RTC: Link Schedule Based MAC Design in Multi-hop Wireless Network

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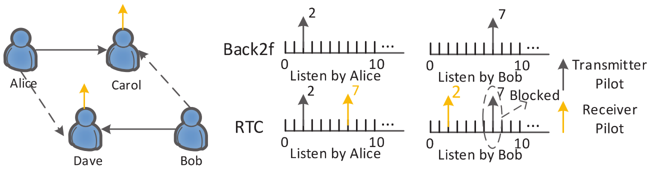
***Abstract*—The performance of an ad-hoc network is greatly limited by collisions due to hidden terminals. In this paper, we propose a receiver tracking contention (RTC) scheme, which achieves high throughput by allowing the receivers to assist for channel contention. In RTC, link is the basic unit for channel access contention. Specifically, transmitter is used to contend for the channel and receiver is used to announce the potential collision. Based on INT message coding scheme, transmitter and its corresponding receiver can be well coordinated. In such mechanism, hidden terminals are avoided and exposed terminals are encouraged to transmit simultaneously. Based on OFDM modulation, RTC packets several subcarriers as subcontention unit and operates channel contention over multiple subcontention units. Furthermore, each subcontention unit maintains a transmission set, where collision-free links are allowed to merged into the transmission set. In this case, the transmission set of subcontention unit can be aggregated after each contention period. When the subcontention unit i is the smallest index of non-empty subcontention unit, the transmission set of unit i will win the channel contention and transmitters of unit i will start to transmit in the following data transmission period. Analysis and simulation results show that RTC achieves a notable throughput gain over Back2f as high as 190% through simulation.**

I. INTRODUCTION

Collision caused by hidden terminals and spectrum waist caused by exposed terminals are well discussed issues in wireless network [1]–[5]. Due to collisions, Severe packet lose for 10% of sender-receiver pairs is experienced in WLAN [6]. Furthermore, as shown by [3], the concurrent transmission probability of exposed terminals could greatly enhance the network performance. Recently, Numerous works [7]–[10] is proposed to reduce the coordination overhead by transferring the channel contention from temporal domain into frequency domain. Normally, at least one transmitter in a collision domain is chosen after each contention period. However, due to lack of receiver assistance, the intended receivers have highly probability to be interfered by hidden terminals.

Conventionally, coordination is deployed commonly in wireless network to handle the hidden terminal problem. RTS/CTS is proposed in the four-way handshaking in IEEE 802.11 to prevent hidden terminals from transmitting. However, enabling RTS/CTS has been verified to dramatically decrease network performance [12]. When the physical data rate reaches Gbps, that time-consuming handshaking mechanism seems intolerant. In [1], CSMA/CN allows receiver to broadcast a collision notification message when some errors are detected during the data transmission. Based on full-duplex technique [13], FD-MMAC [2] develops a immediate backward transmission by receiver along with the data transmission, where the receiving mode of receiver is broadcasted to surroundings. In such mechanism, hidden terminals are alleviated without obvious coordination overhead. However, either collision notification or backward transmission could not be activated until the preamble and MAC header of the ongoing transmission has been decoded successfully. Compared with the interval of data transmission, that postponed feedback can not be ignore (e.g., only 20 us is required for 1500 Bytes data transmission, but 40 us for decoding the preamble and MAC header at 600Mbps [9]). Therefore, when conflicting frame is transmitted before $2/3$ of an ongoing transmission, the ongoing data frame is still interfered and none of the aforementioned methods could perform well.



(a) Network topology of four nodes.

(b) Scheduling of TRC in each node.

Fig. 1: Simple example of TRC in adhoc network.

The basic reason for the inefficiency of MAC schedule is that transmissions are conducted by transmitters and receivers could not assist for transmission until they are informed by transmitters. Due to this issue, hidden terminal problem is hard to overcome. Recently, receiver assisted based channel contention [3], [11] is proposed to address this problem, where receivers are activated before the beginning of contention starts. Specifically, REPICK [11] allows receiver to contend and reserve channel for the following transmission. Nevertheless, the benefit of this reservation mechanism can only be achieved when two or more same links of one transmitter are scheduled continually. In [3], the involved receivers are informed by INT coding scheme during the last data transmission period. Therefore, receivers could assist for the channel contention with the coordinated parameter. However,

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only one transmission could be survived from multiple collided transmissions.

