Abstract—In this paper a novel decentralized and interference aware medium access control (MAC) protocol combined with a dynamic subchannel selection algorithm for OFDM (orthogonal frequency division multiplexing) is presented. The protocol resolves several drawbacks of the existing radio resource allocation techniques for OFDM systems, such as the hidden and exposed node problem, and the requirement for a time-invariant channel. The proposed scheme enables the transmitter to determine the level of interference it would cause to already active links prior to any transmission. This is achieved through a busy-slot signaling that exploits the channel reciprocity offered by the TDD mode. Compared to existing radio resource allocation schemes the required signaling overhead is significantly reduced. The interference awareness allows the system to avoid significant co-channel interference (CCI) and to operate with full frequency reuse. When applied to a broadband OFDM air interface, this principle can also exploit the frequency selective fading channel on the intended as well as the interference links. This results in an autonomous subcarrier allocation algorithm which can dynamically adapt to time-varying channels. Due to its decentralized nature, the algorithm can be utilized in both cellular and ad hoc networks. Simulation results for a cellular system show that the new decentralized medium access and channel assignment algorithm is capable of achieving spectral efficiencies of up to 2.25 bits/Hz/cell using 16 QAM (quadrature amplitude modulation).

I. INTRODUCTION

Recently there has been an intensive research on OFDM as a wireless data transmission technology in broadband cellular networks. In particular, OFDM is used in the IEEE 802.16 based worldwide interoperability for microwave access (WiMAX) standard. WiMAX uses OFDM-FDMA (frequency division multiple access), also referred to as OFDMA (see [1]), with frequency-reuse of one. Such network configuration may potentially result in severe CCI.

Earlier works have shown how the spectral utilization of a dynamic OFDMA network can be increased through total power or throughput optimization [2–5]. However, these algorithms have a number of drawbacks, such as the unrealistic assumption of perfect channel knowledge or time-invariant channel, or involve centralized control and significant overhead. Besides, these algorithms do not take into account the hidden and exposed node problems, while protocols dealing with those [3, 6] use out-of-band signaling and do not take into account the specifics of OFDMA.

Dynamic channel allocation (DCA) brings improvements in the total spectral efficiency in comparison with the fixed channel allocation (FCA). However, these improvements are offset by the required additional signaling overhead. It is therefore essential that the overhead is kept at minimum. This is achieved in the proposed algorithm by exploiting the channel reciprocity of time division duplexing (TDD) in a signaling mechanism where receivers broadcast busy-bursts in dedicated timeslots in the frame [7]. The proposed protocol combines medium access control (MAC) and dynamic subcarrier re-assignment based on the potential CCI that would be caused at the victim receivers in already active links, and the achieved SINR (signal-to-interference-plus-noise-ratio) at the intended receiver. The protocol works in a completely decentralized fashion and can therefore be applied to self-organizing networks which may consist of cellular as well as ad hoc network topologies.

The channel bandwidth in future 4G (fourth generation) cellular systems is nearly an order of magnitude larger than in 3G (third generation) systems. This results in a highly frequency selective channel. The frequency selectivity applies to both the intended and the unwanted interference links. Since in general case both links are uncorrelated, this effect can be exploited for subcarrier assignment in an OFDMA air-interface such that CCI is minimized and SINR at the desired receiver is maximized.

The remainder of this paper is organized as follows: Section II outlines the CCI problem in OFDM/TDD networks with full frequency reuse. Section II-A reviews some existing methods to reduce the CCI. In Section II-B, a decentralized MAC algorithm for an OFDM/TDD network is described in detail. The system model is described in Section III and simulation results are presented in Section IV. Finally, conclusions are drawn in Section V.

