ROBUST RANK PREDICTION FOR A MIMO SYSTEM

Claim of Priority under 35 U.S.C. §119

[0001] The present application claims priority to provisional U.S. Application Serial No. 60/691,723, entitled "ROBUST RANK PREDICTION FOR INTERFERENCE, POWER CONTROL, CHANNEL ESTIMATION, PACKET FORMATS AND ADMISSION CONTROL," filed June 16, 2005, assigned to the assignee hereof and incorporated herein by reference.

BACKGROUND

I. Field

[0002] The present disclosure relates generally to communication, and more specifically to techniques for transmitting data in a multiple-input multiple-output (MIMO) system.

II. Background

[0003] In a wireless communication system, a transmitter (e.g., a base station or a terminal) may utilize multiple (T) transmit antennas for data transmission to a receiver equipped with multiple (R) receive antennas. The multiple transmit and receive antennas form a MIMO channel that may be used to increase throughput and/or improve reliability. For example, the transmitter may transmit T data streams simultaneously from the T transmit antennas to improve throughput. Alternatively, the transmitter may transmit a single data stream redundantly from all T transmit antennas to improve reception by the receiver.

[0004] The transmission from each transmit antenna causes interference to the transmissions from the other transmit antennas. In some instances, improved performance may be achieved by transmitting fewer than T data streams simultaneously from the T transmit antennas. For example, a subset of the T transmit antennas may be selected, and a data stream may be sent from each selected transmit antenna. The transmit antenna(s) that are not used for transmission do not cause interference to the transmit antenna(s) that are used for transmission. Hence, improved performance may be achieved for the data stream(s) sent on the selected transmit antenna(s).

[0005] Rank prediction refers to the determination of the rank of a MIMO channel or, equivalently, the number of data streams that can be transmitted simultaneously via the MIMO channel. If too many data streams are sent, then excessive interference may be observed by each of these data streams and the overall performance may suffer. Conversely, if too few data streams are sent, then the capacity of the MIMO channel is not fully utilized.

[0006] There is therefore a need in the art for techniques to determine the rank of a MIMO channel.

SUMMARY

[0007] Techniques for performing rank prediction in a MIMO system are described herein. In an embodiment, rank prediction is achieved by evaluating the performance of different possible ranks of a MIMO channel and selecting the rank with the best or near best performance. In an embodiment, the rank prediction accounts for system losses, which may include any type of loss that may be observed by data transmission.

[0008] In an embodiment of rank prediction, performance metrics for a plurality of ranks are initially determined. Each rank is indicative of a different number of data streams to send simultaneously via a MIMO channel. The performance metrics may relate to the capacity of the MIMO channel, the throughput of data transmission sent via the MIMO channel, signal quality of the MIMO channel, and so on. Adjustments are applied to the performance metrics for the plurality of ranks to obtain adjusted performance metrics for these ranks. The adjustments account for system losses such as losses due to an error correction code used for data transmission, channel estimation errors at a receiver, variation in interference observed by the receiver, variability in transmit power due to power control, and/or other factors. A rank is then selected based on the adjusted performance metrics for the plurality of ranks. The rank with the best adjusted performance metric may be selected. Alternatively, the lowest rank with an adjusted performance metric that is within a predetermined percentage of the best adjusted performance metric may be selected. At least one channel quality indicator (CQI) for the selected rank is determined based on the adjusted performance metric for the selected rank. The selected rank and CQI(s) may be quantized and sent to a transmitter.

[0009] Various aspects and embodiments of the invention are described in further detail below.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] The features and nature of the present invention will become more apparent from the detailed description set forth below when taken in conjunction with the drawings in which like reference characters identify correspondingly throughout.

[0011] FIG. 1 shows a transmitter station and a receiver station.

[0012] FIG. 2 shows processing units at the transmitter station.

[0013] FIG. 3 shows a rank predictor that performs capacity-based rank prediction.

[0014] FIG. 4 shows a rank predictor that performs throughput-based rank prediction.

[0015] FIG. 5 shows a capacity adjustment unit within a rank predictor.

[0016] FIG. 6 shows a process for performing rank prediction.

[0017] FIG. 7 shows an apparatus for performing rank prediction.

DETAILED DESCRIPTION

[0018] The word "exemplary" is used herein to mean "serving as an example, instance, or illustration." Any embodiment or design described herein as "exemplary" is not necessarily to be construed as preferred or advantageous over other embodiments or designs.

[0019] **FIG. 1** shows a block diagram of an embodiment of two stations 110 and 150 in a wireless communication system 100. For downlink (or forward link) transmission, station 110 may be part of, and may contain some or all of the functionality of, a base station, an access point, a Node B, and/or some other network entity. Station 150 may be part of, and may contain some or all of the functionality of, a terminal, a mobile station, a user equipment, a subscriber unit, and/or some other device. For uplink (or reverse link) transmission, station 110 may be part of a terminal, a mobile station, a user equipment, and so on, and station 150 may be part of a base station, an access point, a Node B, and so on. Station 110 is a transmitter of a data transmission and is equipped with multiple (T) antennas. Station 150 is a receiver of the data transmission and is equipped with multiple (R) antennas. Each transmit antenna and each receive antenna may be a physical antenna or an antenna array.

[0020] At transmitter station 110, a transmit (TX) data processor 120 receives traffic data from a data source 112, processes (e.g., formats, encodes, interleaves, and symbol maps) the traffic data in accordance with a packet format, and generates data symbols. As used herein, a data symbol is a symbol for data, a pilot symbol is a symbol for pilot, and a symbol is typically a complex value. The data symbols and pilot symbols may be modulation symbols from a modulation scheme such as PSK or QAM. Pilot is data that is known *a priori* by both the transmitter and receiver. A packet format may indicate a data rate or information bit rate, a coding scheme or code rate, a modulation scheme, a packet size, and/or other parameters. A packet format may also be referred to as a rate, a transport format, or some other terminology. TX data processor 120 demultiplexes the data symbols into M streams, where $1 \leq M \leq T$ and is determined by the rank provided by a controller/processor 140. The data symbol streams are sent simultaneously via a MIMO channel and may also be referred to as data streams, spatial streams, output streams, or some other terminology.

[0021] A TX spatial processor 130 multiplexes pilot symbols with the M data symbol streams, performs transmitter spatial processing on the multiplexed data and pilot symbols, and provides T streams of output symbols to T transmitters (TMTR) 132a through 132t. Each transmitter 132 processes (e.g., modulates, converts to analog, filters, amplifies, and upconverts) its output symbol stream and generates a modulated signal. T modulated signals from transmitters 132a through 132t are transmitted from antennas 134a through 134t, respectively.