In this paper, we propose a novel link level schedule RTC, Receiver Tracking Contention based MAC design, to aggregate a set of frame from distinct links and transmit them simultaneously. Each frame set contains multiple concurrent links and is aggregated along with the proceeding of subcontention. Note that, each link sends pilot signal in coordinated subcontention by both transmitter and its corresponding receiver for channel contention. Two types of link are involved in subcontention: authorised link and new contending link. When a new contending link is collision-free with the authorised links in one subcontention, the new link can be transferred into authorised link in the following contention period. In this case, authorised links have the higher priority for channel access and the frame set of each subcontention is enlarged subcontention by subcontention. Moreover, only authorised links of subcontention i are enabled to transmit frame when i is the smallest index of subcontention among nodes in the vicinity. Taking a simple example, the network topology of four nodes shown in Fig. 1(a), where Alice and Bob are hidden terminal to each other. When Alice and Bob start to contend for the channel, as shown in Fig. 1(b), Alice and Bob pick up subcarrier 2 and subcarrier 7 for contention, respectively. In convention frequency channel contention, like Back2f [7], both Alice and Bob will win the channel contention, but collisions will happen and none of those transmissions will succeed. However, with the assistance of Carol and Dave, both Alice and Bob could overheard the contention message from each other. As a result, the node with the bigger index is blocked (Bob) and Alice will win the channel contention.

The requirement that link level schedule should be well coordinated between transmitters and the corresponding receivers, which poses several technical challenges.

(1) Cooperatively. Link based contention give us a new overlook on channel contention, where both transmitter and its corresponding receiver contributes for the channel contention. To this ends, cooperation between transmitters and receivers should be well coordinated. Otherwise, if transmitter and its corresponding receiver contend for the channel in respective different subcontentions, benefit of link based schedule will not be achieved and the performance lose may be induced by the unnecessary receiver contention. Therefore, It is a challenge to coordinate the transmitters and receivers to operate cooperatively.

(2) Efficiently. The advantage of link based channel contention is that hidden terminals are avoided by the announcement of receiver and exposed terminals are activated and recontend for the channel. Through such schedule mechanism, the number of concurrent transmission is aggregated. Further, the network performance can be maximized by enlarging the concurrent transmission as far as possible. In this situation, none of conventional contention methods works well.

We have conducted simulations and theoretical analysis to evaluate the performance of RTC. It is shown that, RTC outperforms significantly Back2f [7] in terms of throughput. For example, the throughput gain over Back2f is up to 145% through simulation.

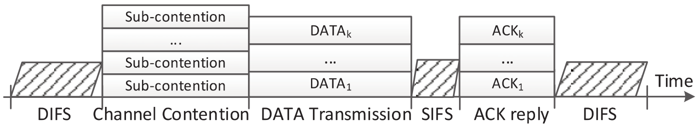


Fig. 2: The overview of RTC.

The rest of this paper is organized as follows. Section II describes the design of RTC. In Section III, we provide simulation results and analysis to validate our scheme. Finally, Section IV concludes this paper.

II. DESIGN OF RTC

Consider a multi-hop ad-hoc network with multiple stationary nodes. Each node is equipped with at least two antennas, one for transmitting and others for listening. Based on the full duplex technique [13], nodes have the capability to transmit and receive simultaneously. Assume that all data frames have the same size and are transmitted at a fixed data rate. Hence, the data transmission interval is constant in the network. For simplicity, we consider a $\{0,1\}$ interference model, in which a data frame can be decoded successfully at the receiver only if no other frame that overlaps with the desired data frame at the receiver is transmitted by any node.

We first introduce the basic idea of OFDM system. The OFDM modulation has been verified to be an promising technique for wireless communication. Specifically, instead of transmitting on the frequency-selective wide-band channel, OFDM system transfers the channel into multiple narrow-band channels, called subcarriers. In such modulation mechanism, digital data are encoded over multiple orthogonal subcarriers, where each subcarrier takes part of the payload. Upon receiving those signals, channel equalization is adopted to recover the data message. Further, OFDMA develops the technique by allowing nodes to select one or more subcarrier(s) to send or receive transmission separately. In this paper, the channel contention of RTC is operated in OFDMA mode, where each node can act as transmitter and receiver to contend for the channel, respectively. In the case of data transmission, we note that frequency selective fading will affects the communication in multi-carriers system. However, numerous works are proposed to cope with the this problem and can be deployed in our system directly. For simplicity, we assume that all the subcarriers are always available for data transmission.

