PAPER

Decentralized Dynamic Sub-Carrier Assignment for OFDMA-Based Adhoc and Cellular Networks*

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SUMMARY In this paper, a novel decentralised dynamic sub-carrier assignment (DSA) algorithm for orthogonal frequency division multiple access (OFDMA)-based adhoc and cellular networks operating in time division duplexing (TDD) mode is proposed to solve the hidden and exposed node problem in media access control (MAC). This method reduces the co-channel interference (CCI), and thus increases the overall throughput of the network. Reduced CCI and increased throughput can be achieved, if time and frequency selectivity of the multi-path fading channel and the channel reciprocity offered by the TDD are fully exploited. The time and frequency selectivity of the channel are usually the main problem in mobile communication. However, in the context of channel assignment for OFDMA-based networks in TDD mode, the time and frequency selectivity of the channel are the key to reduce the interference. In the proposed channel assignment mechanism, several clusters of sub-carriers are assigned for data transmission between a transmitter and a receiver only if the corresponding channels of those sub-carriers linking this transmitter to potential victim receivers are deeply faded. In addition, the proposed algorithm works in a fully decentralised fashion and, therefore, it is able to effectively support ad hoc and multihop communication as well as network self-organisation. Numerical results show that the throughput obtained by the proposed approach for a given quality of service is higher than those of the conventional methods in any precondition of adhoc geographic scenario.

key words: *decentralized dynamic sub-carrier assignment, MAC protocol, OFDMA/TDD, adhoc and cellular networks*

1. Introduction

A major challenge in designing MAC protocol for multi-hop communications is the hidden node problem, which is addressed in [1]. This problem occurs, when a node is in the range of the receiver, but not in the range of the transmitter. Since the hidden node is out of the range of the transmitter, it is not able to sense the out-going transmission. If this node is not properly notified, its communication with other nodes will degrade the network performance. Similarly, an exposed terminal is a node which is in the range of the transmitter, but not in the range of the receiver [2]. This node may transmit at the same time as the other transmitters do without causing a network performance degradation. But its transmission will be blocked by the traditional carrier sense multiple acces (CSMA) mechanism to prevent the channel collision. Consequently, the network capacity will be decreased. In IEEE 802.11 MAC scheme [3], the RTS/CTS dialogue is applied to reduce the effects of those problems. Analysis and development for RTS/CTS mechanism are carried out in many research works, e.g. [4], [5]. However, most of previous works focused on single carrier systems, and MAC layer is still transparent to the physical layer. In other words, the information from physical layer is not used in the MAC layer for a possible cross-layer optimization.

Recently, orthogonal frequency division multiplexing (OFDM) has been intensively investigated for wireless data transmission in broadband cellular and adhoc networks. The multiple access technique for those networks is OFDMA [6]. The concept of this technique is to assign different users to different sub-carriers for avoiding interference.

In broadband OFDMA networks with 100% frequency-reuse, such as in IEEE 802.16 standard, the CCI is a major problem. This is because all users in all cells have to use the same carrier frequency. Suppose that a terminal is receiving data, while another node at the same time and using the same sub-carriers, but in the neighbor cell, is transmitting. In that situation, the CCI will be introduced. The transmitter causing CCI is, actually, a hidden node. Thus, the hidden node problem remains a challenge in designing a MAC mechanism for OFDMA networks with full frequency-reuse. The exposed node problem can arise, if the channel sensing by listening to the signal power from other transmiting nodes is applied.

In this paper, a channel assignment mechanism for OFDMA/TDD networks is proposed. The CCI, namely the hidden node problem, can be mitigated by applying a concept of busy signal for sensing the channel. The busy signal is an in-band short signal, which is sent out by a receiver after successfully receiving a data packet. The busy signal is broadcasted only from the sub-carriers, which should be preserved to continue the current communication. Based on the received busy tone signal, the hidden node (or an intending transmitter) can make a decision whether it starts transmitting data or refrains from the networks. The proposed algorithm works fully in decentralized mechanism, and thus

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can be applied to both adhoc and cellular networks. The initial idea to use the busy signal concept for a multi-carrier system is described in [8]. This concept with an interference aware MAC structure is carefully considered for a cellular OFDMA/TDD networks in [9]. In our previous work however, the threshold optimization issue is not studied in depth. This paper presents a complete description for the proposed approach. Condition for selecting the threshold is given. Application of the proposed mechanism for both cellular and adhoc network are investigated.

The paper is organized as follows: In Sect. 2, conventional sub-carrier assignment methods are briefly described. Section 3 is dedicated to the description of the proposed DSA algorithm. The selection of an important parameter for the proposed method is discussed in Sect. 4. Cellular and adhoc scenarios setup and simulation results are presented in Sects. 5 and 6. Finally, conclusions are provided in Sect. 7.

2. Review of Several Traditional Sub-Carriers Allocation Methods

2.1 OFDM-FDMA Fixed Allocation

The OFDM-FDMA fixed allocation method for multiuser communications is proposed in [6], where different users are assigned to different sub-carriers and the assigned sub-carriers for each user are maintained for the whole time the user remains active. Therefore, this scheme offers neither adaptiveness nor interference avoidance mechanism.

2.2 OFDM-FDMA Random Allocation

In the OFDM-FDMA random allocation method, a new user randomly selects a required number of sub-carriers from the available resource. However, it does not pay any attention to the current active users from the neighbor cells. After selection, the user starts transmitting on the selected sub-carriers. Nevertheless, only the selected sub-carriers, which ensures the required QoS, are maintained for the next MAC-frame of communication. Thus, it offers an adaptive mechanism but no interference avoidance in this approach.

3. Proposed DSA Algorithm

In an OFDMA/TDD network with 100% frequency reuse, the fixed channel assignment (FCA) algorithm provides poor throughput performance because of high CCI, especially when the offered traffic load of the network is high. This is because, the CCI is not taken into account in the resource assignment process, i.e. at the MAC protocol level. A simple scenario consisting of two base stations (BSs) and three mobile stations (MSs) is depicted in Fig. 1 in order to illustrate the problem. As an example, let us assume the following scenario. The mobile stations MS_1^{Rx} and MS_3^{Rx} receive data from the base station BS_1^{Tx}, while at the same time the mobile station MS_2^{Tx} transmits its data to the base station BS_2^{Rx}. In this scenario, MS_2^{Tx} causes CCI to MS_1^{Rx}

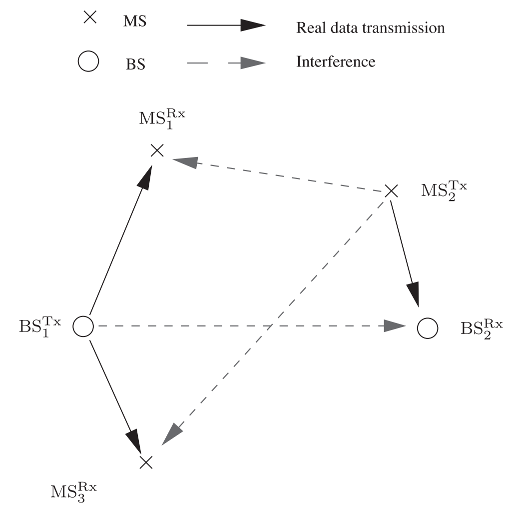

Fig. 1 Co-channel interference in OFDM/TDD networks with 100% frequency reuse.

