

A METHOD OF TRANSMITTING DATA TO A RECEIVER

The present application claims the benefit of United States provisional
5 application 60/929,022 (filed on 8 June, 2007), the entire contents of which
are incorporated herein by reference for all purposes.

FIELD OF THE INVENTION

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Embodiments of the invention relate to the field of wireless communication
systems, such as ad hoc wireless ultra-wideband radio communication
systems, for example. By way of example, embodiments of the invention
relate to a method of transmitting data to a receiver, as well as a
15 corresponding communication device.

BACKGROUND OF THE INVENTION

20 It is known that in general, the transmission range of a signal is primarily
determined by the transmit power of the signal. In the case where the transmit
power of the signal is limited due to Federal Communications Commission
(FCC) regulations, for example, the transmission range of the signal is also
limited. For example, according to the IEEE 802.15.3a technical requirements,
25 in view of the FCC transmit Power Spectral Density (PSD) mask, the
expected signal transmission range may be only about 10 meters for a data
transmission of 100 Mbps, or about 4 meters for a data transmission of 200
Mbps, or about 2 meters for a data transmission of 480 Mbps.

30 Such a short signal transmission range (for example as discussed above) for
a communication system in general puts severe constraints on the potential
applications of the said communication system. It is therefore desirable to
increase the signal transmission range for such a communication system

while still adhering to the transmission power restrictions due to FCC regulations, for example.

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SUMMARY OF THE INVENTION

In one embodiment of the invention, a method of transmitting data to a receiver, wherein the data is transmitted using a plurality of sub-carriers, is provided. The method provided includes selecting, for each sub-carrier, an
10 antenna of a plurality of antennas to be used for the transmission of the sub-carrier based on a transmission characteristic of a transmission of the sub-carrier between the antenna and the receiver.

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BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the
20 invention. In the following description, various embodiments of the invention are described with reference to the following drawings, in which:

Figure 1 shows a communication system according to an embodiment of the invention.

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Figure 2 shows a flow diagram describing the data transmission carried out in the communication system according to one embodiment of the invention.

Figure 3 shows a block diagram of a communication device according to one
30 embodiment of the invention.

Figure 4 shows an illustration of the frequency domain representation of the method of transmitting data to a receiver according to one embodiment of the invention.

- 5 Figure 5 shows an illustration of a first implementation of the method of transmitting data to a receiver according to one embodiment of the invention.

Figure 6 shows an illustration of a second implementation of the method of transmitting data to a receiver according to one embodiment of the invention.

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Figure 7 shows an illustration of a third implementation of the method of transmitting data to a receiver according to one embodiment of the invention.

- 15 Figure 8 shows an illustration of a fourth implementation of the method of transmitting data to a receiver according to one embodiment of the invention.

Figure 9 shows a signal flow representation of the data transmission carried out in a communication system according to one embodiment of the invention.

- 20 Figure 10 shows a block diagram illustrating a first method for determining the calibration factors according to one embodiment of the invention.

Figure 11 shows a block diagram illustrating a second method for determining the calibration factors according to one embodiment of the invention.

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Figure 12 shows an illustration of how the compensation of mismatches in the process of antenna and sub-carrier selection may be carried out based on the calibration factors and the estimated channel state information according to one embodiment of the invention.

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Figure 13 shows a table describing the channel models used in the simulations carried out on embodiments of the invention.

Figure 14 shows the packet error rate (PER) performance results for the data transmission rate of 480 Mbps in CM3 (4-10m) for a communication device with and without using one embodiment of the invention.

- 5 Figure 15 shows the packet error rate (PER) performance results for the data transmission rate of 200 Mbps in CM3 (4-10m) for a communication device with and without using one embodiment of the invention.

- 10 Figure 16 shows the packet error rate (PER) performance results for the data transmission rate of 480 Mbps in CM3 (4-10m) for a communication device with and without using one embodiment of the invention.

- 15 Figure 17 shows the packet error rate (PER) performance results for the data transmission rate of 480 Mbps for a communication device with and without using one embodiment of the invention.

- 20 Figure 18 shows the packet error rate (PER) performance results for the data transmission rate of 200 Mbps for a communication device with and without using one embodiment of the invention.

- 25 Figure 19 shows the packet error rate (PER) performance results for the data transmission rate of 480 Mbps over the channel realization for Case B, for a communication device with and without using one embodiment of the invention.

DETAILED DESCRIPTION OF THE INVENTION

- 30 Illustratively, a communication device with a single antenna may only have a short signal transmission range and may not be robust enough to overcome indoor shadowing or fading, for example, when its transmit power is limited by FCC regulations, for example. In order to overcome the above disadvantages, spatial diversity via a plurality of transmit antennas may be used in such a

communication device where its transmit power may be limited by the said FCC regulations, for example.

In more detail, for a communication device where the data to be transmitted may be modulated on a plurality of sub-carriers, a mapping between the sub-carriers and the antennas may be carried out according to a predetermined criterion. With a suitable mapping, spatial diversity via the plurality of transmit antennas may be achieved and the transmit power for each of the transmit antennas may also be controlled such that it meets the said FCC regulations.

According to one embodiment of the invention, a method of transmitting data to a receiver, wherein the data is transmitted using a plurality of sub-carriers, is provided. The method provided includes selecting, for each sub-carrier, an antenna of a plurality of antennas to be used for the transmission of the sub-carrier based on a transmission characteristic of a transmission of the sub-carrier between the antenna and the receiver.

According to one embodiment of the invention, a communication system for transmitting data is provided, wherein the data is transmitted using a plurality of sub-carriers. The communication system provided includes a receiver, and a selection unit configured to select, for each sub-carrier, an antenna of a plurality of antennas to be used for the transmission of the sub-carrier based on a transmission characteristic of a transmission of the sub-carrier between the antenna and the receiver.

The selection may be carried out in the transmitter or the receiver. For example, the receiver selects the antennas to be used and signals the selection to the transmitter. Alternatively, the transmitter carries out the selection itself based on the transmission characteristic.

When the selection has been carried out, the data may be transmitted from the transmitter to the receiver according to the selection, i.e. using the sub-

carriers and using, for each sub-carrier, the selected antenna (or the selected antennas) for the transmission of the sub-carrier.

Embodiments of the invention emerge from the dependent claims.

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In one embodiment, the data to be transmitted using the plurality of sub-carriers is the data of a communication channel of an upper communication layer. For example, the data to be transmitted are useful data of the same logical channel or the same transport channel. For example, the data to be
10 transmitted is data which should all be transmitted to the same receiver. The transmission using the sub-carriers is for example based on the same transmission technology (for example based on the same modulation). For example, the sub-carriers are sub-carriers according to an OFDM transmission or another multi-carrier transmission technology.

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In one embodiment, the antenna is selected based on a predetermined criterion with respect to the transmission characteristic.

In one embodiment, the method provided further includes receiving, by a
20 transmitter, a signal from the receiver, and determining the transmission characteristic based on the received signal.

In one embodiment, the data is to be transmitted from the transmitter to the receiver and the selection is carried out by the transmitter.

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In one embodiment, the data is to be transmitted from the transmitter to the receiver and the selection is carried out by the receiver. In another embodiment, the receiver signals the selection to the transmitter.

30 In one embodiment, the transmission characteristic is information about a property of the communication channel used for transmitting the sub-carrier between the antenna and the receiver. In another embodiment, the transmission characteristic is information about the quality of the

communication channel. In yet another embodiment, the transmission characteristic is a channel state information.

5 In one embodiment, the data is transmitted by modulation of the plurality of sub-carriers and transmitting the modulated sub-carriers using the antennas.

10 In one embodiment, the selection is carried out based on a comparison of the transmission characteristics of a transmission of the sub-carrier for different transmission antennas.

In one embodiment, for each sub-carrier of the plurality of sub-carriers, an antenna of the plurality of antennas is selected to be used for transmitting the sub-carrier.

