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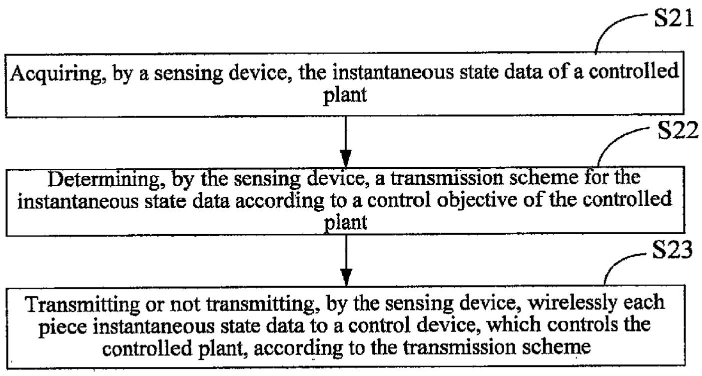

FIG. 2

(57) **Abstract**: A method, a sensing device and a control device for transmission of plant state data are disclosed by the present disclosure. The method includes: acquiring, by a sensing device, the instantaneous state data of a controlled plant, determining a transmission scheme for the instantaneous state data according to a control objective of the controlled plant, and wirelessly transmitting or not transmitting each piece of instantaneous state data to a control device, which controls the controlled plant, according to the transmission scheme. By the above means, the resource occupation and power consumption on the sensing device can be reduced.

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METHOD AND SENSING DEVICE AND CONTROL DEVICE FOR TRANSMISSION OF PLANT STATE DATA

FIELD OF THE DISCLOSURE

The present disclosure relates to the field of information transmission technologies, and more particularly, to methods, sensing devices and control devices for transmission of plant state data.

BACKGROUND OF THE DISCLOSURE

A networked control system (NCS) is a fully distributed and networked real-time feedback control system, it is a gathering of an unstable controlled plant and its sensing device, a control device and a communication network, within a site. The sensing device detects a state of the controlled plant and transmits the state information to the control device, which transmits a command to the controlled plant according to the state information, in order to stabilize the unstable controlled plant. NCSs have become quite popular recently due to their growing applications in industrial automation, smart transportation, remote robotic control, etc.

However, in a current NCS, the existing sensing device will transmit all the detected state information to the control device, through all the communication channels established. This massive amount of information transmission will occupy a majority of the sensing device's resources, and also vastly consumes the battery power of the sensing device.

SUMMARY OF THE DISCLOSURE

A method, a sensing device and a control device for transmission of plant state data are provided according to the disclosure, and can reduce the resource occupation and power consumption on the sensing device.

According to a first aspect of the disclosure, a method for transmission of plant state data includes: acquiring, by a sensing device, the instantaneous state data of a controlled plant, determining a transmission scheme for the instantaneous state data according to a control objective of the controlled plant, and wirelessly transmitting or not transmitting each piece of instantaneous state data to a control device, which controls the controlled plant, according to the transmission scheme.

The block of determining the transmission scheme for the instantaneous state data according to the control objective of the controlled plant may include: selecting at least a part of wireless MIMO eigen-channels according to at least one of a state estimation error, the wireless MIMO channel conditions and a local battery status of the sensing device, such that the control device receives the instantaneous state data through the selected wireless eigen-channels and controls the controlled plant accordingly, wherein the state estimation error is obtained by a comparison of the instantaneous state data with the corresponding reference state data of the controlled plant.

The block of selecting at least a part of the wireless MIMO eigen-channels according to the at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device may include: when the following equation 21 is satisfied, selecting an i-th wireless MIMO eigen-channel;

$$g_1(h_i\sigma_i) > C \qquad (21)$$

wherein, h_i is the i-th largest singular value of a wireless MIMO channel state matrix H and represents a condition of the i-th wireless MIMO eigen-channel, σ_i is the i-th largest singular value of the state estimation error covariance matrix, g_1 is a non-decreasing function of σ_i and h_i, and C is a constant.

The local battery status of the sensing device may include the available energy in the local battery of the sensing device, and the block of selecting at least a part of the wireless MIMO eigen-channels according to the at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device may include: when the following equation 22 is satisfied, selecting an i-th wireless MIMO eigen-channel;

$$g_1(h_i\sigma_i) > g_2(E) \qquad (22)$$

wherein, σ_i is the i-th largest singular value of the state estimation error covariance matrix, h_i is the i-th largest singular value of a wireless MIMO channel state matrix H and represents a condition of the i-th wireless MIMO eigen-channel, and g_1 is a non-decreasing function of σ_i and h_i, E is the available energy in the local battery of the sensing device, and g_2 is a decreasing function of E.

The block of determining the transmission scheme for the instantaneous state data according to the control objective of the controlled plant may include: selecting at least a part of the instantaneous state data according to at least one of a state estimation error, wireless MIMO channel conditions and a local battery status of the sensing device, such that the control device receives the selected instantaneous state data to control the controlled plant accordingly, wherein the state estimation error is obtained by a comparison of the instantaneous state data with the corresponding reference state data of the controlled plant.

The block of selecting at least a part of the instantaneous state data according to the at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device may include: when the following equation 23 is satisfied, selecting an i-th piece of instantaneous state data;

$$f_1(h_i) > \sigma_i^{-1} \qquad (23)$$

wherein, σ_i is the i-th largest singular value of the state estimation error covariance matrix, h_i is the i-th largest singular value of a wireless MIMO channel state matrix H and represents a condition of the i-th wireless MIMO eigen-channel, and f_1 is a non-decreasing function of h_i.

The local battery status of the sensing device may include the available energy in the local battery of the sensing device, and the block of selecting at least a part of the instantaneous state data according to the at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device may include: when the following equation 24 is satisfied, selecting an i-th piece of instantaneous state data;

$$f_2(h_i E^{-1}) > \sigma_i^{-1} \qquad (24)$$

wherein, σ_i is the i-th largest singular value of the state estimation error covariance matrix, h_i is the i-th largest singular value of a wireless MIMO channel state matrix H and represents a condition of the i-th wireless MIMO eigen-channel, E is the available energy in the local battery of the sensing device, and f_2 is a non-decreasing function of h_i and E^{-1}.

The wireless MIMO channel state matrix H may be fed back from the control device.

The method may further include, before the block of wirelessly transmitting or not transmitting each piece of instantaneous state data to the control device, which controls the controlled plant, according to the transmission scheme: performing analog encoding on the instantaneous state data using an analog encoder.

The block of performing analog encoding on the instantaneous state data may include: acquiring the quantized amplitude of the instantaneous state data, where the quantized amplitude is to be directly loaded onto a carrier and transmitted to the control device.

The block of acquiring the quantized amplitude of the instantaneous state data may include: performing analog-to-digital conversion on the instantaneous state data to obtain a corresponding bit stream of the instantaneous state data, where the value represented by the bit stream is taken as the quantized amplitude of the instantaneous state data.

The method may further include, after the block of performing analog-to-digital conversion on the instantaneous state data: performing serial-to-parallel conversion on the corresponding bit stream of the instantaneous state data.

The method may further include, after the block of acquiring, by the sensing device, the instantaneous state data of the controlled plant: limiting the amplitude of the acquired instantaneous state data.

According to a second aspect of the disclosure, a method for transmission of plant state data includes: receiving, by a control device, the instantaneous state data that is wirelessly transmitted from a sensing device, wherein a transmission scheme of the instantaneous state data is determined according to a control objective of a controlled plant, and the sensing device may or may not transmit each piece of instantaneous state data to the control device, which controls the controlled plant, according to the transmission scheme, analyzing the received instantaneous state data and generating a corresponding control command, and transmitting the control command to the controlled plant, which thus performs a corresponding operation according to the control command.

According to a third aspect of the disclosure, a sensing device includes an acquisition module configured to acquire the instantaneous state data of a controlled plant, a determination module configured to determine a transmission scheme for the instantaneous state data according to a control objective of the controlled plant, and a transmission module configured to wirelessly transmit or not transmit each piece of instantaneous state data to a control device, which controls the controlled plant, according to the transmission scheme.

The determination module may select at least a part of wireless MIMO eigen-channels according to at least one of a state estimation error, the wireless MIMO channel conditions and a local battery status of the sensing device, such that the control device receives the instantaneous state data through the selected wireless eigen-channels to control the controlled plant accordingly, wherein the state estimation error is obtained by a comparison of the instantaneous state data with the corresponding reference state data of the controlled plant.

The determination module may select at least a part of the instantaneous state data according to at least one of a state estimation error, wireless MIMO channel conditions and a local battery status of the sensing device, such that the control device receives the selected instantaneous state data to control the controlled plant accordingly, wherein the state estimation error is obtained by a comparison of the instantaneous state data and the corresponding reference state data of the controlled plant.

The sensing device may further include an analog encoder configured to perform analog encoding on the instantaneous state data, and the transmission module may wirelessly transmit or not transmit each of the instantaneous state data, which is outputted from the analog encoder, to the control device, which controls the controlled plant, according to the transmission scheme.

The analog encoder may specifically acquire the quantized amplitude of the instantaneous state data, where the quantized amplitude is to be directly loaded to a carrier and thus transmitted to the control device.

According to a fourth aspect of the disclosure, a sensing device includes a detection circuit, a central processing unit (CPU), a radio frequency-RF circuit and an MIMO antenna, which are connected in a sequential order. The detection circuit may detect the instantaneous state data of a controlled plant and output the instantaneous state data to the CPU. The CPU may determine a transmission scheme for the instantaneous state data according to a control objective of the controlled plant, and output the instantaneous state data to the RF circuit. The RF circuit may transmit the instantaneous state data to the MIMO antenna, which may wirelessly transmit or not transmit each piece of instantaneous state data to a control device, which controls the controlled plant, according to the transmission scheme.

The CPU may select at least a part of wireless MIMO eigen-channels according to at least one of a state estimation error, wireless MIMO channel conditions and a local battery status of the sensing device, such that the control device receives the instantaneous state data through the selected wireless MIMO eigen-channels and controls the controlled plant accordingly, wherein the state estimation error is obtained by a comparison of the instantaneous state data with the corresponding reference state data of the controlled plant.

The CPU selecting at least a part of the wireless MIMO eigen-channels according to the at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device may include: when the following equation 25 is satisfied, selecting an i-th wireless MIMO eigen-channel;

$$g_1(h_i\sigma_i) > C \qquad (25)$$

wherein, h_i is the i-th largest singular value of a wireless MIMO channel state matrix H and represents a conditions of the i-th wireless MIMO eigen-channel, σ_i is the i-th largest singular value of the state estimation error covariance matrix, g_1 is a non-decreasing function of σ_i and h_i, and C is a constant.

The local battery status of the sensing device may include the available energy in the local battery of the sensing device, and the CPU selecting at least a part of the wireless MIMO eigen-channels according to the at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device may include: when the following equation 26 is satisfied, selecting the i-th wireless MIMO eigen-channel;

$$g_1(h_i\sigma_i) > g_2(E) \qquad (26)$$

wherein, σ_i is the i-th largest singular value of the state estimation error covariance matrix, h_i is the i-th largest singular value of a wireless MIMO channel state matrix H and represents the condition of the i-th wireless MIMO eigen-channel, g_1 is a non-decreasing function of σ_i and h_i, E is the available energy in the local battery of the sensing device, and g_2 is a decreasing function of E.

The CPU may select at least a part of the instantaneous state data according to at least one of a state estimation error, wireless MIMO channel conditions and a local battery status of the sensing device, such that the control device receives the selected instantaneous state data and controls the controlled plant accordingly, wherein the state estimation error is obtained by a comparison of the instantaneous state data with the corresponding reference state data of the controlled plant.

The CPU selecting at least a part of the instantaneous state data according to the at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device may include: when the following equation 27 is satisfied, selecting an i-th piece of instantaneous state data;

$$f_1(h_i) > \sigma_i^{-1} \qquad (27)$$

wherein, σ_i is the i-th largest singular value of the state estimation error covariance matrix, h_i is the i-th largest singular value of a wireless MIMO channel state matrix H and represents a condition of the i-th wireless MIMO eigen-channel, and f_1 is a non-decreasing function of h_i.

The local battery status of the sensing device may include the available energy in the local battery of the sensing device, and the CPU selecting at least a part of the instantaneous state data according to the at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device may include: when the following equation 28 is satisfied, selecting an i-th piece of instantaneous state data;

$$f_2(h_i E^{-1}) > \sigma_i^{-1} \qquad (28)$$

wherein, σ_i is the i-th largest singular value of the state estimation error covariance matrix, h_i is the i-th largest singular value of a wireless MIMO channel state matrix H and represents a condition of the i-th wireless MIMO eigen-channel, E is the available energy in the local battery of the sensing device, and f_2 is a non-decreasing function of h_i and E^{-1}.

The wireless MIMO channel state matrix H may be fed back from the control device.

The sensing device may further include an analog encoder connected to the CPU and the RF circuit, such that the CPU is connected to the RF circuit via the analog encoder. The analog encoder is configured to perform analog encoding on the instantaneous state data before it is outputted to the RF circuit.

The analog encoder may specifically acquire the quantized amplitude of the instantaneous state data, where the quantized amplitude is to be directly loaded to a carrier and further transmitted to the control device.

The analog encoder may specifically perform analog-to-digital conversion on the instantaneous state data and thus obtain the corresponding bit stream of the instantaneous state data, where the value represented by the bit stream is taken as the quantized amplitude.

The analog encoder may further perform serial-to-parallel conversion on the corresponding bit stream of the instantaneous state data.

The sensing device may further include an amplitude limiter connected to the detection circuit and configured to limit the amplitude of the instantaneous state data before it is outputted to the CPU.

According to a fifth aspect of the disclosure, a control device includes a reception module configured to receive the instantaneous state data that is wirelessly transmitted from a sensing device, wherein a transmission scheme of the instantaneous state data is determined according to a control objective of a controlled plant, and the sensing device may or may not wirelessly transmit each piece of instantaneous state data to the control device, which controls the controlled plant, according to the transmission scheme, a generation module configured to analyze the received instantaneous state data and generate a corresponding control command, and a transmission module configured to transmit the control command to the controlled plant, which thus performs a corresponding operation according to the control command.

According to a sixth aspect of the disclosure, a control device includes a central processing unit (CPU), a RF circuit, a MIMO antenna and an output, wherein the CPU is connected to the RF circuits and the output, the RF circuit is connected to the MIMO antenna, The RF circuit is configured to receive, through the MIMO antenna, instantaneous state data wirelessly transmitted from a sensing device, wherein a transmission scheme of the instantaneous state data is determined according to a control objective of a controlled plant, and the sensing device wirelessly transmits or not transmits each piece of instantaneous state data to a control device, which controls the controlled plant, according to the transmission scheme. The CPU is configured to analyze the received instantaneous state data and generate a corresponding control command, and output the control command to the output. The output is configured to transmit the control command to the controlled plant, which performs a corresponding operation according to the control command.

According to the solutions above, the sensing device can determine a transmission scheme for the instantaneous state data according to the control objective of the controlled plant, and may or may not transmit each piece of instantaneous state data according to the determined transmission scheme. Thus, the sensing device can transmit, selectively, its sensing data, in which a smart data transmission is achieved. In particular, when the sensing device selects to transmit only a part of the state data, the resource consumption and the amount of data transmitted can be reduced, which thus can save the communication resources and the power consumption on the sensing device.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a networked control system (NCS) according to an embodiment of the present disclosure.

FIG. 2 is a flow chart illustrating a method for transmission of plant state data according to an embodiment of the present disclosure.

FIG. 3 is a flow chart illustrating a method for transmission of plant state data according to another embodiment of the present disclosure.

FIG. 4 shows a schematic diagram of wireless MIMO channel between a sensing device and a control device of the embodiment discussed in FIG. 3.

FIG. 5a illustrates the transmission of state data with analog encoding.

FIG. 5b illustrates the transmission of state data with digital encoding.

FIG. 6 is a flow chart illustrating a method for transmission of plant state data according to yet another embodiment of the present disclosure.

FIG. 7 is a block diagram of a sensing device according to an embodiment of the present disclosure.

FIG. 8 is a block diagram of a sensing device according to another embodiment of the present disclosure.

FIG. 9 is a block diagram of a sensing device according to yet another embodiment of the present disclosure.

FIG. 10 is a block diagram of a control device according to an embodiment of the present disclosure.

FIG. 11 is a block diagram of a control device according to another embodiment of the present disclosure.

FIG. 12 is a block diagram of a sensing device according to yet another embodiment of the present disclosure.

