C^2SMA/CA: Enabling Co-Channel Concurrency in WLANs using Positional Information

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***Abstract*—An attractive approach to overcome capacity limitations in a densely deployed WLAN environment is to enable transmission concurrency. In this paper, we propose a co-channel concurrent transmission scheme, referred to as C^2SMA/CA, which determines whether to allow multiple concurrent transmissions based on interference estimation using positional information. A distributed multi-link concurrency scheduling algorithm is implemented, and its performance is evaluated through extensive simulations.**

I. INTRODUCTION

Wireless Local Area Networks (WLANs) today are characterized by their high device density and high bandwidth demands for multimedia services. Consequently, limited capacity has become one of the biggest challenges in such networks.

The Distributed Coordination Function (DCF) scheme defined in the IEEE 802.11 standard is the dominant Medium Access Control (MAC) approach in WLANs due to its simple implementation and distributed nature [1]. However, the inherent Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) mechanism does not always make correct sensing decisions, especially in the presence of exposed and hidden terminals. The Request-to-Send/Clear-to-Send (RTS/CTS) virtual carrier sensing mechanism has been standardized as a solution to tackle the hidden terminal problem at a cost of lower throughput. On the other hand, no recognized solutions exist for the exposed terminal problem which is caused by the overcautious channel assessment for interference estimation at receivers. More specifically, according to the DCF scheme, a transmission is deferred if the node senses the channel as busy. However, in certain cases this new transmission and the ongoing transmission may not generate interference that is severe enough to disrupt the packets at their respective receivers. In other words, many transmission attempts are blocked unnecessarily, leading to the degradation of network throughput.

In order to enhance spatial reuse in WLANs to improve channel utilization efficiency, different approaches have been proposed in the literature, such as smart antennas [2], transmission power control, and carrier sense adaptation [3]. Another novel solution is to enable concurrency of co-channel transmissions when the receptions at their corresponding receivers are not affected by each other. In fact, it is observed that in a dense Wi-Fi network with multiple Access Points (APs), many clients that are associated with different APs are exposed terminals to each other [4]. This observation indicates that the network performance in infrastructure WLANs could be significantly improved by allowing interference-tolerant concurrent transmissions with accurate concurrency-decision-making and smart traffic scheduling.

There have been a few proposals to increase concurrency in wireless networks [5]∼[10]. A novel carrier sensing mechanism, Directional Virtual Carrier Sensing (DVCS), is proposed in [5] to enhance the original access control scheme with directional antennas. A Conflict Map (CMAP) system is proposed in [7], where a reactive channel access scheme first allows nodes to transmit concurrently even if there is a possibility of collisions, then determines whether to prohibit concurrent transmissions based on the observed loss ratios. Similarly, an Interference MAP (IMAP) system is adopted in [8] to consult the opportunity of the concurrent transmission. APs start concurrent transmission to their clients, and keep the concurrent transmission results (delivery ratio) accumulated in the IMAP. [10] introduces symbiotic coding at the transmitters to encourage transmission concurrency, targeting a specific class of collision scenario named asymmetric collisions. Another solution is proposed in [6] to mitigate the exposed terminal problem by identifying exposed links through an offline training process. RTS-Simultaneously (RTSS) and CTS-Simultaneously (CTSS) messages are introduced to provide the coordination of simultaneous transmissions over the exposed links. In [9], the authors propose a Spatial Reuse DCF (SRDCF) scheme based upon the RTS/CTS scheme, which utilizes location information and transmission parameters to make accurate channel assessments and to permit concurrent transmissions by adjusting transmission power. There also exist another group of concurrent transmission schemes, which employ Multiple-Input and Multiple-Output (MIMO) techniques at the physical layer for decoding and interference cancellation of concurrent transmissions [11] [12] [13]. However, in those schemes, multiple antennas are assumed at all nodes including clients in the network, which is unrealistic in current WLAN deployment scenarios.

In contrast to the aforementioned approaches, the scheme proposed in this paper is based on the basic transmission scheme, which is widely used to avoid the high overhead introduced by RTS/CTS. It does not need any maps to record and maintain the statistical results of concurrent transmission attempts. No additional control packets or new coding strate-

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gies are introduced, and neither are directional transmissions or multiple antennas at clients required. The proposed scheme targets at a dense Wi-Fi network scenario with multiple APs sharing the same channel. The concurrency decision is made based on interference calculations using location estimation algorithms at APs [14] [15]. We refer to the scheme as Concurrent CSMA/CA (C^2SMA/CA) since it is based on the original CSMA/CA and enables co-channel concurrency. The C^2SMA/CA scheme keeps the legacy of CSMA/CA and is compatible with traditional transmissions.

