Proc. IEEE Pacific Rim Conf. Commun., Computers, and Signal Processing (Victoria, BC), pp. 490-493, Aug. 2005

LOADING ALGORITHMS FOR MULTICARRIER SPATIAL DIVERSITY SYSTEMS EMPLOYING ANTENNA SUBSET SELECTION

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***Abstract* – This paper presents two novel loading algorithms for multicarrier systems performing spatial diversity. The algorithms use bit allocation techniques to increase throughput while ensuring the system remains below a specified error rate. One algorithm uses the same signal constellation across all subcarriers while the other varies the signal constellations. To reduce hardware costs, power consumption, and complexity, the proposed algorithms simultaneously perform antenna subset selection, choosing array configurations that yield further increases in the overall throughput. Our results show that the combination of multiple antennas and bit allocation by the proposed algorithms substantially increases throughput. Furthermore, hardware costs are reduced with a negligible penalty in throughput when antenna subset selection is employed.**

1 INTRODUCTION

Two technologies receiving significant attention for their potential in enabling future high data rate wireless access are multiple transmit/receive antennas and multicarrier modulation [1]. Multiple antennas employed in a spatial diversity configuration could enhance the error robustness of the system, while multicarrier modulation can transform a frequency-selective fading channel into a collection of approximately flat subchannels. It has been shown that the combination of multicarrier modulation and multiple antennas, configured for spatial diversity, can yield performance gains greater than the gains offered by each individual technology [2–4]. Nevertheless, there exists the potential for further enhancements in performance and implementation.

To increase throughput, multicarrier systems can tailor the subcarrier signal constellation sizes according to the channel environment via a technique called *bit allocation* [5]. Both Thoen *et al.* [6] and Bartolome, Perez-Neira, & Ibars [7] examined the performance benefits of bit allocation employed in multicarrier systems employing multiple antennas. However, the bit allocation techniques employed in these implementations either used approximations of the closed form expressions for the bit error rate (BER), which may yield solutions far from the optimal allocation, or used an incremental approach, which is computationally expensive. To reduce hardware costs, power consumption, and complexity, a transceiver can be implemented with fewer RF chains than antennas, resulting in choosing a subset of antennas that yield the largest improvement to system performance. This technique is known as *antenna subset selection* [4, 8]. Although antenna subset selection has been implemented for multicarrier systems with multiple antennas, these systems have not also exploited the benefits of bit allocation.

This research was partially funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) and Le Fonds "Nature et Technologies" du Québec (NATEQ).

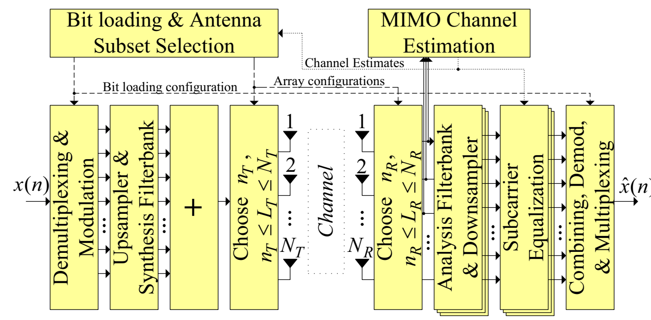

Fig. 1 Schematic of a multicarrier spatial diversity system employing bit loading and antenna subset selection.

In this paper, we present two novel loading algorithms that perform both bit allocation and antenna subset selection simultaneously for multicarrier systems employing multiple antennas in a spatial diversity configuration. The bit allocation is based on the authors' previous algorithm for single-input/single-output (SISO) multicarrier systems, which quickly provides solutions that are close to the optimal allocation [5].

2 MULTICARRIER SPATIAL DIVERSITY FRAMEWORK

A schematic of the multicarrier transceiver employing multiple antennas is shown in Fig. 1. The high-speed data stream $x(n)$ is demultiplexed into N parallel data streams of different rates, and each stream is modulated using one of several available signal constellations. The choice of subcarrier signal constellation and data rate is determined by the loading algorithm employed by the system (refer to Section 3 for details). These streams are then upsampled by a sampling factor N and filtered by one of N bandpass filters constituting the synthesis filterbank.

