Single-radio multi-subchannel random access for OFDMA wireless networks

Jia Xu, Pin Lv and Xudong Wang

Orthogonal frequency division multiple access (OFDMA) is a promising technology owing to its flexibility in subcarrier/subchannel allocation. Since most applications in OFDMA wireless networks generate bursty traffic, it is efficient and flexible to employ a random access mechanism in such networks. A single-radio multi-subchannel carrier sense multiple access with collision avoidance (CSMA/CA)-based random access protocol (called SRMC-CSMA/CA) is proposed for OFDMA wireless networks. By means of intermittent carrier sense and cumulative update of backoff counters, a terminal with a single radio can utilise multiple subchannels to transmit packets concurrently. Simulation results indicate that the SRMC-CSMA/CA protocol apparently improves the channel utilisation, especially when the traffic loads of the terminals are unbalanced.

Introduction: Orthogonal frequency division multiple access (OFDMA) is adopted by many next generation wireless networks, including WiMAX [1] and LTE [2]. A channel in OFDMA is divided into a large number of orthogonal subcarriers, and different terminals can be allocated with different subcarriers to transmit data concurrently without crosstalk. To facilitate the maintenance in a practical system, the minimum resource unit is not a subcarrier but a block of subcarriers, referred to as a ‘subchannel’.

Since most applications in OFDMA-based data networks generate bursty traffic, it is inefficient to employ a reservation-based medium access control mechanism. Hence, several random access protocols have been proposed for OFDMA wireless networks [3–5]. A slotted ALOHA-based scheme is proposed in [3], but the throughput of such a scheme is fairly low owing to high collision probability. Kwon *et al.* [4] put forward a random access scheme based on carrier sense multiple access with collision avoidance (CSMA/CA), which outperforms the ALOHA protocol. However, the channel utilisation efficiency of the protocol in [4] is still low because a terminal uses only one backoff timer for all the subchannels, and the timer cannot reflect different traffic loads in different subchannels. This problem is then solved in [5], where a terminal maintains one backoff timer for each subchannel. Thus, the transmission status of one subchannel does not affect other subchannels. For a terminal with a single radio, when seizing a subchannel for transmission, it cannot continue conducting carrier sense on other subchannels due to the half-duplex nature of the wireless radio. As a result, the terminal cannot know when to start the transmission on the other subchannels, and therefore the terminal can only use one subchannel in most instances. However, traffic loads of different terminals are usually unbalanced in practice. For terminals with heavy traffic loads, their throughputs have to be limited by the bandwidth of a single subchannel. To improve transmission concurrency on multiple subchannels, the authors of [5] suggest utilising an additional radio for carrier sense on all the other subchannels when the original radio is busy in transmission on a certain subchannel. Nevertheless, such a mechanism with a dedicated sensing module cannot be applied to the terminal with a single radio.

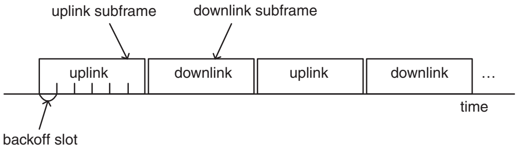

Fig. 1 *TDMA frames of OFDMA wireless network*

In this Letter, we propose a CSMA/CA-based single-radio multi-subchannel random access protocol for OFDMA wireless networks, referred to as SRMC-CSMA/CA. Using the SRMC-CSMA/CA protocol, a single-radio terminal is able to utilise multiple subchannels to transmit data packets simultaneously.

System model: Consider a typical OFDMA wireless network (such as a WiMAX or cellular network) with one base station (BS) and n terminals, forming a point-to-multipoint topology. The link from a terminal to the BS is called ‘uplink’, whereas its reversed link is termed ‘downlink’. To coordinate the uplink and the downlink transmissions, the terminals and the BS are synchronised to follow a repetitive time division multiple access (TDMA) frame structure as indicated in Fig. 1.

In the uplink period, the terminals access subchannels based on the SRMC-CSMA/CA protocol, and send packets to the BS simultaneously via different subchannels. The uplink subframe is further divided into many timeslots, and a terminal starts to send a packet only at the beginning of a timeslot. If a terminal finishes a packet transmission in an uplink subframe, it will receive the corresponding acknowledgement (ACK) in the coming downlink subframe; otherwise, it suspends its transmission when the downlink subframe arrives, and restarts the transmission in the next uplink subframe. As for the downlink phase, only the BS occupies the channel to transmit ACKs or data packets. Similar to the strategy in [5], the BS sets the number of subchannels equal to the number of terminals, and broadcasts such information in the downlink subframes. Hence, the entire channel is evenly divided into n subchannels. The set of subchannels is represented by C, where $C = \{c_1, c_2, \ldots, c_n\}$. The bandwidth of the channel is denoted as B. Thus, the bandwidth of a subchannel is B/n.