and MS_3^{Rx}; the base station BS_1^{Tx} causes CCI to the base station BS_2^{Rx}. To reduce the CCI of the network, a new concept of decentralized DSA for OFDMA/TDD is proposed as shown in Fig. 2. In this channel assignment strategy, the transmitter, before sending data, must find suitable sub-carriers which do not cause significant interference to the other network participants. As it is known, in a multi-path transmission environment, the channel is usually frequency selective. This selectivity of the channel can be exploited to find such sub-carriers mentioned above. In the scenario illustrated in Fig. 2, we assume that the mobile stations MS_1^{Rx}, MS_2^{Tx} and MS_3^{Rx} enter the network one after another at the time instants t_1, t_2 and t_3, respectively. The mobile station MS_1^{Rx} requests the base station BS_1^{Tx} to transmit its data, but before BS_1^{Tx} can send data to MS_1^{Rx}, it must find a set of sub-carriers which do not disturb the other receivers significantly.

In order to enable the base station BS_1^{Tx} to fulfill such a requirement to connect to MS_1^{Rx}, the other receivers (excluding MS_1^{Rx}) have to broadcast the busy tone at the time instant t_1 to reserve sub-carriers for the next data transmissions. At the time instant t_1, the base station BS_1^{Tx} receives the busy tone transmitted from some other receivers. The received busy tone power will be compared with a given threshold in order to find which clusters of sub-carriers receive the busy tone below the threshold (assume clusters #n and #m in the example). These clusters of sub-carriers are selected for data transmission between BS_1^{Tx} and MS_1^{Rx}. This is because the connections (channel path gain) on these sub-carriers from BS_1^{Tx} to other receivers are strongly attenuated. Similarly, the mobile station MS_2^{Tx} has to find clusters of sub-carriers for the data transmission with BS_2^{Rx}, and in the time instant t_3 the base station BS_1^{Tx} has again to find also clusters of sub-carriers for the data transmission with MS_1^{Rx} and so forth. The sub-carriers are therefore dynamically assigned for each transmission based on the frequency selectivity of the received busy tone. Thereby, the channel reciprocity in-

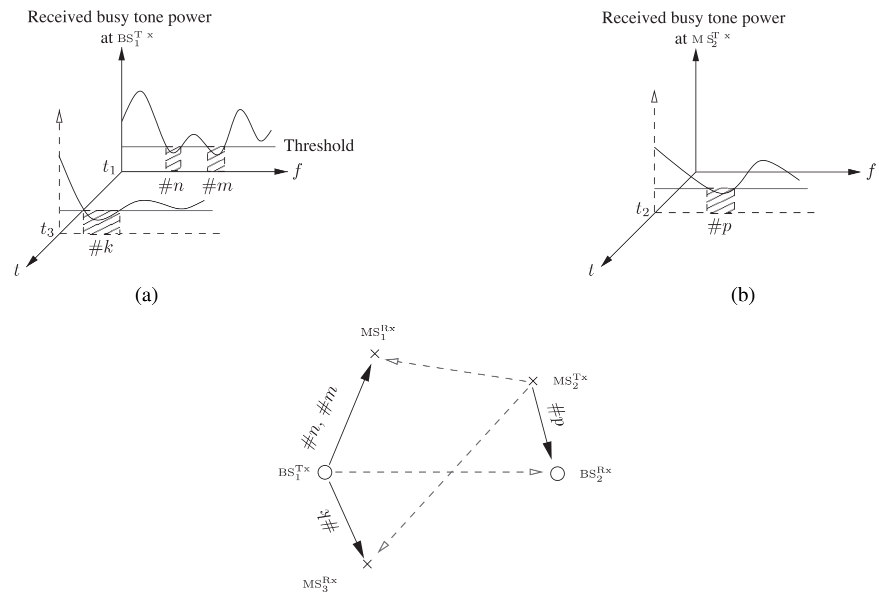

Fig. 2 Concept of the decentralised DCA for OFDM/TDD networks with 100% frequency reuse.

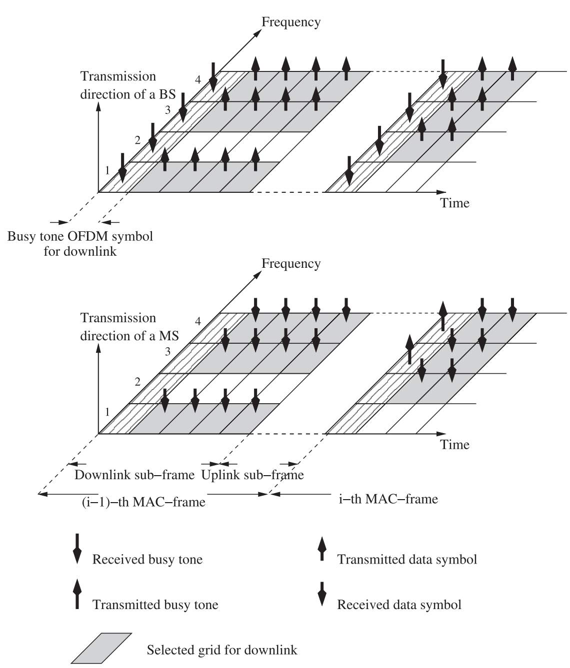

Fig. 3 MAC-Frame structure for the proposed algorithm.

herent to TDD is constructively exploited. In the context of hidden node problem, the transmitter MS_2^{Tx} could be in the 'range' of the receiver MS_1^{Rx} or MS_3^{Rx}, similarly to BS_1^{Tx} in connection with BS_2^{Rx}. The meaning of the 'range' in this paper relates not only to the spatial domain, but also to the time and the frequency domain. The 'range' of the receiver is defined as the areas where the intending transmitter can hear the busy signal, which is sent out from this receiver.

In order to incorporate the busy tone in a OFDMA/TDD network, we propose a MAC-frame structure depicted in Fig. 3. The upper part of this illustration shows a MAC frame of a node that is firstly active in Tx mode, then in Rx mode. In the context of a cellular network, the upper part is considered as the MAC-frame of a BS, the lower one is of a MS. Each MAC-frame consists of two Sub-MAC frames for two opposite directions of transmission (downlink and uplink). A Sub-MAC frame is composed by a header for transmitting or receiving the busy signal, and a number of OFDM data symbols. The header of each Sub-MAC frame is simply a time slot of an OFDM symbol. If the network is perfectly synchronized, then there will be no interference raised by the transmitting busy signal to the useful data symbol. To simplify the network analysis, perfect synchronization is assumed in this work.

