustrated in FIG. **3**, the first radio-frequency signal **114** within an angle of coverage **118** may interact with the first electromagnetic polarizer **140**. The first radio-frequency signal **114** outside the angle of coverage **118** is not affected by the first electromagnetic polarizer **140**.

The second antenna **120** is located at a second antenna position **122** near the conductive ground plane **160**. The second antenna position **122** may be inside or outside the vehicle **70**. The second antenna **120** transmits and receives a second radio-frequency signal **124** at a second frequency with another polarization **126**. The second antenna **120** may define a same ground side **162** as the first antenna **110**. The second frequency may be a similar frequency, or a same frequency as the first frequency (e.g., the first antenna **110** provides an in-cabin Wi-Fi antenna and the second antenna **120** provides an external Wi-Fi antenna. In various embodiments, the other polarization **126** may be a same polarization (e.g., vertical) as the first polarization **116**. In some embodiments, the polarization **126** may be circular (e.g., left-handed or right-handed) or elliptical. In still other embodiments, the other polarization **126** may be horizontal. Other directions of the other polarization **126** may be implemented to meet the design criteria of a particular application. Similar to the first radio-frequency signal **114**, the second radio-frequency signal **124** within a corresponding angle of coverage may interact with the second electromagnetic polarizer **150**. The second radio-frequency signal **124** outside the angle of coverage is not affected by the second electromagnetic polarizer **150**.

An alignment direction **130** may be defined between the first antenna **110** and the second antenna **120**. In some embodiments, the alignment direction **130** may be parallel to the longitudinal axis **74** of the vehicle **70**. In other embodiments, the alignment direction **130** may be non-parallel (e.g., perpendicular) to the longitudinal axis **74** of the vehicle **70**.

The first electromagnetic polarizer **140** implements a linear-to-linear electromagnetic polarizer, a circular-to-linear electromagnetic polarizer, or a linear-to-circular electromagnetic polarizer. In various embodiments, the first electromagnetic polarizer **140** may implement a wire grid. The first electromagnetic polarizer **140** is operational to change a polarization of the first radio-frequency signal **114** within the angle of coverage **118** from the first polarization **116** to a second polarization **146**. In cases of linear-to-linear polarization, the first radio-frequency signal **114** may be considered to have a vertical first component **116*a*** and possibly a small horizontal first component **116*b***. The second polarization **146** may be spatially rotated while travelling from a first side **141*a*** of the first electromagnetic polarizer **140** to a second side **141*b*** of the first electromagnetic polarizer **140**. The spatial rotation may be to a first predetermined angle **148** on the second side **141*b*** relative to the conductive ground plane **160**. For example, the first electromagnetic polarizer **140** may rotate the polarization of the first radio-frequency signal **114** by 40 to 50 degrees (e.g., 45 degrees). The first radio-frequency signal **114**, were viewed between the first electromagnetic polarizer **140** and the second electromagnetic polarizer **150** (e.g., with the second polarization **146**), may be considered to have a rotated second component **146*a*** and a nonrotated second component **146*b***. The vertical component of the rotated second component **146*a*** may be an attenuated version of the vertical first component **116*a*** by approximately −3 decibels.

The first electromagnetic polarizer **140** is located between the first antenna **110** and the second antenna **120** at a first electromagnetic polarizer position **142** along the alignment direction **130**. In various embodiments, a first separation **144** between the first antenna **110** and the first electromagnetic polarizer **140** may be approximately a quarter wavelength of the first radio-frequency signal **114**. In various embodiments, an attenuation of the first radio-frequency signal **114** passing through the first electromagnetic polarizer **140** may be −3 decibels (e.g., the polarization of the first electromagnetic polarizer **140** is offset from the first polarization **116** of the first antenna **110** by approximately 45 degrees).