15 In one embodiment, the selection is carried out individually for each of the plurality of sub-carriers.

20 In one embodiment, the predetermined criterion includes the antennas being selected for the sub-carriers such that the antenna with the highest quality in the transmission characteristic is selected for each sub-carrier.

25 In one embodiment, the predetermined criterion includes a maximum number of sub-carriers to be distributed to each antenna. In another embodiment, the predetermined criterion further includes the antennas being selected for the sub-carriers such that the antenna with the highest quality in the transmission characteristic is selected for each sub-carrier. In yet another embodiment, the predetermined criterion further includes the antennas being selected for the sub-carriers such that for each antenna, the number of sub-carriers for which the antenna has been selected is below or equals to the determined
30 maximum number of sub-carriers.

In one embodiment, the method provided further includes determining a transmission characteristic of a transmission of the sub-carrier from the

receiver to the antenna. In another embodiment, the method provided further includes compensating the difference between the properties of the transmission of the sub-carrier from the receiver to the antenna and the properties of the transmission of the sub-carrier from the antenna to the receiver.

In one embodiment, the communication system provided further includes a transmitter including a receiving unit configured to receive a signal from the receiver, and a first determining unit configured to determine the transmission characteristic based on the received signal. In another embodiment, the communication system provided further includes a second determining unit configured to determine a transmission characteristic of a transmission of the sub-carrier from the receiver to the antenna. In yet another embodiment, the communication system provided further includes a compensating unit configured to compensate the difference between the properties of the transmission of the sub-carrier from the receiver to the antenna and the properties of the transmission of the sub-carrier from the antenna to the receiver.

In one embodiment, the communication system is an ad hoc radio communication system.

In one embodiment, the communication system is a WiMedia communication system. In another embodiment, the communication system is a Bluetooth communication system.

In one embodiment, the communication system is a Firewire communication system. In another embodiment, the communication system is a Certified Wireless Universal Serial Bus (USB) communication system.

Fig. 1 shows a communication system 100 according to an embodiment of the invention.

In this illustration, the communication system 100 may include a first communication device (A) 101, a second communication device (B) 103 and a third communication device (C) 105.

5 Illustratively, it can be seen that the transmission range between the first communication device (A) 101 and the second communication device (B) 103 may be limited to, say, 2 meters (m), for example. The limitation in the transmission range may be the result of an existing limitation on the transmit power due to FCC regulations, for example.

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In this illustration, the communication system 100 may represent an ultra-wideband radio communication system, such as the WiMedia communication system, for example. The WiMedia communication system may operate in a high data rate transmission, such as at 480 Mbps, for example. Subsequently,
15 the WiMedia communication system may be used for further illustration of the embodiments of invention.

Further, it can be seen that the transmission range between the second communication device (B) 103 and the third communication device (C) 105
20 may be limited to, say, 4m, for example. This transmission range is about two times larger than the transmission range between the first communication device (A) 101 and the second communication device (B) 103. The larger transmission range between the second communication device (B) 103 and the third communication device (C) 105 may be due to the third
25 communication device (C) 105 using more than one antenna in conjunction with signal processing techniques, according to an embodiment of the invention.

As a further illustration, the transmission range on the reverse link (i.e., from
30 the second communication device (B) 103 to the third communication device (C) 105) may be extended by using a smart antenna array, or a plurality of antennas, at the receiver side to achieve an improved signal to noise ratio (SNR) for the received signal (and thus achieve an extended transmission

range), for example. In this context, the Maximum Ratio Combining (MRC) signal processing technique may be used to exploit the spatial diversity of the plurality of antennas at the receiver, for example.

- 5 In more detail, in the Maximum Ratio Combining (MRC) signal processing technique, each individually demodulated received signal (for each sub-carrier) is linearly combined before the process of equalization is carried out. As such, the Maximum Ratio Combining (MRC) signal processing technique effectively optimizes the signal to noise ratio (SNR) for each sub-carrier.

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On the other hand, the transmission range on the forward link (i.e., from the third communication device (C) 105 to the second communication device (B) 103) may be extended by deploying the plurality of antennas as multiple transmit antennas.

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In this context, it should be noted that a large number of conventional transmit diversity techniques may not be used in conjunction with the plurality of (transmit) antennas on the third communication device (C) 105, for various reasons. For example, the optimal transmit beamforming (or eigen-beamforming or water-filling) technique, which is typically used for

20 conventional narrowband systems, may not be used on the third communication device (C) 105 to extend the transmission range, as so doing will result in violating the transmit power limitations of the said FCC regulations, for example.

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As a further example, the Space Time Coding (STC) technique, for example, may be used in conjunction with multiple transmit antennas to achieve transmit diversity, in order to achieve improved performance as well as an extended transmission range. However, a corresponding decoding may be

30 required at the receiver side. As such, the third communication device (C) 105 using the Space Time Coding (STC) technique may not maintain interoperability with a conventional communication device, such as the first

communication device (A) 101 and the second communication device (B) 103, for example.

5 The transmit diversity techniques used in conjunction with the plurality of antennas for the third communication device (C) 105 will be discussed in more detail in relation to **Fig. 3** later.

Fig. 2 shows a block diagram 200 describing the data transmission carried out in the communication system 100 according to one embodiment of the invention.

10 In this illustration, Node A 201 may be the third communication device (C) 105 shown in **Fig. 1** and Node B 203 may be the second communication (B) 103 shown in **Fig. 1**, for example. Further, it can be seen that Node A 201 may use multiple transmit antennas, while node B 203 may use a single antenna.

In one embodiment, the transmission range may be extended on the forward transmission link from node A 201 to node B 203 using the multiple transmit antennas. Meanwhile, the transmission range may be extended on the reverse link from node B 203 to node A 201 using the Maximum Ratio Combining (MRC) signal processing technique at node A 201, in order to achieve an improved signal to noise ratio (SNR) (and hence achieve an extended transmission range as well). As such, node A 201 may transmit and receive data with node B 203 over the extended transmission range.

25 In this context, node B 203 may represent a standard WiMedia communication device, for example, which uses only one antenna. Further, node A 201 may represent an enhanced WiMedia communication device, for example, which may use a plurality of antennas, and which may employ signal processing techniques such as the Maximum Ratio Combining (MRC) signal processing technique, for example.

Fig. 3 show a block diagram 300 of the third communication device (C) 105 according to one embodiment of the invention.

The communication device (c) 105 may include a transmit unit 301 and a
5 receive unit 303.

The transmit unit 301 may be used to transmit data on the forward link, to other communication devices, for example. The transmit unit 301 may include a coding/interleaving unit 305, a constellation mapping unit 307, a multi-band
10 space frequency transmit selection (SFTS) unit 309, a plurality of serial to parallel (S/P) converter units 311, a plurality of Inverse Fast Fourier Transform (IFFT) units 313, a plurality of parallel to serial (P/S) converter units 315, a plurality of radio frequency (RF) units 317 and a plurality of antennas 319.

15 The data to be transmitted may be first processed by the coding/interleaving unit 305 and the constellation mapping unit 307. According to one embodiment, the multi-band space frequency transmit selection (SFTS) unit 309 may implement the method of transmitting data to a receiver, in conjunction with the plurality of parameter estimation units 321 of the receiver
20 unit 303. The multi-band space frequency transmit selection (SFTS) unit 309 and plurality of parameter estimation units 321 will be discussed in more detail subsequently.

It should be noted that the plurality of serial to parallel (S/P) converter units
25 311, the plurality of Inverse Fast Fourier Transform (IFFT) units 313 and the plurality of parallel to serial (P/S) converter units 315 may be conventional units which may be used together in order to generate an OFDM symbol, for example.

30 The processed data signal (after the plurality of parallel to serial (P/S) converter units 315) may then be passed to the plurality of radio frequency (RF) units 317 for further processing, before being transmitted using the plurality of antennas 319.

