Loading Algorithm for Multicarrier Spatial Diversity Systems with Antenna Selection

Alexander M. Wyglinski, *Member, IEEE,* Fabrice Labeau, *Senior Member, IEEE,* and Peter Kabal, *Member, IEEE*

***Abstract*— In this paper, a novel loading algorithm consisting of four variants is proposed for a multicarrier transceiver employing multiple antennas configured for spatial diversity. The primary objective of the proposed algorithm is to increase the overall throughput while ensuring the mean bit error rate (BER) is below a specified limit. To achieve this, spatial diversity is employed to improve the subcarrier signal-to-noise ratio (SNR) values. Simultaneously, (uniform or non-uniform) bit allocation, which is a function of subcarrier SNR, is performed to increase throughput. To reduce power consumption, spatial processing complexity, and hardware costs, antenna subset selection is also performed by the proposed algorithm to choose a set of active transmit/receive antennas. The results show that combining bit allocation with spatial diversity (employing antenna subset selection) can yield substantial throughput increases.**

***Index Terms*— Multicarrier modulation, bit loading, antenna selection, spatial diversity, adaptive modulation.**

I. 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], [2]. Employing multiple antennas in a *spatial diversity* configuration enhances the error robustness of the system by transmitting copies of the same signal down several uncorrelated communications paths [3]. Multicarrier modulation (MCM) is capable of transforming a frequency-selective fading channel into a collection of approximately frequency-flat subchannels [2], [4], yielding a lower implementation and computational complexity at the receiver with respect to equalization [3].

Several researchers have investigated combining conventional MCM, where the same signal constellation configuration is employed across all subcarriers, with multiple antennas configured for spatial diversity [5], [6]. Their results show that the achieved performance gains are greater than the gains offered by each individual technology. When adaptive allocation techniques, e.g., *bit allocation* [7], and multiple antennas are employed by an MCM transceiver[1] [4], the bandwidth efficiency is enhanced while an acceptable degree of link reliability is simultaneously maintained using spatial diversity [8].

Although spatial diversity can improve system error robustness, there is a point where the increase in power consumption, array processing complexity, and number of employed radio frequency (RF) chains do not justify the improvement in performance, which follows a law of diminishing returns [9]. One possible solution is *antenna subset selection* [9]–[11], where only a subset of antennas are activated due to the reduced number of RF chains. Antenna subset selection has been applied to both single carrier [9] and conventional MCM systems [5]. However, to the best of the authors' knowledge, adaptive bit allocation has never been combined with antenna subset selection. Moreover, most transceiver implementations do not perform antenna subset selection simultaneously at the transmitter and the receiver. Finally, the choice of active antenna configurations are usually constrained to be equivalent across all subcarriers, resulting in a loss of flexibility which may impact performance.

In this paper, we propose a novel loading algorithm that performs bit allocation with antenna subset selection. The proposed algorithm is based on the single input-single output (SISO) bit allocation algorithm proposed by the authors that quickly achieves a bit allocation close to the optimal solution [7]. However, unlike the authors' previous work, the primary focus of the proposed algorithm is to improve the subcarrier signal-to-noise (SNR) values by using spatial diversity combining techniques *prior to* performing the bit allocation. The rationale for this process is that the overall throughput of the system is a function of the subcarrier signal constellations, which depend on the antenna array configuration yielding the subcarrier SNR values.

Antenna subset selection is performed at both the transmitter and receiver. The proposed algorithm consists of four variants that differ with respect to their flexibility of choosing a transceiver configuration, i.e., different search space sizes[2]. Specifically, two of the variants can choose active antenna configurations that are different across the subcarriers. Moreover, two of the variants perform uniform bit allocation while the other two variants employ non-uniform bit allocation.

Manuscript received November 4, 2005; revised June 29, 2006; accepted September 26, 2006. The associate editor coordinating the review of this paper and approving it for publication was R. Mallik. This work was partially funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) and Le Fonds Nature et Technologies du Quebec. This paper was presented in parts at the 2005 IEEE Pacific Rim Conference on Communications, Computers, and Signal Processing, Victoria, BC, Canada, and the 62nd IEEE Vehicular Technology Conference, Dallas, TX, USA.