II. THE CCI PROBLEM IN OFDM/TDD NETWORKS WITH FULL FREQUENCY REUSE

Future wireless networks for high peak data rate transmission rely on full frequency re-use and dynamic, self-organizing network configuration capabilities [8]. It is well known that in an OFDM/TDD network with full frequency reuse, pure OFDMA provides poor throughput performance because of the excessive CCI. This is due to the fact that CCI is generally not taken into
account during the channel assignment process, i.e., at the MAC protocol and radio resource management level. To illustrate the problem of CCI a simple scenario consisting of two base stations (BSs) and three mobile stations (MSs) is depicted in Fig. 1. In this scenario, MS\(^1\)\(_{Rx}\) and MS\(^3\)\(_{Rx}\) receive from the BS\(^1\)\(_{Tx}\), while at the same time MS\(^2\)\(_{Tx}\) transmits to BS\(^2\)\(_{Rx}\). In this case, BS\(^2\)\(_{Tx}\) causes CCI to MS\(^1\)\(_{Rx}\) and MS\(^3\)\(_{Rx}\). Similarly, BS\(^1\)\(_{Tx}\) causes CCI to BS\(^2\)\(_{Rx}\). Due to the potentially small spatial separation between transmitter and 'victim' receiver in a full frequency reuse network, CCI poses a major challenge on the MAC protocol design and channel assignment procedure.

**A. Existing CCI mitigation techniques**

It was shown in [2] how the spectral efficiency of an OFDMA system can be increased by using the frequency, time, and spatial diversity of the wireless channel. However, this algorithm requires perfect instantaneous channel knowledge. A channel assignment algorithm that performs well even in fast fading scenarios was presented in [3], but it inherently requires high signaling overhead. The latter problem was addressed in [5], however the algorithm presented there only brings significant improvement in very slowly varying channels with high correlation in time. The region-based allocation algorithm proposed in [4] tries to minimize the CCI in the system, but it does not allow decentralized operation and, like all the former algorithms, does not solve the hidden and exposed node problems. The hidden node problem leads to collisions and arises when a transmitter cannot sense that there is a transmission to a 'victim' receiver within its range due to high path loss from the transmitter in the interfered link. In an exposed node scenario, a transmitter holds back its transmission because it can sense another transmission within its range, even though the path loss to the potential victim receiver is too high and the two transmissions can be carried out concurrently, and this leads to a drop in the network capacity. Earlier protocols that solve the hidden and exposed node problems [3,6] use out-of-band signaling and this compromises their functionality in the frequency selective OFDMA. In [9], a decentralized dynamic channel assignment method is proposed for cellular OFDM-TDMA/TDD networks, however in this protocol the frequency-selectivity of the channel is not taken into consideration. In the following section, a novel MAC protocol without the above drawbacks is proposed, which is shown to minimize the CCI and to increase the throughput of the network.

**B. Decentralized MAC and Resource Allocation Based on Busy-Signals**

To mitigate severe CCI a combined medium access and dynamic subcarrier selection and adaptation algorithm for an OFDM/TDD network is proposed. The basic working mechanism is shown in Fig. 2. Before sending data, the transmitter senses a particular time multiplexed channel, the busy-tone channel, in order to find suitable subchannels for transmission, i.e. such channels which do not affect co-existing, already established links. Due to the frequency selectivity of the broadband channel, some subchannels may experience favorable fading and channel conditions with respect to the desired and the interference link. In the scenario illustrated in Fig 2, it is assumed that the mobile station MS\(^2\)\(_{Tx}\) enters the network...
and wants to transmit to the base station BS\(^\text{Rx}\) in the uplink, while at the same time MS\(^\text{Rx}_1\) and MS\(^\text{Rx}_3\) are already receiving in the neighboring cell. Thus, MS\(^\text{Rx}_1\) and MS\(^\text{Rx}_3\) are potential victim receivers of MS\(^\text{Tx}\). To avoid jamming, both receivers MS\(^\text{Rx}_1\) and MS\(^\text{Rx}_3\) broadcast on successful reception a busy-signal with known transmit power in a time-multiplexed mini-slot on those subchannels which are used for transmission. The new transmitter, MS\(^\text{Tx}\), listens to all subchannels of the busy-channel first and compares the received signal power on all the subchannels against a given threshold. If the busy-signal power is below the threshold, the actual channel gain to the potential victim receivers is small. This, in turn, means that when using that particular subcarrier only negligible interference would be caused. Clearly, the channel reciprocity which is only possible in TDD is the key enabler for this ‘implicit’ signaling. In the example, assume that the busy-signal received on subchannels \#p and \#q is below the threshold. Consequently, these subchannels are selected for transmission by MS\(^\text{Tx}\).