The rest of the paper is organized as follows. After the network scenario and assumptions are introduced in Sec. II, the principle of the proposed concurrency scheme is described in Sec. III. The multi-link concurrency scheduling solution is introduced in Sec. IV., followed by the simulation results in Sec. V. Finally, the paper is concluded in Sec. VI.

II. NETWORK SCENARIO AND ASSUMPTIONS

Consider a dense wireless local network with multiple APs sharing the same channel, [1] as shown in Fig. 1. In this network, all APs and clients are in the transmission range of each other. We assume multiple antennas at APs and a *single antenna at clients*, which is the typical configuration in current Wi-Fi networks.

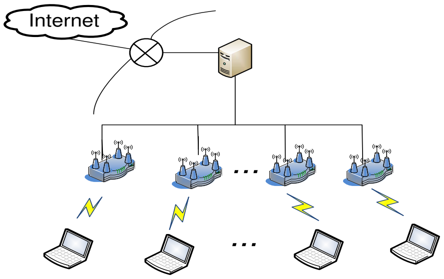

Fig. 1. System Model for Concurrent Transmissions.

We further assume that APs can get the position information of clients associated with them using for example cooperative positional carrier sensing through multiple antenna elements [15] or other methods in the literature [14]. The position information of each client (i.e., direction and distance) is shared among APs through wired connection. Omni-tranmission is assumed at both APs and clients.

In this network, APs listen to the channel and keep track of ongoing transmissions. They are capable of processing multiple-packet reception with interference cancelation to obtain traffic information [16], such as MAC address, packet length as well as Modulation and Coding Scheme (MCS).

III. CONCURRENT TRANSMISSION PRINCIPLE

Based on the observation that concurrent transmissions do not necessarily result in the loss of either colliding packet, we need to identify the opportunities of successful concurrent transmissions and enable them. In what follows, the overview of the proposed C^2SMA/CA scheme is presented first. After that, a double-link concurrency case is taken as an example to explain the concurrency principle. The link scheduling procedure is introduced in the end.

A. Concurrency Scheme Overview

Two key problems for transmission concurrency need to be solved in the proposed C^2SMA/CA scheme: identification of a concurrent transmission opportunity and scheduling of multiple concurrent transmissions.

To allow a new frame transmission despite ongoing traffic on the same channel, the following two criteria must be satisfied:

- The ongoing transmission(s) should not be disrupted by the new one; and
- the new transmission should be successful as well.

With C^2SMA/CA, the above conditions are calculated at the *new* transmitting AP, using the corresponding position and traffic information. If concurrency is allowed even though the channel is busy, C^2SMA/CA will arrange new transmissions according to the proposed concurrency scheduling algorithm. If the concurrent transmission is not allowed, C^2SMA/CA follows the same contention procedure as specified in the legacy CSMA/CA.

B. Concurrency Conditions for the Double-Link Scenario

Two APs (A1 and A2) and two clients (B1 and B2) are set up in the network. Without losing generality, we assume that there is an ongoing frame (DATA1) from A1 to B1, and at the same time, A2 intends to send a packet (DATA2) to B2. Before sending DATA2, A2 needs to calculate the potential consequence of the concurrent transmission based on the provided position information and channel conditions.

According to CSMA/CA, if a receiver decodes the DATA packet successfully, an ACK packet is sent back to the transmitter after a Short InterFrame Space (SIFS). Therefore, four possible concurrency cases might happen if the communication between A2 and B2 takes place concurrently with the communication between A1 and B1, namely, DATA1 with DATA2, DATA2 with ACK1, DATA1 with ACK2, or ACK2 with ACK1, as shown in Fig. 2.

In a given scenario, not all the concurrent transmissions in Fig. 2 are detrimental to data receptions at the receivers. If the data reception at each receiver survives from the interference caused by another transmission, concurrency should be allowed. Assume that the Signal-to-Noise-Ratio (SNR) threshold for each transmission is known at each AP. By calculating the resulted Signal-to-Interference-Noise-Ratio (SINR) values of the packets in each possible concurrency case and comparing them with the corresponding SNR thresholds, we can determine whether a concurrent transmission should be allowed or not.