A. M. Wyglinski is with the Information and Telecommunication Technology Center, The University of Kansas, Lawrence, Kansas, USA (e-mail: alexw@ieee.org).

F. Labeau and P. Kabal are with the Department of Electrical and Computer Engineering, McGill University, Montreal, Canada (e-mail: {fabrice.labeau, peter.kabal}@mcgill.ca).

Digital Object Identifier 10.1109/TWC.2007.05884.

---

[1] The bit allocation algorithms employed by these transceivers are either based on: (i) approximations of the closed form expressions for the bit error rate (BER), which may yield solutions far from the optimal allocation, or (ii) an incremental approach, which is computationally expensive (see [7] for explanation).

[2] The more complex variants of the proposed algorithm may be impractical to implement in an actual system due to very large search spaces. Thus, they are used in this work to benchmark their potential performance improvements.

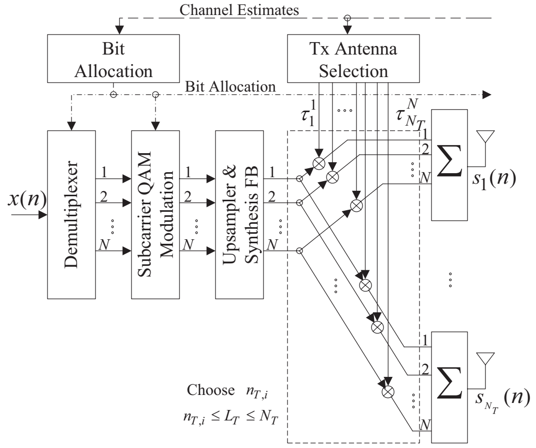
The rest of this paper is organized as follows: Section II presents a description of the multicarrier spatial diversity framework studied in this work. In Section III, we present four variants of the proposed allocation loading algorithm. The throughput results of a multicarrier spatial diversity system employing the proposed algorithm are presented in Section IV. Finally, several concluding remarks and observations are made in Section V.

II. MULTICARRIER SPATIAL DIVERSITY FRAMEWORK

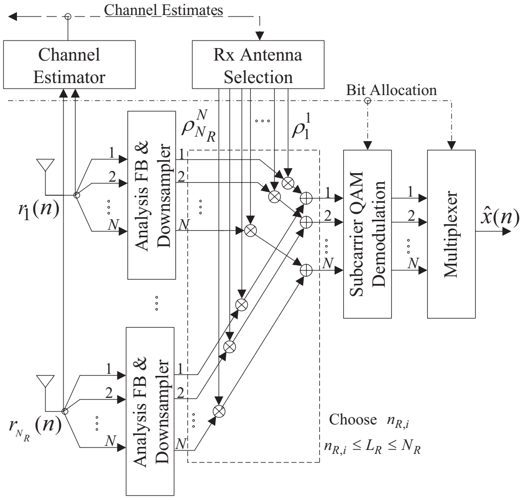
The transceiver design studied in this work is shown in Fig. 1. It combines multicarrier modulation with spatial diversity at both the transmitter and receiver, where the antenna array elements are assumed to be sufficiently far apart such that the signal paths are uncorrelated [12]. We see in Fig. 1(a) that the high-speed data stream $x(n)$ is demultiplexed into N parallel data streams of different rates. Without loss in generality, the demultiplexed data streams are then modulated using one of several available M-QAM signal constellations, although other modulation schemes can also be employed. The choice of subcarrier signal constellation and data rate is determined via *bit allocation*, also known as *bit loading* or *adaptive modulation* [7]. In this work, the bit allocation approach is based on the algorithm proposed in [7]. The subcarriers are then upsampled by a sampling factor N and filtered by one of N bandpass filters constituting the synthesis filterbank. This process modulates the subcarriers onto different center frequencies within a contiguous bandwidth.