The second electromagnetic polarizer **150** implements another linear-to-linear electromagnetic polarizer, a circular-to-linear electromagnetic polarizer, or a linear-to-circular electromagnetic polarizer. In various embodiments, the second electromagnetic polarizer **150** may implement another wire grid. The second electromagnetic polarizer **150** is operational to change a polarization of the first radio-frequency signal **114** from the second polarization **146** to a third polarization **156**. In cases of linear-to-linear polarization, the third polarization **156** may be spatially rotated while travelling from a third side **151*a*** of the second electromagnetic polarizer **150** to a fourth side **151*b*** of the second electromagnetic polarizer **150**. The spatial rotation may be to a second predetermined angle **158** relative to the conductive ground plane **160**. For example, the second electromagnetic polarizer **150** may rotate the polarization of the first radio-frequency signal **114** leaking through the first electromagnetic polarizer **140** by −40 to −50 degrees (e.g., −45 degrees). In other words, an orientation (or slant) of the third side **151*a*** of the second electromagnetic polarizer **150** is rotated approximately 90 degrees (e.g., perpendicular) to the orientation (or slant) of the second side **141*b*** of the first electromagnetic polarizer **140**. The second electromagnetic polarizer **150** has a polarization that is perpendicular to the first electromagnetic polarizer **140** and so rejects most of the first radio-frequency signal **114** with the second polarization. The first radio-frequency signal **114**, where viewed between the first electromagnetic polarizer **140** and the second electromagnetic polarizer **150**, may be considered to have the rotated second component **146*a*** and the nonrotated second component **146*b***. A fourth component **147** of the first radio-frequency signal **114** (e.g., a component not aligned with the polarization of the second electromagnetic polarizer **150** on the third side **151*a***) may be rejected by the second electromagnetic polarizer **150**. The rejected fourth component **147** may be up to 98.5 percent of the signal. The first radio-frequency signal **114**, where viewed between the second electromagnetic polarizer **150** and the second antenna **120** (e.g., with the third polarization **156**), may be considered to have a rotated third component **156*a*** and a nonrotated third component **156*b***. The rotated third component **156*a*** may be an attenuated version of the rotated second component **146*a***.

The second electromagnetic polarizer **150** is located between the first electromagnetic polarizer **140** and the second antenna **120** at a second electromagnetic polarizer position **152** along the alignment direction **130**. In various embodiments, a second separation **154** between the second antenna **120** and the second electromagnetic polarizer **150** may be approximately a quarter wavelength of the second radio-frequency signal **124**. In various embodiments, an attenuation of the second radio-frequency signal **124** passing through the second electromagnetic polarizer **150** may be −3 decibels (e.g., the polarization of the second electromagnetic polarizer **150** is offset from the polarization **126** of the second antenna **120** by approximately 45 degrees). In various embodiments, the first electromagnetic polarizer **140** and the second electromagnetic polarizer **150** may be copies of each other and mounted with different orientations.

The conductive ground plane **160** is positioned on the ground side **162** of the first antenna **110** and the second antenna **120**. The conductive ground plane **160** is generally operational to improve the operations of the first antenna **110** and the second antenna **120**. A gap **164** is defined in the conductive ground plane. The gap **164** includes a first area **166** that extends under the first electromagnetic polarizer **140** and a second area **168** that extends under the second electromagnetic polarizer **150**. The gap **164** within the conductive ground plane **160** helps maintain a horizontal component **170** (e.g., the horizontal component of the rotated second component **146***a*) of the first radio-frequency signal **114** across the gap **164** (FIG. **2**) (e.g., maintains between and under the electromagnetic polarizers **140** and **150**). Where the conductive ground plane **160** is not implemented, the first antenna **110** and the second antenna **120** may be treated as residing in free space. A size of the first electromagnetic polarizer **140** and a size of the second electromagnetic polarizer **150** may also be extended to below the bottoms of the first antenna **110** and the second antenna **120** as the conductive ground plane **160** is absent.