FIG. 13 is a block diagram of a control device according to yet another embodiment of the disclosure.

FIG. 14a is a curve diagram illustrating the normalized state estimation MSE (mean square error) versus SNR (signal noise ratio) under contiguous repetition coding according to a case A of a simulation example of the disclosure.

FIG. 14b is a curve diagram illustrating the normalized state estimation MSE versus coverage distance under contiguous repetition coding according to a case A of a simulation example of the disclosure.

FIG. 14c is a curve diagram illustrating the normalized state estimation MSE versus SNR under distributed repetition coding according to a case A of a simulation example of the disclosure.

FIG. 14d is a curve diagram illustrating the normalized state estimation MSE versus coverage distance under distributed repetition coding according to a case A of a simulation example of the disclosure.

FIG. 15a is a curve diagram illustrating the normalized state estimation MSE versus SNR under contiguous repetition coding according to a case B of a simulation example of the disclosure.

FIG. 15b is a curve diagram illustrating the normalized state estimation MSE versus coverage distance under contiguous repetition coding according to a case B of a simulation example of the disclosure.

FIG. 15c is a curve diagram illustrating the normalized state estimation MSE versus SNR under distributed repetition coding according to a case B of a simulation example of the disclosure.

FIG. 15d is a curve diagram illustrating the normalized state estimation MSE versus coverage distance under distributed repetition coding according to a case B of a simulation example of the disclosure.

FIG. 16a is a curve diagram illustrating the normalized state estimation MSE versus SNR under contiguous repetition coding according to a case A of another simulation example of the disclosure.

FIG. 16b is a curve diagram illustrating the normalized state estimation MSE versus coverage distance under contiguous repetition coding according to a case A of another simulation example of the disclosure.

FIG. 16c is a curve diagram illustrating the normalized state estimation MSE versus SNR under distributed repetition coding according to a case A of another simulation example of the disclosure.

FIG. 16d is a curve diagram illustrating the normalized state estimation MSE versus coverage distance under distributed repetition coding according to a case A of another simulation example of the disclosure.

FIG. 17a is a curve diagram illustrating the normalized state estimation MSE versus SNR under contiguous repetition coding according to a case B of another simulation example of the disclosure.

FIG. 17b is a curve diagram illustrating the normalized state estimation MSE versus coverage distance under contiguous repetition coding according to a case B of another simulation example of the disclosure.

FIG. 17c is a curve diagram illustrating the normalized state estimation MSE versus SNR under distributed repetition coding according to a case B of another simulation example of the disclosure.

FIG. 17d is a curve diagram illustrating the normalized state estimation MSE versus coverage distance under distributed repetition coding according to a case B of another simulation example of the disclosure.

DETAILED DESCRIPTION OF THE DISCLOSURE

For a thorough understanding of the disclosure, numerous specific details are set forth in the following description for purposes of illustration, but not of limitation, such as system architectures, interfaces and technologies, etc. However, it should be appreciated by those of skill in the art that, in absence of these specific details, the disclosure may also be achieved by other implementations. In other instances, detailed descriptions for well-known devices, circuits and methods are omitted, in order to avoid unnecessary details from hindering the description of the disclosure.

Hereinbelow, a description will first be rendered on a system to which the methods of the disclosure are directed. Referring now to FIG. 1, a networked control system (NCS) includes a controlled plant 11, a sensing device 12 and a control device 13. The control device 13 may establish a communication channel, for example, a wired or wireless channel, with the controlled plant 11 for data transmission. For example, when a wired channel is applied, the control device 13 may be physically attached and connected to the controlled plant 11 in a wired manner. The sensing device 12 may also establish a communication channel with the control device 13 for data transmission. In this embodiment, the control device 13 is physically attached to an actuator of the controlled plant 11, and wireless MIMO channel are established between the sensing device 12 and the control device 13. The data transmission over the estabilished wireless MIMO channel can improve the efficiency and reliability, and can thus improve the system stability.

The sensing device 12 detects the state data of the controlled plant 11, periodically or when a trigger-command is received, and transmits the state data to the control device 13 through the wireless MIMO channel. The state data may be multi-dimensional state data, which may include different pieces of state data of the controlled plant 11. Only one exemplary sensing device is shown in FIG. 1, however, this NCS can include multiple sensing devices 12, which may connect to the control device 13 and transmit all the detected state data to the control device 13.

The control device 13 computes a state estimation of the controlled plant 11 according to the received state data and local information, generates a corresponding control command according to the state estimation, and transmits this control command to the controlled plant 11.

The controlled plant 11 executes the control command transmitted from the control device 13, which thus can achieve a corresponding control over the controlled plant 11. In one implementation, the controlled plant 11 may be a potentially unstable dynamic plant. The control device 13 may stablize the controlled plant 11 according to the state data, in order to control the controlled plant 11 accordingly.

In this NCS, the more the state data transmitted from the sensing device 12 or the more the employed wireless channel, the greater the occupied resources and the power consumption. Rather, the more the transmitted state data, the more accurate the analysis, by the control device 13, of the controlled plant 11, namely, the more accurate the controlled plant 11 is controlled. The consumed resources on the sensing device 12 and the control accuracy over the controlled plant 11 are both considered in the disclosure. In order to achieve an efficient control over the controlled plant 11 with fewer resources or minimal possible resources, the sensing device 12 may be capable of intelligently adjusting the transmission scheme for each piece of state data. Specifically, the sensing device 12 may transmit the state data to the control device 13 with the following example methods. See the following description for details.

Referring now to FIG. 2, there is shown a flow chart of a method for transmission of plant state data according to an embodiment of the disclosure. The method according to this embodiment can be applied to the NCS as shown in FIG. 1, and implemented by the sensing device shown in FIG. 1. The method includes the following steps.

In a first step S21, a sensing device obtains the instantaneous state data of a controlled plant.

For example, the sensing device may be disposed in the vicinity of the controlled plant, and detect the instantaneous state data of the controlled plant using a corresponding sensing circuit that is built internal or external to the sensing device. The instantaneous state data may include the temperatures at different positions, the velocities of different positions, etc. It should be noted that, the "INSTANTANEOUS state data" is not limited to the data obtained at the present moment, but the data that is obtained at any moment and may affect the controlled plant, including the old data. The method can continue to step S22.

In a following step S22, the sensing device determines a transmission scheme for the instantaneous state data according to a control objective of the controlled plant.

Specifically, the control objective of the controlled plant refers to an accuracy, stability or preset objective of the control device's control over the controlled plant, namely, the accuracy of the target state in which the controlled plant works under the control of the control device. In the NSC there would be a number of factors that may affect the control accuracy or control stability such as, for example, an error between the state estimation obtained by the control device and the reference state data (hereinbelow, the state estimation error all refers to the error between the state estimation obtained by the control device and the reference state data of the controlled plant), system channel conditions, a battery status of the sensing device in the system, etc. The reference state data can be the preset fixed state data, or the state data that is previously detected by the sensing device, for example, the state data detected at the previous time, or an average value of the state data that is previously detected for a number of times. The greater the state estimation error, the larger the error of the control device's analysis, judgment and control on the controlled plant, and thus the lower the control accuracy; the worse the channel conditions, the larger the error of the outputted data, and thus the larger the error of the control device's analysis and judgment and control on the controlled plant, and the lower the control accuracy; and the lower the battery status of the sensing device, the lower the control accuracy, for example, when the battery is almost completely drained, the sensing device cannot work properly causing that the NCS cannot perform a regular control operation, such that the control accuracy will be low. Thus, the above factors are closely related to the control objective of the controlled plant, and can be considered in order to determine the transmission scheme for the instantaneous state data, such that the control device can transmit the state data according to this transmission scheme to stablize the controlled plant, thus enabling the controlled plant to achieve the control objective.

The transmission scheme of the instantaneous state data includes whether to transmit each piece of the instantaneous state data and/or which wireless channel are chosen. The more the state data and wireless eigen-channels are selected, the more the sensing device's resources are occupied and the larger the power is consumed. Thus, in this embodiment, the sensing device may, according to at least one of a state estimation error, channel conditions and a device battery status, select an appropriate part of the wireless eigen-channels and transmit only a part of the state data to the control device, to meet the control objective of the controlled plant. The larger the state data error and the better the channel condition, the larger the chance that the corresponding state data and wireless eigen-channels will be selected; the lower the device battery status is, the less state data and fewer wireless eigen-channels will be selected. The method can proceed to step S23.

In step S23, the sensing device wirelessly transmits or not transmits each piece of instantaneous state data to the control device, which controls the controlled plant, according to the transmission scheme.

For example, the instantaneous state data detected by the sensing device may include a first piece of state data, a second piece of state data and a third piece of state data. According to the above control factors, the first and second pieces of state data with comparatively larger errors may be transmitted, and the second and third wireless eigen-channels with comparatively better conditions, of the multiple wireless eigen-channels between the sensing device and control device, may be selected. The sensing device may transmit to the control device the first and second pieces of state data through the second and third wireless eigen-channels, respectively.

It should be noted that, in the disclosure the amount of state data selected by the sensing device needs not correspond to the number of wireless eigen-channels selected. Specifically, the number of pieces of state data may not be equal to the number of wireless eigen-channels. For example, the number of the pieces of selected state data may be less than that of the selected wireless eigen-channels. In addition, the sensing device may select only a part of the state data or a part of the wireless eigen-channels, which can also achieve the purposes of saving resources and power and increasing the performance gain of this NCS. Rather, simultaneous selection of the state data and the wireless eigen-channels may achieve much better saving effects.

In this embodiment, the sensing device determines the transmission scheme for the instantaneous state data according to the control objective of the controlled plant, and may or may not transmit each piece of instantaneous state data by the determined transmission scheme. Thus, the sensing device can selectively transmit its sensing data, thus a smart data transmission can be achieved. Specifically, when the sensing device selects to transmit only a part of the state data, the resource consumption and the amount of data transmitted would be reduced, which thus can save the communication resources and the power consumption on the sensing device.

Referring now to FIG. 3, there is shown a flow chart of a method for transmission of plant state data according to another embodiment of the disclosure. This method can be applied to the NCS as shown in FIG. 1, and implemented by the sensing device shown in FIG. 1. The method includes the following steps.

In a first step S31, the sensing device receives a wireless MIMO channel state matrix H that is fed back from a control device, and acquires the i-th largest singular value h_i in the matrix H as the condition of the i-th wireless MIMO eigen-channel between the sensing device and the control device.

In this embodiment, the state data is transmitted between the sensing device and the control device, through the wireless MIMO channel as shown in FIG. 4. In addition, an uplink a (shown in FIG. 1) is configured between the sensing device and the control device, and used to transmit the condition information of the wireless MIMO channel, which is fed back from the control device, to the sensing device. For example, the control device may transmit, periodically, to the sensing device the wireless MIMO channel state matrix H, as shown in FIG. 4, and $H = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1M} \\ h_{21} & h_{22} & \cdots & h_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N1} & h_{N2} & \cdots & h_{NM} \end{bmatrix}$. The sensing device may compute the singular values of this matrix H, and obtains the i-th largest singular value h_i of this matrix as the condition of the i-th wireless MIMO eigen-channel between the sensing device and the control device. The greater the singular value h_i, the better the condition of the i-th wireless MIMO eigen-channel.

It should be noted that, the i-th largest singular value refers to the i-th singular value acquired on the basis of a descending order.

Alternatively, the uplink a may not be applied between the sensing device and the control device, and the wireless MIMO channel state information can be transmitted directly through the wireless MIMO channel between the sensing device and the control device. The method can proceed to step S32.

In step S32, the sensing device obtains the instantaneous state data of a controlled plant.

See step S21 in the previous embodiment for specific details. The method can continue to step S33.

In step S33, the sensing device limits the amplitude of the obtained instantaneous state data.

For example, the sensing device may pass the detected instantaneous state data through an amplitude limiter for amplitude limiting process, such that the amplitude higher than the preset amplitude will be lowered to the preset one, thus the peak transmission power of the sensing device can be constrained.

The amplitude limiter of the sensing device may dynamically adapt its limit range according to locally computed state estimation error so as to maintain a small (target) probability of saturation. The limit range can be referred to as the amplitude upper limit of the amplitude limiter. When saturation occurs, the limiter may stop the sensing device from transmitting. The method can continue to step S34.

In step S34, the sensing device selects at least a part of the wireless MIMO eigen-channels according to at least one of a state estimation error, wireless MIMO channel conditions and a local battery status of the sensing device, and selects at least a part of the instantaneous state data according to at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device, such that the control device receives the selected instantaneous state data through the selected wireless eigen-channels, and controls the controlled plant accordingly.

The state estimation error is obtained by a comparison between the instantaneous state data and the corresponding reference state data of the controlled plant, where the reference state data is the preset state data or the data derived based on the state information of the controlled plant, for example, the state data previously detected by the sensing device, the state estimate fed back from the control device to the sensing device, or the target state data of the controlled plant at the current moment that is determined by the sensing device based on the current state of the controlled plant. In one implementation, the sensing device may detect the instantaneous state data $x(i)$ before calculating a difference between the instantaneous state data $x(i)$ and the corresponding state data $x'(i)$ that is previously detected, so that the estimation error $\Delta x(i)$ of this state data can be obtained.

The local battery status of the sensing device may include the available energy in the local battery of the sensing device. The local battery can be a power supply system utilizing energy harvesting technologies, or can be a lithium battery, a rechargeable battery, a heat-activated battery, a water-activated battery, and so on. The sensing device may be equipped with an energy harvesting device, thus the service life of the sensing device can be prolonged due to persistent powering, and the sensing device can be avoided from stop working because of the power running out, thus the NCS can be prevented from stop working and the stability of the system can be improved.

To enable the control device to control the controlled plant to work according to certain control objective , the selection strategy can be as following: when the i-th state estimation error is larger than the preset error, then selecting the i-th piece of state data and the corresponding wireless eigen-channel (for example, the i-th eigen-wireless channel); when value of the i-th wireless channel condition is larger than the preset condition value, then selecting the corresponding state data (for example, the i-th piece of state data) and the i-th wireless eigen-channel; when the more the energy in the local battery of the sensing device is available, then the smaller the preset error and the value of preset condition are, and the more the wireless eigen-channels are selected.

In this embodiment, the sensing device may determine a transmission scheme for the instantaneous state data according to all three of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device. Specifically, in step S32 the selecting at least a part of the wireless MIMO eigen-channels according to the at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device may include: when the following equation 11 is satisfied, selecting the i-th wireless MIMO eigen-channel;

$$g_1(h_i\sigma_i) > g_2(E) \qquad (11)$$

Alternatively, in step S32 the selecting at least a part of the wireless MIMO eigen-channels according to the at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device may include: when the following equation 12 is satisfied, selecting the i-th piece of instantaneous state data among the multiple pieces of instantaneous state data;

$$f_2(h_i E^{-1}) > \sigma_i^{-1} \qquad (12)$$

wherein, σ_i is the i-th largest singular value of the state estimation error covariance matrix, and represents the estimation error of one or more corresponding pieces of state data, h_i is the i-th largest singular value of the wireless MIMO channel state matrix H and represents the condition of the i-th wireless MIMO eigen-channel, where h_i may be obtained through step S31, g_1 is a non-decreasing function of σ_i and h_i, where the bigger the σ_i and h_i, the larger the value of the function, E is the available energy in the local battery of the sensing device, g_2 is a decreasing function of E, where the larger the E, the smaller the value of the function, and f_2 is a non-decreasing function of h_i and E^{-1}, where the larger the h_i and E^{-1}, the larger the value of the function. In a specific implementation, this sensing device is powered by the energy harvesting device, and $g_1(h_i\sigma_i) = \sqrt{\dfrac{\left\|AA^T\right\| h_i^2 \sigma_i^2}{(\theta - E + \beta)\tau L(\Sigma)^2}}$, $g_2(E) = \beta - [\theta - E]^+$, $f_2(h_i E^{-1}) = \dfrac{h_i}{L(\Sigma)} \sqrt{\dfrac{\left\|AA^T\right\|}{(\theta - E + \beta)\tau}}$, wherein $L(\Sigma)$ is the limit range of the amplitude limiter, A is the state transmission matrix of the controlled plant, θ is the battery size of the sensing device, β is a constant related to energy availability, and τ is the time slot duration.

In other embodiments, the sensing device may select the instantaneous state data and/or the wireless eigen-channels, according to any one or two of the above three control factors.