Spatial transmit diversity [13] is then performed, with copies of the synthesis filterbank outputs sent to $n_{T,i}$ transmit antennas, for $i = 1, \ldots, N$. The allocated subcarriers at each antenna are summed together, and the composite signals from all the antennas are broadcasted simultaneously[3]. The value of $n_{T,i}$ is constrained to be $n_{T,i} \leq L_T \leq N_T$, where N_T and L_T are the number of available transmit antennas and RF chains. Transmit antenna subset selection, controlled by the proposed algorithm in Section III, is performed to determine which antennas get to transmit a specific subcarrier. Using estimates of the multiple input-multiple output (MIMO) channel, the algorithm computes the weights $\tau_i^j \in \{0, 1\}$, for $i = 1, \ldots, N_T$ and $j = 1, \ldots, N$.

Spatial receive diversity [9], [12], [14] is performed at the receiver, where the signals transmitted across the MIMO channel are intercepted by N_R receive antennas, as shown in Fig. 1(b). For each antenna, the received signal is decomposed into N subcarriers. Then, receive antenna subset selection is performed to assign real-valued combining weights ρ_i^j, for $i = 1, \ldots, N_R$ and $j = 1, \ldots, N$, to all the subcarriers from all the antennas prior to summing the corresponding subcarriers together. Since some of the weights may be equal to zero, subcarriers from $n_{R,i}$ receive antennas will be combined to form an estimate of the original subcarriers. The value of $n_{R,i}$ is constrained to be $n_{R,i} \leq L_R \leq N_R$, where N_R and L_R are the number of available receive antennas and RF chains. Equalization is then performed per subcarrier (not shown in Fig. 1(b)) to remove the distortion introduced to the transmitted signals by the MIMO channel. The equalized subcarrier signals are then demodulated and multiplexed to form the reconstructed high-speed data stream $\hat{x}(n)$.



(a) Multicarrier transmitter with multiple antennas.



(b) Multicarrier receiver with multiple antennas.

Fig. 1. Schematics of the multicarrier transmitter and receiver employing multiple antennas in a diversity configuration. Note the antenna selection and bit allocation blocks used by the system.

A. Spatial Diversity Framework

From the above description of the transceiver, we see that antenna subset selection is a combination of *antenna selection diversity* (also known as *switch diversity*), and either *equal gain combining* (EGC) or *maximal-ratio combining* (MRC), which are applied to the active antennas [9]. Therefore, the value of the SNR for subcarrier i, γ_i, for $i = 1, \ldots, N$, when multiple antennas are employed by the transceiver is equal to the composite SNR value due to the recombining of different signal paths between the transmitter and receiver. Mathematically, γ_i can be expressed as:

$$\gamma_i = \frac{\left(\frac{\pi_i}{n_T} \cdot \left| \sum_{k=1}^{N_R} \sum_{j=1}^{N_T} \rho_k^i \cdot H_{i,(j,k)}(\omega) \right|^2 \right)}{\left(\sigma_\nu^2 \cdot \sum_{k=1}^{N_R} (\rho_k^i)^2 \right)}, \qquad (1)$$

---

[3] The total transmit power level per subcarrier is equivalent for all possible transmit antenna array configurations. If there is more than one active transmit antenna in a given configuration, the total power is divided evenly between the active antennas.

TABLE I

FRAMEWORK OF THE PROPOSED LOADING ALGORITHM EMPLOYING ANTENNA SUBSET SELECTION WITH BIT ALLOCATION.