A total attenuation of the first radio-frequency signal **114** as transmitted from the first antenna **110** until reception by the second antenna **120** may be at least 20 decibels, relative to the same antenna system without the electromagnetic polarizers (e.g., a free space attenuation between the first antenna **110** and the second antenna **120** without implementation of the first electromagnetic polarizer **140** and the second electromagnetic polarizer **150**). Therefore, while the first transceiver **102** and the first antenna **110** are transmitting and the second transceiver **104** and the second antenna **120** are receiving, the first radio-frequency signal **114** may be attenuated to a point where the first radio-frequency signal **114** would not disrupt conversion of the second radio-frequency signal **124** to a useable form in the second transceiver **104**. Without the attenuation of the first electromagnetic polarizer **140** and the second electromagnetic polarizer **150**, the second transceiver **104** may be unable to distinguish between the first radio-frequency signal **114** and the second radio-frequency signal **124**. Likewise, while the first transceiver **102** and the first antenna **110** are receiving and the second transceiver **104** and the second antenna **120** are transmitting, the second radio-frequency signal **124** may be attenuated to a point where the second radio-frequency signal **124** would not disrupt conversion of the first radio-frequency signal **114** to a useable form in the first transceiver **102**.

In some embodiments, the first antenna **110**, the first electromagnetic polarizer **140**, the second electromagnetic polarizer **150** and the second antenna **120** are positioned along a flat plane. The flat plane may be on the exterior surface **72** (FIG. **1**) of the vehicle **70**, such as the roof, or another flat surface inside or outside the vehicle **70**. In contrast, if the two antennas **110** and **120** are placed on a curved surface, the electromagnetic polarizers **140** and **150** may not be aligned, the polarizations may not be perpendicular to each other, and so the attenuation performance is decreased. In such cases, the electromagnetic polarizers **140** and **150** may be positioned so that the facing surfaces (e.g., **141***b* and **151***a* in FIG. **2**) are parallel to each other and therefore the polarizations would be perpendicular to each other.

Referring to FIG. **5**, a schematic diagram of an example linear-to-circular and circular-to-linear electromagnetic polarizers is shown in accordance with one or more exemplary embodiments. A linear-to-circular type of first electromagnetic polarizer **140***a* may convert the first radio-frequency signal **114** from the first polarization **116** to a circular polarization **176** (e.g., left-handed or right handed). A circular-to-linear type of second electromagnetic polarizer **150***a*, with a circular polarization perpendicular to that of the first circular-to-linear electromagnetic polarizer **140***a* (e.g., right-handed or left-handed), rejects most of the first radio-frequency signal **114** and converts a minor portion of the first radio-frequency signal **114** from the circular polarization **176** to the third polarization **156**. An attenuation of the first radio-frequency signal **114** through the first electromagnetic polarizer **140***a* and the second electromagnetic polarizer **150***a* may be at least 20 decibels, relative to free space attenuation between the first antenna **110** and the second antenna **120**. In various embodiments, the first electromagnetic polarizer **140***a* and the second electromagnetic polarizer **150***a* may be copies of each other and mounted with different orientations.

Referring to FIG. **6**, a schematic diagram of example circular-to-linear and linear-to-circular electromagnetic polarizers is shown in accordance with one or more exemplary embodiments. In various embodiments, a circular-to-linear type of first electromagnetic polarizer **140***b* converts the first radio-frequency signal **114** from the circular polarization **180** to a linear polarization **182**. A linear-to-circular type of second electromagnetic polarizer **150***b*, with a linear polarization perpendicular to that of the first circular-to-linear electromagnetic polarizer **140***b*, may convert the first radio-frequency signal **114** from the polarization **182** to the circular polarization **180**. In various embodiments, the first electromagnetic polarizer **140***b* and the second electromagnetic polarizer **150***b* may be copies of each other and mounted with different orientations.

The first antenna **110** may generate the first radio-frequency signal **114** with the circular polarization **180**. The first electromagnetic polarizer **140***b* is operational to change a polarization of the first radio-frequency signal **114** from the circular polarization **180** to the linear polarization **182**. The first radio-frequency signal **114**, where viewed between the first electromagnetic polarizer **140** and the second electromagnetic polarizer **150** (e.g., with the linear polarization **182**), may be considered to have a vertical component **182***a* and a horizontal component **182***b*. The vertical component **182***a* may represent an attenuated version of the first radio-frequency signal **114**.

