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Generalized dynamic spectrum access: An order statistics design perspective

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Abstract

A new adaptive multiple access scheme based on the theory of order statistics is introduced. The proposed algorithm employs a semi-random allocation mechanism that limits subchannel selection to the highest-gain subchannels. Because the proposed low-complexity method requires relatively small channel information overhead and processing delays, it can be feasible for higher data rates where the bit duration approaches the channel coherence time. Since by its nature this method is non-iterative, it is suitable for networks with large number of users. Numerical results reveal significant system performance improvement over conventional approaches.

Keywords: Diversity; Fading channels; General order selection; Multiple access; Spectrum allocation

1. Introduction

Diversity and radio resource management are key techniques that can increase system capacity in wireless multipath environments. In many future wireless applications it is desirable to adopt distributed methods with minimum processing requirements that can efficiently and fairly allocate resources among multiple users. The burgeoning demand for mobile data networks has led to the emergence of many new wireless network technologies, such as ad hoc networks, ultra-wide-band (UWB) and wireless personal area networks (WPAN) technologies, and mesh networks (e.g., as a wireless backbone) [1,2]. An ad hoc wireless network consists of a number of self-organized mobile terminals (or nodes) that may form a temporary network without the aid of any established infrastructure [3].

Many papers have demonstrated that significant performance improvement can be achieved if adaptive subchannel allocation is exploited (see [4–10] and the citations therein). However, most of them concentrate on centralized channel allocation techniques. Moreover, most of the proposed schemes in literature concentrate on channel allocation techniques for multicarrier systems. While frequency diversity can be obtained in multicarrier transmission; power consumption, cost of electronics, and high peak-to-average power ratio (PAPR) [11] of the transmit signal are major drawbacks. This motivates us to consider an adaptive multiple access technique that processes only one subchannel from the available diversity subchannels.

It is well known that multipath fading is a main obstacle to achieving reliable communication in radio communication systems. Various widely used diversity techniques, such as selection combining (SC), equal-gain combining (EGC), maximal-ratio combining (MRC), and generalized-selection combining (GSC) are used in wireless systems to mitigate the detrimental effects of channel fading. Among these techniques, SC offers good performance with the lowest implementation complexity [12]. SC involves processing only the signal on the diversity subchannel with the highest

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gain. However, this technique is not particularly appropriate in multiple access scenarios due to the fact that the highest-gain subchannel may not be available for all users. Alternatively, in a multiple access network, we are interested in the performance of not only the user with the highest signal-to-noise ratio (SNR), but more so, those of other users. For example in [13], a multiuser scheduling scheme was proposed for the downlink of a CDMA system, in which among all K users awaiting transmission, the scheduler ranks the instantaneous channel gains of all the K users and selects the K_s users with the highest absolute and normalized gains for channel access. In [14] an iterative centralized scheduling algorithm was proposed within the framework of frequency hopping, in which each user is allocated a single subchannel. The subchannel allocation for each user is based on selecting the subchannel with the highest gain for that user. If multiple users contend for the same subchannel, then that subchannel is allocated to the user with the highest gain; and the other users are considered in subsequent iterations for subchannel contention and allocation. In such multiple access scheduling scenarios, studying the overall system performance demands for the marginal statistics of the i-th order statistic. An effective means to combat multipath fading and compensate for the unacceptable signal fades in a multiple access scenario is general order selection (GOS) [15,16]. Namely, a single subchannel is utilized from the total available diversity subchannels. With GOS, the subchannel with the i-th highest gain is selected from a set of L total subchannels ($1 \leqslant i \leqslant L$) for transmission. The selection criteria depends on, among other factors; fairness considerations, quality-of-service requirements, and design of transmission and/or reception algorithms.

In this paper, we address the subchannel allocation problem for a multiuser wireless communication network to mitigate the deleterious effects of channel fading and improve the overall received SNR. Specifically, we consider the case of dynamically allocating only a single subchannel to each user in a distributed fashion. In our proposed random order-based allocation (ROBA) algorithm, each user randomly selects an *available* subchannel from its N highest-gain subchannels for transmission (out of L possible subchannels). The term *available* implies an unoccupied subchannel (i.e., free for use) for a particular user. We derive the exact and asymptotic analytical expression for the average error rate for a network with arbitrary number of users. Because of its simple form, this expression readily allows the numerical evaluation of practical and effective subchannel allocation. Through reduced channel state information (CSI) feedback and processing delay, the proposed method will be highly desirable in high-speed communication systems.