1) **Initialization**: Compute P_i, $i = 1, \ldots, N$, for all available modulation schemes and antenna configurations. Choose initial values of $\hat{P}$ and δ for the iterative algorithm, where $\hat{P}$ is the peak BER limit per subcarrier, and δ is the stepsize.
2) **Early Exit Check**: If the largest P_i for the largest available signal constellation is less than P_T, set all subcarriers to that constellation, employ one transmit antenna, employ one receive antenna, and exit algorithm, else go to Step 3.
3) **Early Exit Check**: 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) Select the subcarrier transmit/receive antenna configurations with the largest subcarrier signal constellations satisfying $P_i < \hat{P}$, for $i = 1, \ldots, N$. Specifically:
   - **Var2:** For each subcarrier, find the antenna configuration yielding the largest b_i for which $P_i \le \hat{P}$, $i = 1, \ldots, N$, and $b_1 = b_2 = \cdots = b_N$.
   - **Var3:** Determine the largest signal constellation per subcarrier per antenna configuration such that $P_i < \hat{P}$. Select the antenna configuration common to all subcarriers which yields the largest overall throughput.
   - **Var4:** Find largest signal constellation for all subcarriers and antenna configurations such that $P_i < \hat{P}$. Select antenna configuration with largest b_i, $i = 1, \ldots, N$.
5) Compute $\bar{P}$, the mean BER, using (2).
6) If $\bar{P} < P_T$, let $\hat{P} = \hat{P} + \delta$, else $\hat{P} = \hat{P} - \delta$.
7) Select the subcarrier transmit/receive antenna configurations with the largest subcarrier signal constellations satisfying $P_i < \hat{P}$, for $i = 1, \ldots, N$. Specifically:
   - **Var2:** For each subcarrier, find the antenna configuration yielding the largest b_i for which $P_i \le \hat{P}$, $i = 1, \ldots, N$, and $b_1 = b_2 = \cdots = b_N$.
   - **Var3:** Determine the largest signal constellation per subcarrier per antenna configuration such that $P_i < \hat{P}$. Select the antenna configuration common to all subcarriers which yields the largest overall throughput.
   - **Var4:** Find largest signal constellation for all subcarriers and antenna configurations such that $P_i < \hat{P}$. Select antenna configuration with largest b_i, $i = 1, \ldots, N$.
8) Compute $\bar{P}'$, the new value of the mean BER.
9) If both $\bar{P} > P_T$ and $\bar{P}' > P_T$ (resp. $\bar{P} \le P_T$ and $\bar{P}' \le P_T$), and no previous straddling of P_T, let $\bar{P} = \bar{P}'$, $\hat{P} = \hat{P} - \delta$ (resp. $\hat{P} = \hat{P} + \delta$), and go to Step 7, else go to Step 10.
10) If both $\bar{P} \le P_T$ and $\bar{P}' \le P_T$, and P_T was straddled before, let $\bar{P} = \bar{P}'$, $\hat{P} = \hat{P} + \delta$, and go to Step 7, else go to Step 11.
11) If both $\bar{P}$ and $\bar{P}'$ are straddling P_T and the number of times this occurred is less than a specified amount β, reduce δ, let $\bar{P} = \min(\bar{P}, \bar{P}')$, set $\hat{P} = \hat{P} \pm \delta$ (the future $\bar{P}'$ should be on the same side of P_T as $\bar{P}$), and go to Step 7. Otherwise, finalize the allocation and end the algorithm.

where π_i is the transmit subcarrier signal power[4], σ_ν^2 is the power of the noise $\nu(n)$, $H_{i,(t,r)}(\omega)$, are the channel frequency responses across subcarrier i due to multipath propagation between transmit antenna t and receive antenna r, and ρ_r^i, $r = 1, \ldots, N_R$ are a set of combining weights.

In the following section, the proposed algorithm will use values for γ_i, computed using (1), in order to choose an appropriate active antenna configuration, as well as a set of subcarrier signal constellations.

III. PROPOSED ALGORITHM

The primary objective of the proposed algorithm 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. Note that this approach has been used in several SISO multicarrier bit loading algorithms (see [7] and references therein). To satisfy this objective, the algorithm is designed to search for the appropriate number of bits per symbol, b_i, and the transmit/receive antenna configuration, $s_i \in \mathcal{S}_{\text{config}}$, for subcarrier i, where the set $\mathcal{S}_{\text{config}}$ contains all possible transmit and receive antenna configurations[5]. The secondary objective 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 algorithm attempts to solve a two-step optimization problem, where the first step is of the form:

$$\max_{s_i, b_i} \sum_{i=1}^{N} b_i \qquad \text{subject to} \qquad \bar{P} = \frac{\left(\sum\limits_{i=1}^{N} b_i P_i\right)}{\left(\sum\limits_{i=1}^{N} b_i\right)} \le P_T, \quad (2)$$

where P_i is the BER for subcarrier i, which is computed from the subcarrier SNR γ_i via closed form expressions [15], P_T is the mean BER limit, and b_i is the number of bits per symbol epoch for subcarrier i. Note that γ_i is a function of the antenna subset configuration s_i, as observed in (1). Now let $\mathcal{S}_{\max} \subseteq \mathcal{S}_{\text{config}}$ denote the set of antenna configurations that yield the largest throughput in (2). The algorithm then solves the second step:

$$\min_{s_i \in \mathcal{S}_{\max}} \left(\mu_{T,i} \cdot n_{T,i}(s_i) + \mu_{R,i} \cdot n_{R,i}(s_i)\right) \quad (3)$$

where $0 \le n_{T,i}(s_i) \le L_T$ and $0 \le n_{R,i}(s_i) \le L_R$ are the number of active transmit and receive antennas for antenna configuration s_i, L_T and L_R are the number of available transmit and receive RF chains, N_T and N_R are the total number of transmit and receive antennas, and $\mu_{T,i}$ & $\mu_{R,i}$ are weights such that $\mu_{T,i} + \mu_{R,i} = 1$. In this work, since minimizing the number of transmit and receive antennas is equally important, these weights are set to $\mu_{T,i} = \mu_{R,i} = 0.5$.

The proposed algorithm is presented in Table I. As mentioned previously, it has four variants that are based on how the algorithm chooses the bit assignment and antenna configuration per subcarrier, corresponding to Steps 4 and 7 in Table I. These constraints can be represented mathematically by:

$$b_1 = b_2 = \cdots = b_N, \quad (4)$$

$$s_1 = s_2 = \cdots = s_N, \quad (5)$$

---

[4] This is the subcarrier transmit power value when one active transmit antenna is employed. To satisfy regulatory requirements, each of the n_T active transmit antennas use $\frac{\pi_i}{n_T}$, such that the total power equals π_i.

[5] 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.

where (4) and (5) constrains the modulation schemes and the antenna subset configurations to be identical for all subcarriers. In particular, adaptive bit allocation algorithms that employ (4) are available in the current standards [16]. The four variants of the proposed algorithm can be defined as:

Var1: *Signal-level antenna subset selection* (i.e., employs both (4) and (5)),
Var2: *Subcarrier-level antenna subset selection* (i.e., employs only (4)),
Var3: *Signal-level antenna subset selection with non-uniform bit allocation* (i.e., employs only (5)),
Var4: *Subcarrier-level antenna subset selection with non-uniform bit allocation* (i.e., employs neither constraint).

Note that these constraints are employed to vary the level of computational complexity of the algorithm.

The proposed algorithm of Table I is described as follows: Steps 2 and 3 are performed to allow a quick exit in case it is not worth performing antenna subset selection and bit allocation. In Step 4, variants Var2, Var3, and Var4 of the algorithm all search for the transmit/receive antenna configurations that yields the largest possible throughput per subcarrier, subject to constraints. In the case of a tie for the largest possible throughput, the configuration employing the fewest antennas is chosen. Then the mean BER $\bar{P}$ is computed and the value of $\hat{P}$ is modified by an amount δ. Steps 4 and 5 are then repeated as Steps 7 and 8, using the new value of $\hat{P}$ to yield a new configuration, from which the mean BER $\bar{P}'$ is computed. The values of $\bar{P}$ and $\bar{P}'$ are compared with P_T and their relation with the mean BER threshold will determine the next steps the algorithm will perform. The algorithm stops when it has found a configuration and allocation that has maximized the throughput while satisfying $\bar{P} \leq P_T$.

Note that the proposed algorithm based on variant Var1 is substantially simplified due to the constraints (4) and (5). Thus, Steps 4 through 11 can be replaced with the following three steps:

4) Set $b_1, \cdots, b_N$ equal to the largest available subcarrier signal constellation.
5) Choose the antenna configuration common to all subcarriers for which $\bar{P} \leq P_T$ (in case of tie, choose antenna configuration with smallest total sum of antennas). If none of the configurations satisfy $\bar{P} \leq P_T$, proceed to Step 6, else exit the algorithm.
6) Reduce $b_1, \ldots, b_N$ to the number of bits used to represent the next largest available signal constellation and go to Step 5. In the case of $b_1 = b_2 = \cdots = b_N = 0$, exit the algorithm.