The outputs of the synthesis filterbank are summed together and sent out simultaneously on n_T antennas using simple transmit diversity techniques[1]. The value of n_T

[1]The total transmit power level is equivalent for all transmit antenna array configurations. If there is more than one active transmit antenna in

is constrained to be $n_T \leq L_T \leq N_T$, where N_T and L_T are the number of available transmit antennas and RF chains. As a result, the loading algorithm performs antenna subset selection by choosing n_T transmit antennas, out of N_T and L_T available antennas and RF chains, that yield the largest overall throughput. Similarly, the loading algorithm performs receive antenna subset selection by choosing n_R receive antennas yielding the largest overall throughput, where n_R is constrained to be $n_R \leq L_R \leq N_R$, given that N_R and L_R are the number of available receive antennas and RF chains.

Each analysis filterbank, corresponding to one of the n_R antennas, separates its intercepted signal into N subcarriers and downsamples it by a sampling factor N. Equalization is then performed per subcarrier to remove the distortion introduced to the transmitted signals by the multiple input/multiple output (MIMO) channel. The equalized subcarrier signals are then combined (e.g., maximum ratio combining (MRC)), followed by demodulation, and multiplexing to form the reconstructed high-speed data stream $\hat{x}(n)$. In the next section, the proposed loading algorithms used to determine the antenna subsets and the bit allocations will be presented.

3 ALGORITHM DESCRIPTION

The primary objective of the proposed algorithms is to increase the overall throughput of the system while ensuring the mean BER, $\bar{P}$, is below a specified mean BER limit, P_T. To satisfy this objective, the proposed algorithms are designed to iteratively search for the appropriate number of bits per symbol per subcarrier, $b_i, i = 0, \ldots, N-1$, and the transmit/receive antenna array configuration, s, $s \in \mathcal{S}_{\text{config}}$, where the set $\mathcal{S}_{\text{config}}$ contains all possible transmit and receive antenna configurations[2]. The secondary objective of the proposed algorithms is to use as few antennas as possible to achieve the largest possible throughput. Thus, if several array configurations in $\mathcal{S}_{\text{config}}$ achieve the same throughput, the configuration using the fewest antennas is chosen.

Mathematically, the proposed algorithms attempt to solve a two-step optimization problem, where the first step is of the form:

$$\max_{s, b_i} \sum_{i=0}^{N-1} b_i \quad (1)$$

subject to :

$$\bar{P} = \left(\sum_{i=1}^{N} b_i P_i \right) \bigg/ \left(\sum_{i=1}^{N} b_i \right) \leq P_T, \quad (2)$$

where P_i is the BER for subcarrier i, which is computed from the subcarrier signal-to-noise ratio (SNR)[3], γ_i, via closed form expressions [9][4]. Now let $\mathcal{S}_{\max}$ denote the set of transmit/receive antenna array configurations that yield the largest throughput in Eq. (1), where $\mathcal{S}_{\max} \subseteq \mathcal{S}_{\text{config}}$. The algorithms then solve the second step:

$$\min_{s \in \mathcal{S}_{\max}} (\mu_T \cdot n_T(s) + \mu_R \cdot n_R(s)) \quad (3)$$

where $0 < n_T(s) \leq L_T$ and $0 < n_R(s) \leq L_R$ are the number of active transmit and receive antennas for array configuration s, and μ_T & μ_R, where $\mu_T + \mu_R = 1$, are weights[5].

The difference between the two proposed algorithms is how the bit allocation is performed. The proposed uniform bit allocation algorithm imposes the constraint:

$$b_0 = b_1 = \cdots = b_{N-1}, \quad (4)$$

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 1. Initialization:  Compute P_i, i = 0,...,N-1, for
    all available modulation schemes and antenna
    configurations.  Choose initial values of P̂
    and δ for the iterative algorithm, where P̂ is
    the peak BER limit per subcarrier, and δ is the
    stepsize.
 2. If the largest P_i for the largest available
    signal constellation is less than P_T, set all
    subcarriers to that constellation, employ 1
    transmit antenna, employ 1 receive antenna, and
    exit algorithm, else go to Step 3.
 3. If smallest P_i for the smallest (non-zero)
    signal constellation is greater than P_T, turn
    off all subcarriers and exit algorithm, else
    proceed to Step 4.
 4. Find largest signal constellation for all
    subcarriers and antenna configurations such
    that P_i < P̂.
 5. Select the transmit/receive antenna
    configuration that yields the largest overall
    throughput (in case of a tie in the total
    number of bits, choose configuration with
    fewest overall antennas).
 6. Compute P̄ using Eq. (2).
 7. If P̄ < P_T, let P̂ = P̂ + δ, else P̂ = P̂ - δ.
 8. Find largest signal constellation for all
    subcarriers and antenna configurations such
    that P_i < P̂.
 9. Select the antenna configuration which yields
    the largest overall throughput (in case of
    a tie in the total number of bits, choose
    configuration with fewest overall antennas).
10. Compute P̄', the new value of the mean BER.
11. If both P̄ > P_T and P̄' > P_T (resp. P̄ ≤
    P_T and P̄' ≤ P_T), and no previous straddling of
    P_T, let P̄ = P̄', P̂ = P̂ - δ (resp. P̂ = P̂ + δ),
    and go to Step 8, else go to Step 12.
12. If both P̄ ≤ P_T and P̄' ≤ P_T, and P_T was
    straddled before, let P̄ = P̄', P̂ = P̂ + δ, and go
    to Step 8, else go to Step 13.
13. If both P̄ and P̄' are straddling P_T and
    the number of times this occurred is less
    than a specified amount β, reduce δ, let
    P̄ = min(P̄, P̄'), set P̂ = P̂ ± δ (the future
    P̄' should be on the same side of P_T as P̄),
    and go to Step 8.  Otherwise, finalize the
    allocation and end the algorithm.
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Fig. 2 Proposed loading algorithm employing antenna subset selection with non-uniform bit allocation.

a given configuration, the total power is divided evenly between the active antennas.

[2]The largest transmit (receive) antenna array size in $\mathcal{S}_{\text{config}}$ is constrained by the number of available transmit (receive) RF chains, L_T (L_R), which may be fewer than the number of available transmit (receive) antennas.

[3]The value of γ_i is equal to the composite SNR value due to the recombining of the different signal paths from the transmitter to the receiver. Thus, γ_i is also a function of the antenna subset configuration s.

[4]In a practical implementation, the BER values would be stored in a look-up table.

[5]Minimizing the number of transmit and receive antennas is assumed equally important, hence these weights are set to $\mu_T = \mu_R = 0.5$.

such that the signal constellations across all subcarriers are identical[6]. The proposed non-uniform bit allocation algorithm does not employ Eq. (4), resulting in additional flexibility in the bit allocation process. A detailed description of the proposed loading algorithm performing antenna subset selection with non-uniform bit allocation is shown in Fig. 2. Note that the description of Fig. 2 would be similar for the other proposed loading algorithm except that Eq. (4) would be included in Steps 5 and 9. In the next section, simulation results for multicarrier spatial diversity systems employing the two proposed loading algorithms are presented.

4 RESULTS

To evaluate the performance of the proposed algorithms, a multicarrier system based on some of the operating parameters used in the IEEE 802.11a standard are employed [10][7]. The option to null subcarriers also exists in circumstances where the prevailing channel conditions are too poor. Results from all the proposed algorithms were obtained for a target mean BER value of $P_T = 10^{-5}$. Moreover, the limit $\beta = 10$ is used in Step 13 of Fig. 2 since this gives the algorithm enough flexibility to zoom in to the final configuration.

The antenna elements employed by the arrays are $\lambda/2$ omnidirectional dipole antennas[8] placed in a uniformly-spaced linear array with adjacent antenna separation of d and oriented such that they are all perpendicular to the xy-plane, i.e., vertically polarized. The largest array configuration studied in this work possessed 3 antennas, although the proposed algorithms could be employed in systems with larger array sizes. Simple transmit diversity is employed at the transmitter while maximal ratio combining (MRC) is performed at the receiver to recombine the received signals. The physical separation between the transmitter and receiver was varied between 1 m and 60 m[9]. The MIMO channel consists of a collection of frequency-selective fading SISO channel responses generated using the method proposed by Saleh and Valenzuela [11][10]. The SISO components of the MIMO channel were assumed to be uncorrelated in most of this work since the adjacent antenna separation was set to $d = 5\lambda$. However, the effect of correlation due to antenna separation was also examined for $d = 0.25\lambda$ using the model proposed in [12]. Finally, for each MIMO channel realization, the algorithms were operating at 70 different averaged SNR values equally spaced in the logarithmic domain. The trials were repeated for 10 000 different MIMO channel realizations and the results averaged.