The performance of our proposed ROBA is compared with the conventional random allocation (RA) [17,18]. In RA, each user randomly selects a single narrow-band subchannel for its transmission, from the *available* set of subchannels. It is shown that ROBA can offer significant performance improvements over RA. Moreover, we compare the performance of ROBA with an optimal exhaustive search allocation (ESA) scheme [19]. Using ESA, it is difficult to solve the overall optimization problem in real-time. Finding a real-time optimal channel allocation scheme is not a trivial task. ROBA can be looked at as a generalized allocation scheme that approaches the performance of ESA when the network is lightly loaded, and approaches that of RA when the network is heavily loaded.

The remainder of this paper is organized as follows. Section 2 describes the system model. A discussion of relevant probability density functions (pdfs) is given in Section 3. In Section 4, the ROBA algorithm is described. An expression for the exact and asymptotic bit error rate (BER) of ROBA is obtained in Section 5. Numerical results are presented in Section 6, and in Section 7, some concluding remarks are drawn.

2. System model

Consider a multiple access communication system, in which K users transmit over L subchannels, such that $K \leqslant L$. The complex baseband signal received over the i-th diversity subchannel of user k is

$$r_i^{(k)}(t) = G_i^{(k)} s^{(k)}(t) \mathrm{e}^{-\mathrm{j}\psi_i^{(k)}} + n_i^{(k)}(t), \tag{1}$$

where $s^{(k)}(t)$ is the transmitted baseband information-bearing signal of user k, $G_i^{(k)}$ is the random magnitude and $\psi_i^{(k)}$ the random phase for the i th diversity gain subchannel of user k, and $n_i^{(k)}(t)$ represents the complex additive white Gaussian noise (AWGN) with zero mean and one-sided power spectral density N_0. Without loss of generality, it suffices to consider one of the users and hence the superscript is omitted.

Let $G_1, G_2, \ldots, G_L$ be L independent, identically distributed random variables (rvs) corresponding to the subchannel gains in a diversity communication system. The corresponding subchannel SNRs are denoted by $\Gamma_1, \Gamma_2, \ldots, \Gamma_L$, with

$$\Gamma_\ell \triangleq [G_\ell]^2 E/N_0, \quad \ell = 1, 2, \ldots, L, \tag{2}$$

where E is the transmitted bit energy and N_0 is the one-sided noise power spectral density. The instantaneous SNR, Γ, on each subchannel is distributed according to an exponential distribution given by

$$f_\Gamma(\gamma) = \frac{1}{\gamma_0} \mathrm{e}^{-\gamma/\gamma_0}, \quad \gamma \geqslant 0, \tag{3}$$

where γ_0 is the average value of Γ.

3. Relevant PDF

If $G_1, \ldots, G_L$ are arranged in increasing order of their magnitudes and written as

$$G_{L:L} \leqslant \cdots \leqslant G_{1:L} \tag{4}$$

we refer to the i-th highest gain, $G_{i:L}$, as the i-th order statistic. Accordingly, the SNR of the i-th order statistic is then

$$\Gamma_{i:L} = [G_{i:L}]^2 E/N_0. \tag{5}$$

If a random sample of size L is drawn from $f_\Gamma(\gamma)$, the pdf for the i-th order statistic can be obtained using a standard result in order statistics [20] as

$$f_{\Gamma_{i:L}}(\gamma) = \frac{L!}{(L-i)!(i-1)!}[F_\Gamma(\gamma)]^{L-i} \times [1 - F_\Gamma(\gamma)]^{i-1} f_\Gamma(\gamma),$$

where $F_\Gamma(\gamma)$ is the cumulative distribution function (cdf) of Γ. For Rayleigh gain samples, by combining (3) and (6), we have

$$f_{\Gamma_{i:L}}(\gamma) = \frac{L!}{(L-i)!(i-1)!}(1 - \mathrm{e}^{-\gamma/\gamma_0})^{L-i} \times \frac{1}{\gamma_0}\mathrm{e}^{-i\gamma/\gamma_0}.$$

4. ROBA for subchannel allocation: the algorithm

In our ROBA algorithm with $K \leqslant L$ active users, the N highest-gain subchannels (out of L possible subchannels) for each user are identified as *good* candidates. Each user then selects an *available* subchannel from its N candidates for transmission. The selection across the N highest-gain subchannels is of equal chance. This randomized selection policy is adopted so as to guarantee fairness. In particular, this policy would be suited to situations where users with fixed local clock offsets from a global clock contend for network access.