For example, the sensing device may select the wireless eigen-channels according to the state estimation error and the wireless MIMO channel conditions. Specifically, when the following equation 13 is satisfied, the i-th wireless MIMO eigen-channel will be selected,

$$g_1(h_i\sigma_i) > C \qquad (13)$$

Alternatively, the sensing device may make the selection according to one single factor. For example, when one of the equations $g(h_i) > C$, $g(\sigma_i) > C$ and $C > g_2(E)$ is satisfied, the i-th wireless MIMO eigen-channel would be selected, wherein, σ_i is the i-th largest singular value of the state estimation error covariance matrix, g_1 is a non-decreasing function of σ_i and h_i, in which the larger the h_i and σ_i, the larger the value of the function, g is a non-decreasing function of σ_i or h_i, in which the larger the h_i or the σ_i, the larger the value of the function, g_2 is a decreasing function of E, in which the larger the E, the smaller the value of the function, and C is a constant. The constant C is predefined and can be tuned according to application scenarios.

As another example, the sensing device may select the instantaneous state data according to the state estimation error and the wireless MIMO channel conditions. Specifically, when the following equation 14 is satisfied, the i-th piece of instantaneous state data, of the multiple pieces of instantaneous state data, will be selected,

$$f_1(h_i) > \sigma_i^{-1} \qquad (14)$$

Alternatively, the sensing device may make the selection according to one single factor. For example, when one of the equations $f(h_i) > C$, $C > \sigma_i^{-1}$ and $f(E^{-1}) > C$ is satisfied, the i-th piece of instantaneous state data, of the multiple pieces of instantaneous state data, would be selected, wherein, σ_i is the i-th largest singular value of the state estimation error covariance matrix, h_i is the i-th largest singular value of the wireless MIMO channel state matrix H and represents the condition of the i-th wireless MIMO eigen-channel, and f is a non-decreasing function of h_i or E^{-1}, in which the larger the h_i or E^{-1}, the larger the value of the function.

It should be appreciated that, when the sensing device does not base on the wireless channel conditions to determine the transmission scheme for the instantaneous state data, the sensing device needs not to execute step S31.

The transmission scheme of the instantaneous state data that is determined through step S34 can reduce the resource occupation and power consumption on the sensing device, and can meanwhile guarantee that the controlled plant achieves the control objective. The method can continue to step S35.

In step S35, the sensing device performs analog encoding on the selected instantaneous state data.

The analog encoding refers to that the sensing device may directly acquire the quantized amplitude of the instantaneous state data. The quantized amplitude may be directly loaded to a carrier for transmission. Since the quantized amplitude serves as modulated signals, it can have an infinite number of states, specifically, the instantaneous state with different values will also have different quantized amplitude, which thus is referred to as analog encoding.

Prior art sensing devices generally use digital encoding to encode the data to be transmitted. However, digital encoding requires to perform transport block check, block segmentation, rate matching, etc. on the digital signals-in the form of bit streams-that is acquired through analog-to-digital conversion, and transmit the modulated digital signals to the control device, which may receive the data and perform corresponding decoding processing and digital-to-analog conversion, after which can the converted analog signals be further processed. Whereas in analog encoding, the analog amplitude of the analog signals is directly modulated for transmission. Thus, compared with digital encoding, analog encoding does not require the digital encoding and decoding as above, and thus the transmission paths and structures of the sensing device and control device can be simplified, and the costs of the sensing device and the control device can also be reduced.

Furthermore, as is shown in FIG. 5b, if during the process of the transmission of the digital signals, which are digitally encoded, to the control device through the wireless channel, other sensing devices also transmit digital signals to the control device, then the digital signals transmitted from different sensing devices may be collided, such that the control device cannot decode the correct signal from the collided digital signals, causing the signals invalid. However, when analog encoding is used, as is shown in FIG. 5a, even the signals from multiple sensing devices are overlapped, the control device does not need to decode the overlapped signals and can directly use the overlapped signals for plant stabilization, which means the signals are still valid. Thus, the sensing device according to the disclosure uses analog encoding to encode the instantaneous state data, which improves the communication reliability and allows multiple sensing devices, in the NCS, to simultaneously transmit data to the same control device.

It should be appreciated that, in other embodiments where, for example, there is only one sensing device in the NCS, then the sensing device may not execute step S35, but performs digital encoding on the instantaneous state data before transmitting it to the control device.

In addition, if the transmission scheme for the instantaneous state data, determined by the sensing device in step S34, includes only the selection of the wireless eigen-channels, then the current step S35 can be that the sensing device performs analog encoding on all the detected instantaneous state data using an analog encoder. The method can proceed to step S36.

In step S36, the sensing device transmits the encoded instantaneous state data to a control device, which controls the controlled plant, through the selected wireless eigen-channels.

For example, in the NCS, as shown in FIG. 1, the sensing device periodically detects and acquires multiple pieces of instantaneous state data $\mathrm{X}(n)$ (i.e., $x(1), x(2) \cdots x(n)$) of the controlled plant, and limits the amplitude of the instantaneous state data to obtain $\mathrm{Q}(n)$ (i.e., $\mathrm{q}(1), q(2) \cdots q(n)$). The sensing device obtains a condition h_i of each wireless eigen-channel according to the wireless MIMO channel state matrix H that is fed back from the control device, and computes a state estimation error $\Delta \mathrm{X}(n)$ (i.e., $\Delta x(1), \Delta x(2) \cdots \Delta x(n)$) by a comparison between the instantaneous state data $\mathrm{X}(n)$ and the reference state data. The sensing device makes a judgment on each of the wireless MIMO eigen-channels using the above equation 11 to select the wireless MIMO eigen-channel $\mathrm{H}(k)$ (i.e., $h(1), h(2) \cdots h(k)$), makes a judgment on each piece of state data using the above equation 12 to select the state data $\mathrm{Q}(j)$ (i.e., $\mathrm{q}(1), q(2) \cdots q(j)$), performs analog encoding $F(j)\mathrm{Q}(j)$ on the selected state data and outputs the same, and transmits the outputted data $F(j)\mathrm{Q}(j)$ to the control device through the wireless MIMO eigen-channels $H(k)$, such that the control device computes the state estimation of the controlled plant based on the received data and thus performs a corresponding control operation to stabilize the controlled plant.

Alternatively, the execution of the step S35 by the sensing device can be that the sensing device acquires the quantized amplitude of the instantaneous state data. The quantized amplitude can be directly loaded to a carrier and transmitted to the control device. The quantized amplitude may be a numeral that can be identified by the sensing device. For example, suppose the instantaneous state data is 14.8012, but the sensing device can handle only one decimal place, then the instantaneous state data would be transformed to 14.8.

The sensing device may then directly modulate the quantized amplitude and transmit the modulated signals carrying the quantized amplitude to the control device.

Referring now to FIG. 12, specifically, the sensing device may pass the instantaneous state data to an analog-to-digital converter 121 for analog-to-digital conversion such that a corresponding bit stream of the instantaneous data can be obtained, and the value represented by the bit stream would be taken as the quantized amplitude. For example, suppose the instantaneous state data is 14.001, it will be passed through the analog-to-digital converter to output a corresponding bit stream 1110, and the value represented by this bit stream is 14, which will be taken as the amplitude of this instantaneous state data. The sensing device can also perform the quantization processing on the state data by other means other than the analog-to-digital conversion. After the sensing device acquires the quantized amplitude of the instantaneous state data that is represented by the value of the bit stream, it will load this quantized amplitude onto a carrier and further generate a radio frame. For example, the quantized amplitude may be sequentially passed through the transform precoder 123 for precoding, the resource element mapper 124 for resource block mapping, the SC-FDMA signal generator 125 for generating complex-valued time domain SC-FDMA signals, and finally through the frame generator 126 where the radio frame would be generated. The generated radio frame will be transmitted through the corresponding wireless channel to the control device.

Furthermore, some sensing devices may use two-way parallel transmission, for example, for the transmission of complex-valued signals. To be compatible with this transmission scheme, the sensing device may further perform serial-to-parallel conversion on the corresponding bit stream of the instantaneous state data, after obtaining the bit stream through analog-to-digital conversion. Namely, when the sensing device needs to transmit multiple pieces of instantaneous state data, it will convert the multiple pieces of serial state data to parallel state data, such that two-way transmission can be achieved and thus the transmission efficiency can be improved. After the serial-to-parallel transmission, the quantized amplitude of the two-way bit streams will be loaded to a carrier, thus generating and transmitting a radio frame to the control device.

The control device may receive the radio frame carrying the quantized amplitude and convert this radio frame to a numeral that can be identified by the control device. The control device may then demodulate this radio frame to obtain the quantized amplitude, and further carry out the state estimation based on the quantized amplitude and the channel estimation, so as to generate a corresponding control command. For example, referring to FIG. 13, the control device may pass the received radio frame through the analog-to-digital converter 131 for analog-to-digital conversion to obtain the corresponding bit stream of this radio frame, which is a numeral that can be handled by the control device and represents the quantized amplitude of the received state data. The bit stream may then pass through the frame synchronization module 132 for frame synchronization, the fast fourier transform (FFT) module 133 for demodulation to obtain the loaded quantized amplitude, which may then be outputted to the channel estimation module 134 and the state estimator 135. The state estimator 135 may carry out the state estimation based on the outputs of the FFT module 133 and the channel estimation module 134.

It should be appreciated that, though the above proposed analog encoding manner uses analog-to-digital conversion to obtain the bit stream, the objective of analog-to-digital conversion is rather not to transmit every information bit, but to supply the amplitude information constituted by multiple bits that can be handled by the device. Thus, compared with digital encoding, the control device can perform state estimation based on the received amplitude information, but not to judge every information bit, thus resulting in a more efficient and robust state estimation performance.

To better illustrate the advantages of the proposed analog encoding manner, below a brief description will be rendered on digital encoding. In digital encoding, the source signal needs to pass through an analog-to-digital converter for analog-to-digital conversion in which a bit stream would be generated, a transport block CRC (cyclic redundancy check) attachment module and a block segmentation module for transport block check and block segmentation, and a rate matching module for rate matching. The bit stream may then pass through a transform precoder, a resource element mapper, an SC-FDMA signal generator, and a frame generator, and may then be transmitted through transmission channel. After the receiving terminal receives the signal frame, it may need to pass the signal frame through a demodulator, a channel deinterleaver, a channel decoder and CRC decoder, etc. for digital decoding, after which the state estimation can be carried out. The signal received at the receiving terminal can be modeled as $y_d(j)=r(j)x(j)+Z_q(j)[1]$, where $Z_q(j)$ is the quantization noise, $x(j)$ is the state data, and $r(j)\in\{0,1\}$ is a binary random variable, where $r(j)=1$ if all the data symbols that correspond to $x(j)$ are correctly decoded after the channel and CRC decoder, and $r(j)=0$ if the received signal do not contain any information about the source signal $x(j)$ but only the quantization noise, hence the state estimation performance deteriorates.

Whereas in the analog encoding manner proposed by the disclosure, the signal received by the control device can be modeled as $y_a(j)=H(j)x(j)+Z_c(j)$, where $H(j)$ is the wireless channel state, $Z_c(j)$ contains the channel noise and the quantization noise, and $x(j)$ is the state data. Therefore, the received signals would always contain the information of the state data $x(j)$, whereby the state estimation performance can be improved.

Furthermore, the analog encoding method can be directly realized by simply replacing the digital modulation modules in existing digital encoding with the corresponding modules in analog encoding discussed above. For example, in the sensing device all the modules before the precoder in existing digital encoding can be replaced with the aforementioned analog-to-digital converter and serial-to-parallel converter, and the existing digital decoding part can be removed, for example, removing all the demodulation related modules before the FFT module in the control device. Since the remaining modules perform the same functions as they are applied for digital encoding, this analog encoding manner is in effect compatible to existing network physical layer, such as the LTE physical layer. In addition, the analog encoding manner adopted by the present disclosure does not require digital encoding and decoding, thus the device structure can be further simplified.

In addition, in existing digital encoding manner, the bit stream is uncoded or coded with very simple channel coding scheme such as repetition code. This will result in a very high bit error rate (BER) at the encoded signals, which would lead to poor estimation performance. Whereas the analog encoding manner does not require digital encoding for the bit stream, thus the above problem can be avoided. In addition, the digital encoding manner is not suitable for low transmission power devices, since if a sensing device has a low transmission power, a sufficient signal noise ratio (SNR) cannot be guaranteed for certain state estimation performance, which will lead to high bit error rate (BER), and thus in turn limited coverage area, whereas in the analog encoding manner, the received signals would always contain the state data information, which thus can guarantee a better coverage performance.

According to a specific application example, the data processing in analog encoding manner can follow: the source signal $\begin{bmatrix} 6 \\ 15 \end{bmatrix}$ of the instantaneous state data contains two real numbers 6 and 15. The source signal $\begin{bmatrix} 6 \\ 15 \end{bmatrix}$ is first passed through an ADC to obtain the corresponding bit stream 10101101, which is then passed through a serial-to-parallel converter to obtain a repeated data symbol sequence **s:** 5.8+i15.2, where one resource block contains 84 symbols, thus the data symbol sequence s is repeated 84 times in one resource block. This repeated data symbol sequence s may then be outputted to the transform precoder for corresponding processing, and then be transmitted through the wireless channel to the control device. The control device may receive the signal and pass it to a DAC, a frame synchronization module and an FFT module to obtain 12+i2.1, finally the state estimator may calculate and obtain the state estimation data $\begin{bmatrix} 6.1 \\ 15.1 \end{bmatrix}$ based on the output 12+i2.1 of the FFT and the channel estimator output 1.1+i2.6. As can be seen, the state estimation performance is excellent.

Furthermore, according to the analog encoding manner, since the data symbol sequence corresponds to the quantized amplitude, the corresponding data symbol sequence of each piece of instantaneous state data would contain only one symbol, and thus the symbol can be repeated 84 times in one resource block. Whereas in the digital encoding manner, each piece of instantaneous state data corresponds to multiple bits, thus the corresponding data symbol sequence would contain multiple symbols, for example, the symbols would be -1-i1,1-i1,1+i1,-1+i1 based on the conditions of the above specific application example. Thus, the set of data symbols can only be repeated 21 times in one resource block. As a result, the repetition times in analog encoding manner is far greater than in digital encoding manner, when the control device receives such a resource block and performs processing based on the repeated data symbols in this resource block, for example, dividing the noise of this resource block by the repetition times, then the bigger the repetition times, the more the noise of each data symbol sequence can be decreased, namely, the bigger the repetition times, the higher the SNR.

To better illustrate the excellent state estimation performance of the analog encoding manner, simulation examples are provided as following.

Simulation Example 1: Performance Enhancement in LTE-M.

1) Source Model: The controlled plant state dynamics is given by $x(n+1) = Ax(n) + \mathrm{B}u(n) + w(n), n \geq 0$, $x(0)=0$, where $x(n) \in R^{4\times1}$ is the controlled plant state process, $u(n) \in R^{4\times1}$ is the controlled plant control action and $w(n) \in R^{4\times1}$ is the controlled plant noise being i.i.d. Gaussian distribution with zero mean and unit variance. We consider two cases. In case A, the open loop response of the dynamic controlled plant is unstable with $(A,B) = (1.1I_{4\times4}, I_{4\times4})$, where $I_{4\times4}$ is the 4-by-4 identity matrix, and the sensing device senses the state measurements x(n) and transmits to the control device periodically to form a stabilizing closed loop feedback loop as illustrated in Figure 1 via the LTE-M and NB LTE-M. In case B, the open-loop response of the dynamic plant is stable with $(A,B) = (0.9I_{4\times4}, 1I_{4\times4})$, and the sensing device periodically send the state measurements x(n) to the control device to improve the steady state error of the controlled plant.

2) Channel model: The channel is generated according to the LTE channel model for Urban Micro Scenario in Section B.1.2.2 in 3GPP TR 36.814. The sensing device antenna pattern is assumed omni directional with an antenna gain of 3dB. The path loss model is given by $PL(dB) = 40\log10(d) - 12.6$, where d is distance in meters. The channel model parameters are chosen according to Table B.1.2.2.1-4 in

3GPP TR 36.814.

3) System configuration: The system parameters are summarized in the following Table 1.

Table 1

Number of Resource Block	6
Modulation Level	QPSK and 16QAM
TTI	1ms
Coding	Distributed and Contiguous Repetition Coding
Quantization bits	16 bit
Sensing Device Transmission Power	20dBm
Number of Sensing Device Antenna	1
Number of Control Device Antenna	1
Periodic Access	Period of 2

4) Performance Comparison: We consider the normalized state estimation error at the control device (defined as $\frac{E\left[\left\|x(n)-\hat{x}(n)\right\|_F^2\right]}{E\left[\left\|x(n)\right\|_F^2\right]}$) as the performance metric.