Based on the CSMA/CA protocol, a terminal maintains a backoff counter k_i for each subchannel c_i, and decreases k_i by 1 in one timeslot if c_i is sensed idle. If the terminal finds that c_i is busy, its corresponding backoff counter k_i is freezed to remain unchanged until c_i is released. When k_i is decreased to zero, the terminal starts to occupy c_i to transmit packets. If more than one terminal happens to access the same subchannel simultaneously, and thus a collision takes place, these terminals will follow a binary exponential backoff as defined in the IEEE 802.11 standards.

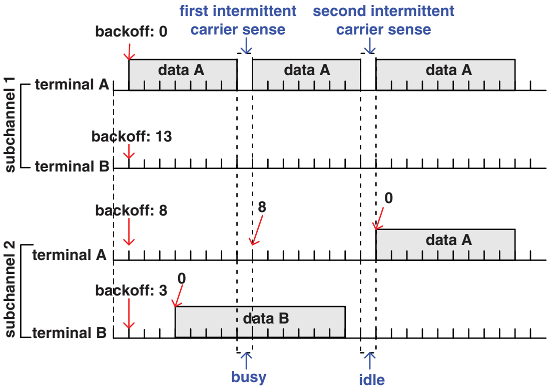

Fig. 2 *Example scenario*

Here, we use l_i to denote the traffic load of the ith terminal, and $t_i (t_i \leq l_i)$ to represent its achieved throughput. Considering that the traffic loads of different terminals vary greatly, the throughput thus can be normalised as t_i/l_i for a fair comparison.

The overall throughput of the network (T) and the max–min fairness (F) are used to measure the performance of the SRMC-CSMA/CA protocol. These two metrics are defined, respectively, as follows:

$$T = \sum_{i=1}^{n} t_i \tag{1}$$

$$F = \max \frac{t_i}{l_i} - \min \frac{t_i}{l_i} \tag{2}$$

SRMC-CSMA/CA protocol description: Owing to the half-duplex nature, a wireless radio cannot conduct carrier sense when it transmits packets. If a terminal has seized a subchannel, it cannot know when to start transmissions on the other subchannels. To improve the transmission concurrency, an ‘intermittent carrier sense’ scheme is introduced.

When a backoff counter k_i of a terminal is decreased to zero and the terminal starts to access its corresponding subchannel c_i, the terminal will find out the minimal backoff counter (denoted as k_{m}) from all the other nonzero backoff counters. After $(k_{\mathrm{m}} - 1)$ timeslots, the terminal suspends its transmission on the occupied subchannel c_i, and takes one timeslot to conduct actual carrier sense on all the subchannels. Except for the occupied subchannel c_i, if another subchannel $c_j (j \neq i)$

is idle, its associated backoff counter k_j is updated by subtracting k_m from it, which is called ‘cumulative update’. In the case that c_j is sensed to be busy, its backoff counter will remain unchanged. After the intermittent carrier sense phase, the terminal selects the minimal backoff counter again for the next intermittent carrier sense.

For c_m with the minimal backoff counter, there exist two cases, as demonstrated in Fig. 2.

Case I: c_m is busy. In Fig. 2, when terminal A begins its transmission on subchannel 1, its backoff counter for subchannel 2 is eight. After seven timeslots (i.e. $8-1=7$), terminal A suspends its transmission on subchannel 1, and spends one timeslot for the intermittent carrier sense. During the first intermittent carrier sense, terminal A finds that subchannel 2 is busy (occupied by terminal B). Thereby, the value of the backoff counter for subchannel 2 will remain unchanged.

Case II: c_m is idle. After seven timeslots again, terminal A conducts intermittent carrier sense for the second time, and finds that subchannel 2 is idle at this time. Therefore, terminal A sets its backoff counter to zero (subtracting eight from its original count), and then transmits data on both subchannels 1 and 2 concurrently from the following timeslot, which indicates that the transmission concurrency has improved.