We address a practical scenario where the following is taken into account: (1) the set of L subchannel gains seen by each user is different (although each user is looking at the same set of L subchannels), and hence the set of N highest-gain subchannels is different for each user, (2) the number of users accessing and/or in the network at any particular point in time is variable, and (3) the users randomly access the network without a predetermined policy.

Algorithm 1. ROBA.

```
1:   Ch ← NULL
2:   i ← [1 ... L]
3:   for all i do
4:     estimate G_i for subchannel ℂℍ(G_i)
5:   end for
6:   G_{i:L} ← Sort(G_i)
7:   i ← Permute([1 ... N])
8:   for all i do
9:     Ch ← ℂℍ(G_{i:L})
10:    if Subchannel_Available(Ch) then
11:      Transmit(Ch)
12:      BREAK
13:    end if
14:  end for
```

More specifically, our proposed ROBA algorithm pseudo-code for an arbitrary user is described in Algorithm 1. In the pseudo-code, Steps: 1 → 5 perform channel sounding, Step: 6 performs subchannel gain ordering, Step: 7 shuffles the N highest-gain subchannels, Steps: 8 → 14 select an *available* subchannel from the shuffled set of subchannels. $\mathbb{CH}(x)$ represents the subchannel with gain x, **Sort**(X) sorts vector X in descending order, **Permute**(X) generates a random permutation of vector X, **Subchannel_Available**(x) checks availability of subchannel x using a channel-sensing mechanism, and **Transmit**(x) indicates that subchannel x is selected for transmission. Subchannel x will not be available for other users accessing the network.

Consider the example in Fig. 1, we identify the $N = K = 3$ highest-gain subchannels for each user as *good* candidates. Each user then selects an *available* subchannel from its N candidates. In the shown example, user 1 selects subchannel 3 as $G^{(1)}_{3:6}$, user 2 selects subchannel 1 as $G^{(2)}_{1:6}$, and user 3 selects subchannel 4 as $G^{(3)}_{3:6}$, where $G^{(k)}_{i:L}$ denotes the i-th highest gain out of L subchannels of user k. This selection policy across the N candidates is an effective method which allows subchannels to be efficiently utilized, since a subchannel is not considered for selection only if it appears to be in deep fade for all users (i.e., subchannels 2 and 5 in the shown example).

This new ROBA algorithm eliminates the need for a centralized controller. Each user allocates its subchannel in a distributed fashion based only on knowledge of its local channel conditions and instantaneous channel measurements. Since by its nature this method is non-iterative, it is suitable for networks with large number of subchannels and large number of users. The amount of overhead and processing delays involved in selecting the favorable subchannel is low. This makes ROBA highly desirable for delay-constrained applications that can demand high data rates in fast-varying communication channels.

4.1. A note on subchannel selection

The subchannel selection is assumed to be done at discrete instants of time $t = nT$, where T is the selection period. This can be accommodated by introducing a short guard interval every selection period, during which the receiver performs channel estimations and necessary comparisons for subchannel selection. To avoid the frequent selection operation between subchannels, we assume that the receiver updates the subchannel selection only during this guard

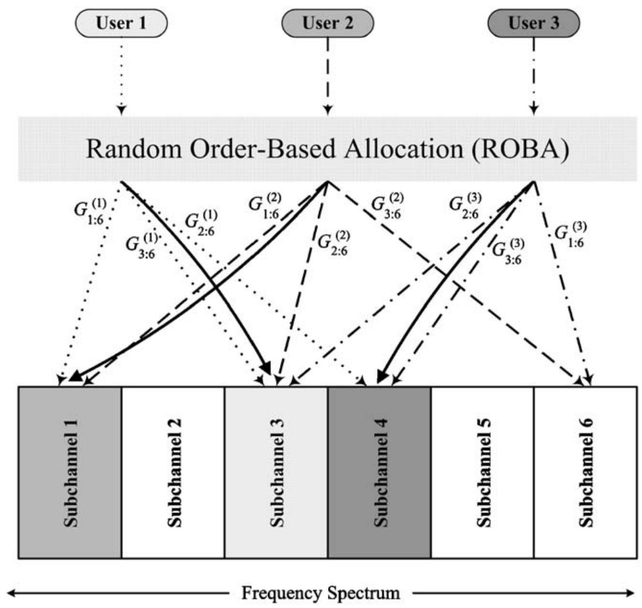

Fig. 1. ROBA for $K=3$, $L=6$, and $N=K$. Each user randomly transmits to an *available* subchannel selected among its N *good* candidates (N highest-gain subchannels), via a distributed mechanism and based on instantaneous end-to-end channel conditions. The N candidates for each user are shown as dotted, dashed, or dotted/dashed arrows. The subchannel used for transmission by each user is indicated as solid arrow.

interval before each data burst, and that the length of the data burst is of the order of the channel coherence time.