[0022] At receiver station 150, R antennas 152a through 152r receive the T modulated signals, and each antenna 152 provides a received signal to a respective receiver (RCVR) 154. Each receiver 154 processes (e.g., filters, amplifies, downconverts, digitizes, and demodulates) its received signal to obtain received symbols. Each receiver 154 provides received symbols for traffic data to a receive (RX) spatial processor 160 and provides received symbols for pilot to a channel processor 194. Channel processor 194 estimates the response of the MIMO channel from station 110 to station 150 based on the received symbols for pilot (and possibly the received symbols for traffic data) and provides channel estimates to RX spatial processor 160. RX spatial processor 160 performs MIMO detection on the received symbols for traffic data with the channel estimates and provides data symbol estimates. An RX data

processor 170 further processes (e.g., deinterleaves and decodes) the data symbol estimates and provides decoded data to a data sink 172.

[0023] Receiver station 150 may evaluate the channel conditions and send feedback information to transmitter station 110. The feedback information may indicate, e.g., the rank to use for transmission, channel quality indicators (CQIs), the packet format to use for transmission, acknowledgments (ACKs) and/or negative acknowledgments (NAKs) for packets decoded by receiver station 150, other types of information, or any combination thereof. The feedback information is processed (e.g., encoded, interleaved, and symbol mapped) by a TX signaling processor 180, spatially processed by a TX spatial processor 182, and further processed by transmitters 154a through 154r to generate R modulated signals, which are transmitted via antennas 152a through 152r.

[0024] At transmitter station 110, the R modulated signals are received by antennas 134a through 134t, processed by receivers 132a through 132t, spatially processed by an RX spatial processor 136, and further processed (e.g., deinterleaved and decoded) by an RX signaling processor 138 to recover the feedback information. Controller/processor 140 controls the data transmission to receiver station 150 based on the feedback information.

[0025] Controllers/processors 140 and 190 control the operation at stations 110 and 150, respectively. Memories 142 and 192 store data and program codes for stations 110 and 150, respectively.

[0026] The rank prediction techniques described herein may be used for any MIMOwireless communication system, e.g. MIMO wireless communication systems such as Frequency Division Multiple Access (FDMA) systems, Code Division Multiple Access (CDMA) systems, Time Division Multiple Access (TDMA) systems, Spatial Division Multiple Access (SDMA) systems, Orthogonal FDMA (OFDMA) systems, Single-Carrier FDMA (SC-FDMA) systems, and so on. An OFDMA system utilizes Orthogonal Frequency Division Multiplexing (OFDM), and an SC-FDMA system utilizes Single-Carrier Frequency Division Multiplexing (SC-FDM). OFDM and SC-FDM partition the system bandwidth into multiple (K) orthogonal subcarriers, which are also called tones, bins, and so on. Each subcarrier may be modulated with data. In general, modulation symbols are sent in the frequency domain with OFDM and in the time domain with SC-FDM.

[0027] The MIMO channel formed by the T antennas at transmitter station 110 and the R antennas at receiver station 150 may be characterized by an $R \times T$ MIMO channel response matrix $\underline{\mathbf{H}}(k)$ for each subcarrier k, which may be expressed as:

$$\underline{\mathbf{H}}(k) = \begin{bmatrix} h_{1,1}(k) & h_{1,2}(k) & \cdots & h_{1,T}(k) \\ h_{2,1}(k) & h_{2,2}(k) & \cdots & h_{2,T}(k) \\ \vdots & \vdots & \ddots & \vdots \\ h_{R,1}(k) & h_{R,2}(k) & \cdots & h_{R,T}(k) \end{bmatrix}, \qquad k = 1, ..., K, \qquad \text{Eq (1)}$$

where entry $h_{i,j}(k)$, for $i = 1, ..., R$ and $j = 1, ..., T$, is the coupling or complex gain between transmit antenna j and receive antenna i for subcarrier k.

[0028] The MIMO channel may be decomposed into S spatial channels, where $S \leq \min\{T, R\}$. The spatial channels may also be referred to as spatial layers, layers, independent channels, and so on. The MIMO channel response matrix $\underline{\mathbf{H}}(k)$ may be diagonalized to obtain S eigenmodes of the MIMO channel, which may be viewed as orthogonal spatial channels. S data symbol streams may be sent on the S eigenmodes by performing eigen-beamforming at the transmitter. S data symbol streams may also be sent on the S spatial channels with some other spatial processing or without any spatial processing at the transmitter.

[0029] The number of eigenmodes (or the number of spatial channels) is referred to as the rank of the MIMO channel. The MIMO channel is considered full rank if $S = \min\{T, R\}$ and is less than full rank if $S < \min\{T, R\}$. The rank is generally determined by channel conditions. For example, the rank is typically higher in wireless channels with rich scattering and is typically lower in spatially correlated channels and line-of-sight (LOS) channels.

[0030] Good performance (e.g., higher overall throughput) may be achieved by transmitting data such that the number of data symbol streams is matched to the rank of the MIMO channel. In a low-rank channel, reducing the number of data symbol streams may substantially reduce inter-stream interference and increase the received signal qualities of the transmitted data symbol streams, which may allow these streams to be sent at higher rates. Thus, it may be possible to achieve a higher overall throughput with fewer data symbol streams. Conversely, in a full-rank channel, the maximum

number of data symbol streams may be sent to fully utilize all of the spatial channels of the MIMO channel and to maximize MIMO gains.

[0031] The rank prediction techniques described herein determine the number of data symbol streams to transmit such that good performance can be achieved.

[0032] The rank prediction techniques may be used with various operational modes such as a single codeword (SCW) mode and a multiple codeword (MCW) mode. In the SCW mode, a single packet format is used for all data symbol streams, which may simplify operation at the transmitter and receiver. In the MCW mode, a different packet format may be used for each data symbol stream, which may improve performance in some channel conditions.

[0033] The rank prediction techniques may also be used for various spatial processing schemes such as a direct mapping scheme, a pseudo-random mapping scheme, a beam-forming scheme, and so on. In the direct mapping scheme, one data symbol stream is sent from each transmit antenna without any spatial processing. In the pseudo-random mapping scheme, each data symbol stream is sent from all T transmit antennas, and all data symbol streams achieve similar received signal qualities. In the beam-forming scheme, each data symbol stream is sent on a different eigenmode, and the data symbol streams may achieve the same or different received signal qualities. In general, signal quality may be quantified by signal-to-noise ratio (SNR), signal-to-noise-and-interference ratio (SINR), energy-per-symbol-to-noise ratio (Es/No), and so on. For clarity, SNR is used to represent signal quality in the description below.

[0034] For clarity, the rank prediction techniques are described below for an OFDM-based system, e.g., an OFDMA system. Furthermore, the techniques are described for the SCW mode with the pseudo-random mapping scheme.