INT (information of next transmission) coding scheme [3] is proposed to inform the next intended receiver by embedding INT message into the ongoing transmission. In this case, INT code reception activates the intended node as receiver so that it can assist the transmitter for channel contention. Based on pilot detection and INT modulation mechanism, INT messages can be recovered even if two or more concurrent transmissions are overheard by the involved receiver. In this paper, we adopt the idea of INT coding scheme to inform next intended receivers and then allow them to assist channel contention.

A. *The Overview of RTC*

The overview of RTC is illustrated in Fig. 2, RTC divides the channel contention into M subcontentions. In each subcontention, channel contention time is further operated over four slots: two contending slots, a notification slot and a confirming slot. In each slot, K subcarriers are composed a contention unit, where channel contention operates depending on cooperations among units. Specifically, each new link pair picks up a coordinated subcontention and subcarrier for channel contention. If those new links are detected collision-free during the subcontention period, they will be added into the transmission set of this subcontention and regarded as authorised links in the following contention. Meanwhile, those authorised links occupy the first subcarrier of their own subcontention units and own the highest priority in these subcontention. In this way, potential collisions caused by new link pair will be informed in notification slot and then confirming slot is used to unify the coordination between transmitters and receivers.

Several design issues are required to further discuss. Firstly, in order to enable the link level schedule, transmitter and its corresponding receiver should be well coordinated and integrated as one virtual node (e.g., link) to contend for the channel. It is a challenging to coordinate them with an acceptable overhead. Secondly, the network performance increases linearly with the number of concurrent transmission. Therefore, it is challenging to aggregate the concurrent links as much as possible in each frame set.

B. Design and Detection of Pilot Signal

The design of pilot signal is important to the success of the RTC approach. Firstly, RTC encodes the INT message into multiple pilot positions. Based on each position, pilot signal is embedded with the ongoing data transmission. For the decoding process of INT message, pilot signal should be detected accurately. Moreover, since INT message is transmitted along with data transmission, the detection of pilot signal should be robust against interference. To address those challenges, a 20 Bytes PN sequence is enough for reliable detection, even if the SINR is as low as -16dB [1]. Therefore, we modulate a common 20 Bytes PN sequence into symbols and regards them as pilot signals PS. Additionally, the conjugation of pilot signal $\overline{PS}$ is used to detect the PS,

$$Cor(PS, \overline{PS}) = \sum_{1 \le i \le S_{PS}} PS[i] * \overline{PS[i]}, \tag{1}$$

where S_{PS} is the length of PS. If a spike is detected, we will record the accurate position of each pilot. Due to the random nature of PN sequence, the magnitude of match result between pilot signal and normal data signal should be much lower compared with that of detected spike.

C. Link Schedule based MAC Design

RTC operates the channel contention based on link schedule, where each link is coordinated by the transmitter and its corresponding receiver to contend in a random subcontention. We first introduces subcontention unit based multi-hop channel contention in frequency domain. Then, RTC describes the insight of subcontention unit. Finally, we elaborate on the detailed design of new components in RTC.

1) Multi-hop Channel Contention in Frequency Domain: Back2f [7] firstly provides an operable channel contention mechanism in frequency domain. In such method, Back2f has the capability to divide distinct transmitters into different subcarriers. However, the collision caused by hidden terminals is not considered in the system. Consequently, performance lose is induced by those hidden terminals in multi-hop network.

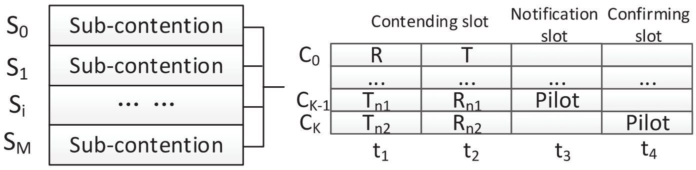


Fig. 3: The overview of RTC.