Figs. 3 and 4 show the throughput of multicarrier diversity systems employing the two proposed loading algorithms for different number of antennas and RF chains (in brackets). In both figures, the results indicate that the throughput increases relative to the number of antennas[11]. However, with respect to non-uniform bit allocation, the throughput results for the same antenna configurations are higher in Fig. 4 than in Fig. 3 due to the additional flexibility of the algorithm to increase throughput. Moreover, the throughput is nearly the same for ($N_T = 3(3)$, $N_R = 3(3)$) and ($N_T = 3(2)$, $N_R = 3(2)$) array configurations. Thus, for similar throughput performance, a hardware savings of 1 RF chain at each end of the transceiver is achieved (i.e., 33%). Finally, when antenna subset selection and non-uniform bit allocation is performed together, it is possible for the system to achieve a large increase in throughput[12].

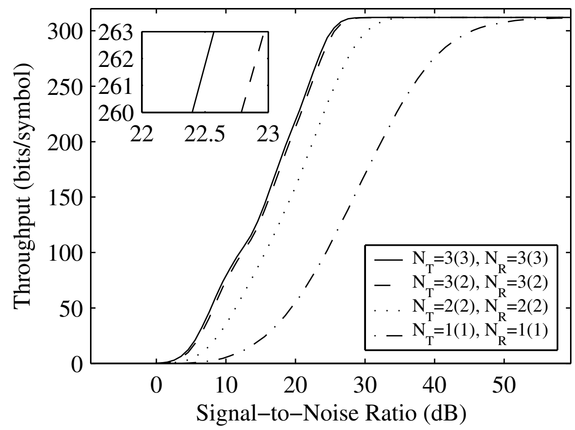

Fig. 3 Throughput results for multicarrier transceivers performing uniform bit allocation and employing antenna subset selection for different transmitter and receiver array sizes (number of available RF chains in brackets).

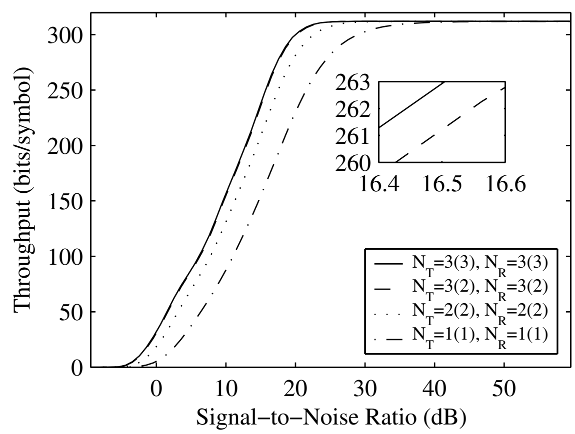

Fig. 4 Throughput results for multicarrier transceivers performing non-uniform bit allocation and employing antenna subset selection for different transmitter and receiver array sizes (number of available RF chains in brackets).

[6] This form of bit allocation is available in current standards [10].

[7] The system possesses $N = 64$ subcarriers (6 "guard subcarriers" at each end of the 16.6 MHz bandwidth), uses BPSK, QPSK, square 16-QAM, and square 64-QAM modulation, and operates at a frequency of 5 GHz.

[8] The wavelength is equal to $\lambda = 1/(5\text{ GHz}) = 0.06$ m.

[9] The change in transmitter/receiver separation distance corresponds to an SNR change ranging from 59 dB to -11 dB.

[10] The SISO components were assumed to be time-invariant, non-line-of-sight, and uncorrelated.

[11] There is a diminishing returns relationship between an increase in the number of antennas and throughput gains.

[12] At an SNR of 20 dB and an ($N_T = 2(2)$,$N_R = 2(2)$) configuration, the throughput is 82 bits/symbol when all antennas are always on and uniform bit allocation is used. However, with antenna subset selection and non-uniform bit allocation, the throughput is 280 bits/symbol.