For case A, where the open loop response of the dynamic controlled plant is unstable, Figure 14a and Figure 14b show the performance enhancement of the proposed analog encoding transmission compared with the existing digital encoding transmission schemes under contiguous repetition coding. And Figure 14c and Figure 14d show the performance enhancement of the proposed analog encoding transmission under distributed repetition coding. In the case of contiguous repetition coding, the proposed scheme has a performance gain of 14.75dB and 15.71dB compared with digital encoding transmission with QPSK and 16QAM, respectively, at the MSE of -16.87dB. In the case of in the case of distributed repetition coding, the proposed scheme has a performance gain of 12.31dB and 15.85dB compared with digital encoding transmission with QPSK and 16QAM, respectively, at the MSE of -19.27dB.

For case B, where the open loop response of the dynamic controlled plant is stable, Figure 15a and Figure 15b show the performance enhancement of the proposed analog encoding transmission compared with the existing digital encoding transmission schemes under contiguous repetition coding. And Figure 15c and Figure 15d show the performance enhancement of the proposed analog encoding transmission under distributed repetition coding. In the case of contiguous repetition coding, the proposed scheme has a performance gain of 4.21dB and 6.52dB compared with digital encoding transmission with QPSK and 16QAM, respectively, at the MSE of -7.19dB. In the case of in the case of distributed repetition coding, the proposed scheme has a performance gain of 3.75dB and 4.96dB compared with digital encoding transmission with QPSK and 16QAM, respectively, at the MSE of -7.79dB.

Simulation Example 2: Performance Enhancement in NB LTE-M

1) Source Model: The controlled plant state dynamics is given by $x(n+1)=Ax(n)+\mathrm{B}u(n)+w(n)$, $n\geq 0$, $x(0)=0$, where $x(n)\in R^{4\times 1}$ is the controlled plant state process, $u(n)\in R^{4\times 1}$ 1 is the controlled plant control action and $w(n)\in R^{4\times 1}$ is the controlled plant noise being i.i.d. Gaussian distribution with zero mean and unit variance. We consider two cases. In case A, the open loop response of the dynamic plant is unstable with $(A,B)=(1.1I_{4\times 4},I_{4\times 4})$ and the sensing device senses the state measurements x(n) and transmits to the control device periodically to form a stabilizing closed loop feedback loop as illustrated in Figure 1 via the LTE-M and NB-LTE-M. In case B, the open-loop response of the dynamic plant is stable with $(A,B)=(0.9I_{4\times 4},I_{4\times 4})$ and the sending device periodically send the state measurements x(n) to the control device to improve the steady state error of the controlled plant.

2) Channel model: The channel is generated according to the LTE channel model for Urban Micro Scenario in Section B.1.2.2 in 3GPP TR 36.814. The sensing device antenna pattern is assumed omni directional with an antenna gain of 3 dBi. The path loss model is given by $PL(dB)=40\log 10(d)-12.6$, where d is distance in meters. The channel model parameters are chosen according to Table B.1.2.2.1-4 in 3GPP TR 36.814.

3) System configuration: The system parameters are summarized in the following Table 2.

Table 2

Number of Resource Block	1

Modulation Level	QPSK and 16QAM
TTI	1ms
Coding	Distributed and Contiguous Repetition Coding
Quantization bits	16 bit
Sensing Device Transmission Power	23dBm
Number of Sensing Device Antenna	1
Number of Control Device Antenna	1
Periodic Access	Period of 2

4) Performance Comparison: For case A, where the open loop response of the dynamic controlled plant is unstable, Figure 16a and Figure 16b show the performance enhancement of the proposed analog encoding transmission compared with the existing digital encoding transmission schemes under contiguous repetition coding. And Figure 16c and Figure 16d show the performance enhancement of the proposed analog encoding transmission under distributed repetition coding. In the case of contiguous repetition coding, the proposed scheme has a performance gain of 10.41dB and 13.14dB compared with digital encoding transmission with QPSK and 16QAM, respectively, at the MSE of -13.86dB. In the case of in the case of distributed repetition coding, the proposed scheme has a performance gain of 14.98dB and 16.26dB compared with digital encoding transmission with QPSK and 16QAM, respectively, at the MSE of -18.01dB.

For case B, where the open loop response of the dynamic controlled plant is stable, Figure 17a and Figure 17b show the performance enhancement of the proposed analog encoding transmission compared with the existing digital encoding transmission schemes under contiguous repetition coding. And Figure 17c and Figure 17d show the performance enhancement of the proposed analog encoding transmission under distributed repetition coding. In the case of contiguous repetition coding, the proposed scheme has a performance gain of 4.96dB and 6.85dB compared with digital encoding transmission with QPSK and 16QAM, respectively, at the MSE of -3.32dB. In the case of in the case of distributed repetition coding, the proposed scheme has a performance gain of 4.67dB and 5.87dB compared with digital encoding transmission with QPSK and 16QAM, respectively, at the MSE of -3.52dB.

As can be concluded from the above simulation examples, the analog encoding transmission manner brings a significantly performance gain compared with existing digital encoding transmission manner.

Referring now to FIG. 6, there is shown a flow chart of a method for transmission of plant state data according to yet another embodiment of the present disclosure. This method can be applied to the NCS as shown in FIG. 1, and implemented by the control device shown in FIG. 1. The method includes the following steps.

In a first step S61, a control device receives the instantaneous state data wirelessly transmitted from a sensing device, wherein a transmission scheme of the instantaneous state data is determined according to a control objective of a controlled plant, and the sensing device may or may not wirelessly transmit each piece of instantaneous state data to the control device, which controls the controlled plant, according to the transmission scheme.

In one implementation, the signals received by the control device through the communication channel are the faded state data with channel noise. The sensing device may use the methods of the preceding method embodiments to transmit the detected instantaneous state data, see the description of the above method embodiments for details. The method can continue to step S62.

In step S62, the control device analyzes the received instantaneous state data to generate a corresponding control command, and the method can continue to step S63.

When the sensing device adopts the above analog encoding transmission manner, the control device may process the instantaneous state data by the above corresponding manner, as is shown in FIG. 13.

In step S63, the control device transmits the control command to the controlled plant, which performs a corresponding operation according to the control command.

For example, the control device may compute a state estimation of the controlled plant according to the received instantaneous state data and local information, generate a corresponding control command according to this state estimation, and transmit the control command to the controlled plant such that the controlled plant executes this control command and thus maintains a stable state, thereby the control objective of the controlled plant can be achieved.

Referring now to FIG. 7, there is shown a block diagram of a sensing device according to an embodiment of the present disclosure. In this embodiment, the sensing device is the sensing device 12 as shown in FIG. 1, and includes an acquisition module 71, a determination module 72 and a transmission module 73.

The acquisition module 71 is configured to acquire the instantaneous state data of a controlled plant.

The determination module 72 is configured to determine a transmission scheme for the instantaneous state data according to a control objective of the controlled plant.

The transmission module 73 is configured to wirelessly transmit or not transmit each piece of instantaneous state data to a control device, which controls the controlled plant, according to the transmission scheme.

Alternatively, the determination module 72 may select at least a part of the wireless MIMO eigen-channels according to at least one of a state estimation error, wireless MIMO channel conditions and a local battery status of the sensing device. The transmission module 73 may transmit the instantaneous state data to the control device through the selected wireless eigen-channels, such that control device receives the instantaneous state data through the selected wireless eigen-channels, and further controls the controlled plant accordingly. The state estimation error is obtained by a comparison between multiple pieces of instantaneous state data and the corresponding reference state data of the controlled plant.

Alternatively, the wireless MIMO channel state matrix H may be fed back from the control device, and the sensing device may further include a reception module configured to receive a wireless MIMO channel state matrix H that is fed back from the control device, and acquire an i-th largest singular value h_i of the matrix H as the condition of the i-th wireless MIMO eigen-channel.

Alternatively, the determination module 72 selecting at least a part of the wireless MIMO eigen-channels according to the at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device may include: when the above equation 11 is satisfied, selecting the i-th wireless MIMO eigen-channel.

Alternatively, the local battery status of the sensing device may include the available energy in the local battery of the sensing device, and the determination module 72 selecting at least a part of the wireless MIMO eigen-channels according to the at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device may include: when the above equation 12 is satisfied, selecting an i-th wireless MIMO eigen-channel.

Alternatively, the determination module 72 may select at least a part of the instantaneous state data according to at least one of a state estimation error, wireless MIMO channel conditions and a local battery status of the sensing device, such that the control device receives the selected instantaneous state data and controls the controlled plant accordingly, wherein the state estimation error is obtained by a comparison between the instantaneous state data and the corresponding reference state data of the controlled plant.

Alternatively, the determination module 72 selecting at least a part of the instantaneous state data according to the at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device may include: when the above equation 13 is satisfied, selecting an i-th piece of instantaneous state data.

Alternatively, the local battery status of the sensing device may include the available energy in the local battery of the sensing device. The determination module 72 selecting at least a part of the instantaneous state data according to the at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device may include: when the above equation 14 is satisfied, selecting the i-th piece of instantaneous state data.

Alternatively, the sensing device may further include an analog encoder configured to perform analog encoding on the instantaneous state data. The transmission module 73 may wirelessly transmit or not transmit each piece of instantaneous state data, which is outputted from the analog encoder, to the control device, which controls the controlled plant, according to the transmission scheme.

The analog encoder may specifically acquire the quantized amplitude of the instantaneous state data. The quantized amplitude may be directly loaded to a carrier and thus transmitted to the control device.

More specifically, the analog encoder may perform analog-digital conversion on the instantaneous state data to obtain the corresponding bit stream of the instantaneous state data, and the value represented by the bit stream may be taken as the quantized amplitude of the instantaneous state data. Furthermore, the analog encoder may further perform serial-to-parallel conversion on the corresponding bit stream of the instantaneous state data. In a specific implementation, the analog encoder may include at least the components 121 and 122 as shown in FIG. 12.

Alternatively, the sensing device may include an amplitude limiter configured to limit the amplitude of the instantaneous state data, which is acquired by the acquisition module 71, and output it to the determination module 72.

Referring now to FIG. 8, there is shown a block diagram of a sensing device according to another embodiment of the disclosure. In this embodiment, the sensing device is the sensing device 12 as is shown in FIG. 1. The sensing device 80 includes an amplitude limiter module 81, a data selection module 82, a transmission scheduling module 83 and an analog encoding module 84.

The amplitude limiter module 81 is configured to limit the amplitude of the detected instantaneous state data of a controlled plant.

The data selection module 82 is configured to select at least a part of the instantaneous state data, from the instantaneous state data outputted from the amplitude limiter module 81, according to at least one of a state estimation error, wireless MIMO channel conditions and a local battery status of the sensing device.

The transmission scheduling module 83 is configured to select at least a part of the wireless MIMO eigen-channels according to the at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device.

The analog encoding module 84 is configured to transmit the selected instantaneous state data to the control device, which controls the controlled plant, through the selected wireless eigen-channels, such that the control device controls the controlled plant accordingly.

In the above sensing device embodiments, the modules of the sensing device are used to execute the corresponding steps of the preceding method embodiments, respectively. See the above method embodiments for more details of the specific execution process.

Referring now to FIG. 9, there is shown a block diagram of a sensing device 90 according to yet another embodiment of the present disclosure. In this embodiment, the sensing device 90 is the same as the sensing device 12 shown in FIG. 1. The sensing device 90 includes a detection circuit 91, a CPU(central processing unit) 92, a radio frequency-RF circuit 94 and an MIMO antenna 93, which are connected in a sequential order.

The detection circuit 91 is configured to detect the instantaneous state data of a controlled plant, and output it to the CPU 92.

The CPU 92 is configured to determine a transmission scheme for the instantaneous state data according to a control objective of the controlled plant, and transmit the instantaneous state data to the RF circuit 94.

The RF circuit 94 is configured to transmit the instantaneous state data to the MIMO antenna 93, which may or may not wirelessly transmit each piece of instantaneous state data to a control device, which controls the controlled plant, according to the transmission scheme.

Alternatively, the CPU 92 may select at least a part of wireless MIMO eigen-channels according to at least one of a state estimation error, the wireless MIMO channel conditions and a local battery status of the sensing device, such that the control device receives the instantaneous state data through the selected wireless eigen-channels and controls the controlled plant accordingly. The state estimation error is obtained by a comparison of multiple pieces of instantaneous state data and the corresponding reference state data of the controlled plant.

Alternatively, the wireless MIMO channel state matrix H may be fed back from the control device, and the CPU 92 may further compute, according to a wireless MIMO channel state matrix H that is fed back from the control device, an i-th largest singular value h_i of the matrix H as the condition of the i-th wireless MIMO eigen-channel.

Alternatively, the CPU 92 selecting at least a part of the wireless MIMO eigen-channels according to the at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device may include: when the above equation 11 is satisfied, selecting the i-th wireless MIMO eigen-channel.

Alternatively, the local battery status of the sensing device may include the available energy in the local battery of the sensing device. The CPU 92 selecting at least a part of the wireless MIMO eigen-channels according to the at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device may include: when the above equation 12 is satisfied, selecting the i-th wireless MIMO eigen-channel. In one implementation, the sensing device can be an energy harvesting sensing device, namely, the sensing device is powered by harvesting the surrounding energy.

Alternatively, the CPU 92 may select at least a part of the instantaneous state data according to at least one of a state estimation error, wireless MIMO channel conditions and a local battery status of the sensing device, such that the control device receives the selected instantaneous state data and controls the controlled plant accordingly, wherein the state estimation error is obtained by a comparison between the instantaneous state data and the corresponding reference state data of the controlled plant.

Alternatively, the CPU 92 selecting at least a part of the instantaneous state data according to the at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device may include: when the above equation 13 is satisfied, selecting the i-th piece of instantaneous state data.

Alternatively, the local battery status of the sensing device may include the available energy in the local battery of the sensing device. The CPU 92 selecting at least a part of the instantaneous state data according to the at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device may include: when the above equation 14 is satisfied, selecting the i-th piece of instantaneous state data.

Alternatively, the sensing device 90 may further include an analog encoder 95 connected to the CPU 92 and the RF circuit 94, such that the CPU 92 is connected to the RF circuit 94 via the analog encoder 95. The analog encoder 95 is configured to perform analog encoding on the instantaneous state data before it is outputted to the RF circuit.

Alternatively, the analog encoder 95 may specifically acquire the quantized amplitude of the instantaneous state data. The quantized amplitude may be directly loaded to a carrier and transmitted to the control device.

Specifically, the analog encoder 95 may perform analog-to-digital conversion on the instantaneous state data to obtain the corresponding bit stream of the instantaneous state data, and the value represented by the bit stream can be taken as the quantized amplitude of the instantaneous state data. Furthermore, the analog encoder 95 may further perform serial-to-digital conversion on the corresponding bit stream. In a specific implementation, this analog encoder 95 may include at least the components 121 and 122 as shown in FIG. 12.

Alternatively, the sensing device 90 may further include an amplitude limiter 96 connected to the detection circuit 91 and configured to limit the amplitude of the instantaneous state data before it is outputted to the CPU 92.

The methods, discussed above and executed by the sensing device 90, can be implemented by the CPU 92. The CPU 92 may be an integrated circuit chip with signal processing capabilities. During the implementation process, the various steps of the methods may be executed by hardwired integrated logic circuits or by software commands in the CPU 92. The CPU 92 may be a general purpose processor, a digital signal processor-DSP, an application specific integrated circuit-ASIC, a field programmable gate array-FPGA or other programmable logic devices, discrete gates or transistor logic devices, discrete hardware components, whichever can implement the methods, steps and logic blocks disclosed in the disclosure. The general purpose processor can be a microprocessor or any conventional processor. The steps of the methods disclosed by the disclosure can be directly executed by a hardware decoding processor, or by a combination of hardware or software modules in the decoding processor. The software modules may reside in any storage medium well-known to the art such as, for example, a random access memory-RAM, a flash memory, a programmable read-only memory-ROM, or an electrically erasable programmable memory or register. The CPU 92 may read the program stored in the storage medium and implement the steps of the above methods.

Referring now to FIG. 10, there is shown a block diagram of a control device according to an embodiment of the disclosure. In this embodiment, the control device is the control device 13 as is shown in FIG. 1. The control device includes a reception module 101, a generation module 102 and a transmission module 103.