The second electromagnetic polarizer **150***b* is operational to change a polarization of the first radio-frequency signal **114** from the linear polarization **182** back to the circular polarization **180**. The first radio-frequency signal **114** converted back to the circular polarization **180** by the second electromagnetic polarizer **150***b* may represent an attenuated version of the first radio-frequency signal **114**, where viewed between the first electromagnetic polarizer **140** and the second electromagnetic polarizer **150**. In various embodiments, attenuation of the first radio-frequency signal **114** through the first electromagnetic polarizer **140***b* and the second electromagnetic polarizer **150***b* may be at least 20 decibels, relative to free space attenuation between the first antenna **110** and the second antenna **120**.

A total attenuation of the first radio-frequency signal **114** as transmitted from the first antenna **110** until reception by the second antenna **120** may be at least −20 decibels. Therefore, while the first transceiver **102** and the first antenna **110** are transmitting and the second transceiver **104** and the second antenna **120** are receiving, the first radio-frequency signal **114** may be attenuated to a point where the first radio-frequency signal **114** would not disrupt conversion of the second radio-frequency signal **124** to a useable form in the second transceiver **104**. Without the attenuation of the first electromagnetic polarizer **140**/**140***a*/**140***b* and the second electromagnetic polarizer **150**/**150***a*/**150***b*, the second transceiver **104** may be unable to distinguish between the first radio-frequency signal **114** and the second radio-frequency signal **124**. Likewise, while the first transceiver **102** and the first antenna **110** are receiving and the second transceiver **104** and the second antenna **120** are transmitting, the second radio-frequency signal **124** may be attenuated to a point where the second radio-frequency signal **124** would not disrupt conversion of the first radio-frequency signal **114** to a useable form in the first transceiver **102**.

Referring to FIG. **7**, a flow diagram of an example method **200** for increasing isolation between antennas is shown in accordance with one or more exemplary embodiments. The method (or process) **200** may be implemented by the antenna system **100**, the first transceiver **102** and the second transceiver **104**. The method **200** may include steps **202** to **212**, as illustrated. The sequence of steps is shown as a representative example. Other step orders may be implemented to meet the criteria of a particular application. The example is based on the linear electromagnetic polarizers **140** and **150**. Similar steps may be implemented for the other types of first electromagnetic polarizers **140***a*-**140***b* and the other types of second electromagnetic polarizers **150***a*-**150***b*.

In the step **202**, the first antenna **110** may transmit the first radio-frequency signal **114** with the first polarization **116** or **180**. Concurrently, the second antenna **120** may receive the second radio-frequency signal **124** with the first polarization **116** or **180** in the step **204**. After passing through the first electromagnetic polarizer **140** and the second electromagnetic polarizer **150**, an attenuated version of the first radio-frequency signal **114** is received at the second antenna **120** in the step **206**. The first radio-frequency signal **114** as transmitted from the first antenna **110** may disrupt conversion of the second radio-frequency signal **124** received by the second antenna **120** to a useable form if the first radio-frequency signal **114** is received unattenuated at the second antenna **120**.

In the step **208**, a portion of the first radio-frequency signal **114** transmitted by the first antenna **110** toward the second antenna **120** is attenuated by approximately 20 decibels with the first electromagnetic polarizer **140** and the second electromagnetic polarizer **150**. The attenuation may include changing the first polarization **116** of the first radio-frequency signal **114** to the second polarization **146** with the first electromagnetic polarizer **140**. The changing of the first polarization **116** of the first radio-frequency signal **114** with the first electromagnetic polarizer **140** includes passing a first component of the first radio-frequency signal through the first electromagnetic polarizer **140** and rejecting a second component of the first radio-frequency signal **114** with the first electromagnetic polarizer **140**.