The proposed algorithm is based on two main steps which are illustrated in Fig. 4. This algorithm is described in the following.

1) **Link initialization:** To simplify the explanation of the initialization process, we make an example illustrated in Fig. 3. This example is valid for both cellular and ad-hoc network, even the communication node is named in the following a BS or MS. It is assumed that the *m*th BS wants to set-up a link to the *k*th MS in the $(i-2)$th MAC frame, i.e. the transmission request arrival is at a random time position in the $(i-2)$th MAC frame, and it is, therefore, not guaranteed that the busy-channel can be heard during this MAC frame period. Therefore, the BS has to delay its transmission until the next MAC-frame, i.e. the $(i-1)$th MAC frame when it gets the first proper chance to listen to the busy-channel. The received busy tone in the header of the $(i-1)$th MAC is compared with a predetermined threshold as explained in Fig. 2. It is assumed that the received busy-signal power of some sub-carriers falls below the threshold

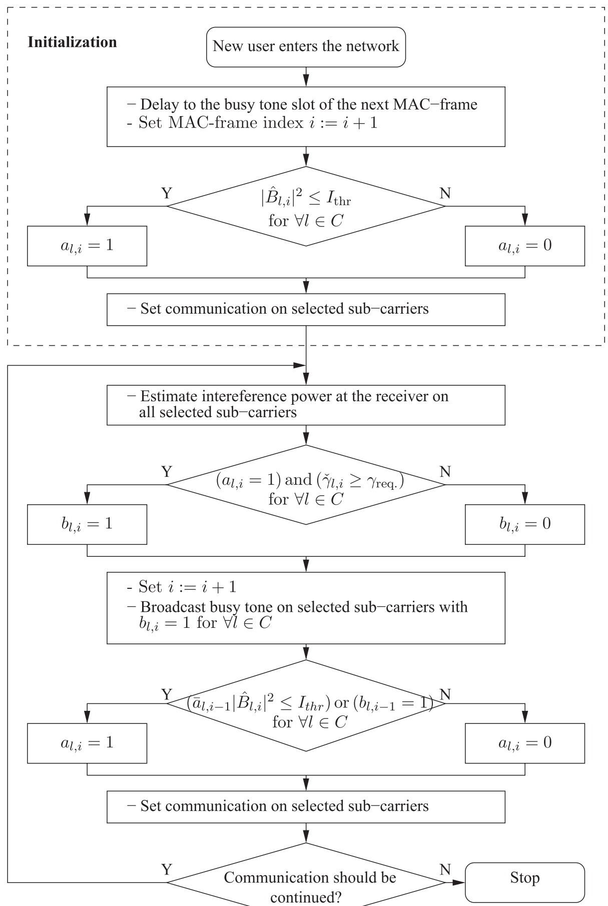

Fig. 4 Flow chart of the proposed DSA algorithm.

(first, third and fourth sub-carrier in the example of Fig. 3) which are subsequently selected for data transmission. This means that the mth BS starts transmitting data to the kth MS on these sub-carriers. The kth MS determines the signal-to-interference plus noise ratio (SINR) on each of these sub-carriers. Based on the QoS requirement for that particular transmission it will decide whether to reserve the respective sub-carrier, or whether to 'release' it. In the latter case it would not transmit the busy-signal on that corresponding sub-carrier, whereas in the former case it would reserve the respective sub-carrier by 'protecting' it using the busy-signal. Note that the SINR at a particular sub-carrier might be low either because the channel of this sub-carrier on the desired link is deeply faded, or because there is high interference resulting from other transmissions. The requirement of QoS depends on the selection of the modulation scheme in the physical layer design. In Fig. 3, it is assumed that the QoS of the first sub-carrier is not satisfied. Therefore, the busy tone is not broadcast on this sub-carrier in the next, ith, MAC-frame, i.e. the MS transmits the busy tone only on the third and fourth sub-carriers in the example.

In order to mathematically model this behavior, let us define $a^{k,m}_{l,i-1}$ which is the channel assignment symbol for the sub-carrier l, at the $(i-1)$th MAC frame for the link between mth BS and kth MS. If sub-carrier l at MAC-frame $(i-1)$ is assigned to the link between mth BS and kth user, then $a^{k,m}_{l,i-1} = 1$, otherwise, $a^{k,m}_{l,i-1} = 0$. The outcome of this assignment, i.e. whether this particular sub-carrier is used for this communication link, is obtained by comparing the received busy tone with the threshold as follows:

$$a^{k,m}_{l,i-1} = \begin{cases} 1 & \text{if} \quad |\hat{B}^m_{l,i-1}|^2 \leq I_{\text{thr}} \\ 0 & \text{otherwise,} \end{cases} \tag{1}$$

where $\hat{B}^m_{l,i-1}$ is the received busy tone signal at the mth BS on the lth sub-carrier in the $(i-1)$th MAC-frame, and I_{thr} is a threshold which is a measure for the interference that this transmission would cause to other co-existing transmissions. At the $(i-1)$th MAC-frame, the receiver, the kth MS, estimates the SINR and decides if this sub-carrier is to be reserved. The outcome of this decision is described by $b^{k,m}_{l,i-1}$, where $b^{k,m}_{l,i-1} = 1$ if the estimated SINR $\breve{\gamma}^k_{l,i-1}$ is above the required SINR $\gamma_{\text{req.}}$, otherwise $b^{k,m}_{l,i-1} = 0$, as described in the following equation:

$$b^{k,m}_{l,i-1} = \begin{cases} 1 & \text{if } (a^{k,m}_{l,i-1} = 1) \\ & \text{and } (\breve{\gamma}^k_{l,i-1} \geq \gamma_{\text{req.}}) \\ 0 & \text{otherwise,} \end{cases} \tag{2}$$

Note that the decision for the value of $a^{k,m}_{l,i-1}$ is made by the transmitter to mitigate CCI, whereas the decision for the value of $b^{k,m}_{l,i-1}$ is made by the receiver to avoid collision and release deeply faded sub-carriers. It is assumed in Eq. (2) that the receiver detects $a^{k,m}_{l,i-1}$ without errors.