Regarding the choice of the final antenna configuration and bit allocation in relation to the optimal solution, the only suboptimal element of the proposed algorithm is the fact that the peak BER is employed as opposed to the mean BER. On the other hand, the rest of the algorithm is optimal, i.e., the search over all configurations. Moreover, previous studies have shown that the peak BER is very close to optimal in SISO cases [7]. As a result, it is expected that the proposed algorithm will work well, but a more in depth characterization of optimality is currently under study.

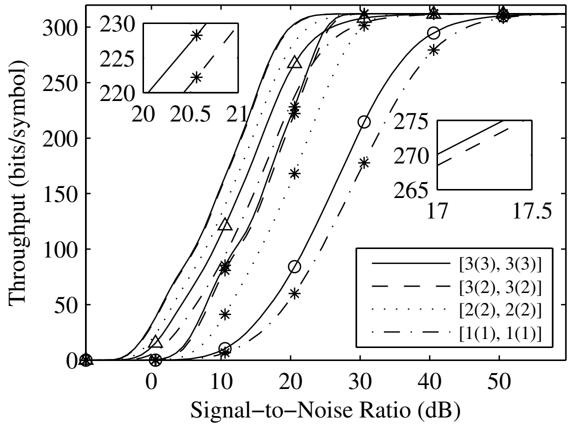


Fig. 2. Throughput results for a multicarrier spatial diversity transceiver employing uniform bit allocation with all antennas active (circle markers), non-uniform bit allocation with all antennas active (triangle markers), uniform bit allocation with antenna subset selection, i.e., variant Var1 (asterisk markers), and non-uniform bit allocation with antenna subset selection, i.e., variant Var3 (no markers). Results are for several antenna/RF chain configurations of $[N_T(L_T), N_R(L_R)]$.

IV. SIMULATION RESULTS

To evaluate the performance of the proposed algorithm, a multicarrier system based on several transceiver parameters defined in the IEEE 802.11a standard [16] are employed[6]. The target BER was specified to be $P_T = 10^{-5}$, while the limit $\beta = 10$ was used in Step 11 of Table I to give the algorithm enough flexibility to zoom in to the final configuration. The operating frequency of the system is 5 GHz, resulting in a wavelength of $\lambda = 0.06$ m, $\lambda/2$ omnidirectional dipole antennas are all perpendicular to the xy-plane, i.e., vertically polarized, and placed in a uniformly-spaced linear array with adjacent antenna separation of d. At the transmitter, the active transmit antennas all broadcast the same subcarrier signals, while MRC is performed at the receiver to recombine the intercepted signals. The physical separation between the basestation (transmitter) and mobile (receiver) was varied between 1 m and 60 m during the experiments, which corresponds to an SNR change ranging from 59 dB to -11 dB. For each of the 10 000 MIMO channel realizations generated, the algorithm was operating at 70 different averaged SNR values equally spaced in the logarithmic domain. The MIMO channel consists of a collection of SISO channel responses, which were generated using the method proposed by Saleh and Valenzuela [17], were assumed to be time-invariant with no line-of-sight existing between the transmitters and receivers. The SISO components of the MIMO channel were assumed to be uncorrelated.

The overall throughput results for a transceiver employing variants Var1 and Var3 of the proposed algorithm are shown in Fig. 2 for different numbers of antennas and RF chains (in brackets), as well as results when the transceiver employs the

---

[6] The system possesses $N = 64$ subcarriers, with six subcarriers at each end of the 16.6 MHz bandwidth turned off in order to avoid interference with adjacent bands. The available modulation schemes for each subcarrier are BPSK, QPSK, square 16-QAM, and square 64-QAM. The option to "null", or turn off, subcarriers also exists in circumstances where the prevailing channel conditions are too poor.

TABLE II

AVERAGE [TRANSMIT ANTENNA, RECEIVE ANTENNA] USAGE FOR THE FOUR VARIANTS OF THE PROPOSED ALGORITHM AT SEVERAL SNR VALUES WITH $[N_T = 2, N_R = 2]$ ANTENNAS AVAILABLE FOR SELECTION (NO LIMIT ON RF CHAINS).