In the step **210**, a horizontal component **170** of the first radio-frequency signal **114** at the second antenna **120** may be maintained across the gap **164** of the conductive ground plane **160**. The second polarization **146** of the first radio-frequency signal **114** is changed to the third polarization **156** with the second electromagnetic polarizer **150** in the step **212**. The changing may include passing a third component of the first radio-frequency signal **114** though the second electromagnetic polarizer **150** and rejecting a fourth component **147** of the first radio-frequency signal **114** with the second electromagnetic polarizer **150**.

In various embodiments, the antenna system **100** includes +/−45 linear electromagnetic polarizers (from linear-to-linear slant of +/−45 degree polarization) to increase isolation between two linear-polarized antennas (both vertical or both horizontal). Placement of the +45 degree electromagnetic polarizer for one antenna and the −45 degree electromagnetic polarizer for the other antenna, where the electromagnetic polarizers are between the antennas, makes the radiation patterns in an angle between the antennas perpendicular, therefor increasing the isolation between the antennas. While increasing isolation between the antennas, the electromagnetic polarizers do not affect a radiation pattern shape of the antennas. In other words, for a small cost of reduced antenna gain in a certain direction, one achieves a better isolation between antennas without redesigning the antennas.

In a case where the antennas are situated above a ground/conducting plane (such as vertical polarized antennas above a metal sheet), the +/−45 polarized signals quickly reduce to a vertical polarized signal, due to the ground effect on the horizontal component. The reduction to vertical may be overcome by making a gap/hole in the conductive ground plane that is between and under the electromagnetic polarizers. Simulations and/or experiments may be used to determine a distance of the antenna to each electromagnetic polarizer, a minimal height and a minimum width of the electromagnetic polarizers, a minimal amount of layers of each electromagnetic polarizer, and a distance between the electromagnetic polarizers

In various embodiments, the antenna system may include more than two antennas. Each pair of antennas may be surrounded by a pair of the linear electromagnetic polarizers, the linear-to-circular electromagnetic polarizers, or the circular-to-linear electromagnetic polarizers such that relative to each other, the polarizations may be perpendicular. A benefit may be achieving a good isolation between antennas (e.g., adding −20 dB of isolation), without having to redesign or increase the distance between the antennas. A trade-off is 3 decibels less gain in the original polarization in the angle of coverage between the antennas and the nearby electromagnetic polarizers. In other embodiments, the antennas may be operated in mutually exclusive states where while one antenna is broadcasting the other antennas are not being utilized.

Embodiments of the disclosure generally provide an antenna system that includes a first antenna, a second antenna, a first electromagnetic polarizer, a second electromagnetic polarizer, and a conductive ground plane. The first antenna is operational to transmit a first radio-frequency signal with a first polarization. The second antenna is operational to receive a second radio-frequency signal with the first polarization and receive the first radio-frequency signal. The first radio-frequency signal would disrupt conversion of the second radio-frequency signal to a useable form if the first radio-frequency signal is received unattenuated at the second antenna. The first electromagnetic polarizer is disposed between the first antenna and the second antenna and operational change the first polarization of the first radio-frequency signal to a second polarization. The second polarization is offset relative to the first polarization by a first predetermined angle. The second electromagnetic polarizer is disposed between the first electromagnetic polarizer and the second antenna and operational change the second polarization of the first radio-frequency signal to a third polarization. The third polarization is offset relative to the first polarization by a second predetermined angle. The first electromagnetic polarizer and the second electromagnetic polarizer may attenuate the first radio-frequency signal at the second antenna so that the second radio-frequency signal is convertible to the useable form. The conductive ground plane is disposed on a ground side of the first antenna and the second antenna. The conductive ground plane defines a gap between the first antenna and the second antenna. The gap extends under the first electromagnetic polarizer. The gap extends under the second electromagnetic polarizer. The conductive ground plane is operational to maintain a horizontal component of the first radio-frequency signal across the gap.

Numerical values of parameters (e.g., of quantities or conditions) in this specification, including the appended claims, are to be understood as being modified in each instance by the term "about" whether or not "about" actually appears before the numerical value. "About" indicates that the stated numerical value allows some slight imprecision (with some approach to exactness in the value; about or reasonably close to the value; nearly). If the imprecision provided by "about" is not otherwise understood in the art with this ordinary meaning, then "about" as used herein indicates at least variations that may arise from ordinary methods of measuring and using such parameters. In addition, disclosure of ranges includes disclosure of values and further divided ranges within the entire range. Each value within a range and the endpoints of a range are hereby disclosed as a separate embodiment.