2) **Dynamic sub-carrier adaptation:** For any MAC frame greater than (or equal to) i, the received busy-signal powers are composed of the signal powers of the intended user, the k-th MS, and the busy-signal powers of all other entities which are potentially subject to interference. This means that the busy-signal power for the sub-carriers used is different from that in the $(i-1)$th MAC-frame in which the communication between the mth BS and the kth MS was initiated, and in which the intended receiver, the kth MS, has not transmitted a busy-signal.
The received busy signal in the downlink sub-frame of the ith MAC frame can be written as follows

$$\begin{aligned} \hat{B}^m_{l,i} &= \sqrt{g^{k,m}} H^{k,m}_{l,i} B^k_{l,i}\, b^{k,m}_{l,i-1} \\ &\quad + \sum_{\forall k' \neq k} \sqrt{g^{k',m}} H^{k',m}_{l,i} B^{k'}_{l,i}\, b^{k',m}_{l,i-1} \end{aligned} \tag{3}$$

where $B^k_{l,i}$ and $\hat{B}^m_{l,i}$ are the transmitted and the received busy tone in the lth sub-carrier and the ith MAC frame of the kth MS and the mth BS, respectively. The notation $H^{k,m}_{l,i}$ represents the CTF (channel transfer function) coefficient for the lth sub-carrier and the ith MAC frame of the transmission between the mth BS and the kth MS, i.e. the desired link. Similarly, the symbol $H_{l,i}^{k',m}$ is the CTF coefficient between the k' th terminal (it could be a MS or BS of a co-existing link) and the mth BS. Similarly, $\sqrt{g^{k,m}}$ and $\sqrt{g^{k',m}}$ are the pathloss coefficients.

Note that this algorithm does not require channel knowledge as the decision is solely based on received busy-signal levels. When the transmitter makes its selection of a sub-carrier that had not been used in the previous frame, it chooses a sub-carrier with low interference level in the busy slot. If the receiver detects the data correctly and replies with a busy tone, this will cause a surge in the busy tone level on the particular sub-carrier in the following frame(s). This will indicate to the transmitter that the receiver confirms the sub-carrier is usable, i.e. that $b_{l,i-1}^{k,m} = 1$. The condition for the sub-carrier assignment on the desired link between the mth BS and the kth MS for the following ith and subsequent MAC frames is given as follows:

$$a_{l,i}^{k,m} = \begin{cases} 1 & \text{if } (\bar{a}_{l,i-1}^{k,m} |\hat{B}_{l,i}^{m}|^2 \leq I_{\text{thr}}) \\ & \text{or } (b_{l,i-1}^{k,m} = 1) \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

where $\bar{a}$ is the logical complement of a. In (4), the condition $(\bar{a}_{l,i-1}^{k,m} |\hat{B}_{l,i}^{m}|^2 \leq I_{\text{thr}})$ means the sub-carrier l had *not* been used in the previous $(i-1)$th MAC frame and the received busy tone on this sub-carrier at the i-th MAC-frame is lower than the given threshold. If this condition is fulfilled, then this sub-carrier is selected for data transmission in the following data transmission of the current MAC-frame. According to this mechanism, in the example in Fig. 3 the second sub-carrier is selected for downlink transmission in the i-th MAC frame. The condition $b_{l,i-1}^{k,m} = 1$ means that the sub-carrier l has been selected in the previous MAC-frame and the required SINR is maintained. In this case, the sub-carrier l remains selected for this link (third and fourth sub-carriers in the example). Note that the first sub-carrier is released as the required SINR $\gamma_{\text{req.}}$ at the kth MS has not been achieved.

Let C denote a set of all sub-carriers in one cell. The notations $\mathcal{A}_i^{k,m}$ and $\mathcal{B}_i^{k,m}$ are sets of the channel assignment symbols $a_{l,i}^{k,m}$ and $b_{l,i}^{k,m}$, respectively. In the proposed protocol, we follow the assumption that each sub-carrier can only be assigned to one user within a given cell [10]. Thus, $\mathcal{A}_i^{k,m} \cap \mathcal{A}_i^{n,m} = \emptyset$ for $k \neq n$, where k and n are the user indices in the cell m. It is also clear that $\mathcal{B}_i^{k,m} \subseteq \mathcal{A}_i^{k,m} \subseteq C$.

The complete proposed algorithm is depicted in Fig. 4 and described as follows:

1. Initialization phase: It is assumed that there is a new arrival in the network in the MAC-frame i. A set of sub-channels will be selected by comparing the square amplitude of the received busy-signal $|\hat{B}_{l,i}|^2$ with the threshold (in Fig. 4, the user indices k and m are neglected for simplicity). Depending on the comparison result, the corresponding value of the channel assignment symbol $a_{l,i}$ will be set. This comparison is executed for $\forall l \in C$, where C is the set of all sub-channels of the system. Subsequently, data symbols are transmitted on the selected sub-channels.
2. In addition to data equalization and detection, the receiver estimates the SINR on the selected sub-channels. A selected sub-channel is continued to be used for the next MAC-frame, i.e. $b_{l,i} = 1$, if the estimated SINR $\check{\gamma}_{l,i}$ on this sub-channel is greater than the required value $\gamma_{\text{req.}}$ which actually depends on the QoS constraint.
3. The MAC-frame index points to the next MAC-frame $i := i + 1$. The busy-signal is transmitted by the receiver at the selected sub-channels with $b_{l,i} = 1$ using the busy-channel.
4. At the busy-channel, the transmitter continuously checks the condition of Eq. (4) to adapt the set of used sub-channels for the respective link.
5. If the communication on the particular link should be continued in the next MAC-frame, Steps 2-5 are repeated.

4. Selection of Threshold

The expression of the received signal at a receiver is similar to that of the received busy signal at a transmitter which is given in (3). Let us observe again the kth MS, the received signal $\hat{R}_{l,i}^{k}$ on the lth sub-carrier and the ith OFDM symbol is written as follows

$$\hat{R}_{l,i}^{k} = \sqrt{g^{k,m}} H_{l,i}^{k,m} S_{l,i}^{m} + \sum_{\forall m' \neq m} \sqrt{g^{k,m'}} H_{l,i}^{k,m'} S_{l,i}^{m'}, \tag{5}$$

where the first and second terms are the received useful signal and the CCI distortion, respectively. The notation m' $(m' \neq m)$ denotes an active transmismitter, which causes interference to the receiver k. The received useful signal power P_{S} is obtained by taking the expectation of the square value of the received useful signal, i.e.,

$$P_{\text{S}} = \mathrm{E}\left[\sqrt{g^{k,m}} H_{l,i}^{k,m} S_{l,i}^{m} \left(\sqrt{g^{k,m}} H_{l,i}^{k,m} S_{l,i}^{m} \right)^{*} \right] \tag{6}$$

Since the pathloss, channel coefficient and the transmitted symbol are statistically independent, it can be further deduced

$$P_{\text{S}} = \mathrm{E}\left[g^{k,m} \right] \mathrm{E}\left[H_{l,i}^{k,m} (H_{l,i}^{k,m})^{*} \right] \mathrm{E}\left[S_{l,i}^{m} (S_{l,i}^{m})^{*} \right] \tag{7}$$