The reception module 101 is configured to receive the instantaneous state data wirelessly transmitted from a sensing device, wherein a transmission scheme of the instantaneous state data is determined according to a control objective of a controlled plant, and the sensing device may or may not wirelessly transmit each piece of instantaneous state data to a control device, which controls the controlled plant, according to the transmission scheme. The sensing device is any sensing device described in the preceding embodiments.

The generation module 102 is configured to analyze the received instantaneous state data to generate a corresponding control command.

The transmission module 103 is configured to transmit the control command to the controlled plant, which thus performs a corresponding operation according to the control command.

Referring now to FIG. 11, there is shown a block diagram of a control device 110 according to another embodiment of the present disclosure. In this embodiment, the control device 110 is the same as the control device 13 as is shown in FIG. 1. The control device 110 includes a CPU (central processing unit) 111, a RF circuit 112, a MIMO antenna 113 and an output 114. The CPU 111 is connected to the RF circuits 112 and output 114, the RF circuit 112 is connected to the MIMO antenna 113.

The RF circuit 112 is configured to receive, through the MIMO antenna 113, the instantaneous state data wirelessly transmitted from a sensing device, wherein a transmission scheme of the instantaneous state data is determined according to a control objective of a controlled plant, and the sensing device may or may not wirelessly transmit each piece of instantaneous state data to a control device, which controls the controlled plant, according to the transmission scheme. The sensing device is any sensing device described in the preceding embodiments.

The CPU 111 is configured to analyze the received instantaneous state data and generate a corresponding control command, and output the control command to the output 114.

The output 114 may further transmit the control command to the controlled plant, which thus performs a corresponding operation according to the control command.

In some embodiments, the output 114 can be a serial port, through which the control devices transfers the command to the controlled plant. In other embodiments, wireless channels are established between the control device and the controlled plant, the output 114 may include another RF module and another MIMO antenna. It should be noted that, the RF circuits 112 and the another RF module may be implemented with one single RF circuit, and the MIMO antennas 113 and the another MIMO antenna may also be implemented by one set of MIMO antennas.

The methods, discussed above and executed by the control device, can be implemented by the CPU 111. The CPU 111 may be an integrated circuit chip with signal processing capabilities. During the implementation process, the various steps of the methods may be executed by hardwired integrated logic circuits or by software commands in the CPU 111. The CPU 111 may be a general purpose processor, a digital signal processor-DSP, an application specific integrated circuit-ASIC, a field programmable gate array-FPGA or other programmable logic devices, discrete gates or transistor logic devices, discrete hardware components, whichever can implement the methods, steps and logic blocks disclosed in the disclosure. The general purpose processor can be a microprocessor or any conventional processor. The steps of the methods disclosed by the disclosure can be directly executed by a hardware decoding processor, or by a combination of hardware or software modules in the decoding processor. The software modules may reside in any storage medium well-known to the art such as, for example, a random access memory-RAM, a flash memory, a programmable read-only memory-ROM, or an electrically erasable programmable memory or register. The CPU 111 may read the program stored in the storage medium and implement the steps of the above methods.

According to the solutions above, the sensing device can determine a transmission scheme for the instantaneous state data according to the control objective of the controlled plant, and may or may not transmit each piece of instantaneous state data by the determined transmission scheme. Thus, the sensing device can selectively transmit its sensing data, thus a smart data transmission can be achieved. In particular, when the sensing device selects to transmit only a part of data, the data transmitted would be reduced, which thus can save the communication resources and the power consumption on the sensing device.

The elements, in different embodiments, with the same name but different reference numerals, may be the same elements and have the same configuration and function.

It is worth noting that, in the embodiments disclosed herein, the disclosed systems, devices and methods can also be implemented by other ways. The device embodiments described are merely illustrative, for example, the division of modules or units is only a division based on logic functions, thus in actual implementations there may be other division manners, for example, multiple units or components may be combined or integrated onto another system, or some features may be ignored or not executed. In addition, the displayed or discussed mutual couplings, direct couplings or communication connections may be achieved through some interfaces, devices or units, and may be achieved electrically, mechanically or in other forms.

The separated units as described may or may not be physically separated. Components displayed as units may or may not be physical units, and may reside at one location or may be distributed to multiple networked units. Part or all of the units may be selected, according to actual requirements, to achieve the objective of the embodiment.

In addition, various functional units in embodiments of the present disclosure may be integrated into one processing unit, and may be present as physically separated units, and two or more units may be integrated into one unit. The integrated units may be implemented by hardware, and may also be implemented as software functional units.

If the integrated units are implemented as software functional units and sold or used as standalone products, they can be stored in a computer readable storage medium. On the basis of such an understanding, the substantial technical solution, or the part which contributes to the prior art, or all or part of the technical solution, of the present disclosure, may be embodied as software products. The computer software products can be stored in a storage medium and can include multiple instructions enabling a computing device (for example, a person computer, a server, a network device, etc.) or a processor to execute all or part steps of the methods as described in the embodiments of the disclosure. The storage medium may include any medium which can store program codes such as, for example, a USB flash disk, a mobile hard drive, a read-only memory-ROM, a random access memory-RAM, a magnetic disk or an optical disk.

CLAIMS

1. A method for transmission of plant state data, comprising:

acquiring, by a sensing device, instantaneous state data of the controlled plant;

determining a transmission scheme for the instantaneous state data according to a control objective of the controlled plant; and

transmitting or not transmitting wirelessly each piece of instantaneous state data to a control device, which controls the controlled plant, according to the determined transmission scheme.

2. The method according to claim 1, wherein the block of determining the transmission scheme for the instantaneous state data according to the control objective of the controlled plant comprises:

selecting, according to at least one of a state estimation error, wireless MIMO channel conditions and a local battery status of the sensing device, at least a part of wireless MIMO eigen-channels, such that the control device receives the instantaneous state data through the selected wireless MIMO eigen-channels and thus controls the controlled plant accordingly;

wherein the state estimation error is obtained by a comparison between the instantaneous state data and corresponding reference state data of the controlled plant.

3. The method according to claim 2, wherein the block of selecting at least a part of the wireless MIMO eigen-channels according to the at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device comprises:

when the following equation 1 is satisfied, selecting an i-th wireless MIMO eigen-channel;

$$g_1(h_i\sigma_i) > C \qquad (1)$$

wherein, h_i is the i-th largest singular value of a wireless MIMO channel state matrix H and represents a condition of the i-th wireless MIMO eigen-channel, σ_i is the i-th largest singular value of the state estimation error covariance matrix, g_1 is a non-decreasing function of σ_i and h_i, and C is a constant.

4. The method according to claim 2, wherein the local battery status of the sensing device comprises available energy in the local battery of the sensing device, and the block of selecting at least a part of the wireless MIMO eigen-channels according to the at least one of the state estimation error, the wireless MIMO channel

conditions and the local battery status of the sensing device comprises:

when the following equation 2 is satisfied, selecting an i-th wireless MIMO eigen-channel;

$$g_1(h_i\sigma_i) > g_2(E) \qquad (2)$$

wherein, σ_i is the i-th largest singular value of the state estimation error covariance matrix, h_i is the i-th largest singular value of a wireless MIMO channel state matrix H and represents a condition of the i-th wireless MIMO eigen-channel, g_1 is a non-decreasing function of σ_i and h_i, E is the available energy in the local battery of the sensing device, and g_2 is a decreasing function of E.

5. The method according to claim 1, wherein the block of determining the transmission scheme for the instantaneous state data according to the control objective of the controlled plant comprises:

selecting, according to at least one of a state estimation error, wireless MIMO channel conditions and a local battery status of the sensing device, at least a part of the instantaneous state data, such that the control device receives the selected instantaneous state data and controls the controlled plant accordingly;

wherein, the state estimation error is obtained by a comparison between the instantaneous state data and corresponding reference state data of the controlled plant.

6. The method according to claim 5, wherein, the block of selecting at least a part of the instantaneous state data according to the at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device comprises:

when the following equation 3 is satisfied, selecting an i-th piece of instantaneous state data;

$$f_1(h_i) > \sigma_i^{-1} \qquad (3)$$

wherein, σ_i is the i-th largest singular value of the state estimation error covariance matrix, h_i is the i-th largest singular value of a wireless MIMO channel state matrix H and represents a condition of the i-th wireless MIMO eigen-channel, and f_1 is a non-decreasing function of h_i.

7. The method according to claim 5, wherein the local battery status of the sensing device comprises available energy in the local battery of the sensing device; and the block of selecting at least a part of the instantaneous state data according to

the at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device comprises:

when the following equation 4 is satisfied, selecting an i-th piece of instantaneous state data;

$$f_2(h_i E^{-1}) > \sigma_i^{-1} \qquad (4)$$

wherein, σ_i is the i-th largest singular value of the state estimation error covariance matrix, h_i is the i-th largest singular value of a wireless MIMO channel state matrix H and represents a condition of the i-th wireless MIMO eigen-channel, E is the available energy in the local battery of the sensing device, and f_2 is a non-decreasing function of h_i and E^{-1}.

8. The method according to claim 1, further comprising, before the block of determining the transmission scheme for the instantaneous state data:

receiving a wireless MIMO channel state matrix H that is fed back from the control device, and acquiring an i-th largest singular value h_i in the matrix H as a condition of the i-th wireless MIMO eigen-channel.

9. The method according to claim 1, further comprising, before the block of wirelessly transmitting or not transmitting each piece of instantaneous state data to the control device, which controls the controlled plant, according to the transmission scheme:

performing analog encoding on the instantaneous state data.

10. The method according to claim 9, wherein the block of performing analog encoding on the instantaneous state data comprises:

acquiring quantized amplitude of the instantaneous state data, wherein the quantized amplitude is to be directly loaded to a carrier and transmitted to the control device.

11. The method according to claim 10, wherein the block of acquiring the quantized amplitude of the instantaneous state data comprises:

performing analog-to-digital conversion on the instantaneous state data to obtain a corresponding bit stream of the instantaneous state data, wherein a value represented by the bit stream is taken as the quantized amplitude.

12. The method according to claim 11, further comprising, after the block of performing analog-to-digital conversion on the instantaneous state data:

performing serial-to-digital conversion on the corresponding bit stream of the instantaneous state data.

13. The method according to claim 9, further comprising, after the block of acquiring, by the sensing device, the instantaneous state data of the controlled plant:

limiting the amplitude of the acquired instantaneous state data.

14. A method for transmission of plant state data, comprising:

receiving, by a control device, instantaneous state data that is wirelessly transmitted from a sensing device, wherein a transmission scheme of the instantaneous state data is determined according to a control objective of a controlled plant, and the sensing device wirelessly transmits or not transmits each piece of instantaneous state data to the control device, which controls the controlled plant, according to the transmission scheme;

analyzing the received instantaneous state data and generating a corresponding control command; and

transmitting the control command to the controlled plant, which thus performs a corresponding operation according to the control command.

15. A sensing device, comprising:

an acquisition module, configured to acquire instantaneous state data of a controlled plant;

a determination module, configured to determine a transmission scheme for the instantaneous state data according to a control objective of the controlled plant; and

a transmission module, configured to wirelessly transmit or not transmit each piece of instantaneous state data to a control device, which controls the controlled plant, according to the transmission scheme.

16. The sensing device according to claim 15, wherein

the determination module is configured to select, according to at least one of a state estimation error, wireless MIMO channel conditions and a local battery status of the sensing device, at least a part of the wireless MIMO eigen-channels, such that the control device receives the instantaneous state data through the selected wireless eigen-channels and controls the controlled plant accordingly;

wherein the state estimation error is obtained by a comparison between the instantaneous state data and corresponding reference data of the controlled plant.

17. The sensing device according to claim 15, wherein

the determination module is configured to select, according to at least one of a state estimation error, wireless MIMO channel conditions and a local battery status of the sensing device, at least a part of the instantaneous state data, such that the control device receives the selected instantaneous state data and controls the controlled plant accordingly;

wherein, the state estimation error is obtained by a comparison between the instantaneous state data and corresponding reference state data of the controlled plant.

18. The sensing device according to claim 15, further comprising:

an analog encoding module, configured to perform analog encoding on the instantaneous state data; and

the transmission module wirelessly transmits or not transmits each piece of instantaneous state data, outputted from the analog encoding module, to the control device according to the transmission scheme.

19. The sensing device according to claim 18, wherein the analog encoding module is configured to acquire quantized amplitude of the instantaneous state data, wherein the quantized amplitude is to be directly loaded to a carrier and thus transmitted to the control device.

20. A sensing device, comprising a detection circuit, a central processing unit (CPU), an RF circuit and an MIMO antenna, which are connected in a sequential order, wherein

the detection circuit is configured to detect instantaneous state data of a controlled plant, and output the detected instantaneous state data to the CPU;

the CPU is configured to determine a transmission scheme for the instantaneous state data according to a control objective of the controlled plant, and to output the instantaneous state data to the RF circuit; and

the RF circuit is configured to transmit the instantaneous state data to the MIMO antenna, which thus wirelessly transmits or not transmits each piece of instantaneous state data to a control device, which controls the controlled plant, according to the transmission scheme.

21. The sensing device according to claim 20, wherein

the CPU is configured to select, according to at least one of a state estimation error, wireless MIMO channel conditions and a local battery status of the sensing device, at least a part of the wireless MIMO eigen-channels, such that the control device receives the instantaneous state data through the selected wireless MIMO eigen-channels and controls the controlled plant accordingly;

wherein the state estimation error is obtained by a comparison between the instantaneous state data and corresponding reference state data of the controlled plant.

22. The sensing device according to claim 21, wherein, the CPU selecting at least a part of the wireless MIMO eigen-channels according to the at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device comprises:

when the following equation 5 is satisfied, selecting an i-th wireless MIMO eigen-channel;

$$g_1(h_i\sigma_i) > C \qquad (5)$$

wherein, h_i is the i-th largest singular value of a wireless MIMO channel state matrix H and represents a condition of the i-th wireless MIMO eigen-channel, σ_i is the i-th largest singular value of the state estimation error covariance matrix, g_1 is a non-decreasing function of σ_i and h_i, and C is a constant.

23. The sensing device according to claim 21, wherein the local battery status of the sensing device comprises available energy in the local battery of the sensing device, and the CPU selecting at least a part of the wireless MIMO eigen-channels according to the at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device comprises:

when the following equation 6 is satisfied, selecting an i-th wireless MIMO eigen-channel;

$$g_1(h_i\sigma_i) > g_2(E) \qquad (6)$$

wherein, σ_i is the i-th largest singular value of the state estimation error covariance matrix, h_i is the i-th largest singular value of a wireless MIMO channel state matrix H and represents a condition of the i-th wireless eigen-channel, g_1 is a non-decreasing function of σ_i and h_i, E is the available energy in the local battery of the sensing device, and g_2 is a decreasing function of E.

24. The sensing device according to claim 20, wherein

the CPU is configured to select, according to at least one of a state estimation error, wireless MIMO channel conditions and a local battery status of the sensing device, at least a part of the instantaneous state data, such that the control device receives the selected instantaneous state data and controls the controlled plant accordingly;

wherein, the state estimation error is obtained by a comparison between the instantaneous state data and corresponding reference state data of the controlled plant.

25. The sensing device according to claim 24, wherein the CPU selecting at least a part of the instantaneous state data according to the at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device comprises:

when the following equation 7 is satisfied, selecting an i-th piece of instantaneous state data;

$$f_1(h_i) > \sigma_i^{-1} \qquad (7)$$

wherein, σ_i is the i-th largest singular value of the state estimation error covariance matrix, h_i is the i-th largest singular value of a wireless MIMO channel state matrix H and represents a condition of the i-th wireless MIMO eigen-channel, and f_1 is a non-decreasing function of h_i.

26. The sensing device according to claim 24, wherein, the local battery status of the sensing device comprises available energy in the local battery of the sensing device, and the CPU selecting at least a part of the instantaneous state data according to the at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device comprises:

when the following equation 8 is satisfied, selecting an i-th piece of instantaneous state data;

$$f_2(h_i E^{-1}) > \sigma_i^{-1} \qquad (8)$$

wherein, σ_i is the i-th largest singular value of the state estimation error covariance matrix, h_i is the i-th largest singular value of a wireless MIMO channel state matrix H and represents a condition of the i-th wireless MIMO eigen-channel, E is the available energy in the local battery of the sensing device, and f_2 is a non-decreasing function of h_i and E^{-1}.