For example, to allow the concurrency of DATA1 and DATA2 in Fig. 2(a), the following two conditions must be

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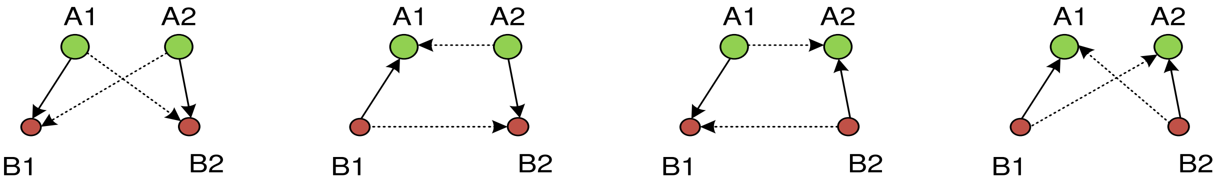
[1] Even in a network where different channels can be assigned to different APs, it is still unavoidable in many cases to have multiple APs sharing the same channel due to the high density of APs and limited number of available channels (e. g., three non-overlapping channels in 802.11b/g).



(a) DATA1 with DATA2 (b) DATA2 with ACK1 (c) DATA1 with ACK2 (d) ACK2 with ACK1

Fig. 2. Possible Concurrency in the Double-Link Scenario.

satisfied in order to have both packets successfully decoded at the receivers:

$$\frac{\frac{P_{A1}G_{A1}G_{B1}\lambda^2}{D_{A1B1}^{\gamma}(4\pi)^2}}{\frac{P_{A2}G_{A2}G_{B1}\lambda^2}{D_{A2B1}^{\gamma}(4\pi)^2}+N_0W} > SNR_{th}(DATA1), \qquad (1)$$

$$\frac{\frac{P_{A2}G_{A2}G_{B2}\lambda^2}{D_{A2B2}^{\gamma}(4\pi)^2}}{\frac{P_{A1}G_{A1}G_{B2}\lambda^2}{D_{A1B2}^{\gamma}(4\pi)^2}+N_0W} > SNR_{th}(DATA2), \qquad (2)$$

where P_{A1} and P_{A2} are the transmission power at A1 and A2; G_{A1}, G_{A2}, G_{B1} and G_{B2} are the transmitting antenna gains at A1 and A2 and receiving antenna gains at B1 and B2, respectively; λ is the wavelength; D_{A1B1}, D_{A2B1}, D_{A2B2} and D_{A1B2} are the distances from A1 to B1, A2 to B1, A2 to B2, and A1 to B2; γ is the path loss coefficient; N_0W is the noise power at the receiver which is assumed to be identical for the whole system; $SNR_{th}(DATA1)$ and $SNR_{th}(DATA2)$ are SNR threshold values in order to successfully decode the DATA1 and DATA2 packets, respectively.

Following the same principle, the concurrency conditions for scenarios in the other three cases in Fig. 2 can be obtained.

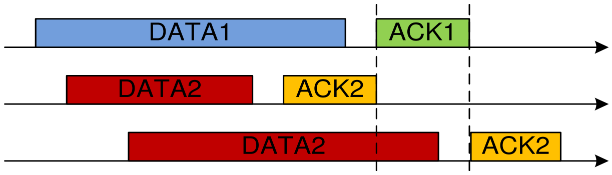
C. Scheduling of the Second Link

Using the results from the previous subsection, we can schedule the secondary transmission according to which Concurrent Transmissions (CTs) are tolerable and which are not.

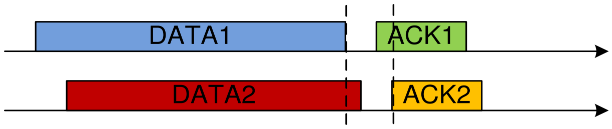
TABLE I
CONCURRENCY DECISION MAKING.