[0035] **FIG. 2** shows a block diagram of an embodiment of TX data processor 120, TX spatial processor 130, and transmitters 132a through 132t at transmitter station 110. Within TX data processor 120, an encoder 210 encodes traffic data in accordance with a coding scheme and generates code bits. The coding scheme may include a Turbo code, a convolutional code, a low density parity check (LDPC) code, a cyclic redundancy check (CRC) code, a block code, and so on, or a combination thereof. A channel interleaver 212 interleaves (or reorders) the code bits based on an interleaving scheme and provides interleaved bits. A symbol mapper 214 maps the interleaved bits in accordance with a modulation scheme and provides data symbols. A demultiplexer

(Demux) 216 demultiplexes the data symbols into M streams, where M is the predicted/ selected rank of the MIMO channel and is provided by controller/processor 140.

[0036] Within TX spatial processor 130, a multiplexer (Mux) 220 receives the M data symbol streams from TX data processor 120 and maps the data symbols and pilot symbols to the proper subcarriers in each symbol period. A spatial mapping unit 222 multiplies the data and/or pilot symbols for each subcarrier k with a $T \times M$ spatial mapping matrix $\underline{\mathbf{P}}_M(k)$ from a matrix selector 224 and provides output symbols for that subcarrier. Matrix $\underline{\mathbf{P}}_M(k)$ may be a sub-matrix of a $T \times T$ Fourier matrix, a $T \times T$ Hadamard matrix, a $T \times T$ orthonormal matrix, or some other matrix. Matrix selector 224 may determine the dimension of $\underline{\mathbf{P}}_M(k)$ based on the rank M from controller/ processor 140. Matrix selector 224 may also provide different spatial mapping matrices for different subcarriers. Spatial mapping unit 222 provides T output symbol streams to T transmitters 132a through 132t.

[0037] Each transmitter 132 includes an OFDM modulator (Mod) 230 and a TX radio frequency (RF) unit 232. Within each transmitter 132, OFDM modulator 230 receives an output symbol stream and generates OFDM symbols. In each symbol period, OFDM modulator 230 performs a K-point IFFT on K output symbols for K subcarriers and appends a cyclic prefix to generate an OFDM symbol for that symbol period. TX RF unit 232 processes the OFDM symbols and generates a modulated signal.

[0038] At receiver station 150, the received symbols from receivers 154a through 154r may be expressed as:

$$\underline{\mathbf{r}}(k) = \underline{\mathbf{H}}(k) \cdot \underline{\mathbf{P}}_M(k) \cdot \underline{\mathbf{s}}(k) + \underline{\mathbf{n}}(k) = \underline{\mathbf{H}}_M(k) \cdot \underline{\mathbf{s}}(k) + \underline{\mathbf{n}}(k) , \qquad \text{Eq (2)}$$

where $\underline{\mathbf{s}}(k)$ is an $M \times 1$ vector of data symbols for subcarrier k,

$\underline{\mathbf{r}}(k)$ is an $R \times 1$ vector of received symbols for subcarrier k,

$\underline{\mathbf{H}}_M(k) = \underline{\mathbf{H}}(k) \cdot \underline{\mathbf{P}}_M(k)$ is an $R \times M$ effective MIMO channel response matrix for subcarrier k, and

$\underline{\mathbf{n}}(k)$ is an $R \times 1$ noise vector for subcarrier k.

[0039] For simplicity, the noise may be assumed to be additive white Gaussian noise (AWGN) with a zero mean vector and a covariance matrix of $\underline{\mathbf{n}}(k) = \sigma_n^2 \cdot \underline{\mathbf{I}}$, where σ_n^2 is the variance of the noise and $\underline{\mathbf{I}}$ is the identity matrix.

[0040] Receiver station 150 may use various MIMO detection techniques to recover the data symbols sent by transmitter station 110. These MIMO detection techniques include (1) linear MIMO detection techniques such as minimum mean square error (MMSE), zero-forcing (ZF), and maximal ratio combining (MRC) techniques and (2) non-linear MIMO detection techniques such as maximum likelihood (ML) decoding, list sphere decoding (LSD), decision feedback equalizer (DFE), and successive interference cancellation (SIC) techniques. Receiver station 150 may derive a spatial filter matrix for each subcarrier k based on the MMSE, ZF or MRC technique, as follows:

$$\underline{\mathbf{M}}_{mmse}(k) = \underline{\mathbf{D}}_{mmse}(k) \cdot [\underline{\mathbf{H}}_{\mathrm{M}}^{H}(k) \cdot \underline{\mathbf{H}}_{\mathrm{M}}(k) + \sigma_n^2 \cdot \underline{\mathbf{I}}]^{-1} \cdot \underline{\mathbf{H}}_{\mathrm{M}}^{H}(k) \ , \qquad \text{Eq (3)}$$

$$\underline{\mathbf{M}}_{zf}(k) = [\underline{\mathbf{H}}_{\mathrm{M}}^{H}(k) \cdot \underline{\mathbf{H}}_{\mathrm{M}}(k)]^{-1} \cdot \underline{\mathbf{H}}_{\mathrm{M}}^{H}(k) \ , \text{ and} \qquad \text{Eq (4)}$$

$$\underline{\mathbf{M}}_{mrc}(k) = \underline{\mathbf{D}}_{mrc}(k) \cdot \underline{\mathbf{H}}_{\mathrm{M}}^{H}(k) \ , \qquad \text{Eq (5)}$$

where $\underline{\mathbf{Q}}_{\mathrm{M}}(k) = [\underline{\mathbf{H}}_{\mathrm{M}}^{H}(k) \cdot \underline{\mathbf{H}}_{\mathrm{M}}(k) + \sigma_n^2 \cdot \underline{\mathbf{I}}]^{-1} \cdot \underline{\mathbf{H}}_{\mathrm{M}}^{H}(k) \cdot \underline{\mathbf{H}}_{\mathrm{M}}(k)$, Eq (6)

$\underline{\mathbf{D}}_{mmse}(k) = [\mathrm{diag}\{\underline{\mathbf{Q}}_{\mathrm{M}}(k)\}]^{-1}$, and

$\underline{\mathbf{D}}_{mrc}(k) = [\mathrm{diag}\{\underline{\mathbf{H}}_{\mathrm{M}}^{H}(k) \cdot \underline{\mathbf{H}}_{\mathrm{M}}(k)\}]^{-1}$.

In equations (3) and (5), $\underline{\mathbf{D}}_{mmse}(k)$ and $\underline{\mathbf{D}}_{mrc}(k)$ are $\mathrm{M} \times \mathrm{M}$ diagonal matrices of scaling values used to obtain normalized estimates of the data symbols.