SNR (dB)	Var1	Var2	Var3	Var4
14.6	[1.1713,1.2447]	[1.0024,1.0017]	[1.2370,1.5684]	[1.0583,1.0615]
24.6	[1.1611,1.2154]	[1.0006,1.0003]	[1.2337,1.4343]	[1.0010,1.0007]
34.6	[1.0470,1.0339]	[1.0000,1.0000]	[1.0490,1.0320]	[1.0000,1.0000]

approach proposed in [4], i.e., all antennas are utilized and (uniform/non-uniform) bit allocation is performed. First, we observe that the throughput increases relative to the number of antennas, and that it follows a diminishing returns relationship. However, with respect to variant Var3, the throughput results for the same antenna configurations are higher relative to variant Var1 due to the additional flexibility. Second, for the case when $[N_T = 3, N_R = 3]$, the throughput when $[L_T = 2, L_R = 2]$ is nearly the same relative to when $[L_T = 3, L_R = 3]$ for both variants. Thus, for similar throughput performance, a hardware savings of one RF chain at each end of the transceiver is achieved, i.e., 33% reduction. Finally, when compared to a transceiver that only employs all the antennas and performs uniform (non-uniform) bit allocation, transceivers employing variant Var1 (Var3) of the proposed algorithm achieve better throughput results due to the redistribution of the transmit power (see Section II-A regarding total power constraint).

Fig. 3 shows the fraction of all possible n_T and n_R array configurations selected by variant Var3 of the proposed algorithm, given a system with $[N_T = 3, N_R = 3]$ antennas and $[L_T = 2, L_R = 2]$ 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, it was determined that an array configuration of one transmit and one receive antenna was chosen 60% of the time when uniform bit allocation was employed, while the same array configuration was chosen only 15% of the time when non-uniform bit allocation was used (see Fig. 3).

The results for the average transmit and receive antenna usage by the four variants of the proposed algorithm at several SNR values are presented in Table II. The transceiver employs $N_T = 2$ transmit antennas and $N_R = 2$ receive antennas. It is observed that none of the results reach the maximum number of transmit and receive antennas. Furthermore, the variants of the proposed algorithm employing (5) possess a relatively higher usage of antennas when compared to variants not employing (5). This is due to the increased flexibility offered by the variants not employing Eq. (5) to tailor the antenna configurations to the prevailing channel conditions. As a result, these variants require fewer antennas to achieve the same performance relative to the signal-level algorithms.

V. CONCLUSION

A novel loading algorithm for multicarrier systems employing multiple antennas in a spatial diversity configuration has been presented. The algorithm, consisting of four variants, performs either uniform or non-uniform bit allocation along with antenna subset selection. Each variant of the proposed algorithm possesses a different amount of flexibility when choosing a final bit allocation and antenna configuration, resulting in a trade-off between overall throughput and system complexity. For instance, results show that an increase in algorithm complexity yields a corresponding gain in flexibility when choosing possible solutions[7]. Moreover, limiting the number of available RF chains results in a hardware savings. When employing the proposed algorithm, bit allocations and antenna configurations can be obtained that yield large throughput values even with a reduced number of RF chains. As a result, a small increase in implementation and computational complexity can yield a decrease in hardware costs in terms of RF chains.

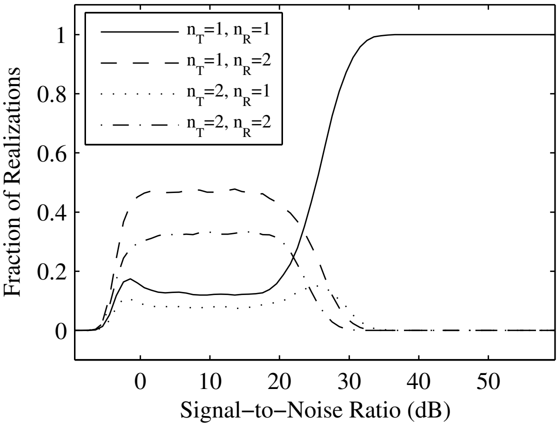


Fig. 3. Fraction of $[n_T, n_R]$ array configurations occurring for the proposed signal-level antenna subset selection employing non-uniform bit allocation. The transceiver has available $[N_T = 3, N_R = 3]$ antennas and $[L_T = 2, L_R = 2]$ RF chains.