The expectation $\mathrm{E}\left[g^{m,k} \right]$ is the mean value of the pathloss g_{mean}, and $E_{\text{S}} = \mathrm{E}\left[S_{l,i}^{m} (S_{l,i}^{m})^{*} \right]$ represents the transmitted signal power. Moreover, it has been proven in [11] that

$$\mathrm{E}\left[H_{l,i}^{k,m} (H_{l,i}^{k,m})^{*} \right] = \int_{\tau=0}^{\tau_{\max}} \rho(\tau) d\tau, \tag{8}$$

where $\rho(\tau)$ is the channel delay profile. The integration of the channel delay profile with respect to the time delay τ gives the channel variance E_h. Finally, the received useful signal power is given by

$$P_{\mathrm{S}} = g_{\mathrm{mean}}\, E_{\mathrm{S}}\, E_h. \tag{9}$$

The interference power at a victim receiver is the sum of all interference powers caused from all other interfering transmitters as follows

$$P_{\mathrm{I}} = \sum_{m'=1, m'\neq m}^{N_a} P_{\mathrm{I}}^{m'}, \tag{10}$$

where $(N_a - 1)$ is the number of active interfering transmitters, and the $P_{\mathrm{I}}^{m'}$ is the interference power caused by the transmitter m' to receiver k. Due to the reciprocity of the channel and with the assumption that the transmitted useful signal power and the transmitted busy signal power are equal, the interference power caused from a interfering transmitter is always smaller than the threshold level, i.e.,

$$P_{\mathrm{I}}^{m'} \leq I_{\mathrm{thr}} \tag{11}$$

It results in

$$P_{\mathrm{I}} \leq (N_a - 1) I_{\mathrm{thr}} \tag{12}$$

Thus, the minimum SINR is

$$\mathrm{SINR}_{\mathrm{min}} = \frac{P_{\mathrm{S}}}{(N_a - 1) I_{\mathrm{thr}}}. \tag{13}$$

In (13), we neglect the presence of additive noise for simplicity. In order to ensure that the SINR on all subcarriers must be larger than the required QoS, i.e. $\gamma_{\mathrm{req.}}$, the minimum $\mathrm{SINR}_{\mathrm{min}}$ must be also larger than $\gamma_{\mathrm{req.}}$, or

$$\frac{P_{\mathrm{s}}}{(N_a - 1) I_{\mathrm{thr}}} \geq \gamma_{\mathrm{req.}} \tag{14}$$

The condition for the selection of the threshold is therefore

$$I_{\mathrm{thr}} \leq \frac{P_{\mathrm{S}}}{(N_a - 1)\gamma_{\mathrm{req.}}} \tag{15}$$

Substituting the expression of the received useful power P_{S} from (9) in (15), we obtain the following condition

$$I_{\mathrm{thr}} \leq \frac{g_{\mathrm{mean}}\, E_{\mathrm{S}}\, E_h}{(N_a - 1)\gamma_{\mathrm{req.}}} \tag{16}$$

or,

$$I_{\mathrm{thr}}\,[\mathrm{dBm}] \leq g_{\mathrm{mean}}\,[\mathrm{dB}] + E_{\mathrm{S}}[\mathrm{dBm}] + E_h[\mathrm{dB}] - \gamma_{\mathrm{req.}}[\mathrm{dB}] - 10\log_{10}(N_a - 1) \tag{17}$$

If the threshold is not fulfilled the condition above, then the throughput of the system is low. This is due to the fact that the SINR at the receiver does not meet the required QoS. However, if the threshold is set to an arbitrary small value, then the throughput is also low, since the network is strictly not tolerant to any amount of interference. The condition in (17) does not provide a close form of the optimum threshold which maximizes the throughput for a given QoS. However, the numerical results in Sect. 5.6.1 show that the optimum threshold is close to the maximum threshold which meets the condition in (16).

5. Scenario Setup and Simulation Results for Cellular Networks

5.1 Cellular Network Model

A cellular network consisting of 7 cells with 500 m radius depicted in Fig. 5 is considered for the analysis of the busy-tone concept for OFDMA.

MSs are uniformly distributed in space, and are assigned to corresponding BSs according to the minimum distance. Both downlink and uplink are assessed. A basic block structure for the downlink communication is illustrated in Fig. 6, where it is assumed that users are assigned to particular subcarriers based on the busy-tone MAC as proposed. A similar procedure is carried out in the uplink transmission.

Cell independent channel asymmetry is assumed. This means that at any instant of time the communication in a cell can be downlink, while the communication in a neighbor cell can be uplink. The length of a downlink sub-frame L_{DL} is set to be equal to the length of a uplink sub-frame L_{UL}, which is 20 OFDM symbols for all simulations. Thus, a MAC-frame consists of $(L_{\mathrm{DL}} + L_{\mathrm{UL}})$ OFDM symbols, in which there are 2 busy tone OFDM symbols used for busy tone signaling for both downlink and uplink. The spectral efficiency of the system will be reduced by:

$$\eta_p = 1 - \frac{2}{L_{\mathrm{DL}} + L_{\mathrm{UL}}}. \tag{18}$$

The penalty factor η_p will be later taken into account in (24) for evaluation of the network throughput.

5.2 Channel Model

An outdoor multi-path channel with the maximum propa-

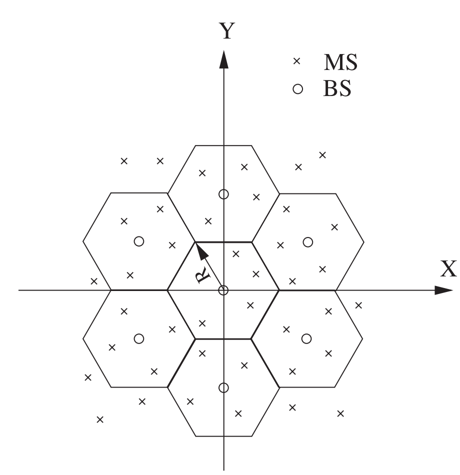

Fig. 5 Scenario for simulations of a cellular network.

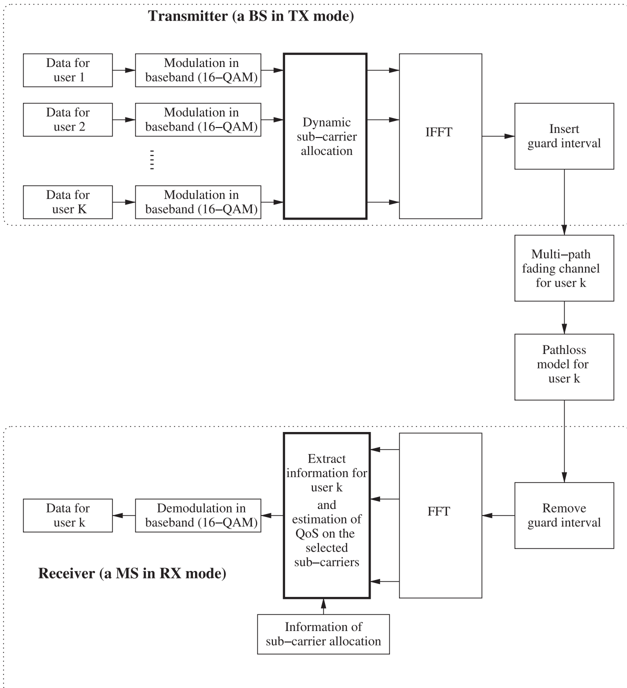

Fig. 6 A simplified model for downlink communication.