The proposed MAC-frame structure which accounts for downlink and uplink transmission is depicted in Fig. 3. The upper part of this illustration shows transmission and reception of signals from the BS point of view. Similarly, the lower part depicts transmission and reception from the MS point of view. The structure of an uplink sub-frame is similar to the structure of a downlink sub-frame and skipped here for the sake of conciseness. Each sub-frame includes a busy-channel (one OFDM symbol) for busy-tone signaling. The MAC-frame duration is selected so that it is within the coherence time of the channel.

The entire procedure can be sub-divided into two phases, (a) the link initialization phase and (b) the continuous and dynamic subchannel adaptation phase. During the initialization phase a new communication link is established and subchannels have to be selected. In the adaptation phase, the target receiver has received data, but channel and interference variations make it necessary to select new subchannels for transmission.

1) Link initialization: It is assumed that BS \(m\) wants to set-up a link to MS \(k\) in the MAC frame \((i-2)\), i.e. the transmission request arrival is at a random time position in the MAC frame \((i-2)\), and it is, therefore, not guaranteed that the busy-channel can be heard during this MAC frame period. Therefore, the BS has to defer its transmission until the next MAC-frame, i.e. the MAC frame \((i-1)\) when it gets the first proper chance to listen to the busy-channel. The received busy tone is compared against a given threshold as explained before. Note that the received busy-signals at this point in time can only originate from non-intended MSs or BSs (nodes which may potentially suffer interference if transmission started), as the target receiver has not yet received any data and a busy-signal could not have been transmitted. It is assumed that the received busy-signal power of some subchannels falls below the threshold (first, third and fourth subchannel in the example of Fig. 3) which are subsequently selected for data transmission. This means that BS \(m\) commences data transmission to MS \(k\) on these subchannels. MS \(k\) determines the signal-to-interference plus noise ratio (SINR) on each of these subchannels. Based on the required QoS requirement for that particular transmission it will decide whether to reserve the respective subchannel, or whether to ‘release’ it. In the latter case it would not transmit the busy-signal on that corresponding subchannel, whereas in the former case it would reserve the respective subchannel by ‘protecting’ it using the busy-signal. Clearly, this protection is only feasible due to the use of TDD. Note that the SINR at a particular subchannel might be low either because this subchannel on the desired link is deeply faded, or because there is high interference resulting from another transmission. In Fig. 3, it is assumed that the SINR on the first subchannel in the downlink is unacceptable. Therefore, the BS does not broadcast the busy-signal on the second subchannel at the MAC frame \(i\) is received below the threshold. Therefore, the second subchannel is selected for downlink transmission in MAC frame \(i\). Note that the first subchannel is released as the required SINR at the intended MS was not achieved in MAC frame \((i-1)\).

In order to mathematically model this behavior, define \(a_{l,i}^k\) as the channel assignment symbol for the subchannel \(l\), at the MAC frame \((i-1)\) for the link between BS \(m\) and MS \(k\). If this subchannel is assigned, then \(a_{l,i-1}^k = 1\), otherwise, \(a_{l,i-1}^k = 0\). The outcome of this assignment is obtained by comparing the
received busy tone with the threshold expressed as:
\[
a_{l,i}^{k,m} = \begin{cases} 
1 & \text{if } |B_{l,i}^{k,m}|^2 \leq I_{\text{thr}} \\
0 & \text{otherwise},
\end{cases}
\]
where \(B_{l,i}^{k,m}\) is the received busy tone signal at BS \(m\) on the subchannel \(l\) in the MAC frame \((i-1)\). The threshold, \(I_{\text{thr}}\), is a measure for the interference that this transmission would cause to other receivers in the network.