[0041] Receiver station 150 may perform MIMO detection as follows:

$$\hat{\underline{\mathbf{s}}}(k) = \underline{\mathbf{M}}(k) \cdot \underline{\mathbf{r}}(k) = \underline{\mathbf{s}}(k) + \tilde{\underline{\mathbf{n}}}(k) \ , \qquad \text{Eq (7)}$$

where $\underline{\mathbf{M}}(k)$ is an $\mathrm{M} \times \mathrm{R}$ spatial filter matrix that may be $\underline{\mathbf{M}}_{mmse}(k)$, $\underline{\mathbf{M}}_{zf}(k)$ or $\underline{\mathbf{M}}_{mrc}(k)$,

$\hat{\underline{\mathbf{s}}}(k)$ is an $\mathrm{M} \times 1$ vector with M data symbol estimates, and

$\tilde{\underline{\mathbf{n}}}(k)$ is a vector of noise after the MIMO detection.

[0042] Receiver station 150 may obtain an estimate of $\underline{\mathbf{H}}(k)$ or $\underline{\mathbf{H}}_{\mathrm{M}}(k)$ based on pilot symbols received from transmitter station 110. Receiver station 150 may then derive $\underline{\mathbf{M}}(k)$ based on $\underline{\mathbf{H}}(k)$ or $\underline{\mathbf{H}}_{\mathrm{M}}(k)$. The dimension of $\underline{\mathbf{M}}(k)$ is dependent on the rank M used for transmission. The data symbol estimates in $\hat{\underline{\mathbf{s}}}(k)$ are estimates of the data symbols in $\underline{\mathbf{s}}(k)$.

[0043] In an embodiment, rank prediction is achieved by evaluating the performance of different possible ranks of the MIMO channel and selecting the rank with the best or near best performance. Performance may be quantified by various metrics such as channel capacity, throughput, signal quality (e.g., SNR), and so on. Channel capacity generally refers to the theoretical transmission capacity of a communication channel. The capacity of a MIMO channel is dependent on the number of spatial channels in the MIMO channel and the signal quality of each spatial channel. Throughput generally refers to the amount of data sent via a communication channel. Throughput is dependent on the channel capacity as well as system parameters, e.g., the packet formats available for use. Channel capacity and throughput may be given in terms of spectral efficiency, which is typically given in units of information bits per second per Hertz (bps/Hz). Channel capacity is referred to as simply capacity in the description below.

[0044] In an embodiment, the rank prediction accounts for system losses. As used herein, system losses refer to any type of loss that may be experienced by data transmission. System losses may include system implementation losses (e.g., due to coding scheme, packet format, etc.), losses due to channel variability (e.g., variability in interference and transmit power), processing losses (e.g., channel estimation errors), and/or other types of losses.

[0045] **FIG. 3** shows an embodiment of a rank predictor 300 that performs capacity-based rank prediction and accounts for system losses. Rank predictor 300 evaluates the performance of each possible rank using capacity as the performance metric. For simplicity, the following description assumes that $T \leq R$, and that up to T data symbol streams may be sent simultaneously from T transmit antennas. Rank predictor 300 includes T processing sections 310a through 310t for T possible ranks of $m = 1$ through T, respectively. Each processing section 310 determines the average capacity for a different possible rank that may be used for data transmission.

[0046] Within processing section 310 for rank m, where $m \in \{1, ..., T\}$, a spatial mapping unit 312 receives the MIMO channel response matrix $\underline{\mathbf{H}}(k)$ for each subcarrier k, multiplies $\underline{\mathbf{H}}(k)$ with a $T \times m$ spatial mapping matrix $\underline{\mathbf{P}}_m(k)$ for rank m, and provides an $R \times m$ effective MIMO channel response matrix $\underline{\mathbf{H}}_m(k)$ for subcarrier k. Unit 312 performs spatial mapping in the same manner as spatial mapping unit 222 at transmitter station 110 assuming that m data symbol streams are transmitted for rank m.

[0047] An SNR calculation unit 314 determines the SNRs of the m data symbol streams or equivalently the m spatial channels for rank m. The SNRs are dependent on the MIMO detection technique used by receiver station 150 as well as the number of data symbol streams sent simultaneously. For the MMSE technique described above, $\underline{\mathbf{Q}}_m(k)$ is first determined based on $\underline{\mathbf{H}}_m(k)$ as shown in equation (6). The SNR of each data symbol stream for rank m may then be expressed as:

$$\text{SNR}_{m,i}(k) = \frac{q_{m,i}(k)}{1 - q_{m,i}(k)}, \qquad \text{for } i = 1, ..., m, \qquad \text{Eq (8)}$$

where $q_{m,i}(k)$ is the i-th diagonal element of $\underline{\mathbf{Q}}_m(k)$ for subcarrier k, and

$\text{SNR}_{m,i}(k)$ is the SNR of data symbol stream i for subcarrier k.

Equation (8) gives SNR in linear unit. SNR is computed in different manners for other MIMO detection techniques.

[0048] The average SNR of all m data symbol streams for rank m may then be computed as follows:

$$\text{SNR}_{\text{avg},m}(k) = \frac{1}{m} \cdot \sum_{i=1}^{m} \text{SNR}_{m,i}(k), \qquad \text{Eq (9)}$$

where $\text{SNR}_{\text{avg},m}(k)$ is the average SNR of all m data symbol streams for subcarrier k.

[0049] A capacity mapper 316 maps the average $\text{SNR}_{\text{avg},m}(k)$ for each subcarrier k to capacity and further accumulates the capacities of all K subcarriers. The capacity mapping may be performed based on an unconstrained capacity function, as follows:

$$C_{\text{avg},m} = \sum_{k=1}^{K} \log_2 [1 + \text{SNR}_{\text{avg},m}(k)] , \quad \text{Eq (10)}$$

where $C_{\text{avg},m}$ is the average capacity of each spatial channel for rank m. In equation (10), the capacity of each subcarrier is given as: $\log_2 [1 + \text{SNR}_{\text{avg},m}(k)]$. The capacities for all K subcarriers are then accumulated to obtain the average capacity for rank m. The unconstrained capacity function assumes no loss from coding or modulation.

[0050] The capacity mapping may also be performed based on a constrained capacity function, as follows:

$$C_{\text{avg},m} = \sum_{k=1}^{K} \log_2 [1 + \eta \cdot \text{SNR}_{\text{avg},m}(k)] , \quad \text{Eq (11)}$$

where $\eta < 1.0$ is a penalty factor that may account for various factors such as modulation scheme, coding scheme, code rate, packet size, and so on. Capacity may also be determined based on other capacity functions or look-up tables.

[0051] A capacity adjustment unit 318 adjusts the average capacity $C_{\text{avg},m}$ to account for various factors, as described below. Unit 318 provides an adjusted capacity $C_{\text{adj},m}$ for rank m.