While the best modes for carrying out the disclosure have been described in detail, those familiar with the art to which this disclosure relates will recognize various alternative designs and embodiments for practicing the disclosure within the scope of the appended claims.

What is claimed is:

1. An antenna system comprising:

a first antenna operational to transmit a first radio-frequency signal with a first polarization;

a second antenna operational to receive a second radio-frequency signal with the first polarization and receive the first radio-frequency signal, wherein the first radio-frequency signal would disrupt conversion of the second radio-frequency signal to a useable form if the first radio-frequency signal is received unattenuated at the second antenna;

a first electromagnetic polarizer disposed between the first antenna and the second antenna and operational change the first polarization of the first radio-frequency signal to a second polarization, wherein the second polarization is offset relative to the first polarization by a first predetermined angle;

a second electromagnetic polarizer disposed between the first electromagnetic polarizer and the second antenna and operational change the second polarization of the first radio-frequency signal to a third polarization, wherein the third polarization is offset relative to the first polarization by a second predetermined angle, and the first electromagnetic polarizer and the second electromagnetic polarizer attenuate the first radio-frequency signal at the second antenna so that the second radio-frequency signal is convertible to the useable form; and

a conductive ground plane disposed on a ground side of the first antenna and the second antenna, wherein the conductive ground plane defines a gap between the first antenna and the second antenna, the gap extends under the first electromagnetic polarizer, the gap extends under the second electromagnetic polarizer, and a horizontal component of the second polarization of the first radio-frequency signal is maintained across the gap.

2. The antenna system according to claim **1**, wherein the first electromagnetic polarizer is operational to:

pass a first component of the first radio-frequency signal; and

reject a second component of the first radio-frequency signal.

3. The antenna system according to claim **2**, wherein the second electromagnetic polarizer is operational to:

pass a third component of the first radio-frequency signal; and

reject a fourth component of the first radio-frequency signal.

4. The antenna system according to claim **1**, wherein a portion of the first radio-frequency signal transmitted by the first antenna toward the second antenna is attenuated approximately 20 decibels after passing through the first electromagnetic polarizer and the second electromagnetic polarizer, relative to free space attenuation between the first antenna and the second antenna.

5. The antenna system according to claim **1**, wherein the second predetermined angle is approximately perpendicular to the first predetermined angle.

6. The antenna system according to claim **5**, wherein:

the first predetermined angle is slanted approximately 45 degrees relative to the conductive ground plane; and

the second predetermined angle is slanted approximately −45 degrees relative to the conductive ground plane.

7. The antenna system according to claim **1**, wherein the first electromagnetic polarizer is operational to change the first radio-frequency signal from a circular polarization to a linear polarization at the first predetermined angle.

8. The antenna system according to claim **7**, wherein the second electromagnetic polarizer is operational to:

change the first radio-frequency signal from the linear polarization to the circular polarization; and

reject a component of the first radio-frequency signal.

9. The antenna system according to claim **1**, wherein the first antenna and the second antenna are mounted on a vehicle.

10. A method for establishing isolation between antennas, comprising:

transmitting a first radio-frequency signal with a first polarization from a first antenna;

receiving a second radio-frequency signal with the first polarization at a second antenna;

receiving the first radio-frequency signal at the second antenna, wherein the first radio-frequency signal would disrupt conversion of the second radio-frequency signal to a useable form if the first radio-frequency signal is received unattenuated at the second antenna;

changing the first polarization of the first radio-frequency signal to a second polarization with a first electromagnetic polarizer, wherein the first electromagnetic polarizer is disposed between the first antenna and the second antenna, and the second polarization is offset relative to the first polarization by a first predetermined angle;