4.2. A note on channel estimation and overhead complexity

Note that the ROBA algorithm bears similar overhead complexity as the conventional RA algorithm. For both ROBA and RA, users have knowledge of subchannel availability via a carrier-sensing mechanism. Note that both ROBA and RA need CSI at the receiver to enable coherent demodulation. It follows therefore, that both schemes will need to have some mechanism for allocating resources for channel sounding/training, and therefore, will have similar overheads. There will be some difference in the actual training waveform, due to the fact that ROBA needs to sound in all subchannels (i.e., it needs a wide-band signal), whereas RA only needs to sound in a single narrow-band subchannel. However, this will not result in any difference in overhead. The only difference arises in the increased number of subchannel estimates needed to be calculated by the ROBA receiver. However, for both schemes, the receiver only feeds back the index of the selected subchannel to the transmitter. Furthermore, because of the distributed non-coordinated (no communication among users) and non-iterative nature of the GOSA algorithm, the amount of overhead and processing delays involved in selecting the favorable subchannel is low.

5. Exact and asymptotic BER evaluation of ROBA algorithm

Based on the ROBA procedure outlined in Section 4, the subchannel assignment across the N highest-gain subchannels is of uniform distribution. Hence, we find that the BER for the ROBA algorithm, P_{ROBA}, can be expressed in terms of $P_{i:L}$ and is calculated as

$$P_{\mathrm{ROBA}} = \frac{1}{N}\sum_{i=1}^{N} P_{i:L}, \tag{6}$$

where $P_{i:L}$ is the average error probability when transmitting on the i-th highest-gain subchannel out of L subchannels over an AWGN channel. The choice of N significantly affects the system performance. For example, we find that a larger value of N will result in a higher BER, since weaker subchannel gains are considered in the selection process. To guarantee subchannel availability for all users, N is lower bounded by the number of users, K, in the network.

It follows that the average error probability when transmitting on the subchannel with the i-th highest gain (out of L subchannels), denoted by $P_{i:L}$, can be calculated as

$$P_{i:L} = \int_0^{\infty} P(e|\gamma) f_{\Gamma_{i:L}}(\gamma)\,\mathrm{d}\gamma, \tag{7}$$

where the conditional error probability for BPSK is given in terms of the standard Q-function as

$$P(e|\gamma) = Q(\sqrt{2\gamma}). \tag{8}$$

Substituting (6) and (8) in (7), we get

$$P_{i:L} = \frac{L!}{2(L-i)!(i-1)!}\sum_{j=0}^{L-i}\frac{(-1)^j}{i+j}\binom{L-i}{j} \times \left[1-\sqrt{\frac{\gamma_0}{\gamma_0+i+j}}\right]. \tag{9}$$

Finally, the BER of ROBA is found by substituting (9) into (6). The optimum value of N for minimum BER can be obtained by formalizing the optimization problem:

$$\begin{aligned} &\underset{N}{\text{minimize}} && P_{\mathrm{ROBA}} \\ &\text{subject to} && K \leqslant N \leqslant L. \end{aligned}$$

Since by definition $P_{i:L}$ is monotonically increasing with i, it follows that P_{ROBA} is a monotonically increasing function with N. The minimum of a monotonically increasing function is achieved at the lower bound of its constraints. Hence, the optimal choice for N to minimize P_{ROBA} is K.

At high SNR, it is possible to take the Taylor series expansion of (6) and use the dominating term to give an expression for P_{ROBA} as $\gamma_0 \to \infty$, as follows

$$P_{\text{ROBA}}^{\infty} = \frac{L![2(L-K+1)-1]!}{2^{2(L-K+1)}(L-K)!K!(L-K+1)!} \times \gamma_0^{-(L-K+1)} + o(\gamma_0^{-(L-K+1)}) \quad (10)$$

where we write $f(x) = o[g(x)]$, $x \to x_0$, if $\lim_{x\to x_0} f(x)/g(x) = 0$. It is clearly shown that an asymptotic diversity order of $L-K+1$ is achieved at high SNR, which reveals the impact of the number of channels and the number of users on the system error performance. For every unit increase in the number of users K, the diversity order decreases by one unit.