gation delay of 2 μs is considered. The Doppler frequency $f_{d,\max}$ of each path is 5 Hz. The channel is therefore a slowly time-variant channel. The multi-path channels of different links are statistically independent, and are modeled by the Monte Carlo method [12], [13],

$$h(\tau_p, t) = \frac{1}{\sqrt{N_h}} \sum_{p=1}^{L} \rho[p] \sum_{q=1}^{N_h} e^{j(2\pi f_{p,q} t + \theta_{p,q})} \delta(\tau - \tau_p), \tag{19}$$

where $f_{p,q} = f_{d,\max} \sin(2\pi u_{p,q})$, $\theta_{p,q} = 2\pi u_{p,q}$, and N_h are called the discrete Doppler frequencies, the Doppler phases, and the number of harmonic functions, respectively. The propagation delay τ_p relates to the p-th channel path. The quantities $u_{p,q}$ are independent random variables, each with a uniform distribution in the range $(0, 1]$ for all $p = 1, 2, \ldots, L$, and $q = 1, 2, \ldots, N_h$. They are independently generated for each link. The number of harmonic functions N_h is chosen to be 40. In Eq. (19), the coefficients of the discrete multi-path profile are modelled by $\rho[p]$.

5.3 Pathloss Model

The pathloss model described in [14], [15] is used,

$$g = A + 10\gamma \log_{10}(d/d_0) + \xi, \tag{20}$$

where $A = 20 \cdot \log_{10}(4\pi d_0/\lambda)$ with $d_0 = 100$ m, and λ is the wavelength. The quantity γ is the path-loss exponent with $\gamma = (a - bh_\mathrm{b} + c/h_\mathrm{b})$, where h_b is the height of the BS and is selected to be 80 m. The constant quantities a, b, and c are selected from the terrain type A given in [14]. The log-normally distributed random variable ξ models shadowing effects and its variance is assumed to be 10 dB. The transmitted power of MSs and BSs is 30 dBm. This is also the transmitted busy signal and useful signal as well.

5.4 OFDM System Parameters

Again, it is assumed that at the moment, the WiMAX standard [16] provides the best framework for this investigation, and therefore, the OFDM system parameters are selected as follows:

- Bandwidth of the system $B = 20$ MHz,
- Sampling interval $t_a = 1/B = 50$ ns,
- FFT-Length $N_\mathrm{FFT} = 256$,
- OFDM symbol duration $T_\mathrm{S} = 12.8\,\mu$s,
- Guard interval length $T_G = 2\,\mu$s.
- Carrier frequency $f_c = 1.9$ GHz.

The selected modulation scheme for all sub-carriers is 16-QAM (quadrature amplitude modulation). Based on the results in [7], the required minimum SINR, $\gamma_\mathrm{req.}$, for data transmission using 16-QAM is 16 dB.

5.5 Traffic Model

The packet arrivals are assumed to be Poisson distributed. The interarrival time T_i and the holding time T_h are two independent random variables with exponential distributions given respectively by

$$p(T_\mathrm{i} > t) = p_{T_\mathrm{i}}(t) = \mathrm{e}^{-t/\nu}, \tag{21}$$

and

$$p(T_\mathrm{h} > t) = p_{T_\mathrm{h}}(t) = \mathrm{e}^{-t/\mu}, \tag{22}$$

where $p(\xi > t)$ is the probability that the random variable ξ takes its value larger than t, and is denoted by $p_\xi(t)$. The average interarrival time ν is varied to evaluate the network performance for different level of the offered load. The average holding time μ is chosen to be 0.15 s.

The offered load of the network is defined as the average number of bits per second per cell which are requested to be transmitted. According to the average arrival rate $1/\nu$ and the average holding time μ, the offered load per cell is calculated as follows,

$$\mathcal{L} = M_\mathrm{ary}\, N_\mathrm{max} \frac{\mu}{N_\mathrm{Cells}\, T_\mathrm{S}\, \nu} \text{ [bits/s/cell]}, \tag{23}$$

where M_ary is the number of bits per symbol, T_S is the OFDM symbol duration, and N_Cells is the number of cells in the network. The modulation scheme is 16-QAM on all sub-carriers, i.e. $M_\mathrm{ary} = 4$. Initially, it is assumed that the network imposes a restriction on the maximum number of sub-carriers N_max that can be assigned to one user. Clearly, $N_\mathrm{max} < N_\mathrm{FFT}$, where N_FFT is the FFT length and also the total number of available sub-carriers. If the number of the selected sub-carriers in the set $\mathcal{A}^k$ is larger than N_max, then N_max sub-carriers will be randomly selected for data transmission from the preselected sub-carriers. This constraint is to prevent situations when a single link uses up a large proportion of the bandwidth and forces the network to deny service to other users.

To evaluate the throughput of the network, let us assume that there are M instantaneously active mobile stations within a given OFDM symbol, and the kth MS can successfully receive[†] on $N_k^{\mathcal{B}}$ sub-carriers ($N_k^{\mathcal{B}} \leq N_{\text{FFT}}$), where $N_k^{\mathcal{B}}$ is the cardinality of the set $\mathcal{B}^k$. The throughput, which is a random variable, in bits per second per cell can therefore be obtained as:

$$\mathcal{T} = \eta_p \frac{1}{N_{\text{Cells}}} \frac{1}{T_{\text{S}}} M_{\text{ary}} \sum_{k=1}^{M} N_k^{\mathcal{B}} \text{ [bits/s/cell].} \tag{24}$$

The symbols which are received below the required SINR $\gamma_{\text{req.}}$ are rejected by the receiver and are considered lost. Based on the values assigned in sets $\mathcal{A}^k$ and $\mathcal{B}^k$, the number of rejected bits at the receiver per second per cell can be computed as follows,

$$\mathcal{R} = \eta_p \frac{1}{N_{\text{Cells}}} \frac{1}{T_{\text{S}}} M_{\text{ary}} \sum_{k=1}^{M} (N_k^{\mathcal{A}} - N_k^{\mathcal{B}}) \text{ [bits/s/cell].} \tag{25}$$

where $N_k^{\mathcal{A}}$ is the cardinality of set $\mathcal{A}^k$. In practice bits on sub-carriers with low SINR (below the given threshold) will not be lost entirely, if link adaptation techniques such as adaptive channel coding techniques and adaptive modulation are employed. This is part of further study in this research work. The definition of data rejected at the receivers will serve only for the purpose of network performance evaluation. Moreover, perfect time and frequency synchronization is assumed. Thus, merely CCI is present in the system.