changing the second polarization of the first radio-frequency signal to a third polarization with a second electromagnetic polarizer, wherein the second electromagnetic polarizer is disposed between the first electromagnetic polarizer and the second antenna, the third polarization is offset relative to the first polarization by a second predetermined angle, and the first electromagnetic polarizer and the second electromagnetic polarizer attenuate the first radio-frequency signal at the second antenna so that the second radio-frequency signal is convertible to the useable form; and

maintaining a horizontal component of the second polarization of the first radio-frequency signal across a gap in a conductive ground plane, wherein the conductive ground plane is disposed on a ground side of the first antenna and the second antenna, the conductive ground plane defines the gap between the first antenna and the second antenna, the gap extends under the first electromagnetic polarizer, and the gap extends under the second electromagnetic polarizer.

11. The method according to claim **10**, wherein the changing of the first polarization of the first radio-frequency signal comprises:

passing a first component of the first radio-frequency signal through the first electromagnetic polarizer; and

attenuating a second component of the first radio-frequency signal with the first electromagnetic polarizer.

12. The method according to claim **11**, wherein the changing of the second polarization of the first radio-frequency signal comprises:

passing a third component of the first radio-frequency signal through the second electromagnetic polarizer; and

rejecting a fourth component of the first radio-frequency signal with the electromagnetic polarizer.

13. The method according to claim **10**, further comprising:

attenuating a portion of the first radio-frequency signal transmitted by the first antenna toward the second antenna by approximately 20 decibels with the first electromagnetic polarizer and the second electromagnetic polarizer, relative to free space attenuation between the first antenna and the second antenna.

14. The method according to claim **10**, wherein the second predetermined angle is approximately perpendicular to the first predetermined angle.

15. The method according to claim **14**, wherein:

the first predetermined angle is slanted approximately 45 degrees relative to the conductive ground plane; and

the second predetermined angle is slanted approximately −45 degrees relative to the conductive ground plane.

16. The method according to claim **10**, wherein the changing of the first polarization of the first radio-frequency signal comprises:

changing the first radio-frequency signal from a circular polarization to a linear polarization at the first predetermined angle with the first electromagnetic polarizer.

17. The method according to claim **16**, wherein the changing of the second polarization of the first radio-frequency signal comprises:

changing the first radio-frequency signal from the linear polarization to the circular polarization with the second electromagnetic polarizer; and

rejecting a component of the first radio-frequency signal with the second electromagnetic polarizer.

18. A vehicle comprising:

an exterior surface;

a first antenna disposed on the exterior surface and operational to transmit a first radio-frequency signal with a first polarization;

a second antenna disposed on the exterior surface and operational to receive a second radio-frequency signal with the first polarization and receive the first radio-frequency signal, wherein the first radio-frequency signal would disrupt conversion of the second radio-frequency signal to a useable form if the first radio-frequency signal is received unattenuated at the second antenna;

a first electromagnetic polarizer disposed between the first antenna and the second antenna and operational change the first polarization of the first radio-frequency signal to a second polarization, wherein the second polarization is offset relative to the first polarization by a first predetermined angle;

a second electromagnetic polarizer disposed between the first electromagnetic polarizer and the second antenna and operational change the second polarization of the first radio-frequency signal to a third polarization, wherein the third polarization is offset relative to the first polarization by a second predetermined angle, and the first electromagnetic polarizer and the second electromagnetic polarizer attenuate the first radio-frequency signal at the second antenna so that the second radio-frequency signal is convertible to the useable form; and

a conductive ground plane disposed on a ground side of the first antenna and the second antenna, wherein the conductive ground plane defines a gap between the first antenna and the second antenna, the gap extends under the first electromagnetic polarizer, the gap extends under the second electromagnetic polarizer, and a horizontal component of the second polarization of the first radio-frequency signal is maintained across the gap.

19. The vehicle according to claim **18**, wherein the first antenna and the second antenna are positioned on a longitudinal axis of the vehicle.

20. The vehicle according to claim **18**, wherein the first radio-frequency signal is a vehicle-to-vehicle signal and the second radio-frequency signal is a Wi-Fi signal.

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