The receive unit 303 may be used to receive data on the reverse link, from other communication devices, for example. The receive unit 303 may include a plurality of antennas 323, a plurality of radio frequency (RF) switching units
5 325, a plurality of serial to parallel (S/P) converter units 327, a plurality of Fast Fourier Transform (FFT) units 329, a plurality of parallel to serial (P/S) converter units 331 and a plurality of parameter estimation units 321.

10 The received signal at the plurality of antennas 323 may be first processed by the plurality of radio frequency (RF) switching units 325, before being passed on to the plurality of serial to parallel (S/P) converter units 327.

It should be noted that the plurality of serial to parallel (S/P) converter units 327, the plurality of Fast Fourier Transform (IFFT) units 329 and the plurality
15 of parallel to serial (P/S) converter units 331 may be conventional units which may be used together in order to extract data or information, for example, from an OFDM symbol, for example.

As mentioned earlier, the plurality of parameter estimation units 321 and the
20 multi-band space frequency transmit selection (SFTS) unit 309 may implement the method of transmitting data to a receiver. In this context, the plurality of parameter estimation units 321 may be used to obtain measurements on a transmission characteristic of the transmission channel.

25 In one embodiment, the transmission characteristic may be information about a property of the communication channel used for transmitting the sub-carrier between the antenna and the receiver. In another embodiment, the transmission characteristic may be information about the quality of the communication channel. In yet another embodiment, the transmission
30 characteristic may be the channel state information.

In this context, the transmission characteristic may be, but is not limited to, a measurement of the signal amplitude, a measurement of the signal power or a measurement of the signal to noise ratio (SNR), for example.

5 As an illustrative example, a measurement of the channel state information (CSI), which may include channel frequency response for each sub-carrier at each sub-band for each antenna, may be obtained using the training pilot symbols from the reverse link.

10 Further, the multi-band space frequency transmit selection (SFTS) unit 309 may include a first band switch unit 333, a plurality of space frequency transmit selection (SFTS) units 335, a second band switch unit 337, a sub-carrier allocation unit 339, a selection criteria unit 341 and a calibration factors unit 343.

15

The first band switch unit 333, the plurality of space frequency transmit selection (SFTS) units 335, the second band switch unit 337 and the sub-carrier allocation unit 339, may be used together to map or allocate a plurality of sub-carriers to their respective antennas in the plurality of antennas 319.

20

The mapping or allocation of the plurality of sub-carriers to their respective antennas may be determined by the selection criteria unit 341, based on the measurements on the transmission characteristic of the transmission channel provided by the plurality of parameter estimation units 321.

25

Additionally, the calibration factors provided by the calibration factors unit 343 may be used by the selection criteria unit 341 to compensate for measurement inaccuracies, for example, in the measurements provided by the plurality of parameter estimation units 321. The function of the calibration factors unit 343 will be discussed in more detail later in relation to **Figs. 10, 11 and 12.**

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The motivation for the embodiments of the method of transmitting data to a receiver is to exploit the statistical nature of multipath fading and to reduce the likelihood of deep fading, and thus, so by doing, achieve the desired diversity. The frequency selective fading channel for each sub-band may be different, and therefore, the respective space frequency transmit selection (SFTS) unit 335 for each sub-band may be different. Based on the respective implementations of the selection criteria unit 341, the SFTS sub-module may be controlled to allocate the sub-carriers for each antenna in each sub-band accordingly.

10

Let there be n_T antennas and n_b sub-bands for the third communication device (C) 105 with multiple transmit antennas. Next, let $H_k^{(i,j)} = H_k(f_0 + j\Delta f)$ ($i = 1, \dots, n_b$; $j = 1, \dots, n_c$; $k = 1, \dots, n_T$) represent the frequency response of the j^{th} sub-carrier for the k^{th} transmitting antenna in the i^{th} sub-band, where f_0 denotes the carrier frequency, Δf denotes the sub-carrier spacing and n_c denotes the total number of sub-carriers.

15

For the j^{th} sub-carrier in the i^{th} sub-band, the best antenna for each SFTS sub-module may then be selected as

$$k_{\text{best}}^{(i,j)} = \arg \max_{k \in \{1, n_T\}} A_{i,j}(k) \quad (1)$$

20

where $A_{i,j}(k)$ represents the selection criteria which may be the function of the adjusted channel state information (CSI), for example, incorporated with the respective calibration factors for the j^{th} sub-carrier and the i^{th} sub-band. For example, $A_{i,j}(k)$ may be determined based on the signal power, such as

$$A_{i,j}(k) = |H_k^{(i,j)}|^2, \text{ for example, or it may be determined based on the signal}$$

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to noise ratio (SNR), such as $A_{i,j}(k) = \text{SNR}_k^{(i,j)}$, for example.

The subsequent discussion will be based on the illustration of $A_{i,j}(k)$ being determined based on the signal power. However, it should be noted that the

subsequent discussion may be easily extended to the alternative methods of determining $A_{i,j}(k)$.

Fig. 4 shows an illustration of the frequency domain representation of the method of transmitting data to a receiver according to one embodiment of the invention.

The illustration in **Fig. 4** shows how one embodiment of the method of transmitting data to a receiver achieves spatial and frequency diversity.

10

In more detail, the mathematical representation of the signal flow may be described as follows.

Let $S(f)$ 401 represent the transmitted orthogonal frequency division multiplexing (OFDM) signal at node A 201 in frequency domain. This signal may be represented as a data symbol $d^{(j)}$ in the j^{th} sub-carrier, which may be multiplied with a delta function.

In this context, it should be noted that the sub-band index i may be dropped from Equation (1) and subsequent equations, for the sake of simplicity and without loss of generality.

20

The transmitted OFDM signal $S(f)$ 401 may then be rewritten as

$$S(f) = \sum_{j=0}^{n_s-1} d^{(j)} \delta(f - f_0 - j\Delta f) \quad (2)$$

25

Next, let $n^{(j)}$ represent the corresponding additive white Gaussian noise (AWGN) term. The received signal may then be written as follows

$$Y(f) = \sum_{j=0}^{n_s-1} [d^{(j)} H_{k_{best}}^{(j)} + n^{(j)}] \delta(f - f_0 - j\Delta f) \quad (3)$$

Let $F_k(f)$ represent an ideal filter in frequency domain for all the allocated sub-carriers at the k^{th} transmit antenna, namely,

30

$$F_k(f) = \sum_{j=0}^{n_c-1} F_k^{(j)} \delta(f - f_0 - j\Delta f) \quad (4)$$

where

$$F_k^{(j)} = \begin{cases} 1, & \text{if } k_{best}^{(j)} = k \\ 0, & \text{otherwise} \end{cases} \quad (5)$$

5 Accordingly, the transmitted OFDM signal in the k^{th} antenna may be written as

$$S_k(f) = \sum_{j=0}^{n_c-1} d^{(j)} F_k^{(j)} \delta(f - f_0 - j\Delta f) = S(f) F_k(f) \quad (6)$$

Additionally, the received signal in frequency domain may be further expressed as

$$10 \quad Y(f) = \sum_{k=1}^{n_T} S_k(f) H_k(f) + N(f) = S(f) \sum_{k=1}^{n_T} F_k(f) H_k(f) + N(f) = S(f) H_o(f) + N(f) \quad (7)$$

where $H_o(f)$ 403 may be defined as the combined channel frequency response, as follows

$$H_o(f) = \sum_{k=1}^{n_T} F_k(f) H_k(f) \quad (8)$$

15

As shown in **Fig. 4**, the combined channel frequency response $H_o(f)$ 403 may have a reduced deep fading characteristic for each sub-carrier (as compared to the respective individual channel frequency responses $H_1(f)$ 405 and $H_2(f)$ 407, for example). Therefore, the embodiment of the method of transmitting data to a receiver leads to an equivalent frequency selective channel $H_o(f)$ 403 with a reduced deep fading characteristic for each sub-carrier.