The error performance of RA is included for comparison. In this case, subchannel selection is across all the available subchannels and the selection across the L subchannels is of equal chance. We find that the BER expression for RA is independent of the number of users, K, and may readily be obtained as a function of $P_{i:L}$ as

$$P_{\text{RA}} = \frac{1}{L}\sum_{i=1}^{L} P_{i:L}. \quad (11)$$

In this case, we can show that (11) reduces to

$$P_{\text{RA}}^{\infty} = \tfrac{1}{4}\gamma_0^{-1} + o(\gamma_0^{-1}) \quad (12)$$

at high SNR. A comparison between (10) and (12) clearly indicates the diversity advantage of ROBA over RA for $K < L$. For $K = 1$ (i.e., SC), we find that (10) reduces to

$$P_{\text{ROBA}}^{\infty} = \frac{(2L-1)!}{2^{2L}(L-1)!}\gamma_0^{-L} + o(\gamma_0^{-L}) \quad (13)$$

and for a fully loaded system where $L = K$, we find that (10) reduces to (12). Note that RA and ESA are two extremes of compromise between performance quality and complexity. On the other hand, ROBA is upper and lower bounded by those of RA and ESA, respectively. The asymptotic performance in (10) stands for a generalization of SC, which can be explained by the fact that for $K = 1$, ROBA converges to SC (or equivalently ESA) and for $K = L$, ROBA converges to RA.

6. Numerical results

The BER performance of ROBA is compared with RA in Fig. 2 for BPSK modulation. The curves are plotted using (6) and (11) for an average SNR of $\gamma_0 = 2$ and 8 dB assuming that $N = K$ and the $L = 16$ subchannels undergo independent Rayleigh fading. The results show that ROBA can provide a much lower BER than RA over a wide range of number of users. Computer simulation for ROBA is obtained in order to ascertain the accuracy of the analysis and is shown in ×'s. It can be seen that simulation agrees closely with the analytic result.

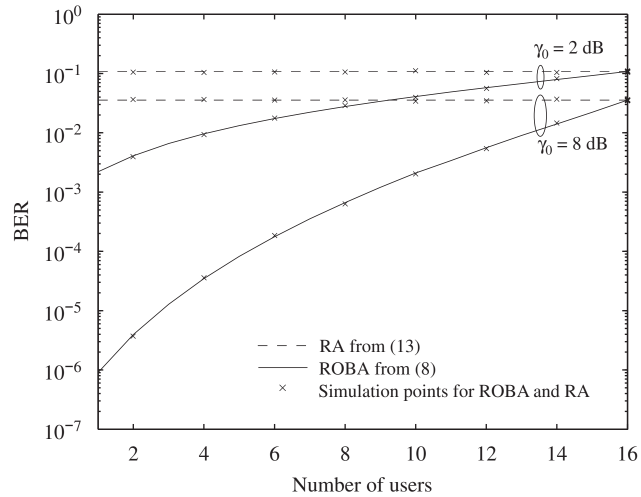

Fig. 2. Performance comparison of ROBA and RA for $\gamma_0 = 2$, 8 dB and $L = 16$ subchannels, for BPSK.

It is shown in Fig. 2 that for higher SNR values, ROBA results in a substantial decrease in BER for a lightly loaded network compared to RA. For example when $K = 4$ users, the performance difference is roughly 10-fold and 1000-fold when operating at $\gamma_0 = 2$ and 8 dB, respectively. When $K = 8$ users, the performance difference is roughly 3-fold and 100-fold when operating at $\gamma_0 = 2$ and 8 dB, respectively. The performance difference is less significant for a heavily loaded network. For example when $K = 12$ users, the performance difference is roughly 2-fold and 10-fold when operating at $\gamma_0 = 2$ and 8 dB, respectively. Eventually, the performance of ROBA converges to that of RA when the network is fully loaded.