At the MAC frame \((i-1)\), the receiver, MS \(k\), estimates the SINR and decides if this subchannel is to be reserved. The outcome of this decision is described by \(b_{l,i}^{k,m}\) where \(b_{l,i}^{k,m} = 1\) if the estimated SINR \(\frac{a_{l,i}^{k,m} - B_{l,i}^{k,m}}{\text{thr}}\) is above the required SINR \(\gamma_{\text{req}}\), otherwise \(b_{l,i}^{k,m} = 0\), described by
\[
b_{l,i}^{k,m} = \begin{cases} 
1 & \text{if } a_{l,i}^{k,m} = 1 \text{ and } (\frac{a_{l,i}^{k,m}}{\text{thr}} \geq \gamma_{\text{req}}) \\
0 & \text{otherwise},
\end{cases}
\]
Note that the decision for the value of \(a_{l,i}^{k,m}\) is made by the transmitter to mitigate CCI, whereas the decision for the value of \(b_{l,i}^{k,m}\) is made by the receiver to ensure that the required SINR is maintained. It is assumed that the receiver detects \(a_{l,i}^{k,m}\) without errors.

2) Dynamic subchannel 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, MS \(k\), and the busy-signal powers of all other entities which are potentially subject to interference. This means that the busy-signal power for the subchannels used is different from that in the MAC frame \((i-1)\) in which the communication between BS \(m\) and the MS \(k\) was initiated, in the way that the intended receiver, MS \(k\), has not transmitted a busy-signal in MAC frame \((i-1)\).

The received busy signal in the downlink sub-frame of the MAC frame \(i\) can be written as follows
\[
\hat{B}_{l,i}^{m} = H_{l,i}^{k,m} B_{l,i}^{k,m} + \sum_{k \neq k'} H_{l,i}^{k',m} B_{l,i}^{k',m} B_{l,i}^{b_{l,i}^{k,m}}
\]
where \(B_{l,i}^{k,m}\) and \(\hat{B}_{l,i}^{m}\) are the transmitted and the received busy tone on the \(l\)-th subchannel and the MAC frame \(i\) of MS \(k\) and BS \(m\), respectively. The notation \(H_{l,i}^{k,m}\) represents the CTF (channel transfer function) for the subchannel \(l\) and the MAC frame \(i\) of the transmission between BS \(m\) and MS \(k\), i.e. the desired link. Similarly, the symbol \(H_{l,i}^{k',m}\) is the CTF coefficient between terminal \(k'\) (it could be a MS or BS of a co-existing link) and entity \(m\).

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 subchannel that has not been used in the previous frame, it chooses a subchannel 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 (modeled as a busy tone margin) in the busy tone level on the particular subchannel in the following frame(s). This will indicate the transmitter that the receiver confirms the subchannel is usable. Therefore, an estimate of \(b_{l,i}^{k,m}\) can be obtained from eqn. (3) as follows,
\[
b_{l,i}^{k,m} = \begin{cases} 
1 & \text{if } (\hat{B}_{l,i}^{m} > \Delta) \\
0 & \text{otherwise},
\end{cases}
\]
where \(\Delta\) is the busy tone margin. The condition for the subchannel assignment on the desired link between BS \(m\) and the MS \(k\) for subsequent MAC frames is given as follows:
\[
a_{l,i}^{k,m} = \begin{cases} 
1 & \text{if } (\hat{B}_{l,i}^{k,m} > \text{thr} \text{ or } (\hat{B}_{l,i}^{k,m} = 1) \\
0 & \text{otherwise}
\end{cases}
\]
where \(\alpha\) is the logical complement of \(a\). In (5), the condition \((\hat{B}_{l,i}^{k,m} > \text{thr})\) means the subchannel \(l\) has not been used in the previous MAC frame \((i-1)\) and the received busy tone on this subchannel at MAC frame \(i\) is lower than the given threshold. If this condition is fulfilled, then this subchannel is selected for data transmission in the following MAC frame.