5.6 Simulation Results

5.6.1 Threshold Optimization

The performance of the proposed MAC heavily depends on the selection of the threshold. The obtained throughput as a function of the threshold for the required QoS $\gamma_{\text{req.}} = 16$ dB are illustrated in Fig. 7. The maximum number of sub-carriers $N_{\max}$ is 64. The numerical results show that if the threshold is too large or too small, a maximum throughput can not be achieved. Therefore, the threshold must be determined for a given QoS to obtain the maximum throughput. Based on the numerical results shown in Fig. 7, the threshold corresponding to the maximum of throughput is −90 dBm.

Table 1 shows theoretical results obtained for the maximum value of the threshold according to (17), where the mean value of the pathloss modeled by Eq. (20) is −88 dB[††]. The number of simulated cells is 7. Thus, the maximum number of active interfering transmitters ($N_a - 1$), which simultaneously could interfere a victim receiver on a selected sub-carrier, is 6. As previously mentioned, the required QoS $\gamma_{\text{req.}}$ is 16 dB. According to (17), the calculation result of the maximum value of the threshold is $I_{\text{thr,max}} = -82$ dBm,

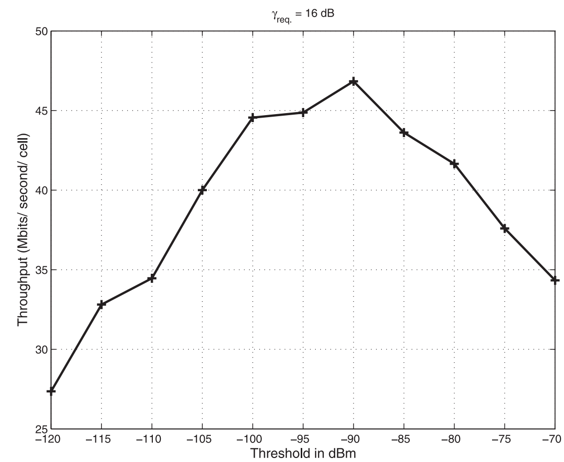

Fig. 7 Throughput of the system versus threshold.

whereas the numerical optimum value of threshold is about −90 dBm. In this paper, a close solution for threshold optimization has not been obtained. Nevertheless, the optimized threshold obtained by simulation is not far from the theoretical calculation of the maximum threshold that could be assigned.

Figure 8 shows, that the lower is the threshold selected, the smaller can be the probability of data rejection obtained at receiver. This is due to the fact that the average interference power of the network is proportional to the level of threshold. For a given QoS, the selection of threshold is the trade off between the throughput and the probability of the data rejection.

Figure 9 shows the dependence of the network throughput on the thresholds I_{thr}. Comparing the performance of the network for three different values of threshold, e.g. $I_{\text{thr}} = -120$ dBm, −90 dBm, and −70 dBm, it can be seen that the corresponding probabilities for achieving a throughput higher than 32.5 Mbits/s are roughly 0.0, 0.82, and 0.31, respectively.

The threshold level of −90 dBm can provide a maximum throughput which is about 50 Mbits/s/cell. The theoretical maximum throughput for this network is $N_{\text{FFT}} \cdot M_{\text{ary}}/t_s = 80$ Mbit/s/cell. This means that 62% of the maximum possible data rate can be achieved by the proposed MAC protocol for the given minimum required SINR $\gamma_{\text{req.}}$=16 dB.

5.6.2 Comparison with Conventional OFDM-FDMA Random Allocation Technique

The performance of the proposed MAC regarding the complementary CDF of the throughput is compared to that obtained by the conventional OFDM-FDMA random alloca-

[†]A data packet is considered to be successfully received on a sub-carrier if the SINR corresponding to this sub-carrier is higher than γ_{req} during the time between two consecutive busy tones.

[††]To obtain the mean value of the pathloss, g_{mean}, all interference links in the scenario depicted in Fig. 5 are realized, then the corresponding pathloss values are averaged.

Table 1 Numerical results of threshold optimization for cellular networks.

E_S [dBm]	E_h [dB]	g_{mean} [dB]	$10*\log(N_a - 1)$	$\gamma_{req.}$ [dB]	$I_{\text{thr,max}}$ [dBm]	I_{opt} [dBm]
30	0	−88	7.8	16	−82	−90

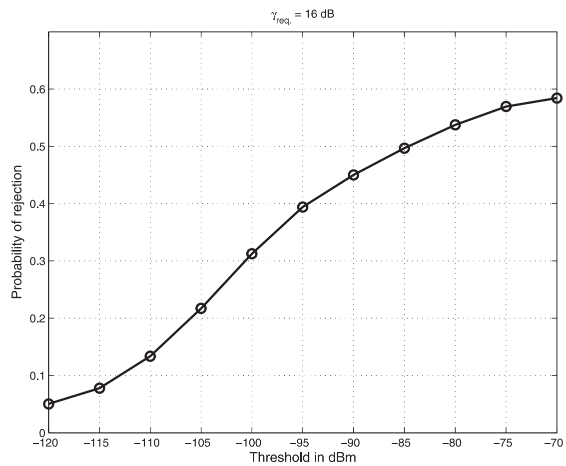

Fig. 8 Probability of data rejection at receiver versus threshold.

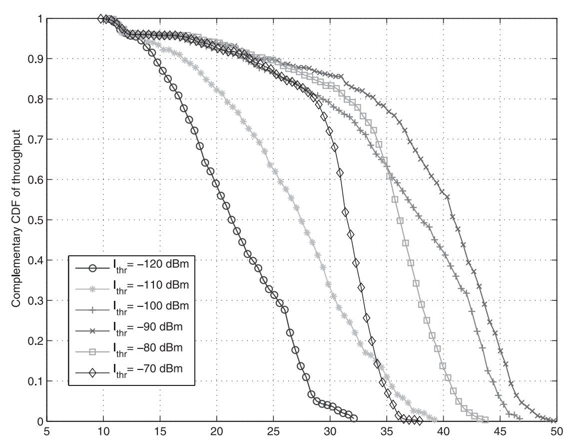

Fig. 9 Complementary CDF of throughput obtained by proposed MAC for different levels of threshould.

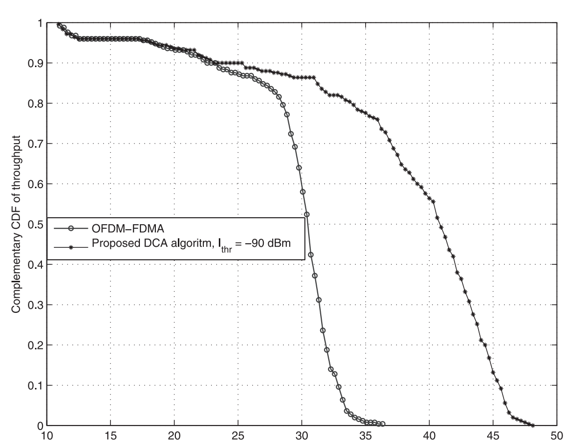

Fig. 10 Comparision of proposed MAC with conventional OFDM-FDMA technique.

tion is shown in Fig. 10. In the case of high offered load, the proposed algorithm significantly outperforms the conventional method in terms of throughput. Only for very low offered load, when there is a redundancy in the network capacity, the conventional OFDMA random allocation is comparable or slightly better than the proposed technique.