To compare the performance of ROBA with an optimal allocation scheme, ESA is considered. ESA examines all possible $L!/(L-K)!$ subchannel allocation permutations across all users and selects the one that offers the lowest BER. Although unpractical, ESA serves as a performance benchmark. Note in Fig. 3 how the BER of ROBA approaches that of ESA when the network is lightly loaded. This can be explained by the fact that only the higher order subchannel gains (i.e., stronger) are considered. The performance difference between ROBA and ESA increases with the number of users. Naturally, this is what we expect since larger K implies that there is a higher chance that lower order subchannel gains (i.e., weaker) are considered. We also find that ROBA performs close to ESA for lower SNR values over a wide range of number of users.

From the standpoint of complexity, we find that ROBA efficiently utilizes the channel by using a distributed non-iterative channel sounding process based on knowledge of subchannel gains for each user independent of all other users. For each user, the algorithm performs L channel soundings per transmission. On the other hand, ESA is a centralized approach which requires knowledge of overall

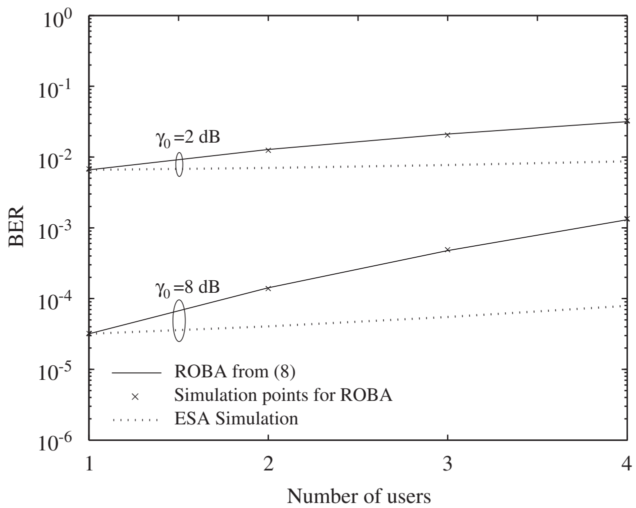

Fig. 3. Performance comparison of ROBA and ESA for $\gamma_0 = 2$, 8 dB and $L = 8$ subchannels, for BPSK.

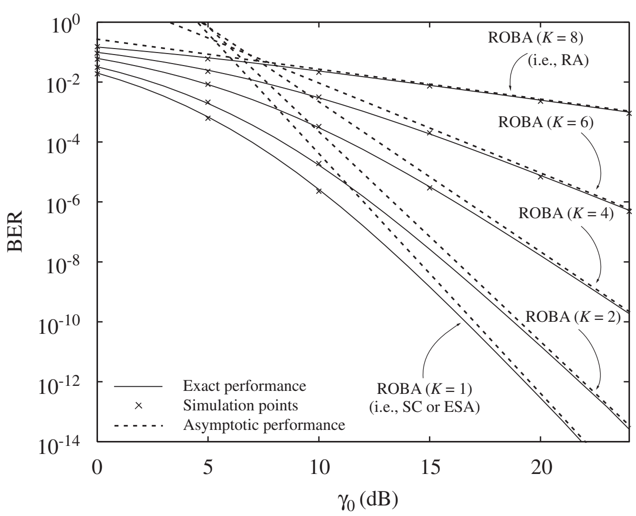

Fig. 4. Performance comparison of the exact and asymptotic expressions for $K = 1$, 2, 4, 6, 8 users and $L = 8$ subchannels, for BPSK.

BER for each of the different subchannel allocation permutations per transmission. This requires $L!/(L-K)!$ channel soundings per transmission which becomes difficult to realize in high-speed communications applications, particularly when the number of users is large. Moreover, system delay should be taken into account. The time taken for ESA to perform subchannel selection must be less than the channel coherence time which can be difficult to achieve.

Fig. 4 presents performance of ROBA for the case of $L=8$ subchannels. We provide comparison of the exact analytical expression in (6), the asymptotic analytical expression in (10), and the simulation for a network with $K=1$, 2, 4, 6, and 8 users. The figure clearly shows that the analytical results match the simulations. It also indicates that (10) asymptotically approaches (6), which is a tight bound of (6) at high SNRs. The same observation applies to the RA case.