According to this mechanism, in the example in Fig. 3 the second subchannel is selected for downlink transmission in MAC frame \(i\). The condition \(\hat{B}_{l,i}^{k,m} = 1\) means that the subchannel \(l\) has been selected in the previous MAC frame and the required SINR is maintained. In this case, the subchannel \(l\) remains selected for this link (third and fourth subchannel in the example). Note that the first subchannel is released as the required SINR \(\gamma_{\text{req}}\) at MS \(k\) has not been achieved.

Note that, the busy tone transmission primarily serves as a reservation mechanism addressing potential other transmitters in the network. However, since all receivers, including the intended receiver, send the busy signal, this implicit feedback mechanism (referred to as reservation indicator in [7]) can additionally be used for a subchannel specific ARQ (automatic repeat request).

Let \(C\) denote a set of all subchannels. The notations \(A_{k}^{b}\) and \(B_{k}^{b}\) are the sets of the subchannels within a arbitrary cell \(m\) for which \(a_{l,i}^{k,m} = 1\) and \(b_{l,i}^{k,m} = 1\), respectively. In the proposed protocol, the assumption is made that each subchannel can only be assigned to one user within a given cell [10]. Thus, \(A_{k}^{b} \subseteq C\) for \(k \neq n\), where \(k\) and \(n\) are the indices. It is also clear that \(B_{k}^{b} \subseteq A_{k}^{b}\).

III. SYSTEM MODEL

A cellular network consisting of 7 cells with 500m radius is assumed. MSs are uniformly distributed in space. The following parameters taken from the WiMAX standard [11] are used:

- Bandwidth of the system \(B = 20\) MHz,
- Sampling interval \(t_{s} = 1/\text{FFT} = 50\) ns,
- FFT-Length \(N_{\text{FFT}} = 256\).

The carrier frequency is \(f_{c} = 1.9\) GHz. A multi-path channel with the maximum propagation delay of 0.45 \(\mu s\) is considered. The Doppler frequency of each path is 5Hz. The channel is therefore a slowly time-variant channel. The multi-path channels of different links are statistically independent. Perfect time and frequency synchronization is assumed. Thus only CCI is present in the system.

The path loss model described in [12, 13] is used,
\[
g = A + 10 \gamma \log_{10}(d/d_{0}) + \xi,
\]
where \(A = 20 \log_{10} (4\pi d_{0}/\lambda)\) with \(d_{0} = 100\) m, and \(\lambda\) is the wavelength. The quantity \(\gamma\) is the path-loss exponent with \(\gamma = (a - bh_{b} + c)/h_{b}\), 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 [13]. The lognormally distributed random variable $\xi$ models shadowing effects and its variance is assumed to be 10dB. Poisson distributed traffic is assumed with an average inter-arrival time of 0.1ms and an average holding time of 0.15s. The transmit power of all MSs and BSs is 30dBm. The minimum SINR, $\gamma_{req}$, which is used to select subchannels at the intended receiver is 16dB.

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. Thus, a MAC-frame consists of ($L_{DL} + L_{UL}$) OFDM symbols, in which there are 2 busy tone OFDM symbols reserved for busy tone signaling for both downlink and uplink. The spectral efficiency of the system will be reduced by:

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

The penalty factor $\eta_p$ is taken into account in eqn. (9) for evaluation of the network throughput.

The offered load of the network is defined as the average number of bits per second per cell which are requested to be transmitted. Let us suppose that there are $M$ active mobile stations during a given OFDM symbol. The offered load of the network is then defined as:

$$L = \frac{\nu M}{T_s N_C} M_{ary} N_{max} \text{ [bits/s/cell]},$$  

where $\nu$ is the traffic intensity, $M_{ary}$ is the number of bits per symbol, $T_s$ is the symbol duration in seconds, $N_C$ is the number of cells in the network, and $N_{max}$ is the maximum number of subcarriers that can be assigned to one user. Clearly $N_{max} < N_{FFT}$, where $N_{FFT}$ is the total number of available subcarriers. Let $|A_i^k|$ be the cardinality of set $A_i^k$.

If $|A_i^k| > N_{max}$, then $N_{max}$ subchannels will be randomly selected for data transmission from the $|A_i^k|$ preselected subchannels. This constraint is necessary for reasons of fairness so 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.