[0052] A rank selector 330 receives the adjusted capacities $C_{\text{adj},1}$ through $C_{\text{adj},T}$ for all T possible ranks 1 through T. Rank selector 330 first determines the total capacity $C_{\text{total},m}$ for each rank m, as follows:

$$C_{\text{total},m} = m \cdot C_{\text{avg},m} . \quad \text{Eq (12)}$$

[0053] Rank selector 330 then selects one of the T possible ranks. In an embodiment, rank selector 330 provides the rank with the largest total capacity, as follows:

$$M = \arg \max_{m \in \{1,\ldots,T\}} (C_{\text{total},m}) . \quad \text{Eq (13)}$$

[0054] In another embodiment, rank selector 330 selects the lowest rank with a total capacity that is within a predetermined percentage of the largest total capacity, as follows:

$$M = \min \{\arg (C_{\text{total},m} > \beta \cdot C_{\max})\}, \quad \text{Eq (14)}$$

where $C_{\max}$ is the largest total capacity for all T possible ranks and $\beta \leq 1.0$. A lower rank is generally more robust against deleterious channel conditions and channel estimation errors. Thus, if a lower rank can achieve a total capacity that is close to the largest total capacity, then the lower rank may be selected for use.

[0055] A CQI generator 332 receives the adjusted capacities $C_{\text{adj},1}$ through $C_{\text{adj},T}$ for all T possible ranks as well as the selected rank M. In an embodiment, CQI generator 332 determines an effective SNR for the adjusted capacity $C_{\text{adj},M}$ of the selected rank M, as follows:

$$\text{SNR}_{\text{eff},M} = 10 \log_{10} (2^{C_{\text{adj},M}} - 1), \quad \text{Eq (15)}$$

where $\text{SNR}_{\text{eff},M}$ is given in units of decibel (dB). CQI generator 332 may also determine the effective SNR based on some other function or a look-up table of SNR versus capacity.

[0056] In an embodiment, CQI generator 332 quantizes the effective SNR to a predetermined number of bits to obtain a CQI for the selected rank M. In another embodiment, CQI generator 332 maps the effective SNR to a packet format based on a rate look-up table of packet format versus required SNR. This rate look-up table contains a required SNR for each packet format supported by the system. The required SNR for each packet format may be the minimum SNR needed to reliably transmit packets in an AWGN channel with a certain target packet error rate (PER), e.g., 1% PER. The rate look-up table may be generated by computer simulation, empirical measurement, testing, and/or some other mechanism.

[0057] **FIG. 4** shows an embodiment of a rank predictor 400 that performs throughput-based rank prediction and accounts for system losses. Rank predictor 400 evaluates the performance of each possible rank using throughput as the performance metric. Rank predictor 400 includes T processing sections 410a through 410t for T possible ranks of $m = 1$ through T, respectively. Each processing section 410 determines the throughput for a different possible rank that may be used for data transmission.

[0058] Within processing section 410 for rank m, where $m \in \{1, ..., T\}$, units 412, 414, 416, and 418 operate in the same manner as units 312, 314, 316, and 318, respectively, in FIG. 3. An SNR calculation unit 420 receives the adjusted capacity $C_{adj,m}$ for rank m and determines the effective SNR, e.g., as shown in equation (15). A rate look-up table 422 receives the effective SNR for rank m and provides the packet format with the largest throughput and a required SNR that is less than the effective SNR.

[0059] A rank selector 430 receives the throughputs TP_1 through TP_T for all T possible ranks and determines the total throughput $TP_{total,m}$ for each rank, as follows:

$$TP_{total,m} = m \cdot TP_m \ . \qquad \text{Eq (16)}$$

[0060] Rank selector 430 then selects one of the T possible ranks. In an embodiment, rank selector 430 provides the rank with the largest total throughput, as follows:

$$M = \arg \max_{m \in \{1,..,T\}} (TP_{total,m}) \ . \qquad \text{Eq (17)}$$

[0061] In another embodiment, rank selector 430 selects the lowest rank with a total throughput that is within a predetermined percentage of the largest total throughput, as follows:

$$M = \min \{\arg (TP_{total,m} > \beta \cdot TP_{max})\} \ , \qquad \text{Eq (18)}$$

where TP_{max} is the largest total throughput for all T possible ranks.

[0062] A CQI generator 432 may receive the effective SNRs for all T possible ranks and provide the effective SNR for the selected rank M as the CQI, as shown in FIG. 4. CQI generator 432 may also receive the packet formats for all T possible ranks and provide the packet format for the selected rank M as the CQI (not shown in FIG. 4).

[0063] FIGS. 3 and 4 show two embodiments of rank prediction based on performance metrics of capacity and throughput, respectively. Throughput may be considered as a quantized version of capacity, where the quantization is determined by the supported packet formats. The difference between capacity and throughput generally decreases with more supported packet formats.

[0064] Rank prediction may also be performed based on other performance metrics. In another embodiment, rank prediction is performed based on a performance metric of signal quality, e.g., SNR. The average SNR of each subcarrier k for rank m may be determined, e.g., as shown in equation (9), and accumulated over the K subcarriers to obtain the average SNR for rank m. Adjustments may then be applied to the average SNR for each rank m to obtain an adjusted SNR for that rank. The adjusted SNRs for the T possible ranks may then be used to select one rank as well as to determine the CQI for the selected rank.

[0065] The average capacity $C_{\text{avg},m}$ in FIGS. 3 and 4 is indicative of the capacity of each spatial channel in the MIMO channel with rank m. The computed average capacity $C_{\text{avg},m}$ is subject to various sources of error such as, e.g., channel estimation errors. The average capacity $C_{\text{avg},m}$ may also not be achievable due to various reasons such as, e.g., a finite set of packet formats supported by the system and usable for data transmission. Furthermore, the capacity computed at one time instant may be different than the capacity at another time instant when data is sent, e.g., due to changes in channel conditions, variations in interference and transmit power, and so on. In addition, certain constraints may be imposed in the selection of rank. The average capacity $C_{\text{avg},m}$ may be adjusted to account for these various factors.

[0066] **FIG. 5** shows an embodiment of a capacity adjustment unit 318x, which may be used for each capacity adjustment unit 318 in FIG. 3 and each capacity adjustment unit 418 in FIG. 4. Within capacity adjustment unit 318x, a unit 510 adjusts the average capacity for rank m to account for coding loss. Different error correction codes may have different amounts of losses, which may be determined by the error correction capabilities of these codes. For example, a convolutional code may have a larger loss than a Turbo code. An adjustment for coding loss, which is also referred to as a gap-to-capacity backoff. In an aspect, it may be computed as follows:

$$\text{SNR}_{\text{avg},m} = 2^{C_{\text{avg},m}} - 1 , \qquad \text{Eq (19)}$$

$$C_{\text{gap},m} = \log_2 [1 + \text{SNR}_{\text{avg},m} / g] , \qquad \text{Eq (20)}$$

where $g \geq 1.0$ is a factor that accounts for coding loss. Different codes may be associated with different values of g.