20

From Equation (8), the spectrum of the combined transmitted OFDM signals from all transmit antennas may be expressed as

25

$$S_{total}(f) = \sum_{k=1}^{n_T} S_k(f) = \sum_{k=1}^{n_T} S(f) F_k(f) = S(f) \sum_{k=1}^{n_T} F_k(f) = S(f) \quad (9)$$

where $\sum_{k=1}^{n_r} F_k(f) = 1$ from Equation (5). Therefore, the embodiment of the method of transmitting data to a receiver allows the spectrum of the combined transmitted OFDM signals ($S(f)$) 401 to be remain below the stipulated FCC regulations, for example.

5

Additionally, the time domain signal representation for the embodiment of the method of transmitting data to a receiver may be shown as follows.

Let $s_k(t)$ represent the transmitted OFDM signal in the time domain for the k^{th} transmit antenna at node A 201. Next, let $h_k(t)$ represent the multipath channel impulse response from the k^{th} transmit antenna at node A 201 to the single receive antenna at node B 203.

10

The received signal $y(t)$ at node B 203 may then be represented as

$$y(t) = \sum_{k=1}^{n_r} s_k(t) * h_k(t) + n(t) \quad (10)$$

where the symbol $*$ denotes the convolution operation.

The transmitted OFDM signal at the k^{th} antenna may be represented by the convolution of the transmitted OFDM signal $s(t)$ and the ideal selected filter

20 $f_k(t)$ as follows

$$s_k(t) = s(t) * f_k(t) \quad (11)$$

Accordingly, the received signal $y(t)$ may be rewritten as follows

$$y(t) = s(t) * \sum_{k=1}^{n_r} f_k(t) * h_k(t) + n(t) = s(t) * h_o(t) + n(t) \quad (12)$$

25 where $h_o(t)$ is the equivalent channel impulse response with a reduced deep fading characteristic.

In this context, it should be noted that the method of transmitting data to a receiver may implemented using different approaches as shown in the following.

- 5 **Fig. 5** shows an illustration of the first implementation of the method of transmitting data to a receiver according to one embodiment of the invention.

In the first implementation of the method of transmitting data to a receiver, the sub-carriers with the highest quality in the transmission characteristic (such as
10 the best frequency response, for example) may be selected for each antenna. In other words, the best antenna for the j^{th} sub-carrier in the i^{th} sub-band may be selected according to the following criteria

$$k_{best}^{(i,j)} = \arg \max_{k \in \{1, n_T\}} |H_k^{(i,j)}|^2 \quad (13)$$

- 15 Then, the selected sub-carriers for each antenna can be rewritten as

$$k_{best}^{(i,j)} \Rightarrow j_{best}^{(i,k)} \quad (14)$$

where $j_{best}^{(i,k)}$ indicates the best sub-carriers allocation for each antenna in the i^{th} sub-band.

- 20 In the illustration of the first implementation shown in **Fig. 5**, two transmit antennas and eight sub-carriers are used.

The first implementation may be carried according to the following steps.

- The channel frequency response for the i^{th} sub-band, namely, $|H_k^{(i,j)}|^2$, may be
25 expressed in the form of a matrix, for example, where the rows of the matrix may be represented by the sub-carrier index and the columns of the matrix may be represented by the antenna index.

- Next, based on to Equation (13), the best antenna for each sub-carrier may
30 be selected (as indicated in bold as shown in **Fig. 5**). In this context, it can be seen in **Fig. 5** that sub-carriers 4 and 5 are allocated to antenna 2, while the

remaining sub-carriers are allocated to antenna 1.

Following which, the channel frequency response for the i^{th} sub-band, namely, $|H_k^{(i,j)}|^2$, may be converted to the sub-carriers allocation for each

5 antenna, namely, $j_{best}^{(i,k)}$, according to equation (14).

In this first implementation, the number of sub-carriers per antenna may be different from one antenna to another, depending on the multipath fading characteristic of the respective antennas. As shown in this illustration, there
10 are 6 sub-carriers allocated to antenna 1, but only 2 sub-carriers to antenna 2. While this first implementation provides an optimal sub-carrier allocation for each antenna, it also leads to a different peak to average ratio (PAPR) value for different antennas (due to the different number of sub-carriers allocated to different antennas).

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Fig. 6 shows an illustration of the second implementation of the method of transmitting data to a receiver according to one embodiment of the invention.

Compared to the first implementation of the method of transmitting data to a receiver, this second implementation provides a constraint on the number of
20 sub-carriers which may be allocated to each antenna. This constraint allows the sub-carriers to be evenly distributed among the plurality of antennas, in order to balance the peak to average ratio (PAPR) value for the plurality of (transmit) antennas.

25

There may be two different approaches to distribute the selected sub-carriers evenly among all the plurality of (transmit) antennas. The first approach uses an optimal way to allocate the sub-carriers evenly, while the second approach uses a simplified way to allocate the sub-carriers in order to achieve a
30 reduced implementation complexity. The second approach will be described in more detail in relation to **Fig. 7** later.

If n_c is divisible by n_T , then the number of sub-carriers transmitted by each antenna may be limited by $\frac{n_c}{n_T}$. If n_c is not divisible by n_T , then each antenna may be limited to transmit up to only $\left\lfloor \frac{n_c}{n_T} \right\rfloor$ or $\left\lfloor \frac{n_c}{n_T} \right\rfloor + 1$ sub-carriers.

- 5 In order to simplify subsequent discussion, it is assumed that n_c is divisible by n_T . It can be seen that the second implementation may be easily extended to the case where n_c is not divisible by n_T as well.

10 In the illustration of the second implementation shown in **Fig. 6**, two transmit antennas and eight sub-carriers are used.

The second implementation may be carried according to the following steps.

- 15 The first step is similar to the one used in the first implementation, where $j_{best}^{(i,k)}$ is first obtained according to equation (14). The selected sub-carriers for each antenna are as shown in the matrix 601 of **Fig. 6**.

- The second step involves initializing the maximum number of sub-carriers allocated for each antenna, $n_k^{\max}$, where $n_k^{\max} = \frac{n_c}{n_T}$. Next, the $n_k^{\max}$ sub-carriers with the highest quality in the transmission characteristic among the selected $j_{best}^{(i,k)}$ sub-carriers are selected for each column, i.e., each antenna. The remaining selected sub-carriers (namely, sub-carriers 2 and 3) are then reset to zero, as shown in the matrix 603 of **Fig. 6**.

- 25 In this context, if the number of selected sub-carriers $j_{best}^{(i,k)}$ is less than $n_k^{\max}$, then all the selected sub-carriers $j_{best}^{(i,k)}$ for that column will be chosen (which is the case for antenna 2 as shown in **Fig. 6**).

The remaining number of sub-carriers allocated for each antenna may then be updated according to the equation $n_k^{\max}(s+1) = n_k^{\max}(s) - n_k^{\text{selected}}(s)$, where s is the step index.

5

In the third step, a new sub-carriers allocation for the remaining sub-carriers may be obtained for each antenna. For example, this may be achieved by repeating the first step among the remaining sub-carriers.

10 Next, the value $n_k^{\max}$ for each antenna may then be updated accordingly.

The third step may then be carried out repeatedly until $n_k^{\max} = 0$ for all antennas (as shown in the matrix 605 of **Fig. 6**).

15 Finally, the first, second and third steps may be carried out for the $(i+1)^{\text{th}}$ sub-band, until all the sub-carriers in all sub-bands have been allocated.

Fig. 7 shows an illustration of the third implementation of the method of transmitting data to a receiver according to one embodiment of the invention.

20

This third implementation is similar to the second implementation of the method of transmitting data to a receiver, with the exception that the third implementation uses a simplified way to allocate the sub-carriers in order to achieve a reduced implementation complexity.