Case	Description	CT
1111	Collision-free transmission	1
1000	Only DATA concurrency	0
1110	No concurrency of ACK1 and ACK2	1
1011	No concurrency of DATA2 and ACK1	1
1101	No concurrency of DATA1 and ACK2	1
1001	Exposed terminals	1
1100	No concurrency of DATA1 and ACK2, ACK1 and ACK2	1
1010	No concurrency of DATA2 and ACK1, ACK1 and ACK2	1
0100	Symbiotic coding [10]	0
0110	Symbiotic coding	0
0010	Symbiotic coding	0
else	No concurrent transmissions allowed	0

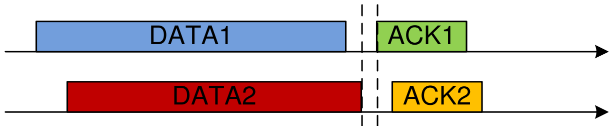
First, we mark each of the cases in Fig. 2 as 1 if the corresponding concurrency criteria are satisfied, otherwise mark it as 0. Consequently, there are 16 possible combinations of different results from the four scenarios in Fig. 2. The description of all the cases is shown in Table I, where Case $X_aX_bX_cX_d$ ($X_i \in 0,1; i \in a,b,c,d$) corresponds to the case that the condition for the concurrency pattern a, b, c, d in Fig. 2 is X_a, X_b, X_c and X_d respectively. With traditional carrier sensing, the second transmission will never be allowed because the nodes are in each other's transmission range. However, with C^2SMA/CA, concurrent transmissions can be enabled in seven out of sixteen cases, as shown in Table I. For a secondary transmission to take place ('1' in the CT field), DATA concurrency has to be supported and ACK transmissions should be allowed after the DATA transmission.



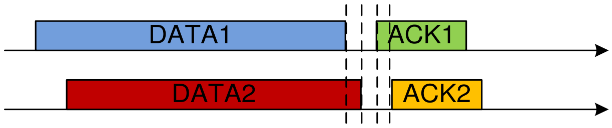
(a) Case 1110: ACK2 finishes before ACK1 or starts after ACK1



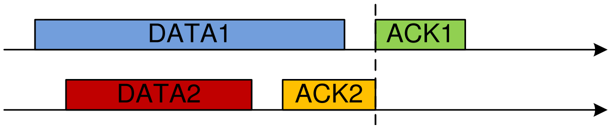
(b) Case 1011: ACK2 starts after DATA1



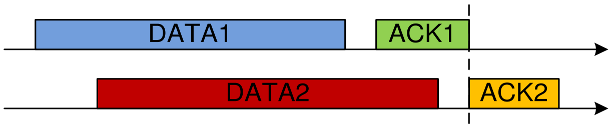
(c) Case 1101: DATA2 finishes before ACK1



(d) Case 1001: ACK2 starts after DATA1, DATA2 finishes before ACK1



(e) Case 1100: DATA2 finishes before ACK1, no ACK concurrency



(f) Case 1010: ACK2 starts after DATA1, no ACK concurrency

Fig. 3. Concurrency Scheduling of the Secondary Transmission.

After identifying potential opportunities of concurrent transmissions, we need to schedule the second transmission to avoid detrimental collisions (indicated as ’0’s). Taking Case 1110 as an example, all concurrent transmissions in Fig. 2 are allowed except concurrent ACK transmissions. Therefore, we need to schedule the second transmission to avoid ACK concurrency, which means that ACK2 has to finish before ACK1 or start after ACK1, as shown in Fig. 3(a). In the second case (Case 1011) shown in Fig. 3(b), the concurrency of DATA1 and ACK2 is detrimental and hence should be prohibited. Therefore, ACK2 needs to be scheduled to start after DATA1. Similarly, the traffic scheduling patterns corresponding to all the other cases with the secondary transmission allowed, are also depicted in the rest of Fig. 3.

The traffic scheduling method is straightforward by using deferring, packet fragmentation or aggregation to follow the concurrency pattern. Indeed, packet deferring and fragmentation are included in the IEEE 802.11 standard [1], while aggregation is included in the 802.11n amendment.

IV. MULTI-LINK CONCURRENCY SCHEDULING

In a dense WLAN network with multiple APs sharing the same channel, the double-link concurrency solution illustrated in the previous section is not sufficient. In this section, the C^2SMA/CA scheme is extended to support multiple link concurrent transmissions.