7. Conclusions

ROBA was proposed as a new decentralized dynamic channel allocation method. Because the proposed method is practical in the sense that it requires relatively small processing delays and minimal channel information overhead, it will be highly desirable in delay-constrained applications that can demand high data rates in fast-varying environments. The analysis and computer simulation show that ROBA can provide a much lower BER than RA over a wide range of SNR and number of users. The performance of ROBA is compared with the optimal ESA method. We find that ROBA can perform close to ESA but with significantly less computational burden. Our proposed algorithm is a generalized allocation method that can be viewed at one extreme as optimal allocation (i.e., ESA) when $K = 1$, and at the other extreme as RA when $K = L$. Devising wireless networks that dynamically adapt to the wireless channel conditions without external means, in a distributed manner, similarly to the idea presented in this work, is an important and fruitful area for future research. ROBA will be a good candidate for future wireless local area networks and wireless ad hoc and sensor networks.

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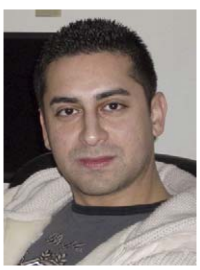
References

[1] Gharavi H. Multichannel mobile ad hoc links for multimedia communications. IEEE Proc 2008;96(1):77–96.
[2] He J, Yang K, Guild K, Chen H-H. Application of IEEE 802.16 mesh networks as the backhaul of multihop cellular networks. IEEE Commun Mag 2007;45(9):82–90.
[3] Conti M, Giordano S. Multihop ad hoc networking: the theory. IEEE Commun Mag 2007;45(4):78–86.
[4] Duel-Hallen A, Hallen H, Yang T-S. Long range prediction and reduced feedback for mobile radio adaptive OFDM systems. IEEE Trans Wireless Commun 2006;5(10):2723–33.
[5] Rong Y, Vorobyov SA, Gershman AB. Adaptive OFDM techniques with one-bit-per-subcarrier channel-state feedback. IEEE Trans Commun 2006;54(11):1993–2003.
[6] Sternad M, Svensson T, Ottosson T, Ahlen A, Svensson A, Brunstrom A. Towards systems beyond 3G based on adaptive OFDMA transmission. IEEE Proc 2007;95(12):2432–55.
[7] Yucek T, Arslan H. MMSE noise plus interference power estimation in adaptive OFDM systems. IEEE Trans Veh Technol 2007;56(6):3857–63.
[8] Xergias S, Passas N, Salkintzis AK. Centralized resource allocation for multimedia traffic in IEEE 802.16 mesh networks. IEEE Proc 2008;96(1):54–63.
[9] Qu Q, Milstein LB, Vaman DR. Cognitive radio based multi-user resource allocation in mobile ad hoc networks using multi-carrier CDMA modulation. IEEE J Select Areas Commun 2008;26(1):70–82.

[10] Jia J, Zhang Q, Shen X. HC-MAC: a hardware-constrained cognitive MAC for efficient spectrum management. IEEE J Select Areas Commun 2008;26(1):106–17.
[11] Ghassemi A, Gulliver TA. Partial selective mapping OFDM with low complexity IFFTs. IEEE Commun Lett 2008;12(1): 4–6.
[12] Brennan D. Linear diversity combining techniques. In: Proceedings of the IRE, vol. 47, June 1959. p. 1075–102.
[13] Ma Y, Jin J, Zhao L. Channel capacity and fairness of SNR-ranking-based parallel multiuser scheduling. In: Proceedings of the IEEE Global Communications Conference (Globecom), San Francisco, CA, November 2006. p. 1–5.
[14] Elkashlan M, Leung C, Schober R. Performance analysis of channel aware frequency hopping. IEE Proc Commun 2006;153(6):841–5.
[15] Elkashlan M, Khattab T, Leung C, Schober R. Statistics of general order selection in correlated Nakagami fading channels. IEEE Trans Commun 2008;56(3):344–6.
[16] Elkashlan M, Leung C, Schober R. Error performance of general order selection in correlated Nakagami fading channels. IET Commun 2008;2(7):928–34.
[17] Skalli H, Ghosh S, Das SK, Lenzini L, Conti M. Channel assignment strategies for multiradio wireless mesh networks: issues and solutions. IEEE Commun Mag 2007;45(11): 86–95.
[18] Wieselthier JE, Nguyen GD, Ephremides A. A group-division multiple access framework for channel access to multiple destinations. J Ad Hoc Networks 2008;6(5):770–90.
[19] Kulkarni G, Adlakha S, Srivastava M. Subcarrier allocation and bit loading algorithms for OFDMA-based wireless networks. IEEE Trans Mobile Comput 2005;12:652–62.
[20] David HA, Nagaraja HN. Order statistics. 3rd ed., Hoboken, NJ: Wiley; 2003.



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