25

In more detail, this third implementation may select $n_k^{\max}$ sub-carriers randomly, for example, instead of the first $n_k^{\max}$ sub-carriers with the highest quality in the transmission characteristic, for example, in order to avoid the sorting operations used in the second implementation. As such, this leads to a simplified implementation and a reduced implementation complexity.

30 However, this may result in a small performance loss.

In the illustration of the third implementation shown in **Fig. 7**, two transmit antennas and eight sub-carriers are used.

- 5 The third implementation may be carried according to the following steps.

The first step is similar to the one used in the second implementation, where $j_{best}^{(i,k)}$ is first obtained according to equation (14). The selected sub-carriers for each antenna are as shown in the matrix 701 of **Fig. 7**.

10

The second step involves initializing the maximum number of sub-carriers allocated for each antenna $n_k^{\max}$, where $n_k^{\max} = \frac{n_c}{n_T}$. Next, the $n_k^{\max}$ sub-carriers among the selected $j_{best}^{(i,k)}$ sub-carriers are selected randomly, for example, for each column, i.e., each antenna. The remaining selected sub-carriers
 15 (namely, sub-carriers 2 and 6) are then reset to zero, as shown in the matrix 703 of **Fig. 7**.

In this context, if the number of selected sub-carriers $j_{best}^{(i,k)}$ is less than $n_k^{\max}$, then all the selected sub-carriers $j_{best}^{(i,k)}$ for that column will be chosen (which
 20 is the case for antenna 2 as shown in **Fig. 7**).

The remaining number of sub-carriers allocated for each antenna may then be updated according to the equation $n_k^{\max}(s+1) = n_k^{\max}(s) - n_k^{\text{selected}}(s)$, where s is the step index.

25

In the third step, a new sub-carriers allocation for the remaining sub-carriers may be obtained for each antenna. For example, this may be achieved by repeating the first step among the remaining sub-carriers.

- 30 Next, the value $n_k^{\max}$ for each antenna may then be updated accordingly.

The third step may then be carried out repeatedly until $n_k^{\max} = 0$ for all antennas (as shown in the matrix 705 of **Fig. 7**).

- 5 Finally, the first, second and third steps may be carried out for the $(i+1)^{\text{th}}$ sub-band, until all the sub-carriers in all sub-bands have been allocated.

As a side remark, it can be seen that the first step and the third step of this third implementation are identical to the first step and the third step of the
10 second implementation, respectively.

Fig. 8 shows an illustration of the fourth implementation of the method of transmitting data to a receiver according to one embodiment of the invention.

- 15 Compared to the second and the third implementations of the method of transmitting data to a receiver, this fourth implementation also provides a constraint on the number of sub-carriers which may be allocated to each antenna. This constraint allows the sub-carriers to be evenly distributed among the plurality of antennas, in order to balance the peak to average ratio
20 (PAPR) value for the plurality of (transmit) antennas.

However, the approach of applying the constraint in this fourth implementation is carried out using a set of threshold values. By so doing, this fourth implementation avoids the use of the highly complex sorting operations of the
25 second implementation and the performance loss as a result of the approach used in the third implementation. In this context, the use of the set of threshold values only requires the compare operation.

In the illustration of the third implementation shown in **Fig. 7**, two transmit
30 antennas and eight sub-carriers are used.

The third implementation may be carried according to the following steps.

The first step involves determining a set of threshold values, a_l , $l = 1, \dots, L$ where L is the total number of threshold values and $a_l > 0$. Next, a_1 and the value $n_k^{\max}$ (where $n_k^{\max} = \frac{n_c}{n_T}$) may be initialized. Following which, $|H_k^{(i,j)}|^2$ may be compared to a_1 for each sub-carrier and the respective antenna.

5

If it is determined that $|H_k^{(i,j)}|^2 > a_1$, then the said sub-carrier and the respective antenna may selected and indicated in bold as shown in matrix 801 of **Fig. 8**. Accordingly, $n_k^{\max}$ may be updated according to the equation

$$n_k^{\max}(s+1) = n_k^{\max}(s) - 1.$$

10

In the second step, the threshold value used may be changed to a_2 , where $a_2 \leq a_1$. Next, $|H_k^{(i,j)}|^2$ may be compared to a_2 , for the unselected sub-carriers and the respective antenna.

15 If it is determined that $|H_k^{(i,j)}|^2 > a_2$, then the corresponding sub-carrier and the respective antenna may be selected and indicated in bold as shown in matrix 803 of **Fig. 8**. Accordingly, $n_k^{\max}$ is updated according to the equation

$$n_k^{\max}(s+1) = n_k^{\max}(s) - 1.$$

20 Following which, the second step is carried out for the remaining threshold values a_l , for all values of l until $l = L$.

In the illustration shown in **Fig. 8**, the number of threshold values selected is 4. The matrices after the processing using the third threshold value ($a_3 = 1.4$)

25 and the fourth threshold value ($a_4 = 0.5$) are labeled as 805 and 807 respectively in **Fig. 8**.

It can be seen that the number of iterations carried out depends on the number of threshold values selected. As such, the performance as well as the efficiency of the fourth implementation depends on the number of threshold values selected.

5

Following which, the allocation of sub-carriers may be updated for each data packet, for example, based on the channel estimation carried out using the preambles of each data packet, for example.

- 10 Turning now to the transmission characteristic used in the method of transmitting data to a receiver, it is known that for a point to point time division duplexing (TDD) communication system (such as a UWB communication system, for example) the propagation channel of the forward link is the reciprocal of the propagation channel of the reverse link, provided the round-
- 15 trip delay is shorter than the propagation channel's coherence time.

However, it is also known that this is not the case for the radio frequency (RF) transceivers, which may exhibit significant amplitude and phase mismatches between the forward and reverse links, as well as across multiple antennas.

- 20 Since these mismatches essentially may compromise the estimation of the channel state information (CSI), they may result in a severe degradation in the performance of the embodiments of the method of transmitting data to a receiver.

- 25 In more detail, the effects of these mismatches are described as follows.

- An ideal transceiver may be considered to have a baseband equivalent channel response of unit amplitude and of zero phase. Due to various random process variations, the actual channel response of the transceiver may exhibit
- 30 a random channel response which may approximate the ideal frequency response. The magnitude of the exhibited deviation from the ideal channel response depends on the magnitude of the random process variations. In this

context, the approximate ideal response may be referred to as a mismatch between the forward and reverse links.

Fig. 9 shows a signal flow representation of the data transmission carried out in the communication system 100 of a according to one embodiment of the invention.

Let $T(f)$ represent the transmit frequency response function in the frequency domain and $R(f)$ represent the receive frequency response function in frequency domain.

The mismatch in the transmit frequency response function may be expressed using the complex gains $T(f) = |T(f)| e^{j \arg(T(f))}$, and likewise, the mismatch in the receive frequency response function may be expressed using complex gains $R(f) = |R(f)| e^{j \arg(R(f))}$, where $|T(f)|$ and $|R(f)|$ are the respective amplitudes of the mismatches, and $e^{j \arg(T(f))}$ and $e^{j \arg(R(f))}$ are the respective phases of the mismatches.

As mentioned earlier, since the selection criterion for the method of transmitting data to a receiver may be based on the signal power of the channel state information (CSI), only the amplitude of the mismatch need to be considered.

In this context, the respective amplitudes $|T(f)|$ and $|R(f)|$ may be modeled as a real Gaussian variable. As such, the mean of the respective amplitudes may be expressed as a unit value (which is the value of the ideal frequency response discussed earlier), and the variance of the respective amplitudes may be denoted as σ^2 .

In this context, it should be noted that the Gaussian variable model is commonly used to model radio frequency (RF) amplitude errors, and it is

typically assumed that the variance σ^2 is small (up to 40%, for example) such that the occurrence of a negative realization is negligible.