REFERENCES

[1] S. Nanda, R. Walton, J. Ketchum, M. Wallace, and S. Howard, "A high-performance MIMO OFDM wireless LAN," *IEEE Commun. Mag.*, vol. 43, no. 2, pp. 101–109, Feb. 2005.

[2] G. L. Stuber, J. R. Barry, S. W. McLaughlin, Y. G. Li, M. A. Ingram, and T. G. Pratt, "Broadband MIMO-OFDM wireless communications," *Proc. IEEE*, vol. 92, no. 2, pp. 271–294, Feb. 2004.

[3] A. J. Paulraj, D. A. Gore, R. U. Nabar, and H. Bolcskei, "An overview of MIMO communications – a key to gigabit wireless," *Proc. IEEE*, vol. 92, no. 2, pp. 198–218, Feb. 2004.

[4] S. Thoen, L. Van der Perre, M. Engels, and H. De Man, "Adaptive loading for OFDM/SDMA-based wireless networks," *IEEE Trans. Commun.*, vol. 50, no. 11, pp. 1798–1810, Nov. 2002.

---

[7] The solution space becomes larger, resulting in solutions that are closer to the mean BER limit P_T and yielding greater throughput values.

[5] X. Ouyang, M. Ghosh, and J. P. Meehan, "Optimal antenna diversity combining for IEEE 802.11a system," *IEEE Trans. Consumer Electron.*, vol. 48, no. 3, pp. 738–742, Aug. 2002.

[6] S. Ben Slimane, "A low complexity antenna diversity receiver for OFDM based systems," in *Proc. IEEE Int. Conf. Commun.*, vol. 4, Helsinki, Finland, June 2001, pp. 1147–1151.

[7] A. M. Wyglinski, F. Labeau, and P. Kabal, "Bit loading with ber-constraint for multicarrier systems," *IEEE Trans. Wireless Commun.*, vol. 4, no. 4, pp. 1383–1387, July 2005.

[8] D. Gesbert, L. Haumonte, H. Bolcskei, R. Krishnamoorthy, and A. J. Paulraj, "Technologies and performance for non-line-of-sight broadband wireless access networks," *IEEE Commun. Mag.*, vol. 40, no. 4, pp. 86–95, Apr. 2002.

[9] A. F. Molisch and M. Z. Win, "MIMO systems with antenna selection," *IEEE Microwave*, pp. 46–56, Mar. 2004.

[10] A. Annamalai and C. Tellambura, "Analysis of hybrid selection/maximal-ratio diversity combiners with Gaussian errors," *IEEE Trans. Wireless Commun.*, vol. 1, no. 3, pp. 498–512, July 2002.

[11] M. Gharavi-Alkhansari and A. B. Gershman, "Fast antenna subset selection in MIMO systems," *IEEE Trans. Signal Processing*, vol. 52, no. 2, pp. 339–347, Feb. 2004.

[12] G. D. Durgin, *Space-Time Wireless Channels*, ser. Prentice Hall Communications Engineering and Emerging Technologies Series. Upper Saddle River, NJ: Prentice Hall, 2003.

[13] D. A. Gore, R. W. Heath, and A. J. Paulraj, "Transmit selection in spatial multiplexing systems," *IEEE Commun. Lett.*, vol. 6, no. 11, pp. 491–493, Nov. 2002.

[14] R. D. Murch and K. B. Letaief, "Antenna systems for broadband wireless access," *IEEE Commun. Mag.*, vol. 40, no. 4, pp. 76–83, Apr. 2002.

[15] J. G. Proakis, *Digital Communications*, 3rd ed. New York: McGraw-Hill, 1995.

[16] Institute of Electronics and Electrical Engineers, "Wireless LAN medium access control (MAC) and physical layer (PHY) specifications: High-speed physical layer in the 5 GHz band," IEEE Standard 802.11a, Nov. 1999.

[17] A. A. M. Saleh and R. A. Valenzuela, "A statistical model for indoor multipath propagation," *IEEE J. Sel. Areas Commun.*, vol. 5, no. 2, pp. 128–137, Feb. 1987.