Simulation results: In the simulations, each timeslot is set to 10 µs, and the packet length is set to 1500 bytes. It is assumed that the bandwidth of the entire channel is 54 Mbit/s. The initial size of the contention window is set to 32, whereas the maximal contention window size is assigned to 1024. The packet generation of a terminal follows a Poisson distribution. Different terminals may have various traffic loads. Our SRMC-CSMA/CA protocol is compared with the CM-CSMA/CA protocol [5] in the following two scenarios.

In the first scenario, there exist three terminals. Their traffic loads are 12, 18 and 24 Mbit/s, and they are referred to as low-load, medium-load and high-load, respectively. As the channel is evenly divided into three subchannels, the bandwidth of each subchannel is 18 Mbit/s. The normalised throughputs of these three terminals are shown in Fig. 3. Based on the CM-CSMA/CA protocol, the normalised throughput decreases with the increase of the traffic load. Since one terminal accesses only one subchannel in most cases, the normalised throughput of the high-load terminal will not exceed 0.63. According to our SRMC-CSMA/CA protocol, one terminal can access multiple subchannels simultaneously. Hence, the throughput of the high-load terminal is not limited by the bandwidth of an individual subchannel. It is also shown in Fig. 3 that the normalised throughputs of all the three terminals are above 0.85, which also indicates a significant improvement in fairness. The overall throughput and max–min fairness comparisons are summarised in Table 1.

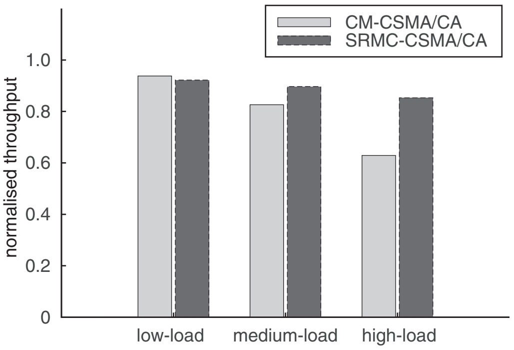

Fig. 3 *Normalised throughputs of terminals with various traffic loads*

Table 1: Overall throughput and max–min fairness comparisons

Metric	CM-CSMA/CA	SRMC-CSMA/CA
T (Mbit/s)	41.22	**47.68**
F	0.31	**0.07**

In the second scenario, the number of terminals is two, and the rate bandwidth of each subchannel is 27 Mbit/s. The traffic load of terminal 1 is fixed at 12 Mbit/s, whereas the load of terminal 2 varies from 0 to 48 Mbit/s. The overall throughput with respect to the varying traffic load of terminal 2 is illustrated in Fig. 4. For the CM-CSMA/CA protocol, the overall throughput does not grow when it reaches about 32 Mbit/s, owing to its single-subchannel access. Based on the SRMC-CSMA/CA protocol, the maximal overall throughput is improved by 40% by virtue of the concurrent transmissions on multiple subchannels.

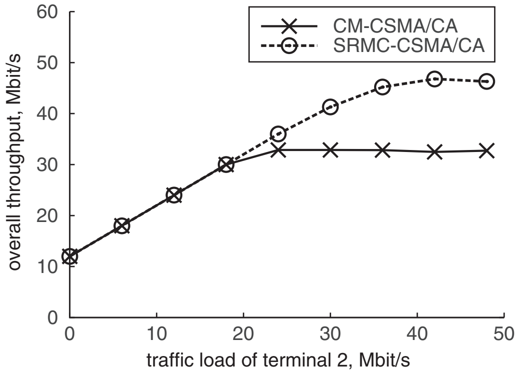

Fig. 4 *Overall throughput comparison*

Conclusion: With the introduction of the intermittent carrier sense and the cumulative update of the backoff counters, the SRMC-CSMA/CA protocol enables a single-radio OFDMA terminal to access multiple subchannels simultaneously. Owing to the concurrent transmission on multiple subchannels, both the network overall throughput and the terminal individual throughput are improved. The simulation results illustrate the effectiveness of our SRMC-CSMA/CA protocol.

Acknowledgments: The work was supported by the National Natural Science Foundation of China (NSFC) (61172066, 61170284, 61202487) and the Oriental Scholar Program of Shanghai Municipal Education Commission. The authors would like to thank these sponsors for their generous support.

10 June 2013
doi: 10.1049/el.2013.1905
One or more of the Figures in this Letter are available in colour online.

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