The combined channel response $C_{fwd}(f)$ and $C_{rvs}(f)$ for the respective
 5 forward and reverse links, which include $T(f)$, $R(f)$ and the channel response $H(f)$, may be defined as follows

$$C_{fwd_k}(f, t) = T_{A_k}(f) H_{fwd_k}(f, t) R_B(f) \quad (15)$$

$$C_{rvs_k}(f, t) = T_B(f) H_{rvs_k}(f, t) R_{A_k}(f) \quad (16)$$

where $k = 1, \dots, N_T$ is the antenna index corresponding to the transmit
 10 antennas at node A. The terms $H_{fwd_k}(f, t)$ and $H_{rvs_k}(f, t)$ represent the respective forward and reverse link channel response function, which may be assumed to have the property of time invariant reciprocity, i.e.,
 $H_{fwd_k}(f, t) = H_{rvs_k}(f, t)$ for $k = 1, \dots, N_T$.

15 In this context, the actual estimation carried out using the preambles is the combined channel response $C_{rvs}(f)$. However, $C_{fwd}(f)$ is the channel response which is used in determining the sub-carriers allocation in the embodiments of the method of transmitting data to a receiver.

20 As such, the relationship between $C_{rvs}(f)$ and $C_{fwd}(f)$ may be described as follows

$$C_{fwd_k}(f, t) = \frac{T_{A_k}(f)}{R_{A_k}(f)} C_{rvs_k}(f) \frac{R_B(f)}{T_B(f)} \quad (17)$$

Accordingly, the sub-carrier allocation criterion may be rewritten as follows

$$25 \quad k_{best}^{(j)} = \arg \max_{k \in \{1, n_T\}} |C_{fwd_k}^{(j)}|^2 = \arg \max_{k \in \{1, n_T\}} \left| \frac{T_{A_k}^{(j)}}{R_{A_k}^{(j)}} C_{rvs_k}^{(j)} \frac{R_B^{(j)}}{T_B^{(j)}} \right|^2 \quad (18)$$

where $C_{fwd_k}^{(j)} = C_{fwd_k}(f_0 + j\Delta f)$, $C_{rvs_k}^{(j)} = C_{rvs_k}(f_0 + j\Delta f)$,

$T_{A_k}^{(j)} = T_{A_k}(f_0 + j\Delta f)$, $R_{A_k}^{(j)} = R_{A_k}(f_0 + j\Delta f)$, $T_B^{(j)} = T_B(f_0 + j\Delta f)$, and

$R_B^{(j)} = R_B(f_0 + j\Delta f)$ for $j = 1, \dots, n_c$.

- 5 Assuming that the respective frequency responses $T^{(j)}$ and $R^{(j)}$ remain unchanged across the sub-carriers, then all the respective calibration factors $T_{A_k}^{(j)}$, $R_{A_k}^{(j)}$, $T_B^{(j)}$ and $R_B^{(j)}$ may be considered as independent from the sub-carrier index j . Accordingly, Equation (18) may be further simplified as follows

$$10 \quad k_{best}^{(j)} = \arg \max_{k \in \{1, n_T\}} \left\{ \left| C_{rvs_k}^{(j)} \right|^2 \left| \frac{T_{A_k}}{R_{A_k}} \frac{R_B}{T_B} \right|^2 \right\} \quad (19)$$

The calibration factor $\left| \frac{T_{A_k}}{R_{A_k}} \frac{R_B}{T_B} \right|^2$ may be determined as follows.

Fig. 10 shows a block diagram illustrating a first method for determining the calibration factors according to one embodiment of the invention.

15

In this first method, a test board 1001 may be used to obtain the

measurements for the calibration factor $\left| \frac{T_{A_k}}{R_{A_k}} \frac{R_B}{T_B} \right|^2$ from the different

transmitters and receivers of the communication device 1003, using the setup shown in **Fig. 10**. As shown in **Fig. 10**, the test board 1001 may be a device
20 external to the communication device 1003.

The switches S_1 1005 and S_2 1007 may form a calibration loop, and may be used to control the measurement sequence from Antenna 1 to Antenna n_T . A binary phase shift keying (BPSK) signal may be used as the test signal.

- 25 Additionally, the channel estimation may be performed at the respective

receivers on the test board 1001 and the communication device 1003, so that estimates of T_{A_k} and R_{A_k} may be obtained.

It can be seen that measurements of the $2n_T$ transfer functions α shown in Equation (20) may also be obtained. As the connections are made via the direct cable connection, the transmission loss due to the cable connection may be assumed to be a constant value L_c . The measurements obtained may then be expressed as

$$\begin{aligned}\alpha_{1,1} &= T_{A_1} L_c R_{B_1} \\ \alpha_{1,2} &= T_{B_1} L_c R_{A_1} \\ &\vdots \\ \alpha_{n_T,1} &= T_{A_{n_T}} L_c R_{B_1} \\ \alpha_{n_T,2} &= T_{B_1} L_c R_{A_{n_T}}\end{aligned}\tag{20}$$

where T_{B_i} and R_{B_i} denote the respective transmit and receive frequency responses for the communication device 1003. The calibration factor cf may then be defined as follows

$$\begin{aligned}cf_1 &= \frac{\alpha_{1,1}}{\alpha_{1,2}} = \frac{T_{A_1}}{R_{A_1}} \frac{R_{B_1}}{T_{B_1}} \\ &\vdots \\ cf_{n_T} &= \frac{\alpha_{n_T,1}}{\alpha_{n_T,2}} = \frac{T_{A_{n_T}}}{R_{A_{n_T}}} \frac{R_{B_1}}{T_{B_1}}\end{aligned}\tag{21}$$

Therefore, the calibration factor matrix **CF** can be formed as follows

$$\mathbf{CF} = \begin{bmatrix} cf_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & cf_{n_T} \end{bmatrix}\tag{22}$$

It can be seen from Equation (22) that the calibration factor matrix **CF** is a diagonal matrix. As such, its values may be stored in the flash memory, for example, and then loaded during an initial setup. In this context, the loading of the values for the calibration factor matrix **CF** may be referred to as a pre-calibration process.

Further, as the matrix $\mathbf{CF}$ is a diagonal matrix, only n_T values may be stored. As such, no additional of built-in calibration circuitry may be needed for the communication device 1003.

5

Accordingly, Equation (19) may be rewritten as

$$k_{best}^{(j)} = \arg \max_{k \in \{1, n_T\}} \left\{ C_{rvs_k}^{(j)} \left| cf_k \text{ const} \right|^2 \right\} \quad (23)$$

where $\text{const} = \frac{R_B}{T_B} \frac{T_{B_i}}{R_{B_i}}$ is a constant which is independent of k , and as such,

may not affect the process of allocating the sub-carriers.

10

Fig. 11 shows a block diagram illustrating a second method for determining the calibration factors according to one embodiment of the invention.

In this second method, an additional calibration circuit 1101 may be used to

15

obtain the measurements for the calibration factor $\left| \frac{T_{A_k}}{R_{A_k}} \frac{R_B}{T_B} \right|^2$ from the different transmitters and receivers of the communication device 1100, using the setup shown in **Fig. 11**. As shown in **Fig. 11**, the additional calibration circuit 1101 may be part of the communication device 1100.

20

The switches S_1 1103 and S_2 1105 form a calibration loop during the initial

setup, which may be used to obtain the measurements for $\left| \frac{T_{A_k}}{R_{A_k}} \frac{R_B}{T_B} \right|^2$ from the different transmitters and receivers of the communication device 1100.

25

Based on the measurements obtained, the calibration factor matrix $\mathbf{CF}$ may be formed according to equation (20) and (21). Following which, the calibration factors may be used for the compensation of the mismatch for the embodiments of the method of transmitting data to a receiver. Further, as these calibration factors may be obtained using the built-in additional

calibration circuit 1101 during the initial setup, these values may not be updated regularly.

In this context, it can be seen that the calibration factors (or the calibration factor matrix) may be used in view that the channel state information is estimated using measurements from the reverse link (instead of the forward link). However, the channel state information may also be estimated using measurements from the forward link as discussed in the following.