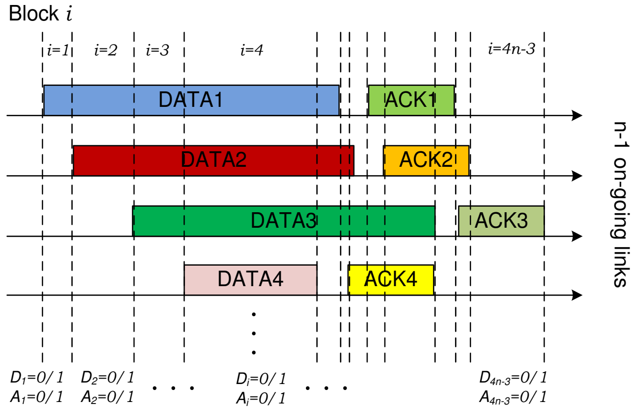


Fig. 4. Multi-link Concurrency Scheduling.

We assume that no new traffic flows arrive at two APs exactly at the same time. The problem can then be generalized as follows. Given n ongoing transmissions, how can an AP with a new frame decide if an additional transmission is allowed, and if so, how to schedule it?

Firstly, we need to analyze the n ongoing traffic patterns along the time axis to locate the time interval when the new data transmission is allowed. Using this available time, new transmissions can be scheduled accordingly. The multi-link concurrency scheduling algorithm is designed as follows.

According to different patterns at each time instance from n ongoing transmissions, time is divided into blocks, as shown in Fig. 4. The concurrency conditions of the new DATA and ACK packets are calculated separately for each time block. D_i and A_i are indicators of the permission of the DATA and ACK transmission in each block i, respectively. For example, if the condition for a new concurrent DATA transmission in block i is satisfied, D_i is set to 1. Otherwise, D_i is 0. The function *DATA-Concurrency-Condition* is described in the following chart. The other function *ACK-Concurrency-Condition* works in a similar way, but allows the ACK transmission instead of the DATA packet transmission in the third step. Besides, no MCS selection is involved in *ACK-Concurrency-Condition*.

Multi-link Concurrency Scheduling algorithm

```
1:  $N \leftarrow 4n$
2:  Divide the time axis into $N$ blocks according to different patterns
    at each time instance from $n$ ongoing traffic information.
3:  for each block $i$ do
4:      $D_i \leftarrow 0$, $A_i \leftarrow 0$
5:      Run function DATA-Concurrency-Condition
6:      if conditiond $= true$ then
7:          $D_i \leftarrow 1$
8:      end if
9:      Run function ACK-Concurrency-Condition
10:     if conditiona $= true$ then
11:         $A_i \leftarrow 1$
12:     end if
13: end for
14: Find the smallest $T_1$ at the time axis, for which there exist $T_2$
    that satisfies:
      1) $T_2 - T_1 > T_{Frag} + SIFS + T_{ACK}$;
      2) when $T_1 < t < T_2 - T_{ACK} - SIFS$, $D_i = 1$;
      3) when $T_2 - T_{ACK} < t < T_2$, $A_i = 1$.
15: if $T_{DATA} > T_2 - T_{ACK} - SIFS$ then
16:     Fragment $DATA_{n+1}$ .
17: else
18:     Aggregate $DATA_{n+1}$ .
19: end if
20: Determine MCS for new transmission (MCSn);
21: Defer transmission til $T_1$;
22: if  new traffic on the channel before $T_1$ then
23:     Reset $n$;
24:     Go to Step 1.
25: else
26:     Transmit $DATA_{n+1}$ .
27: end if
```

Having determined whether the new DATA or ACK transmission is supported in each time block, we need to find and allocate an appropriate time interval to the new frame. However, to study resource allocation and traffic scheduling algorithms is beyond the scope of this paper. In this study, we adopt a straightforward approach to allocate the first qualified time interval to the new transmission, as demonstrated in Step 14 of the scheduling algorithm. In the list of the criteria for the time interval in Step 14, T_{Frag} is the required minimum time interval for data concurrency, and T_{ACK} is the time duration used for ACK transmission. The first criterion indicates that if the available time interval is shorter than T_{Frag}, transmission concurrency is regarded as not worthwhile considering the overhead. T_{Frag} can be configured according to network requirements. The second criterion requires that the new DATA packet has to be supported for at least T_{Frag}, while the third one requires the support of ACK transmission one SIFS interval after the DATA transmission.