27. The method according to claim 21, further comprising, before the block of determining the transmission scheme for the instantaneous state data:

receiving a wireless MIMO channel state matrix H that is fed back from the control device, and acquiring an i-th largest singular value h_i in the matrix H as a condition of the i-th wireless MIMO eigen-channel.

28. The sensing device according to claim 20, further comprising:

an analog encoder, connected to the CPU and the RF circuit, such that the CPU is connected to the RF circuit via the analog encoder, the analog encoder being configured to perform analog encoding on the instantaneous state data before it is outputted to the RF circuit.

29. The sensing device according to claim 28, wherein the analog encoder is configured to acquire quantized amplitude of the instantaneous state data, wherein the quantized amplitude is to be directly loaded to a carrier and thus transmitted to the control device.

30. The sensing device according to claim 29, wherein the analog encoder is configured to perform analog-to-digital conversion on the instantaneous state data to obtain a corresponding bit stream of the instantaneous state data, and a value represented by the bit stream is taken as the quantized amplitude of the instantaneous state data.

31. The sensing device according to claim 30, wherein the analog encoder is configured to further perform serial-to-parallel conversion on the instantaneous state data.

32. The sensing device according to claim 28, further comprising:

an amplitude limiter, connected to the detection circuit and configured to limit the amplitude of the instantaneous state data before it is outputted to the CPU.

33. A control device, comprising:

a reception module, configured to receive instantaneous state data wirelessly transmitted from a sensing device, wherein a transmission scheme of the instantaneous state data is determined according to a control objective of a controlled plant, and the sensing device wirelessly transmits or not transmits each piece of instantaneous state data to a control device, which controls the controlled plant, according to the transmission scheme;

a generation module, configured to analyze the received instantaneous state data and generate a corresponding control command; and

a transmission module, configured to transmit the control command to the controlled plant, which thus performs a corresponding operation according to the control command.

34. A control device, comprising a central processing unit (CPU), a RF circuit,

a MIMO antenna and an output, wherein the CPU is connected to the RF circuits and the output, the RF circuit is connected to the MIMO antenna, wherein

the RF circuit is configured to receive, through the MIMO antenna, instantaneous state data wirelessly transmitted from a sensing device, wherein a transmission scheme of the instantaneous state data is determined according to a control objective of a controlled plant, and the sensing device wirelessly transmits or not transmits each piece of instantaneous state data to a control device, which controls the controlled plant, according to the transmission scheme;

the CPU is configured to analyze the received instantaneous state data and generate a corresponding control command, and output the control command to the output; and

the output is configured to transmit the control command to the controlled plant, which performs a corresponding operation according to the control command.

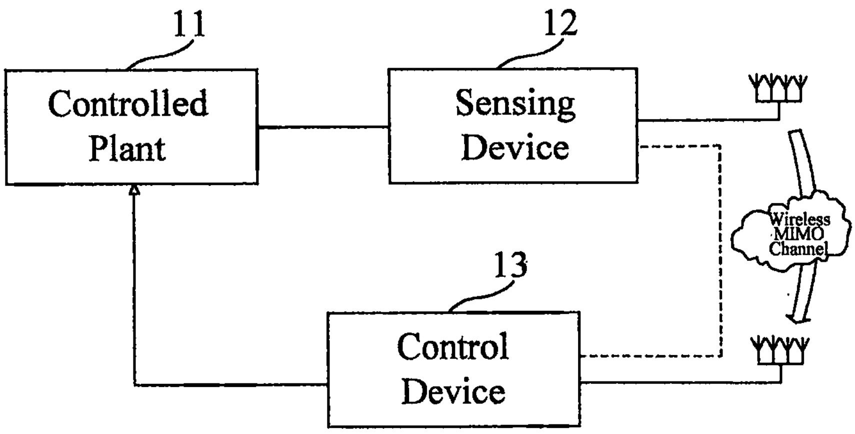
11
12
Controlled Plant
Sensing Device
Wireless MIMO Channel
13
Control Device

FIG. 1

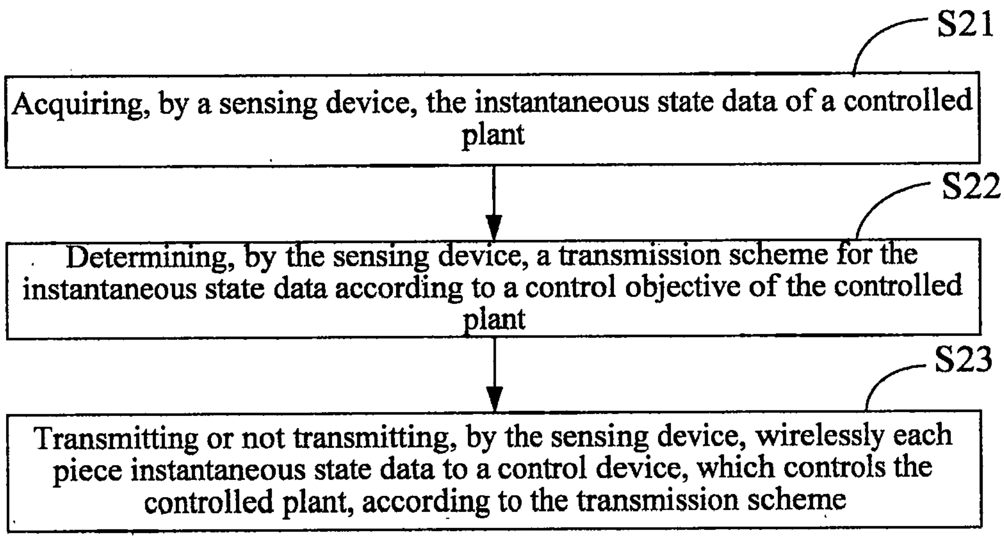
S21
Acquiring, by a sensing device, the instantaneous state data of a controlled plant
S22
Determining, by the sensing device, a transmission scheme for the instantaneous state data according to a control objective of the controlled plant
S23
Transmitting or not transmitting, by the sensing device, wirelessly each piece instantaneous state data to a control device, which controls the controlled plant, according to the transmission scheme

FIG. 2

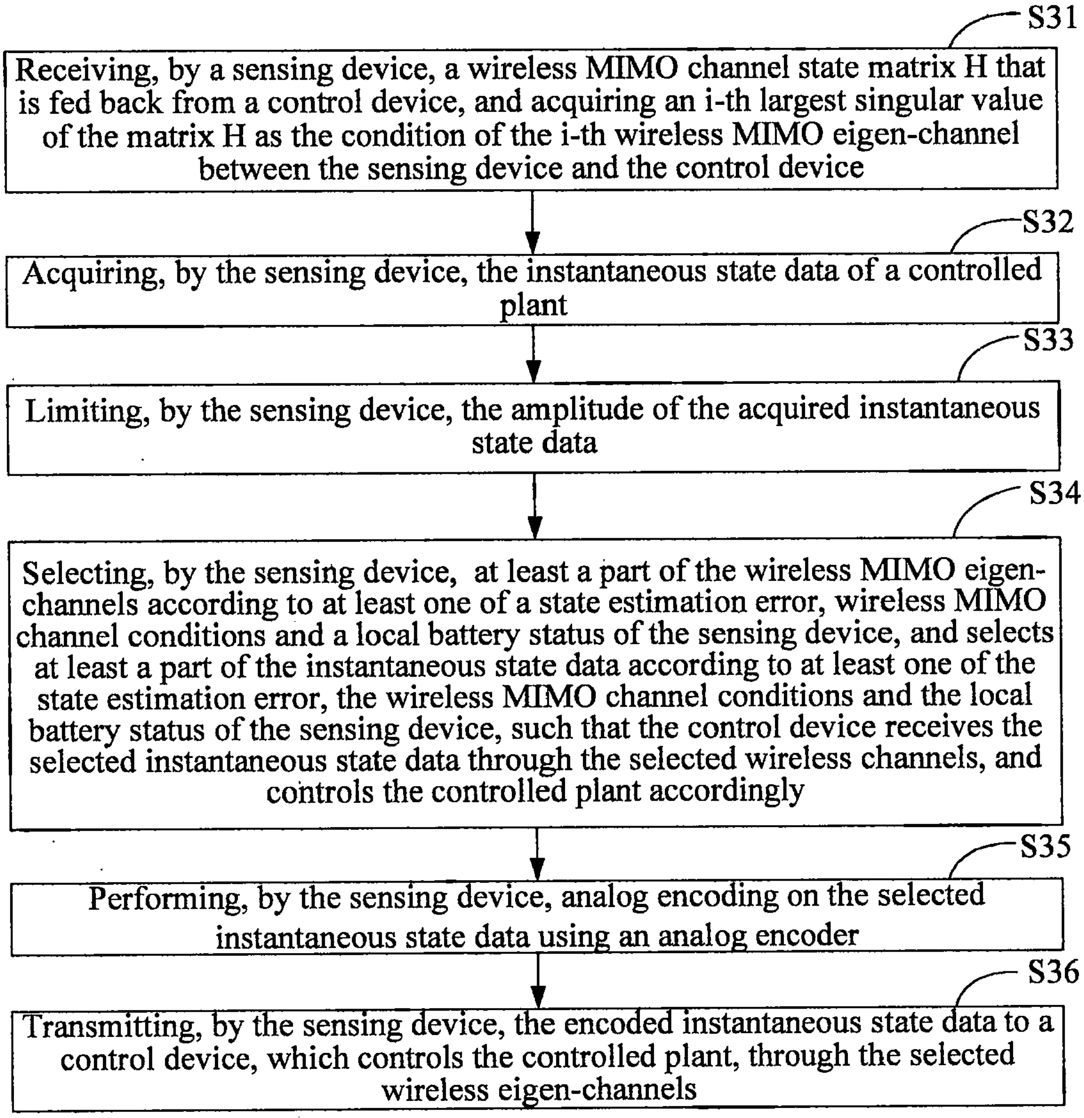
S31
Receiving, by a sensing device, a wireless MIMO channel state matrix H that is fed back from a control device, and acquiring an i-th largest singular value of the matrix H as the condition of the i-th wireless MIMO eigen-channel between the sensing device and the control device
S32
Acquiring, by the sensing device, the instantaneous state data of a controlled plant
S33
Limiting, by the sensing device, the amplitude of the acquired instantaneous state data
S34
Selecting, by the sensing device, at least a part of the wireless MIMO eigen-channels according to at least one of a state estimation error, wireless MIMO channel conditions and a local battery status of the sensing device, and selects at least a part of the instantaneous state data according to at least one of the state estimation error, the wireless MIMO channel conditions and the local battery status of the sensing device, such that the control device receives the selected instantaneous state data through the selected wireless channels, and controls the controlled plant accordingly
S35
Performing, by the sensing device, analog encoding on the selected instantaneous state data using an analog encoder
S36
Transmitting, by the sensing device, the encoded instantaneous state data to a control device, which controls the controlled plant, through the selected wireless eigen-channels

FIG. 3

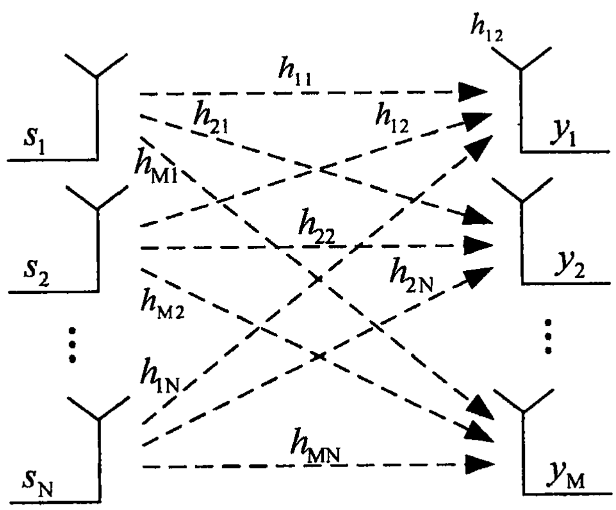
h_{12}
h_{11}
h_{21}
h_{12}
s_1
y_1
h_{M1}
h_{22}
s_2
h_{2N}
y_2
h_{M2}
h_{1N}
h_{MN}
s_N
y_M