In one embodiment, the forward link channel frequency response for each antenna (of the transmitter) may be estimated by arranging the transmission of channel estimation symbols (such as preamble symbols, for example) for each antenna at the transmitter, one at a time, and then performing the channel estimation for each transmit antenna at the receiver side. In another embodiment, the forward link channel frequency response for each antenna (of the transmitter) may be estimated by transmitting orthogonal channel estimation symbol sequences for different transmit antennas at the same time, then performing the channel estimation jointly for all the transmit antennas at the receiver side.

Following this, the estimated channel state information for the respective forward link frequency responses for each transmit antenna may be transmitted back from the receiver side to the transmitter side, for example, using the feedback channel. The received estimated channel state information may then be used in the selection of antennas for sub-carriers.

However, it should be noted that the transmission of the estimated channel state information (frequency response) from the receiver side to the transmitter side may involve considerable transmission overhead for the feedback channel. As such, it may be preferable to implement the antenna selection process directly at the receiver side instead, and then transmit the antenna selection decision information for each sub-carrier via the feedback channel. Using this approach, only 1 bit may be required for each sub-carrier

in the case where two transmit antennas are used, and only 2 bits may be required for each sub-carrier in the case where four transmit antennas are used, and so on.

- 5 In the embodiments discussed above, where the estimation of the channel state information is performed using measurements from the forward link, in order to perform the above discussed steps at the receiver side, hardware and/or software changes may be required. This may lead to an incompatibility with existing communication devices (i.e., the said receiver may not be
10 WiMedia compliant, for example).

Fig. 12 shows an illustration of how the compensation of mismatches in the process of antenna and sub-carrier selection may be carried out based on the calibration factors and the estimated channel state information according to
15 one embodiment of the invention.

As shown in **Fig. 12**, the best antenna may be selected for each sub-carrier or the best set of sub-carriers may be allocated for each antenna using the improved selection criterion based on the estimated channel state information
20 (CSI) and the calibration factors.

Next, possible design modifications to the existing preamble structure and the effects of such modifications on the performance of the embodiments of the method of transmitting data to a receiver are discussed.

25 In each preamble OFDM symbol, the allocation of sub-carriers for each antenna may follow the same characteristic as the data portion described earlier. Based on the equivalent frequency selective channel $H_o(f)$ defined in Equation (8), the preamble OFDM symbol transmission for the embodiments
30 of the method of transmitting data to a receiver may be used for automatic gain control (AGC), synchronization and channel estimation, for example, without any modification.

Since the equivalent frequency selective channel $H_e(f)$ may be expected to exhibit a flattened spectrum as compared to a conventional multi-band OFDM channel, less signal distortion and improved robustness for automatic gain control (AGC), synchronization and channel estimation may be expected, for example. This may further reduce the probability of noise amplification when a simple channel inversion is applied to channel equalization, for example.

Next, the Packet Error Rate (PER) performance results for the embodiments of the method of transmitting data to a receiver, are obtained using simulations. The performance results obtained are then compared to those of the standard WiMedia Ver1.0 communication devices. In this context, the IEEE 802.15.3a UWB indoor channel models [1] have been used in the simulations. There are four types of channel model listed in table 1300 shown in **Fig. 13**.

Fig. 13 shows a table 1300 describing the channel models used in the simulations carried out on embodiments of the invention.

For example, the first channel model, CM1, represents a transmission channel where the transmission range is from about 0m to about 4m. Further, line of sight (LOS) is assumed between the communication devices which may be transmitting on the said transmission channel. Additionally, a maximum transmission delay of 8.92ms is assumed in the said transmission channel.

Additionally, for the embodiments of the method of transmitting data to a receiver, three different channel realizations corresponding to multiple antennas are generated, namely,

Case A: Independent fading channel without shadowing

Case B: Independent fading channel with independent shadowing

Case C: Independent fading channel with correlated shadowing

The channel realization of Case A corresponds to the case where properly spaced antennas with uncorrelated multipath fading are assumed. The channel realization of Case B corresponds to an ideal case where properly spaced antennas with uncorrelated multipath fading and uncorrelated shadowing are assumed. The channel realization of Case C corresponds to the case where properly spaced antennas with uncorrelated multipath fading and correlated shadowing are assumed. Further, the distribution of the channel model for Case C is aligned to the measurement results [2].

10 In this context, it should be noted that the performance results shown in **Figs. 14 to 16** are based on the channel realization of Case A.

Fig. 14 shows the packet error rate (PER) performance results for the data transmission rate of 480 Mbps in CM3 (4-10m) for a communication device with and without using one embodiment of the invention.

It can be seen in **Fig. 14** that a 5.2dB gain may be achieved for a standard WiMedia 1.0 communication device by using an embodiment of the method of transmitting data to a receiver with four transmit antennas. Further, it can also be seen that a 3dB gain may be achieved for a standard WiMedia 1.0 communication device by using an embodiment of the method of transmitting data to a receiver with two transmit antennas.

These performance gains show the effectiveness of the embodiments of the method of transmitting data to a receiver when used in high data rate transmissions. Additionally, it should be noted that channel coding with high code rates (such as $R_c = \frac{3}{4}$, for example) which may be used by a standard WiMedia 1.0 communication device tend to be less effective in high data rate transmissions.

30

Fig. 15 shows the packet error rate (PER) performance results for the data transmission rate of 200 Mbps in CM3 (4-10m) for a communication device with and without using one embodiment of the invention.

It can be seen in **Fig. 15** that a 3.6dB gain may be achieved for a standard WiMedia 1.0 communication device by using an embodiment of the method of transmitting data to a receiver with four transmit antennas. Further, it can also
5 be seen that a 2dB gain may be achieved for a standard WiMedia 1.0 communication device by using an embodiment of the method of transmitting data to a receiver with two transmit antennas.

In this case, it should be noted that part of the performance gain obtained by
10 using the embodiments of the method of transmitting data to a receiver has been offset by the effective channel coding (such as $R_c = 5/8$, for example) used in a standard WiMedia 1.0 communication device.

Fig. 16 shows the packet error rate (PER) performance results for the data
15 transmission rate of 480 Mbps in CM3 (4-10m) for a communication device with and without using one embodiment of the invention.

In more detail, a performance comparison of the first implementation (labeled as Method 1), the second implementation (labeled as Method 2a), the third
20 implementation (labeled as Method 2b) and the fourth implementation (labeled as Method 3) is shown in **Fig. 16**.

It can be seen in **Fig. 16** that the first implementation (Method 1) shows the best performance among all the implementations. It can also be seen that the
25 second implementation (Method 2a) shows a comparable performance with the fourth implementation (Method 3).

When compared to the performance results of the first implementation (Method 1), the degradation in performance as a result of using the constraint
30 on the maximum number of sub-carriers allocated for each antenna in the second implementation (Method 2a) and in the fourth implementation (Method 3) is only less than 1dB. However, the degradation in performance in the third

implementation (Method 2b) is significant as a result of using the random selection in order to achieve an implementation with lower complexity.

Overall, it can be seen from the performance results shown in **Fig. 16** that the first implementation (Method 1) provides the best choice for the selection criteria.

As a side remark, it should be noted that the performance results shown in **Figs. 17 and 18** are based on the channel realization of Case C.

10

Fig. 17 shows the packet error rate (PER) performance results for the data transmission rate of 480 Mbps for a communication device with and without using one embodiment of the invention.

15 In more detail, a performance comparison of the various implementations with and without the calibration process is shown in **Fig. 17**.

It can be seen in **Fig. 17** that a 4.6dB gain may be achieved for a standard WiMedia 1.0 communication device by using an embodiment of the method of transmitting data to a receiver with four transmit antennas. Further, it can be seen that the performance degradation due to mismatch is only about 2dB when calibration is not carried out, but the performance degradation is reduced to only 0.5dB when calibration is carried out.

25 Additionally, it is noted that the performance degradation may be negligible when the measured calibration factors have only about 10% error.