[0067] A unit 512 adjusts the capacity for rank m to account for channel estimation errors. In an aspect, this may be as follows:

$$\mathrm{SNR}_{\mathrm{gap},m} = 2^{C_{\mathrm{gap},m}} - 1 , \quad \text{Eq (21)}$$

$$\mathrm{SNR}_{\mathrm{ch},m} = \mathrm{Channel_Backoff}\,(\mathrm{SNR}_{\mathrm{gap},m},\ m,\ \mathrm{Channel\ model}) , \quad \text{Eq (22)}$$

$$C_{\mathrm{ch},m} = \log_2 [1 + \mathrm{SNR}_{\mathrm{ch},m}] , \quad \text{Eq (23)}$$

where Channel_Backoff is a function that reduces the SNR of rank m to account for channel estimation errors.

[0068] The amount of loss due to channel estimation errors may be dependent on various factors such as the rank of the MIMO channel (e.g., more loss for higher rank), the channel model (e.g., more loss for high mobility), and so on. The channel model may be quantified by antenna configuration, mobility or Doppler, and/or other factors. The amount of loss due to channel estimation errors may be determined based on computer simulation, empirical measurement, testing, and/or some other means. The loss may also be determined for different operating scenarios such as different antenna configurations (e.g., 2×4, 4×2), different candidate ranks, different Doppler, and so on. In general, the Channel_Backoff function may be defined for any number of operation scenarios and based on any number of input parameters as well as any type of input parameters. The Channel_Backoff function may be stored in one or more look-up tables, e.g., one look-up table for each operating scenario.

[0069] A unit 514 adjusts the capacity for rank m to account for interference variations. In an aspect, this may be as follows:

$$\mathrm{SNR}_{\mathrm{ch},m} = 2^{C_{\mathrm{ch},m}} - 1 , \quad \text{Eq (24)}$$

$$\mathrm{SNR}_{\mathrm{int},m} = \mathrm{Interference_Backoff}\,(\mathrm{SNR}_{\mathrm{ch},m}, \mathrm{Interference\ variation}) , \quad \text{Eq (25)}$$

$$C_{\mathrm{int},m} = \log_2 [1 + \mathrm{SNR}_{\mathrm{int},m}] , \quad \text{Eq (26)}$$

where Interference_Backoff is a function that reduces the SNR of rank m to account for variations in interference observed by receiver station 150.

[0070] Receiver station 150 may measure interference over time and/or frequency and determine the variation in interference based on these measurements. The amount of loss due to interference variation may be determined based on computer simulation, empirical measurement, testing, and/or some other means. The Interference_Backoff function may be stored in a look-up table.

[0071] A unit 516 may apply other adjustments to the capacity for rank m. In an embodiment, unit 516 may apply an adjustment to account for (1) variation in transmit power over time due to power control and/or (2) an offset between transmit power of pilot or control channel and transmit power of traffic channel. For example, unit 516 may either reduce or increase capacity depending on whether the transmit power is reduced or increased in an upcoming interval. In an embodiment, unit 516 may disqualify rank m, if $m > 1$ and the SNR of rank m is below a predetermined SNR. A low SNR may indicate that station 110 or 150 is located near coverage edge and is a candidate for handoff. Disqualifying rank m may result in selection of a lower rank (e.g., rank 1), which may be more robust for low SNR conditions. In an embodiment, unit 516 may adjust the capacity for rank m to account for H-ARQ packet termination latency. With H-ARQ, a packet is sent in one transmission and, if needed, one or more retransmissions until the packet is decoded correctly by receiver station 150. H-ARQ packet termination latency refers to the average number of transmission/retransmissions for packets. More latency may indicate inaccuracy in the rank prediction. Hence, more backoff may be applied for more latency. In an embodiment, unit 516 may apply a bias such that a lower rank is selected if variability in rank is observed. In general, unit 516 may apply adjustments for any number of factors and any type of factor that may affect data transmission performance.

[0072] A unit 518 limits the capacity for rank m to within a range of minimum and maximum values. The minimum value is called the floor, is denoted as C_{floor}, and may be set to the lowest throughput of all supported packet formats. The maximum value is called the ceiling, is denoted $C_{ceiling}$, and may be set to the largest throughput of all supported packet formats. The capacity for each rank m may then be constrained to be within the floor and ceiling. In an aspect, this may be as follows:

$$C_{adj,m} = \begin{cases} 0 & \text{if} \quad C_{misc,m} < C_{floor} \\ C_{ceiling} & \text{if} \quad C_{misc,m} > C_{ceiling} \\ C_{misc,m} & \text{if} \quad C_{floor} \le C_{misc,m} \le C_{ceiling} \end{cases}, \qquad \text{Eq (27)}$$

where $C_{misc,m}$ is the capacity for rank m from unit 516. In equation (27), the capacity for rank m is not modified if it is within the range of the floor and ceiling, is set to the ceiling if it is larger than the ceiling, and is set to zero if it is less than the floor. Setting the capacity to zero means that rank m will not be selected for use.

[0073] In general, adjustments may be applied for any number and any type of factors. FIG. 5 shows adjustments being applied for some exemplary factors. Adjustments utilized may also be applied for fewer, different, and/or additional factors. For example, the adjustment for the supported packet formats in equation (27) may be omitted. As another example, adjustments may be applied for only channel estimation errors and interference variation. The adjustments provide margins in the rank prediction so that an appropriate rank may be selected for use in light of the various possible sources of error in rank prediction.

[0074] For clarity, with the exception of unit 516, FIG. 5 shows a separate unit being used to apply an adjustment for each factor. However, the units may be integrated into one or more functional units, e.g. software, hardware, or combinations thereof. Also for clarity, the adjustment for each factor is described separately. In general, the adjustments may be applied individually for each factor, for a subset of factors, or for all factors being considered. Furthermore, the adjustments may be applied in other orders than the order shown in FIG. 5. The adjustments may be applied using any number of functions and/or look-up tables with any number of input parameters and any type of input parameter.

[0075] In the embodiments shown in FIGS. 3 through 5, adjustments are applied to the average capacity of the spatial channels for each rank m. Rank selectors 330 and 430 then determine the total capacity or total throughput for each rank and select the rank with the best or near best performance. Applying adjustments to the average capacity may result in more granularity for higher ranks. Adjustments may also be applied to total capacity or total throughput instead of average capacity or average throughput.

[0076] Receiver station 150 may quantize the selected rank M to a predetermined number of bits, which may be determined based on the highest rank supported by the system. For example, if the system supports a 4×4 configuration as the highest dimensionality configuration, then the highest possible rank is four, and the selected rank M may be conveyed using two bits.

[0077] Receiver station 150 may also quantize the CQI to a predetermined number of bits, which may be determined by the desired accuracy for the CQI. More bits allow the CQI to be reported with finer granularity, which may be beneficial for packet format selection. The number of bits for the CQI may be selected based on (e.g., proportional to) the number of packet formats supported by the system. More packet formats generally imply smaller steps in spectral efficiency between packet formats. More accurate CQI may then be beneficial in selecting a suitable packet format. The CQI may be quantized to three, four, five, six or some other number of bits.