6. Scenario Setup and Simulation Results for Adhoc Networks

A simple adhoc scenario with two communication pairs as depicted in Fig. 11 is set for simulations. For simplification, one terminal labeled in Fig. 11 is either a transmitter or a receiver, and one way of communication is drawn. In the implemented scenario however, two ways of communication are considered. The path loss, and the channel are modeled as the cellular scenario as described in Sect. 5. All other quantities as such the OFDM system parameters, modulation scheme, the required QoS are also identical to those of the cellular network. Certainly, the traffic model is different to that in the cellular network, since two communication pairs are active in a whole simulation time.

In the simulated scenario, we assume that two independent communication pairs at the beginning are very far from each other, and are moving towards. The distances between the transmitter and receiver in the two communication pairs are kept constant, namely 100 meters. The antenna height of each adhoc node is 1 meters. The transmit power is also 30 dBm. Both communication pairs try to occupy the medium resource for themselves by using different sub-carriers allocation methods and cause the CCI to the other. In Fig. 11, the solid lines show the communication links (intended links), and the dot lines show the interference links.

The averaged throughput for each communication link in terms of the selected sub-carriers, which satisfies the required QoS, is observed for different allocation methods: the proposed technique, the OFDM-FDMA random and fixed allocation mechanism. The obtained results are plotted in Fig. 12. It can be seen from the results, that if two communication pairs are far apart, the proposed method and the OFDM-FDMA random allocation method demonstrate the same performance, namely both select all sub-carriers. However, if the two communication pairs are close to each other, the throughput obtained by the OFDM-FDMA random allocation method is significantly reduced, and is even much less than that obtained by the OFDM-FDMA fixed allocation method. This is due to the fact that the random allocation method does not have the interference avoidance mechanism, and thus results in high outage when the two communication pairs approach each other. On the contrary, the proposed method offers the interference avoidance mechanism by using the busy tone signaling. As a result, it

Table 2 Numerical results of threshold optimization for adhoc networks.

E_S [dBm]	E_h [dB]	g_{mean} [dB]	10*log($N_a - 1$)	$\gamma_{req.}$ [dB]	$I_{\text{thr,max}}$ [dBm]	I_{opt} [dBm]
30	0	−71	0.0	16	−57	−60

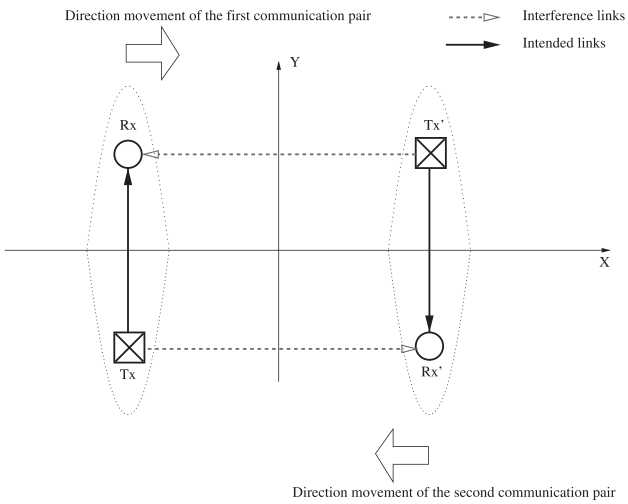

Fig. 11 Simplification of the simulated adhoc scenario.

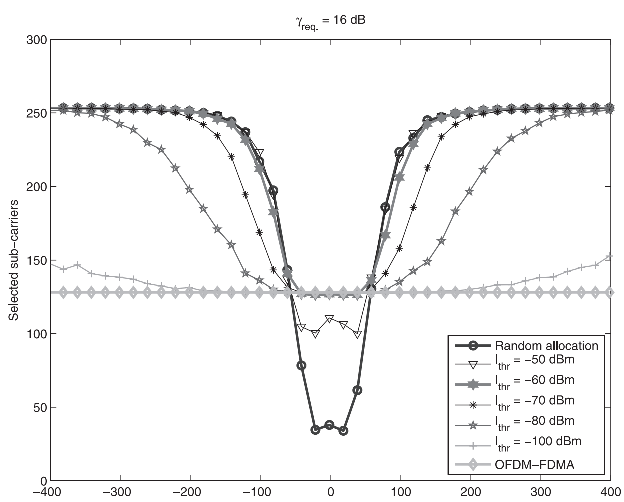

Fig. 12 Number of selected sub-channels obtained by different allocation methods.

provides the same performance as that of the OFDM-FDMA fixed allocation when the potential interference is high. If the two communication pairs move far from each other, the performance obtained by the proposed method with a suitable threshold is comparable with the random allocation method.

Similar to the case of the cellular scenario, the theoretical calculation of the maximum threshold can be obtained from the Eq. (16). However, the mean value of the pathloss between the interfering transmitter to the victim receiver for the adhoc scenario as described in Fig. 11, g_{mean}, is −71 dB. Moreover, the number of interfering transmitter ($N_a - 1$), is 1. The theoretical calculation of the maximum threshold $I_{\text{thr,max}}$ following the Eq. (16) is −58 dBm, whereas the optimal threshold obtained from the simulation results given in Fig. 12 is −60 dBm. Table 2 shows explicitly this comparison.

For the simple OFDM-FDMA fixed allocation method, only 50% of the total resource is assigned to one communication pair. This is independent of their distance. The OFDM-FDMA fixed allocation method does not maximize the throughput. However it is simple and ensures an CCI-free network.

7. Conclusion

In this paper, a decentralized dynamic sub-carrier assignment algorithm is proposed for OFDMA/TDD cellular and adhoc networks. The time-, frequency, and spatial-selectivity, as well as the channel reciprocity in TDD have been exploited for dynamic sub-carrier adaptation. In other words, link adaptation in MAC layer has is carried out on the basis of the interference channel information from the physical layer. The proposed approach solves the hidden and exposed node problem. If a suitable threshold is selected, the overall throughput of the network can be maximized. The QoS for given modulation scheme can be ensured. Simulation results for both cellular and a simple adhoc scenario have been obtained. Compared to conventional methods, it has been shown that our proposed approach offers better system performance. In future works, we consider this concept for multi-hop networks. The combination of the busy tone concept with the space-frequency scheduling promises a more effective algorithm for MIMO-OFDMA networks. The influence of imperfect synchronization on the network performance should be investigated. In addition, adaptive modulation combined with the proposed method promises a higher spectral efficiency. The busy tone signal used in this paper is only to sense the interference power. Clearly, if it is designed to carry the feedback information from the receiver to the transmitter for many other purposes, such precoding information, then the network performance will be increased.

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