It can be seen that the overall performance gain achieved for a standard WiMedia 1.0 communication device by using embodiment of the method of transmitting data to a receiver with calibration to compensate for the mismatch is about 4dB.

30

Fig. 18 shows the packet error rate (PER) performance results for the data transmission rate of 200 Mbps for a communication device with and without using one embodiment of the invention.

- 5 Similar to **Fig. 17**, a performance comparison of the various implementations with and without the calibration process is also shown in **Fig. 18**.

10 It can be seen in **Fig. 18** that a 3.3dB gain may be achieved for a standard WiMedia 1.0 communication device by using an embodiment of the method of transmitting data to a receiver with four transmit antennas. Further, it can be seen that the performance degradation due to mismatch is only about 1.6dB when calibration is not carried out, but the performance degradation is reduced to only 0.4dB when calibration is carried out.

- 15 Additionally, it is also noted that the performance degradation may be negligible when the measured calibration factors have only about 10% error.

20 It can be seen that the overall performance gain achieved for a standard WiMedia 1.0 communication device by using embodiment of the method of transmitting data to a receiver with calibration to compensate for the mismatch is about 2.9dB.

25 **Fig. 19** shows the packet error rate (PER) performance results for the data transmission rate of 480 Mbps over the channel realization for Case B, for a communication device with and without using one embodiment of the invention.

30 Similar to **Figs. 17** and **18**, a performance comparison of the various implementations with and without the calibration process is also shown in **Fig. 19**.

It can be seen in **Fig. 19** that a 6.2dB gain may be achieved for a standard WiMedia 1.0 communication device by using an embodiment of the method of

transmitting data to a receiver with four transmit antennas. In this context, when compared to **Fig. 17**, the larger performance gain achieved in **Fig. 19** is primarily due to the independent shadowing channel. This means the upper bound of the performance gain achievable may even be higher when the
5 embodiments of the method of transmitting data to a receiver are used.

Further, it can be seen that the performance degradation due to mismatch is only about 2.8dB when calibration is not carried out, but the performance degradation is reduced to only 0.8dB when calibration is carried out.
10

Additionally, it is also noted that the performance degradation may be negligible when the measured calibration factors have only about 10% error.

It can be seen that the overall performance gain achieved for a standard
15 WiMedia 1.0 communication device by using embodiment of the method of transmitting data to a receiver with calibration to compensate for the mismatch is about 5.4dB.

Embodiments of the invention may have the following effects.
20

Embodiments of the invention provide an elegant and low cost means to achieve full spatial and frequency diversity, extension of the transmission range as well as enhanced robustness. Embodiments of invention also maintain its interoperability with present communication devices, and as such,
25 may be applied to enhanced communication devices or next generation communication devices.

While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art
30 that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the

appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

In this document, the following publication is cited:

5

[1] J. Foerster, "Channel Modeling Sub-Committee Report Final," Feb. 2003, <http://grouper.ieee.org/groups/802/15/pub/>.

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[2] J. Kunisch and J. Pamp, "Measurement results and modeling aspects for the UWB radio channel," IEEE International Conference on UWB (UWBST 2002), Baltimore, May 2002.

15

CLAIMS

What is claimed is

- 5 1. A method of transmitting data to a receiver, wherein the data is transmitted using a plurality of sub-carriers, the method comprising selecting, for each sub-carrier, an antenna of a plurality of antennas to be used for the transmission of the sub-carrier based on a transmission characteristic of a transmission of the sub-carrier between the antenna and
10 the receiver.
2. The method of claim 1, wherein the data to be transmitted using the plurality of sub-carriers is data of a communication channel of an upper communication layer.
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3. The method of claim 1, wherein the antenna is selected based on a predetermined criterion with respect to the transmission characteristic.
- 20 4. The method of claim 1, further comprising receiving, by a transmitter, a signal from the receiver, and determining the transmission characteristic based on the received signal.
- 25 5. The method of claim 4, wherein the data is to be transmitted from the transmitter to the receiver and the selection is carried out by the transmitter.
6. The method of claim 4, wherein the data is to be transmitted from the transmitter to the receiver and the selection is carried out by the receiver.
30
7. The method of claim 6, wherein the receiver signals the selection to the transmitter.

8. The method of claim 1,
wherein the transmission characteristic is information about a property
of the communication channel used for transmitting the sub-carrier between
the antenna and the receiver.

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9. The method of claim 8,
wherein the transmission characteristic is information about the quality
of the communication channel.

10 10. The method of claim 9,
wherein the transmission characteristic is a channel state information.

11. The method of claim 1,
wherein the data is transmitted by modulation of the plurality of sub-
15 carriers and transmitting the modulated sub-carriers using the antennas.

12. The method of claim 1,
wherein the selection is carried out based on a comparison of the
transmission characteristics of a transmission of the sub-carrier for different
20 transmission antennas.

13. The method of claim 12,
wherein for each sub-carrier of the plurality of sub-carriers an antenna
of the plurality of antennas is selected to be used for transmitting the sub-
25 carrier.

14. The method of claim 12,
wherein the selection is carried out individually for each of the plurality
of sub-carriers.

30

15. The method of claim 3,

wherein the predetermined criterion comprises the antennas being selected for the sub-carriers such that the antenna with the highest quality in the transmission characteristic is selected for each sub-carrier.

5 16. The method of claim 3,
 wherein the predetermined criterion comprises a maximum number of sub-carriers to be distributed to each antenna.

10 17. The method of claim 16,
 wherein the predetermined criterion further comprises
the antennas are selected for the sub-carriers such that the antenna with the highest quality in the transmission characteristic is selected for each sub-carrier.

15 18. The method of claim 17,
 wherein the predetermined criterion further comprises the antennas are selected for the sub-carriers such that for each antenna, the number of sub-carriers for which the antenna has been selected is below or equals to the determined maximum number of sub-carriers.

20 19. The method of claim 4, further comprising
 determining a transmission characteristic of a transmission of the sub-carrier from the receiver to the antenna.

25 20. The method of claim 19, further comprising
 compensating the difference between the properties of the transmission of the sub-carrier from the receiver to the antenna and the properties of the transmission of the sub-carrier from the antenna to the receiver.

30 21. A communication system for transmitting data, wherein the data is transmitted using a plurality of sub-carriers, the communication system comprising

a receiver;

a selection unit configured to select, for each sub-carrier, an antenna of a plurality of antennas to be used for the transmission of the sub-carrier based on a transmission characteristic of a transmission of the sub-carrier between
5 the antenna and the receiver.

22. The communication system of claim 21, further comprising a transmitter comprising

a receiving unit configured to receive a signal from the receiver, and
10 a first determining unit configured to determine the transmission characteristic based on the received signal.

23. The communication system of claim 22, further comprising

a second determining unit configured to determine a transmission
15 characteristic of a transmission of the sub-carrier from the receiver to the antenna.

24. The communication system of claim 23, further comprising

a compensating unit configured to compensate the difference between
20 the properties of the transmission of the sub-carrier from the receiver to the antenna and the properties of the transmission of the sub-carrier from the antenna to the receiver.

25. The communication system of claim 22, wherein the data is to be

25 transmitted from the transmitter to the receiver and the selection is carried out by the transmitter.

26. The communication system of claim 22, wherein the data is to be

transmitted from the transmitter to the receiver and the selection is carried out
30 by the receiver.

27. The communication system of claim 26, wherein the receiver signals the selection to the transmitter.

28. The communication system of claim 21,
wherein the communication system is an ad hoc radio communication
system.

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29. The communication system of claim 28,
wherein the communication system is a WiMedia communication
system.

10 30. The communication system of claim 28,
wherein the communication system is a Bluetooth communication
system.

15 31. The communication system of claim 28,
wherein the communication system is a Firewire communication
system.

32. The communication system of claim 28,
wherein the communication system is a Certified Wireless Universal
20 Serial Bus (USB) communication system.