[0078] Receiver station 150 may determine and report the rank and CQI periodically and at a sufficiently fast rate to achieve good performance for data transmission. The rank and CQI may be determined and reported at the same rate, e.g., every 5, 10 or 20 milliseconds (ms). Alternatively, the rank and CQI may be determined and reported at different rates. For example, the rank may be determined and reported at a first rate, and the CQI may be determined and reported at a second rate. The rank of a MIMO channel may change at a slower rate than the SNR of the spatial channels and may thus be reported at a slower rate than the CQI.

[0079] The rank and CQI may be determined by receiver station 150 and sent back to transmitter station 110, as shown in FIG. 1. The rank and CQI may also be determined by transmitter station 110 using information from receiver station 150. For example, in a time division duplexed (TDD) system, the downlink and uplink share the same frequency channel, and the channel response for one link may be assumed to be reciprocal of the channel response for the other link. In this case, transmitter station 110 may be able to estimate the MIMO channel response based on a pilot sent by receiver station 150. Transmitter station 110 may then determine the rank and the packet format to use for data transmission based on its estimate of the MIMO channel response.

[0080] For clarity, the rank prediction techniques have been described for the SCW mode. The techniques may also be used to select the rank for the MCW mode. The rank prediction for the MCW mode may be performed as described above for the SCW

mode. For each candidate rank *m*, adjustments may be applied to the capacity of each spatial channel or the total capacity of all spatial channels for rank *m*. A CQI may be determined for each spatial channel in the selected rank M. More than one CQI may be generated if M is greater than one.

[0081] **FIG. 6** shows an embodiment of a process 600 for performing rank prediction. Performance metrics for a plurality of ranks are determined (block 612). Each rank is indicative of a different number of data symbol streams to send simultaneously via a MIMO channel or, equivalently, the number of spatial channels to use for data transmission. The performance metrics may relate to the capacity of the MIMO channel, the throughput of data transmission sent via the MIMO channel, signal quality of the MIMO channel, and so on. A performance metric may be determined for each of the ranks.

[0082] Adjustments are applied to the performance metrics for the plurality of ranks to obtain adjusted performance metrics for these ranks (block 614). The adjustments account for for some system loss parameters. The losses, may be, one or more of losses due to an error correction code used for data transmission, channel estimation errors at the receiver, variation in interference observed by the receiver, variability in transmit power due to power control, and/or other factors. In addition, other loss parameters may be utilized. The adjustments may be applied to SNR (as described above), capacity, throughput, and/or other measures, all of which may be related. For example, SNR may be converted to capacity, and vice versa, via a capacity function or a look-up table. Ranks with performance metrics below a predetermined threshold may be omitted from consideration. The performance metrics for the ranks may be limited to within a range of values, which may be determined by the supported packet formats. The adjustments may be applied using look-up tables, calculations, and/or some other means.

[0083] A rank to use for data transmission is selected from among the plurality of ranks based on the adjusted performance metrics (block 616). The rank with the best adjusted performance metric may be selected. Alternatively, the lowest rank with an adjusted performance metric that is within a predetermined percentage of the best adjusted performance metric may be selected. At least one CQI is determined for the selected rank based on an adjusted performance metric for the selected rank (block 618). For example, one CQI may be determined for the SCW mode whereas M CQIs may be

determined for the MCW mode. Each CQI may be a quantized SNR, a packet format, or some other type of information. If the rank prediction is performed at the receiver, then the selected rank and the CQI(s) may be quantized and sent to the transmitter.

[0084] Process 600 may be performed by controller/processor 190 or some other processor at receiver station 150. Process 600 may also be performed by controller/processor 140 or some other processor at transmitter station 110. The adjustments may be performed using look-up tables stored in memory 192 at receiver station 150 or memory 142 at transmitter station 110.

[0085] **FIG. 7** shows an embodiment of an apparatus 700 for performing rank prediction. Apparatus 700 includes means for determining performance metrics for a plurality of ranks (block 712), means for applying adjustments to the performance metrics for the plurality of ranks to obtain adjusted performance metrics for these ranks (block 714), means for selecting a rank to use for data transmission from among the plurality of ranks based on the adjusted performance metrics (block 716), and means for determining at least one CQI for the selected rank based on an adjusted performance metric for the selected rank (block 718).

[0086] The rank prediction techniques described herein may be implemented by various means. For example, these techniques may be implemented in hardware, firmware, software, or a combination thereof. For a hardware implementation, the processing units used to perform rank prediction may be implemented within one or more application specific integrated circuits (ASICs), digital signal processors (DSPs), digital signal processing devices (DSPDs), programmable logic devices (PLDs), field programmable gate arrays (FPGAs), processors, controllers, micro-controllers, microprocessors, electronic devices, other electronic units designed to perform the functions described herein, or a combination thereof.

[0087] For a firmware and/or software implementation, the rank prediction techniques may be implemented with instructions (e.g., procedures, functions, and so on) that may be utilized to perform the functions described herein. The finstructions, e.g. as software or firmware, may be stored in a memory (e.g., memory 192 in FIG. 1) and executed by a processor (e.g., processor 190). The memory may be implemented within the processor or external to the processor.

[0088] The previous description of the disclosed embodiments is provided to enable any person skilled in the art to make or use the present invention. Various

modifications to these embodiments will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other embodiments without departing from the spirit or scope of the invention. Thus, the present invention is not intended to be limited to the embodiments shown herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

[0089] WHAT IS CLAIMED IS:

CLAIMS

1. An apparatus (150; 110) for determining a rank of a multiple-input multiple-output (MIMO) channel, comprising:

at least one processor (190; 140) configured

to determine (612; 712) performance metrics for a plurality of ranks, each rank indicative of a different number of data streams to send simultaneously via a multiple-input multiple-output (MIMO) channel,

wherein the processor determines the performance metrics by performing one or more of (i) applying a spatial-mapper to a response matrix of the MIMO channel to generate a post-processing matrix for one or more sub-carriers of the MIMO channel, (ii) computing signal-to-interference-and-noise ratio (SINR) for one or more sub-carriers of the MIMO channel, (iii) mapping a signal-to-noise ratio (SNR) of a receiver to capacity for one or more sub-carriers of the MIMO channel, and/or (iv) computing an average capacity of two or more sub-carriers of the MIMO channel;

to apply (614; 714) adjustments to the performance metrics for the plurality of ranks to obtain adjusted performance metrics, the adjustments accounting for system losses, and

to select (616; 716) a rank to use for data transmission from among the plurality of ranks based on the adjusted performance metrics; and

a memory (192; 142) coupled to the at least one processor.