Compared with Back2f [7], RTC presents an novel backoff count down operation in frequency domain, where both fairness and efficiency are achieved by link level channel contention. Instead of leveraging the index of OFDM subcarrier as integer numbers, as shown in Fig. 3, we packet $K+1$ subcarriers as a subcontention. Thus, each contending link sends pilot signal on a randomly chosen subcontention for contention. The decrement of backoff counter operates one by one in the scale of subcontention. When link l senses that its occupied subcontention is the smallest among the nodes in the vicinity, it implies that link l wins the channel contention and then it transmits frame in the following data transmission period. The link l can be defined as,

$$l(t,r) = \{(x_t, y_t), (x_r, y_r) | (x_t - x_r)^2 - (y_t - y_r)^2 \le R^2\} \tag{2}$$

where (x_t, y_t) and (x_r, y_r) are the coordinates of transmitter and receiver of link l and R is the transmitting range of each transmitter.

2) Insight of subcontention: The efficiency of subcontention is crucial to the success of link schedule design. where authorised links should be sensed and merged into a transmission set during the subcontention period. Note that, each subcontention maintains a transmission set, which is composed by multiple concurrent authorised links. Two types of link are involved in subcontention k: authorised link and new contending link. Specifically, new contending link can be transferred into authorised link only if the new contending link is collision-free with all the authorised links of the transmission set. $\forall l_1, l_2$, two collision-free links are defined as,

$$\begin{aligned} CF(l_1, l_2) = \{(x_{t1} - x_{r2})^2 - (y_{t1} - y_{r2})^2 > R^2 \&\& \\ (x_{t2} - x_{r1})^2 - (y_{t2} - y_{r1})^2 > R^2\} \end{aligned} \tag{3}$$

Further, the authorised link l_s of subcontention k can be defined as,

$$l_s = \{l | \forall l_i \in \mathcal{U}_k, CF(l, l_i)\} \tag{4}$$

where $\mathcal{U}_k$ is the transmission set in subcontention k. Along with the subcontention, each authorised link is merged into $\mathcal{U}_k = \mathcal{U}_k \bigcup l_s$. Clearly, after each subcontention, the size of transmission set is aggregated and all the links in transmission set remain collision-free.

As illustrated in Fig. 3, four slots are used to coordinate link schedule based MAC design, including two contending slots, a notification slot and a confirming slot. In each slot, the first subcarrier can only be occupied by authorised links and the rest K subcarriers are used for new contending link contention. Specifically, in contending slots, receivers and transmitters of authorised links transmit pilot signal in subcarrier C_0 of slot t_1 and t_2, respectively. In comparison, each transmitter of new contending link sends pilot signals on subcarrier i of slot t_1 and the corresponding receiver sends pilot signals in the same subcarrier i on slot t_2. If the transmitter of new contending link senses pilot signal on the subcarrier C_0 of slot t_1 or the receivers sense pilot signal on the subcarrier C_0 of slot t_2, it implies that the new contending link is collided with authorised links. Based on self-interference cancellation technique, if another pilot signal is detected on the same subcarrier except for its own pilot, collision may happen if both of them transmit concurrently. To avoid the potential collisions, RTC avoids these potential collisions by forcing them give up the channel contention in this period. In such mechanism, nodes of collided contending links or potential collided links send pilot signal in its own subcarrier of slot t_3. In confirming slot, if $\sum_{1\leq s<k} x(i, t_4, s, l) = 0$, the collision-free link l, who occupies subcarrier k, will transmit pilot signal. The state of each subcarrier k in slot j of subcontention i is $x(i, j, k, l)$ and l is the transmitted link in network. The algorithm of channel access of RTC in single subcontention unit is described in Algorithm 1.

3) Receiver Tracking Contention: Conventionally, transmission is activated by transmitter and receiver cannot assist for contention until it has been informed by the notification or MAC header decoding. In comparison, RTC provides a novel vision on link based channel contention, where transmitter and receiver operate cooperatively during the contention period. To achieve this issue, two main challenges remain to be further discuss: (1) Receiver should be informed before the beginning of channel contention. (2) When the channel contention is failure in this period, receiver should have the capability to continually track and assist for the channel contention.

Based on INT coding message [3], the intended receivers are informed by spaced pilot signals. Therefore, each involved receiver could assist its corresponding transmitter for channel contention, where contending subcontention and subcarrier are coordinated by decoding the INT message. Nevertheless, If the first coordinated channel contention is failure, transmitter and its corresponding receiver will choose another random subcarrier to recontend. When link occupies the smallest index of subcontention in the vicinity, receiver broadcasts a notification to block the fames sent by other transmitters. However, in [3], only one available link can be survived from multiple conflictive links. RTC further develops a frame aggregation mechanism by the synergy between transmitters and receivers. Specifically, each receiver assists and tracks the subcontention, where authorised links could be merged into a transmission set. Note that, each subcontention maintains a transmission set. In such aggregated mechanism, the transmission set of subcontention is enlarged with the proceeding of channel contention.