FIG. 4

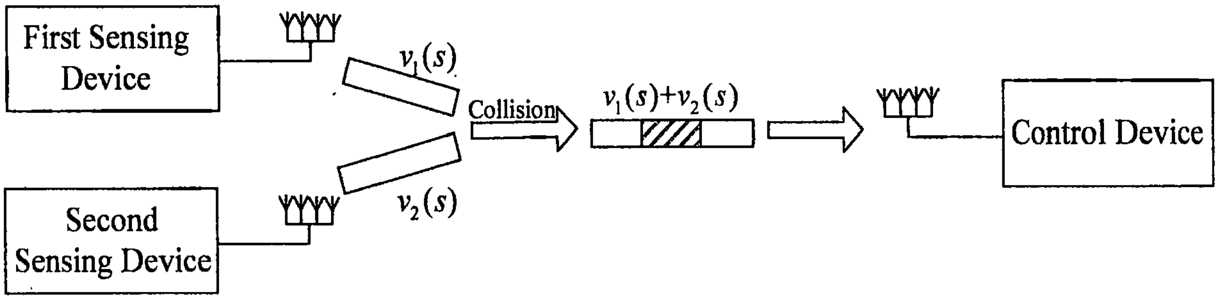

FIG. 5a

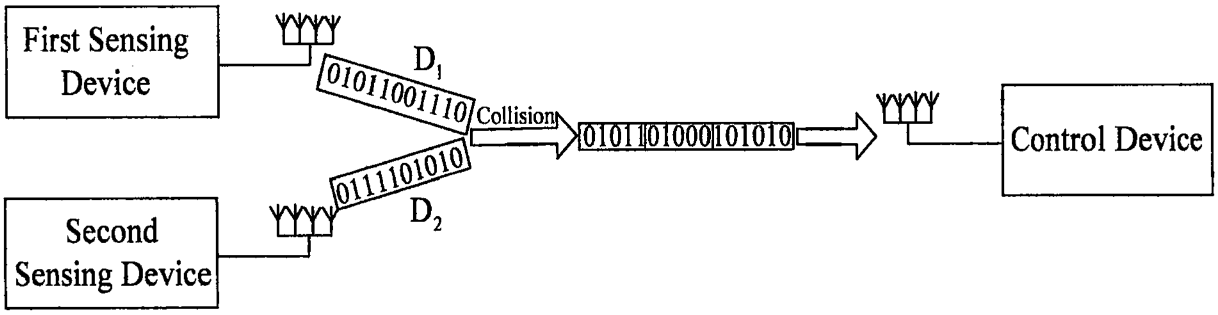

FIG. 5b

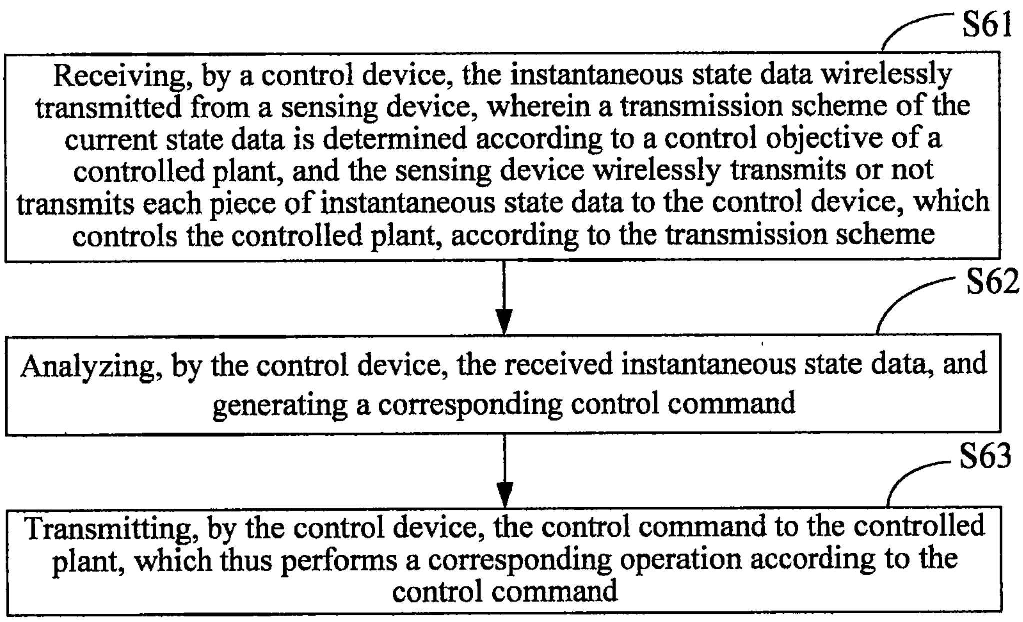

FIG. 6

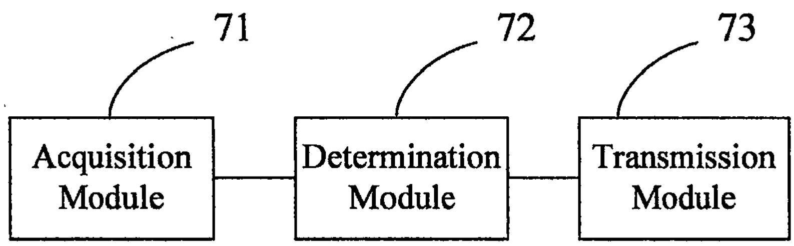

FIG. 7

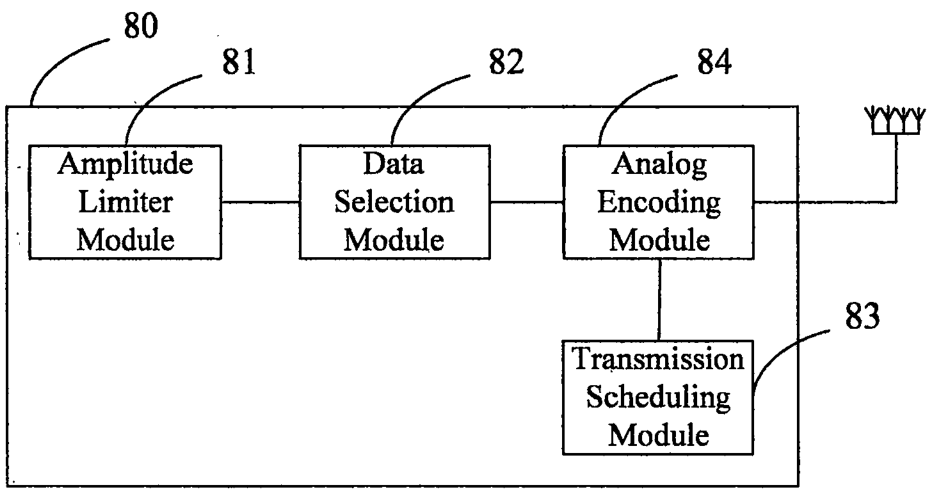

FIG. 8

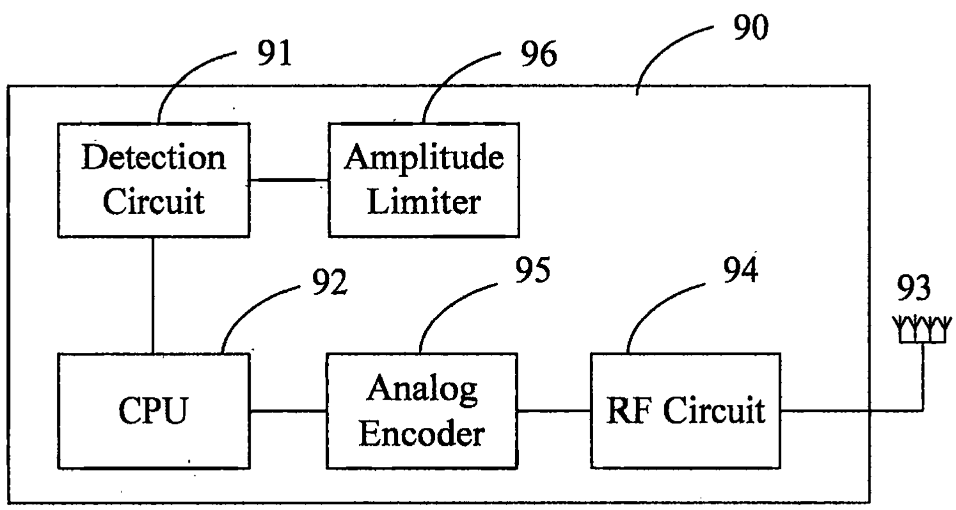

FIG. 9

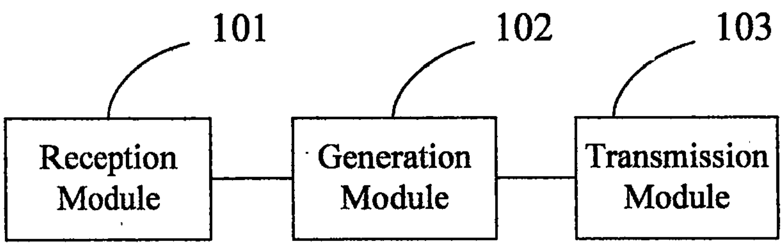

FIG. 10

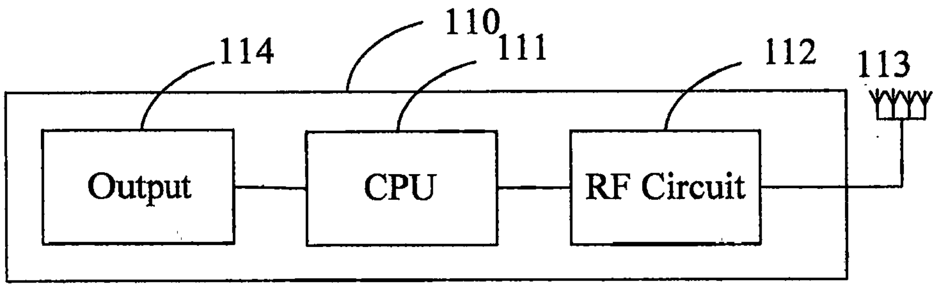

FIG. 11

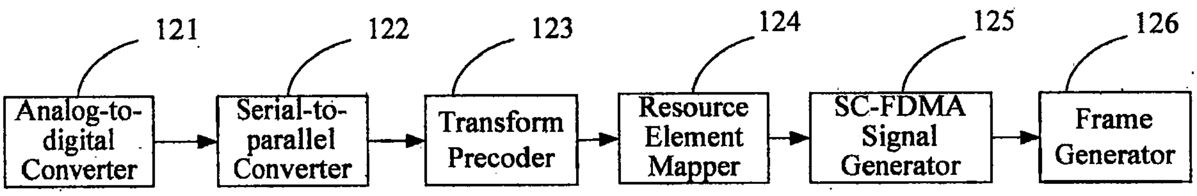

FIG. 12

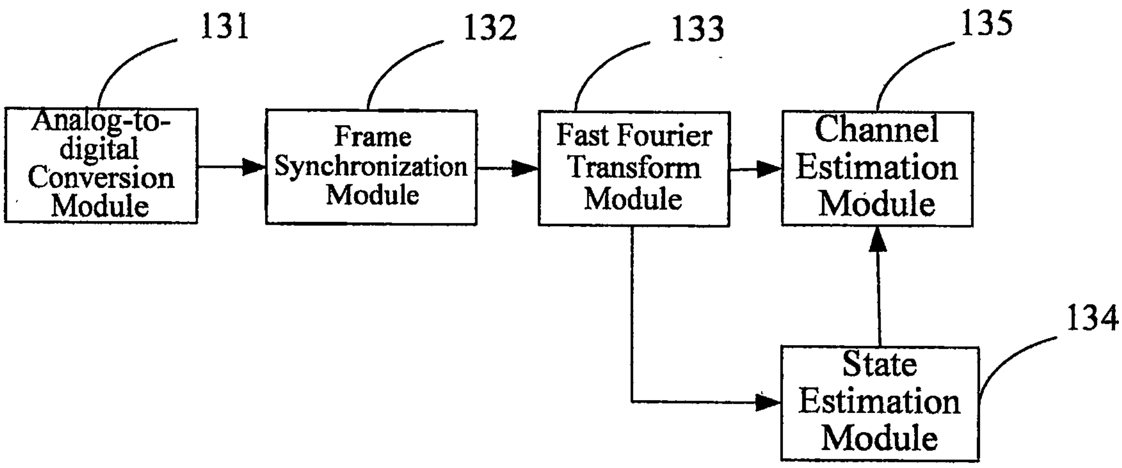

FIG. 13

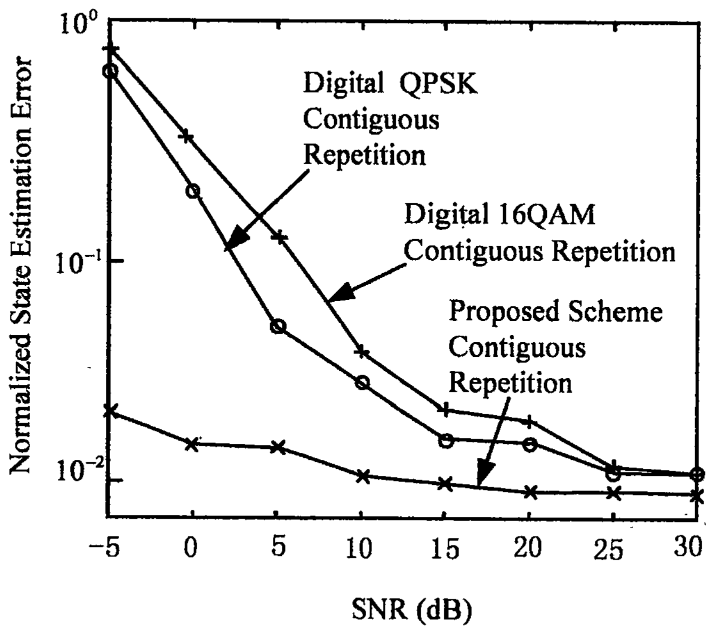

FIG. 14a

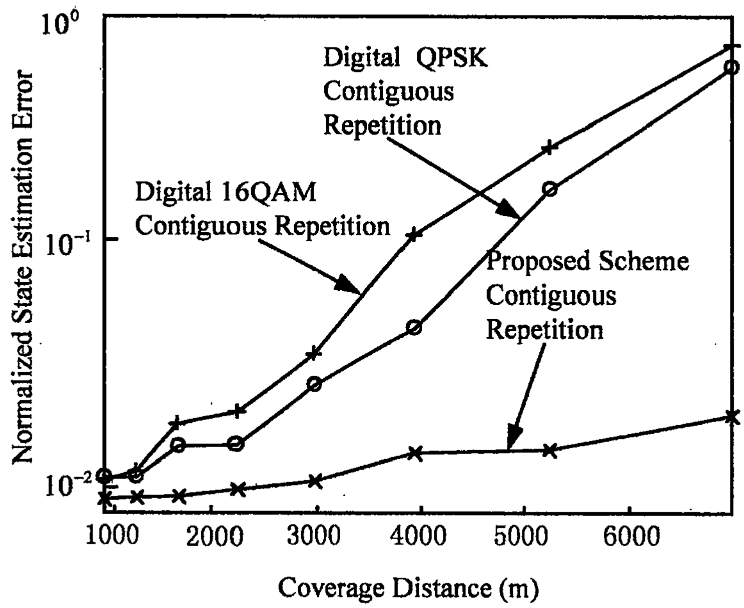

FIG. 14b

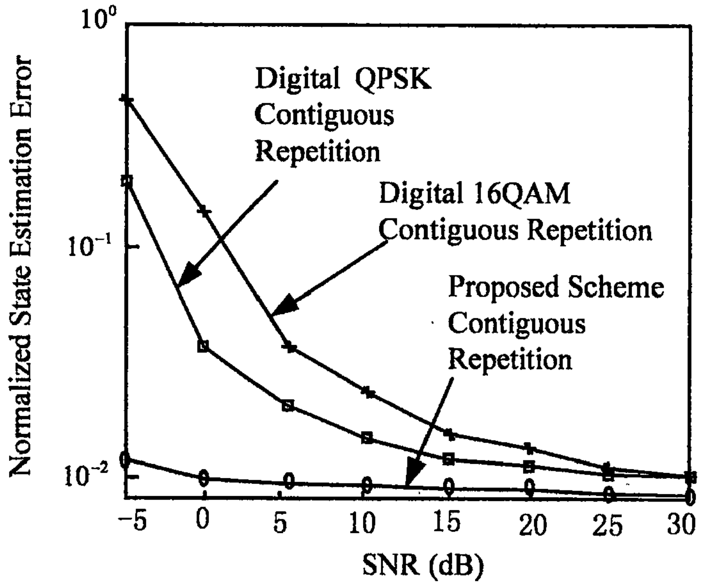

FIG. 14c

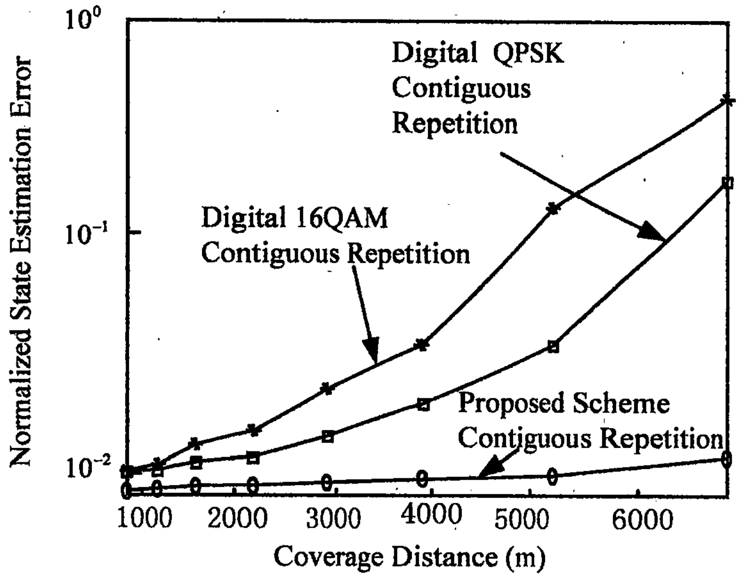

FIG. 14d

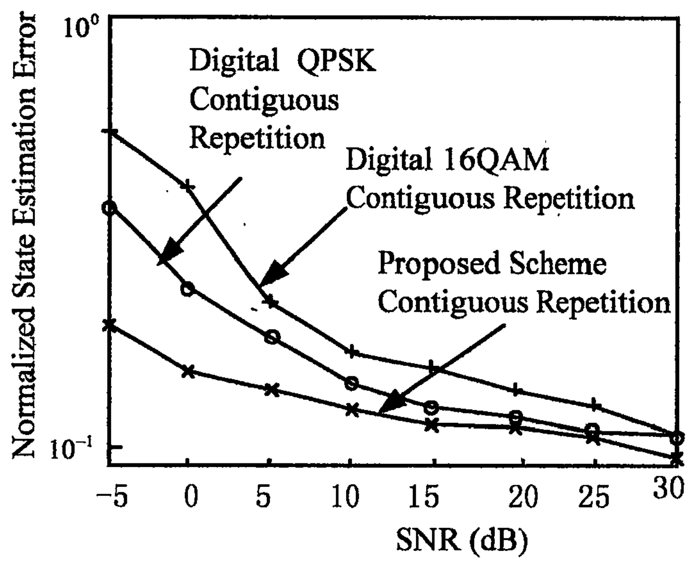

FIG. 15a

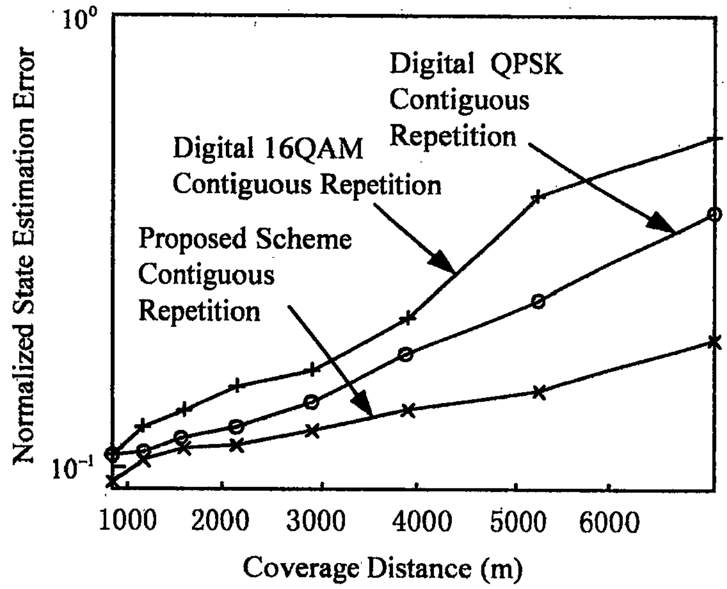

FIG. 15b

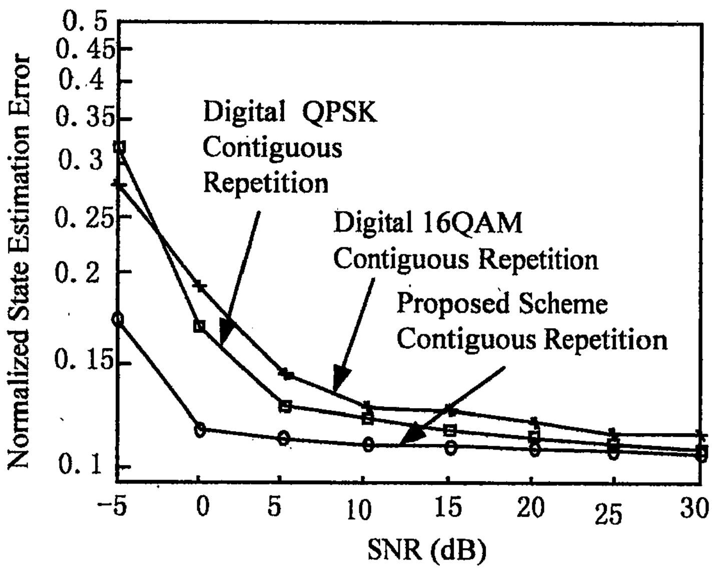

FIG. 15c

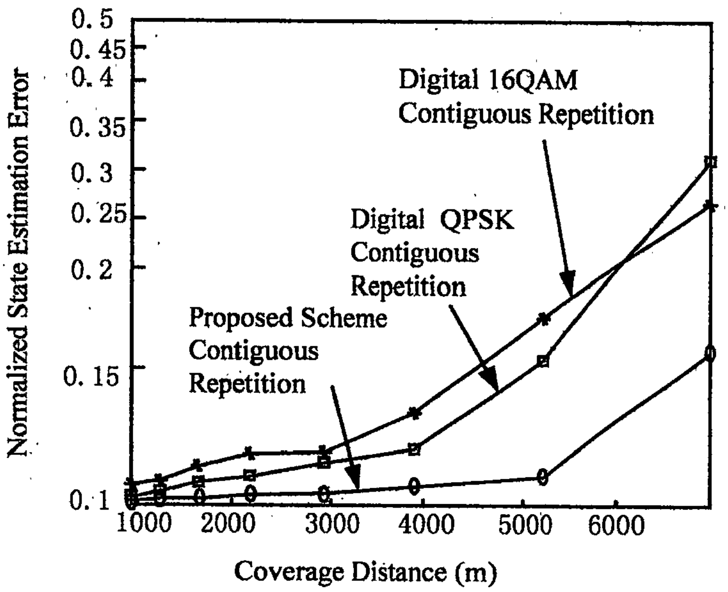

FIG. 15d

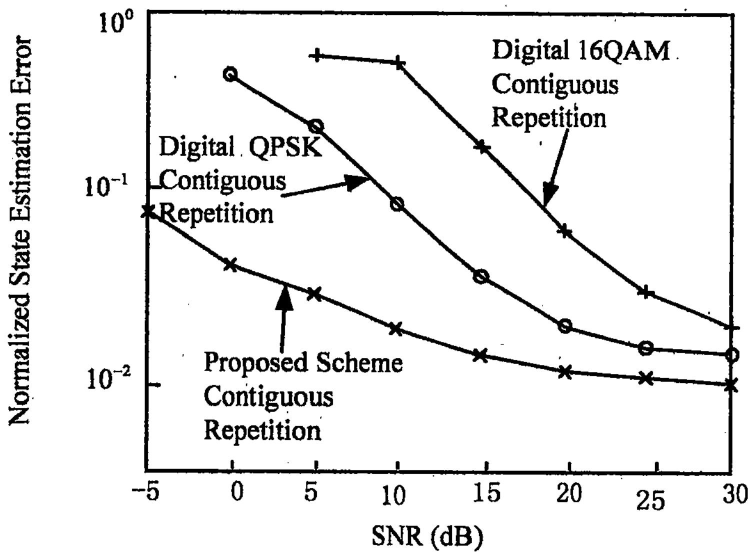

FIG. 16a

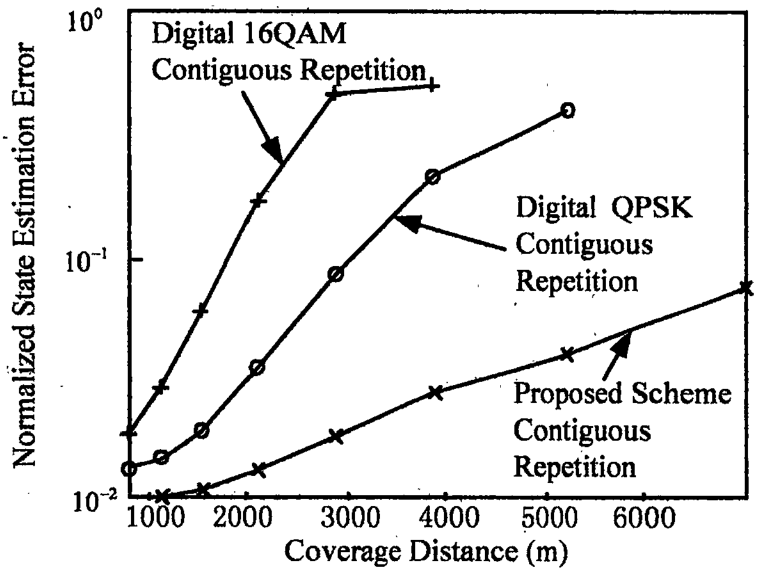

FIG. 16b

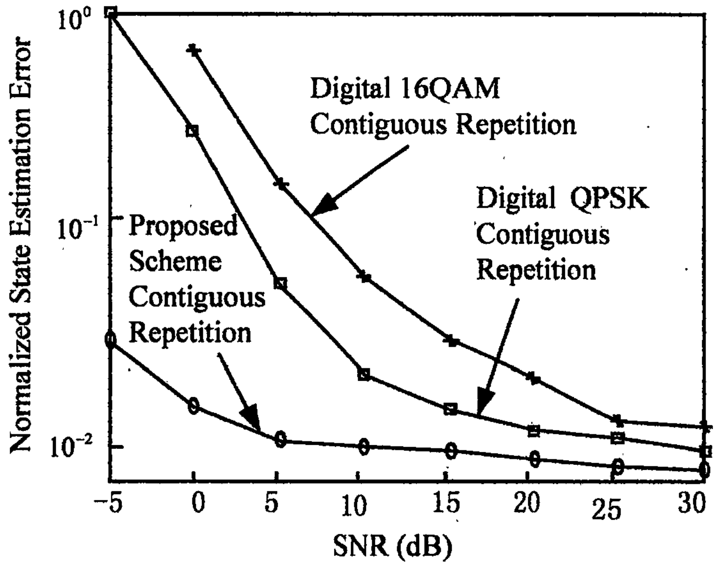

FIG. 16c

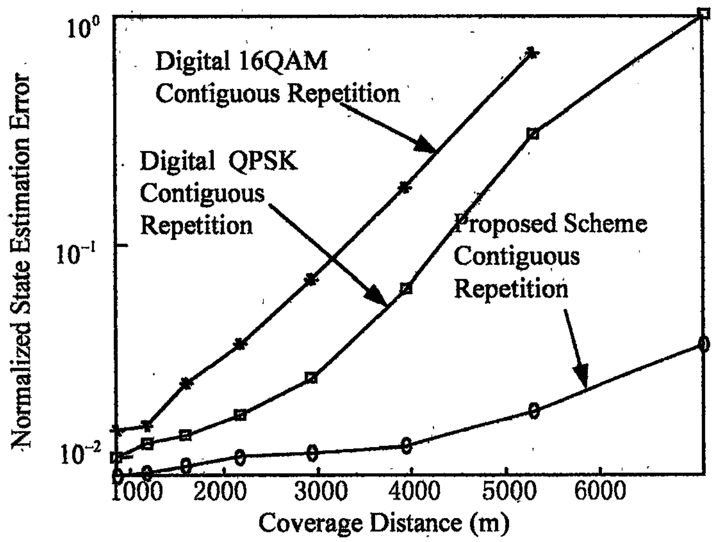

FIG. 16d

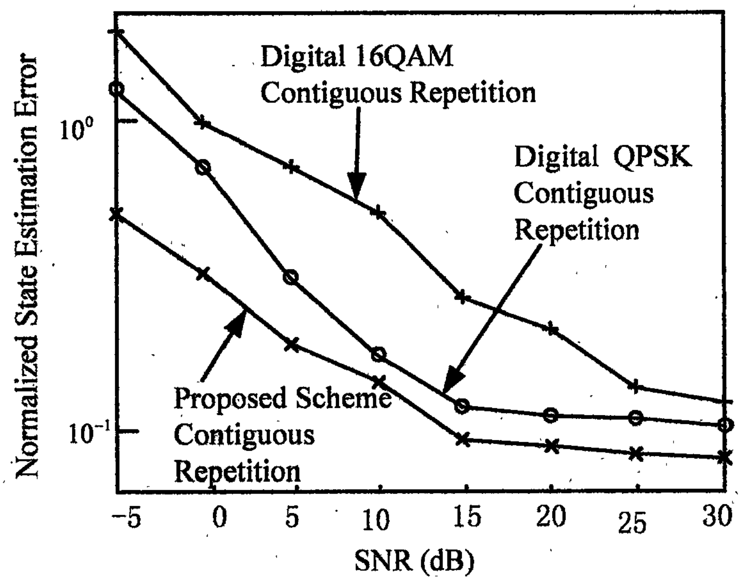

FIG. 17a

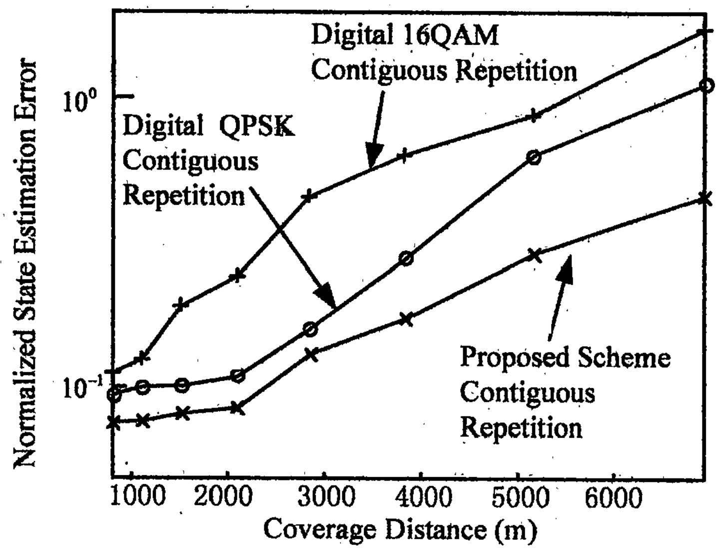

FIG. 17b

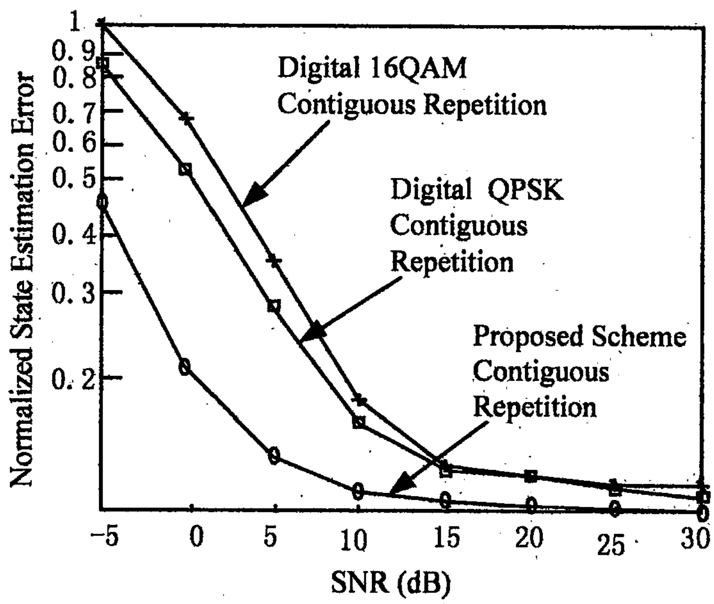

FIG. 17c

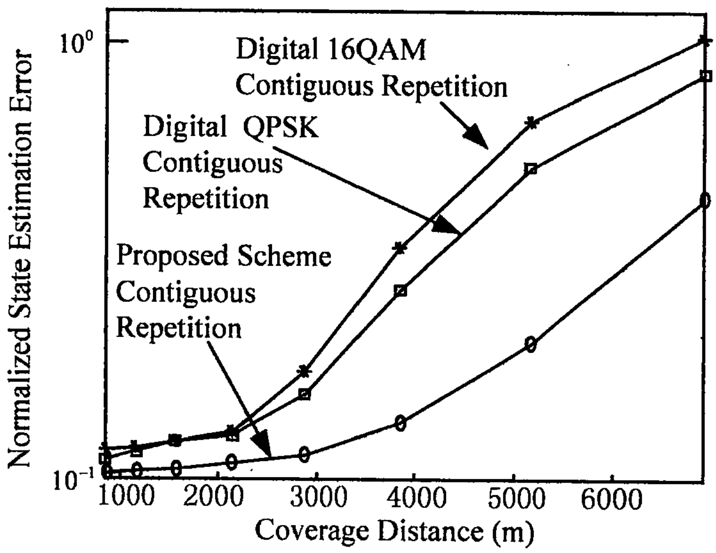
Normalized State Estimation Error
10^0
10^{-1}
Digital 16QAM
Contiguous Repetition
Digital QPSK
Contiguous
Repetition
Proposed Scheme
Contiguous
Repetition
1000
2000
3000
4000
5000
6000
Coverage Distance (m)

FIG. 17d

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CN2016/078250

A. CLASSIFICATION OF SUBJECT MATTER

H04L 29/08(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H04L; H04W

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