2. The apparatus of claim 1, wherein the performance metrics relate to capacity of the MIMO channel.

3. The apparatus of claim 1, wherein the performance metrics relate to throughput of data transmission sent via the MIMO channel.

4. The apparatus of claim 1, wherein the performance metrics relate to signal quality of the MIMO channel.

5. The apparatus of claim 1, wherein the adjustments account for losses due to an error correction code used for data transmission.

6. The apparatus of claim 1, wherein the adjustments account for channel estimation errors at the receiver.

7. The apparatus of claim 1, wherein the adjustments account for variation in interference observed by the receiver.

8. The apparatus of claim 1, wherein the adjustments account for variation in transmit power used for data transmission.

9. The apparatus of claim 1, wherein the at least one processor is configured to omit ranks having performance metrics below a predetermined threshold.

10. The apparatus of claim 1, wherein the at least one processor is configured to apply adjustments to the performance metrics for the plurality of ranks by excluding, from the plurality of ranks, ranks that are associated with performance metrics with values that fall outside of a

given range of values, such that the processor performs the rank selection from only based on ranks among the plurality of ranks associated with performance metrics with values within the given range of values.

11. The apparatus of claim 10, wherein the given range of values is determined by packet formats usable for data transmission.

12. The apparatus of claim 1, wherein each of the adjusted performance metrics is associated with a value, and the at least one processor is configured to select a rank that is expected to provide a highest-level of performance based on the associated values of the adjusted performance metrics.

13. The apparatus of claim 1, wherein each of the adjusted performance metrics is associated with a value, and the at least one processor is configured

to determine a rank that is expected to provide a highest-level of performance based on the associated values of the adjusted performance metrics,

to establish a given range of values based on the adjusted performance metric value of the rank that is expected to provide the highest-level of performance, and

to select a rank that is (i) expected to provide a lowest-level of performance based on the associated values of the adjusted performance metrics (ii) while also having an adjusted performance metric value that falls within the given range of values.

14. The apparatus of claim 1, wherein the at least one processor is configured to represent the selected rank with a predetermined number of bits, and to send the selected rank to a transmitter.

15. The apparatus of claim 1, wherein the at least one processor is configured to determine at least one channel quality indicator (CQI) based on an adjusted performance metric for the selected rank.

16. The apparatus of claim 1, wherein the at least one processor is configured to determine a signal-to-noise ratio (SNR) based on an adjusted performance metric for the selected rank, and to quantize the SNR to obtain a channel quality indicator (CQI) for the selected rank.

17. The apparatus of claim 1, wherein the memory is configured to store at least one look-up table of adjustments for the performance metrics.

18. A method for determining a rank of a multiple-input multiple-output (MIMO) channel, comprising:

determining (612; 712) performance metrics for a plurality of ranks, each rank indicative of a different number of data streams to send simultaneously via a multiple-input multiple-output (MIMO) channel

wherein determining the performance metrics includes one or more of (i) applying a spatial-mapper to a response matrix of the MIMO channel to generate a post-processing matrix for one or more sub-carriers of the MIMO channel, (ii) computing signal-to-interference-and-noise ratio (SINR) for one or more sub-carriers of the MIMO channel, (iii) mapping a signal-to-noise ratio (SNR) of a receiver to capacity for one or more sub-carriers of the MIMO channel, and/or (iv) computing an average capacity of two or more sub-carriers of the MIMO channel;

applying (614; 714) adjustments to the performance metrics for the plurality of ranks to obtain adjusted performance metrics, the adjustments accounting for system losses; and

selecting (616; 716) a rank to use for data transmission from among the plurality of ranks based on the adjusted performance metrics.

19. The method of claim 18, wherein determining performance metrics comprise determining performance metrics for one or more of capacity of the MIMO channel, throughput of data transmission sent via the MIMO channel, or signal quality of the MIMO channel.

20. The method of claim 18, further comprising calculating adjustments for one or more of the performance metrics.

21. The method of claim 20, wherein calculating comprises calculating to account for losses due to one or more of an error correction code used for data transmission, channel estimation errors at the receiver, variation in interference observed by the receiver, variation in transmit power used for data transmission, or a combination thereof.

22. An apparatus (150; 110) for determining a rank of a multiple-input multiple-output (MIMO) channel, comprising:

means for determining (612; 712) performance metrics for a plurality of ranks, each rank indicative of a different number of data streams to send simultaneously via a multiple-input multiple-output (MIMO) channel,

wherein the means for determining determines the performance metrics by performing one or more of (i) applying a spatial-mapper to a response matrix of the

MIMO channel to generate a post-processing matrix for one or more sub-carriers of the MIMO channel, (ii) computing signal-to-interference-and-noise ratio (SINR) for one or more sub-carriers of the MIMO channel, (iii) mapping a signal-to-noise ratio (SNR) of a receiver to capacity for one or more sub-carriers of the MIMO channel, and/or (iv) computing an average capacity of two or more sub-carriers of the MIMO channel;

means for applying (614; 714) adjustments to the performance metrics for the plurality of ranks to obtain adjusted performance metrics, the adjustments accounting for system losses; and

means for selecting (616; 716) a rank to use for data transmission from among the plurality of ranks based on the adjusted performance metrics.

23. The apparatus of claim 22, wherein the means for determining performance metrics comprise means for determining performance metrics for one or more of capacity of the MIMO channel, throughput of data transmission sent via the MIMO channel, or signal quality of the MIMO channel.

24. The apparatus of claim 22, further comprising means for calculating adjustments for one or more of the performance metrics.

25. The apparatus of claim 24, wherein the means for calculating comprises means for calculating to account for losses due to one or more of an error correction code used for data transmission, channel estimation errors at the receiver, variation in interference observed by the receiver, variation in transmit power used for data transmission, or a combination thereof.

26. A processor readable media storing instructions which, when executed by a processor, cause the processor to perform a method for determining a rank of a multiple-input multiple-output (MIMO) channel, the instructions comprising:

instructions for determining (612; 712) performance metrics for a plurality of ranks, each rank indicative of a different number of data streams to send simultaneously via a multiple-input multiple-output (MIMO) channel,

wherein determining the performance metrics includes one or more of (i) applying a spatial-mapper to a response matrix of the MIMO channel to generate a post-processing matrix for one or more sub-carriers of the MIMO channel, (ii) computing signal-to-interference-and-noise ratio (SINR) for one or more sub-carriers of the MIMO channel, (iii) mapping a signal-to-noise ratio (SNR) of a receiver to capacity for one or more sub-carriers of the MIMO channel, and/or (iv) computing an average capacity of two or more sub-carriers of the MIMO channel;

instructions for applying (614; 714) adjustments to the performance metrics for the plurality of ranks to obtain adjusted performance metrics, the adjustments accounting for system losses; and

instructions for selecting (616; 716) a rank to use for data transmission from among the plurality of ranks based on the adjusted performance metrics.