Next, through channel contention among multiple subcontentions and contention units, RTC further assigns involved receivers with the capability of tracking channel contention. Specifically, receivers continually assist its corresponding transmitter for channel contention. Note that, existing link pairs have higher access priority than new contending links. In such channel access mechanism, new contending links are not allowed to merge into the transmission set when collisions is detected by RTC. As a result, collision-free transmission set in each subcontention is aggregated step by step.

Algorithm 1: CARTC-SU (Channel Access of RTC in Subcontention Unit)

```
Input: The transmission set $\mathcal{U}$, the index $i$ of
       Subcontention Unit.
Output: The new transmission set $\mathcal{U}'$, The broadcasting
        mark of transmitter $BMT$, The broadcasting
        mark of receiver $BMR$.
$\mathcal{U}' = \mathcal{U}$;
for all $l_s(t, r) \in \mathcal{U}$ do
    Receiver $r$ transmit pilot message in slot $t_1$ of
    subcarrier $C_0$ and slot $t_3$ of subcarrier $C_0$;
    Transmitter $t$ transmit pilot message in slot $t_2$ of
    subcarrier $C_1$ and slot $t_4$ of subcarrier $C_0$;
end
for each new contending link $l_n(t, r)$ do
    Based on INT message, transmitter $t$ and receiver $r$
    picks up a coordinated subcarrier $C_k$;
    Receiver $r$ transmit pilot signal in slot $t_1$ of
    subcarrier $C_k$;
    Transmitter $t$ transmit pilot signal in slot $t_2$ of
    subcarrier $C_k$;
end
for each new contending link $l_n(t, r)$ do
    if $t$ senses pilot signal in $C_0$ then
        $t$ transmits pilot signal in slot $t_3$ of subcarrier
        $C_k$;
    end
    else if $r$ senses pilot signal in $C_1$ then
        $r$ transmits pilot signal in slot $t_3$ of subcarrier
        $C_k$;
    end
    else
        Both $t$ and $r$ transmit signal in slot $t_4$ of
        subcarrier $C_k$;
    end
    $r$ transmits pilot signal in slot $t_3$ of subcarrier $C_0$;
    $t$ transmits pilot signal in slot $t_4$ of subcarrier $C_0$;
end
for each new contending link $l_n(t, r)$ do
    if $\sum_{1\leq s<C_k} x(i, t_4, s, l_n) = 0$ then
        link $l_n(t, r)$ turns into the authorised link.
        $\mathcal{U}' = \mathcal{U}' \bigcup l_n(t, r)$
    end
end
$BMR$ is equal to the state of slot $t_3$ of subcarrier $C_0$;
$BMT$ is equal to the state of slot $t_4$ of subcarrier $C_0$;
```

4) Link Schedule Based MAC Protocol: Compared with conventional channel access mechanism, RTC proposes a novel link based schedule, where transmitter and its corresponding receiver contend for the channel cooperatively. RTC are proceeded subcontention by subcontention and each subcontention maintains a transmission set. Furthermore, two types of links are involved to coordinate in subcontention unit, including authorised link and new contending link. The transmission set is consisted by authorised links and the new contending link can be transferred to authorised link only if the new link is collision-free with any link in transmission set. Specifically, based on receiver tracking mechanism, each new contending link is allowed to detect whether it could transmit concurrently with the transmission set. When the new contending link is available to transmit concurrently, it merges into the transmission set of the subcontention unit. The algorithm of channel access of RTC in multiple subcontention units is described in Algorithm 2.