WPI, EPODOC, IEEE, CNKI, CNPAT： network, control, NCS, sensing, instantaneous, state, transmission, scheme, MIMO, battery, eigen, channel, controlled, plant

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	CN 101145052 A (ZHEJIANG CENT CONTROL TECHNOLOGY CO., LTD.) 19 March 2008 (2008-03-19) description, page 2 lines 22-28, page 7 line 9-page 11 line 7 and figures 1-3	1-34
Y	CN 103415817 A (YOKOGAWA ELECTRIC CORP.) 27 November 2013 (2013-11-27) description, paragraphs [0066]-[0096] and figure 1	1-34
A	CN 103999528 A (INTERDIGITAL PATENT HOLDINGS INC.) 20 August 2014 (2014-08-20) the whole document	1-34
A	KR 20100047982 A (UNIV. KYUNGPOOK NAT IND ACADEMIC COOP.) 11 May 2010 (2010-05-11) the whole document	1-34

☐ Further documents are listed in the continuation of Box C. ☑ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
25 December 2016	**04 January 2017**

Name and mailing address of the ISA/CN	Authorized officer
STATE INTELLECTUAL PROPERTY OFFICE OF THE P.R.CHINA **6, Xitucheng Rd., Jimen Bridge, Haidian District, Beijing 100088** **China**	**ZHAO,Jingjing**
Facsimile No. **(86-10)62019451**	Telephone No. **(86-10)62413334**

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/CN2016/078250

Patent document cited in search report			Publication date (day/month/year)	Patent family member(s)			Publication date (day/month/year)
CN	101145052	A	19 March 2008	None			
CN	103415817	A	27 November 2013	WO	2009057403	A1	07 May 2009
				EP	2214067	A1	04 August 2010
				US	2011044331	A1	24 February 2011
				JP	2009110180	A	21 May 2009
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				KR	20140071480	A	11 June 2014
				WO	2013049768	A1	04 April 2013
				JP	2014531856	A	27 November 2014
				US	2013083753	A1	04 April 2013
				EP	2761955	A1	06 August 2014
				CA	2850569	A1	04 April 2013
				SG	11201401068	A	28 April 2014
KR	20100047982	A	11 May 2010	None			