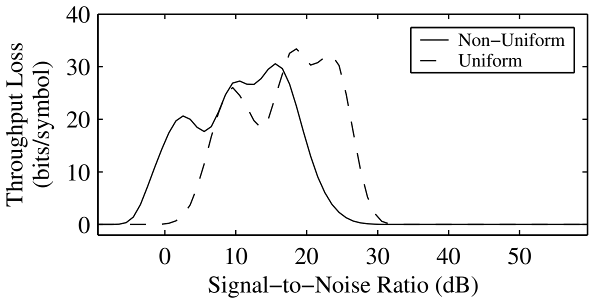

Fig. 5 Throughput loss due to correlation for multicarrier transceivers performing bit allocation & antenna subset selection. Adjacent antenna spacing is 0.25λ and the array configurations are $N_T = 3(2)$, $N_R = 3(2)$.

The loss of throughput due to closely-spaced antennas is shown in Fig. 5. Most of the loss occurs around medium-range SNR values, where the loading algorithms are trying to find the array configuration and bit allocation that yield the largest throughput. Since the antennas in the array are spaced 0.25λ apart, the correlation between them increases, reducing the effectiveness of the spatial diversity. As a result, the flexibility of the algorithms to find an appropriate solution also decreases.

Figs. 6 and 7 show the fraction of all possible (n_T,n_R) array configurations selected by the proposed loading algorithms given a system with $(N_T = 3(2), N_R = 3(2))$ antennas and RF chains. With non-uniform bit allocation, more receive antennas are used due to increased allocation flexibility, where individual subcarrier SNR values have more of an impact on the overall throughput. For instance, at an SNR of 20 dB, an array configuration of 1 transmit and 1 receive antenna was chosen 60% of the time when uniform bit allocation was employed (see Fig. 6), while the same array configuration was chosen only 15% of the time when non-uniform bit allocation was used (see Fig. 7).

5 CONCLUSION

Two novel loading algorithms for multicarrier systems, employing multiple antennas in a spatial diversity configuration, have been presented. The algorithms perform bit allocation (either uniform or non-uniform) and antenna subset selection. The results show a substantial throughput gain when the algorithms are employed by the system. Moreover, with antenna subset selection, the throughput performance remains almost the same when two thirds of the RF chains are available. Finally, non-uniform bit allocation yields a larger throughput increase at the cost of a small increase in complexity.

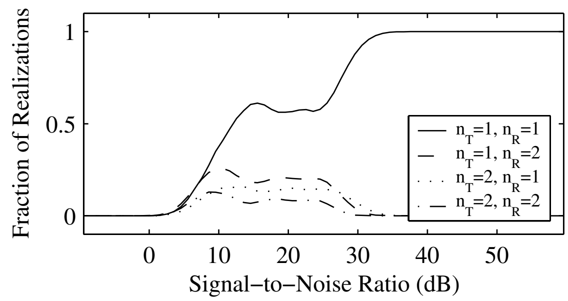

Fig. 6 Fraction of (n_T,n_R) array configurations occurring for a multicarrier transceiver performing *uniform* bit allocation and employing antenna subset selection. The transceiver has available $(N_T = 3(2), N_R = 3(2))$ antennas and RF chains.

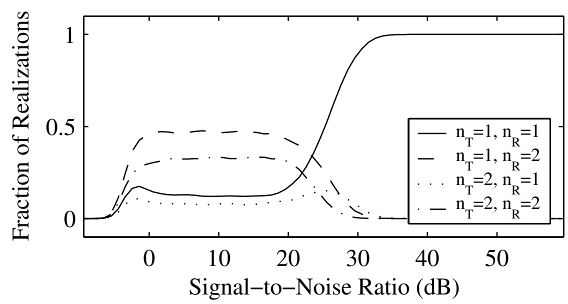

Fig. 7 Fraction of (n_T,n_R) array configurations occurring for a multicarrier transceiver performing *non-uniform* bit allocation and employing antenna subset selection. The transceiver has available $(N_T = 3(2), N_R = 3(2))$ antennas and RF chains.

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