Algorithm 2: CARTC-MS (Channel Access of RTC in Multiple Subcontentions)

```
Input: The transmission set $\mathcal{U}$, the broadcasting mark
       of transmitter $BMT$ and receiver $BMR$ in all
       subcontentions.
for $i$=0 to $M$ do
    if $BMT_i$ and $BMR_i$ is not NULL then
        if $i$ is the smallest index of non-empty
        subcontention then
            CARTC-SU($\mathcal{U}$, 0);
        end
        else
            CARTC-SU($\mathcal{U}$, i-1);
        end
    end
end
```

III. SIMULATION RESULT

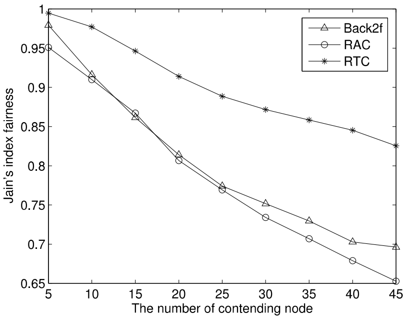
In this section, we evaluate the performance of RTC through an event-driven monitor with 802.11n (e.g. 600Mbps) and the network parameters are shown in TABLE I. Consider all nodes have fully backlogged CBR (Constant Bit Rate) traffic with packet size 1600 Bytes. Simulation results are averaged by 5,000 runs and each run lasts until at least 1000 packets have been transmitted at every node.

Parameter	Value	Parameter	Value
TIMESLOT	9 (us)	Preamble and MAC header	40 (us)
DATA	20 (us)	SIFS	16 (us)
DIFS	34 (us)	ACK	44 (us)

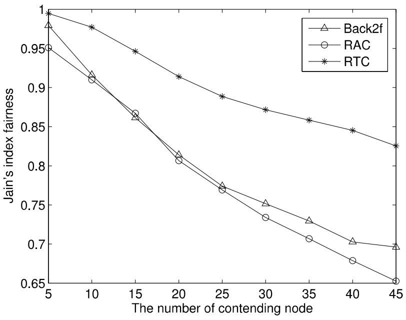
TABLE I: Simulation parameters.

The performance metrics are in terms of throughput and fairness: Throughput gain is defined as $(T_{RTC} - T_{Back2f})/T_{Back2f}$, where T_{RTC} is the throughput when the receiver tracking contention is adopted and T_{Back2f} is that when two rounds Back2f [7] is deployed in network. The normalized Jain's fairness index is also evaluated in our simulation.

Firstly, we compare the performance of RTC with that of RAC and Back2f in simulation. Fig. 4(a) shows the throughput gain of RTC and RAC over Back2f when the SNR is 10 dB and the data transmission rate is 600 Mbps. With the increasing number of contending nodes, the throughput gain of RTC grows up linearly, but the throughput gain of RAC increases gradually. Specifically, when the number of contending nodes is over 30, the throughput gain of RAC is stable on average 143% in simulation. However, the throughput gain of RTC reaches nearly 190% when the contending equal to 45. The performance enhancement is achieved by the avoidance of hidden terminal interference and embedded ACK feedback. Moreover, The concurrent transmitting probability linearly increases with the number of contending node. Therefore, the network performance of RTC and RAC is similar when the number of contending node is small, but the performance gap increases along with the number of contending node increases.



(a) Throughput gain.



(b) Jains fairness index.

Fig. 4: Throughput gain and Jain index of RAC and RTC over Back2f when the number of contending nodes varies from 5 to 45.

In the terms of fairness, a normalized Jain's fairness index is introduced in our simulation. Fig. 4(b) presents the fairness result of RTC, RAC and Back2f with different number of contending nodes. With the increasing number of nodes, the Jain's fairness index of Back2f and RAC decreases from around 0.95 to 0.65. The reason for Baek2F fairness decreasing is caused by interference of hidden terminal and the system is even blocked in some scenarios. In RAC, with the assistance by receiver, hidden terminals are avoided to transmit, but based on the greedy algorithm adopted in RTC, the winners in contending slot will continue to contend in separating slot, where the winner with more nodes in vicinity is likely to lose. Specifically, if the degree of node is only '1', due to high priority of greedy algorithm, the node will always win the contention. As a result, the fairness of RTC is also reduced. In the case of RTC, the fairness index reduces gradually, but RTC keeps a better performance of both Back2f and RAC.

IV. CONCLUSION

Recently, channel contention in frequency domain is widely adopted in wireless network to reduce the coordination overhead. However, collisions caused by hidden terminals greatly limit the performance enhancement. In this paper, we propose an approach RTC to allow receivers for channel contention assistance. The channel contention is operated based on link schedule, where both transmitter and receiver of link attend and contribute cooperatively for the contention. In such cooperation, hidden terminals are avoided and exposed terminals are encouraged to transmit simultaneously. The effectiveness of RTC is verified in simulation, e.g., a 190% throughput gain is achieved.

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