16-QAM (quadrature amplitude modulation) on all subchannels is assumed, i.e. $M_{ary} = 4$. Furthermore, let us assume that MS $k$ can successfully receive data from $|B_i^k|$ subchannels ($|B_i^k|\leq N_{max}$), where $|B_i^k|$ is the cardinality of the set $B_i^k$. The throughput, which is a random variable, in bits per second per cell can therefore be obtained as:

$$T_i = M_{ary} \eta_p \frac{1}{T_s N_C} \sum_{k=1}^{M} |B_i^k| \text{ [bits/s/cell].}$$  

The data bits which had been transmitted but are then received on subchannels with SINR below the required $\gamma_{req}$ are rejected by the receiver and are considered lost for that particular link. Based on sets $A_i^k$ and $B_i^k$, the rejection rate per MAC frame at the receiver can be described as,

$$R_i = M_{ary} \eta_p \frac{1}{T_s N_C} \sum_{k=1}^{M} (|A_i^k| - |B_i^k|) \text{ [bits/s/cell].}$$  

\[1\]

A data packet is considered to be successfully received on a subchannel if the SINR corresponding to this subchannel is higher than $\gamma_{req}$.
busy channel. As a consequence, the likelihood that the SINR on these subchannels at the own receiver is above the required SINR is particularly high. However, only a few subchannels fulfill this condition, i.e., the system is over-cautious. As the busy-signal threshold increases, the number of subchannels in set \( \sum_k A^c_k \) increases up to the total number of subchannels, but at the same time the number of subchannels which are rejected increases as the interference sensitivity in the network decreases. If the busy-signal interference threshold is very high (e.g., \(-50\,\text{dBm}\)), this basically means that no interference protection and awareness exist, and the system behaves as if only a random subchannel selection algorithm is executed. From the results in Fig. 4 it can be observed that there exists an optimum for the busy-signal threshold at around \(-95\,\text{dBm}\) which results in an increase of subchannel utilization of about 30% over the case when only very little or no interference awareness is taken into account, i.e., a busy-signal threshold of \(-50\,\text{dBm}\).

In Fig. 5, the complementary cdf (cumulative density function) of throughput is depicted. For up to a throughput of around 20 Mbps/cell which corresponds to 25% of the maximum theoretical throughput \((N_{\text{FFT}} \cdot M_{\text{ary}} / T_s = 80 \, \text{Mbps/cell})\), the throughput is independent of the actual busy-signal thresholds due to low interference levels. However, the situation is significantly different when considering the 10th percentile. For an ‘optimum’ busy-signal threshold, a peak throughput of about 45 Mbps/cell can be guaranteed. This means that 56.25% of the maximum possible data rate can be achieved by the proposed MAC protocol for the given minimum required SINR \( \gamma_{\text{req}} = 16 \, \text{dB} \). In other words, the spectral efficiency is about 2.25 bits/Hz/cell.

The proposed algorithm has also been compared to conventional OFDMA, i.e., an OFDMA system where each user is randomly assigned a fixed number of consecutive subchannels. As can be seen in Fig. 6, the proposed technique significantly outperforms the conventional OFDMA in terms of throughput. Only for very low offered load, when there is a redundancy in the network capacity, the conventional OFDMA is comparable to the proposed technique.

V. CONCLUSION

This paper proposes a new joint decentralized MAC protocol and dynamic subcarrier assignment algorithm for OFDMA networks. The new technique is able to achieve spectral efficiencies of about 2.25 bits/Hz/cell assuming a WiMAX system with 16 QAM modulation. The system achieves about 56% of the maximum theoretical throughput. A random subchannel allocation algorithm only achieves about 40%. The performance gain can be attributed to a two stage subchannel selection process which ensures that existing transmissions are protected. This mechanism allows a full frequency reuse with a minimum signaling overhead due to the exploitation of the channel reciprocity inherent in TDD. It is anticipated the performance gain for higher order modulation schemes continues to increase due to the inference management properties of the algorithm. Moreover, further significant enhancements are expected in ad hoc and multihop network deployments.

REFERENCES