Thereafter, as shown in Steps 15 to 19, the DATA packet is fragmented or aggregated if necessary to fit in the time

Function DATA-Concurrency-Condition

```
conditiond ← false, MCSn ← 0
for traffic No. 1 : n do
    Calculate new SINR assuming $DATA_{n+1}$ on the channel.
end for
if SINR of all the $n$ on-going packets is above their respective threshold and Eq. (3) is true with the lowest order MCS then
    conditiond ← true
    MCSn ← the highest order of MCS that satisfies
```

$$\frac{\frac{P_{A_{n+1}} G_{A_{n+1}} G_{B_{n+1}} \lambda^2}{D^{\gamma}_{A_{n+1} B_{n+1}} (4\pi)^2}}{\sum_{i=1}^{n} \frac{P_{A_i} G_{A_i} G_{B_{n+1}} \lambda^2}{D^{\gamma}_{A_i B_{n+1}} (4\pi)^2} + N_0 W} > SNR_{th}(DATA_{n+1}) \quad (3)$$

```
end if
return conditiond, MCSn
```

interval available to the new transmission. The highest order of MCS supported during the time interval is selected in Step 20. The AP node defers its transmission until T_1 and keeps carrier sensing. If there is no new frame sent on the channel by time T_1, the new DATA will be sent according to the schedule. Otherwise, the AP needs to run the whole scheduling algorithm again in order to find a new time interval for its traffic.

V. SIMULATIONS AND PERFORMANCE EVALUATION

The proposed C^2SMA/CA scheme is implemented in MATLAB. The simulation parameters are configured using the IEEE 802.11g standard as a reference. The DATA length is set to be 1500 bytes. The ACK length is 14 bytes, and the duration of SIFS is 16 μs. The transmitting power is set to 20 dBm, the antenna gains are set to 1, and the additive Gaussian noise power is -90 dBm. The adaptive MCS scheme as well as the corresponding SNR threshold values for each MCS to decode packets correctly, SNR_n^{th}, are given in Table II [17].

TABLE II
MODULATION AND CODING SCHEME SET.

Data Rate	6 Mbps	9 Mbps	12 Mbps	18 Mbps
SNR_n^{th} (dB)	6.02	7.78	9.03	10.79
Scope (dB)	<7.78	7.78 ∼ 9.03	9.03 ∼ 10.79	10.79 ∼ 17.04
Data Rate	24 Mbps	36 Mbps	48 Mbps	54 Mbps
SNR_n^{th} (dB)	17.04	18.8	24.05	24.56
Scope (dB)	<18.8	18.8 ∼ 24.05	24.05 ∼ 24.56	>24.56

In our channel model, only path loss and Gaussian noise are considered. The backoff procedure is omitted in our implementation for the sake of simplicity. 1000 transmission trials with random network topologies are made for each simulation run. The network throughput performance is investigated considering different factors, such as the number of concurrent links, network density, and uplink/downlink traffic ratio.

A. Influence of Number of Concurrent Links

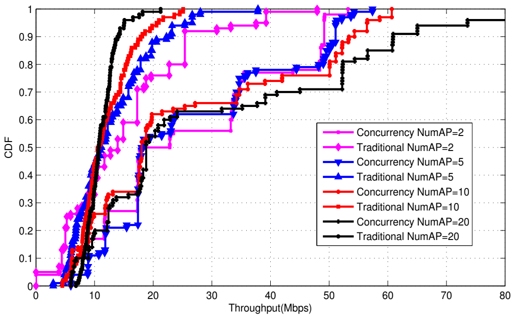


Fig. 5. Throughput CDF with Multiple Concurrent Links.

Different numbers of APs are randomly distributed following the uniform distribution in an area of 50 m× 50 m with γ as 4. Fig. 5 illustrates the throughput CDF of C^2SMA/CA in comparison with the original DCF scheme. The advantage of concurrency transmission over traditional transmission is clearly demonstrated. For example, with traditional transmissions, the throughput of 88 percent of the trials is below 23.4 Mbps and 99 percent is below 41.4 Mbps; whereas with concurrency transmissions, only 50 percent is below 23.4 Mbps and 80 percent is below 41.4 Mbps. A greater percentage of the simulations trials get higher throughput with more APs in the network, because of the higher probability of multiple concurrent transmissions.

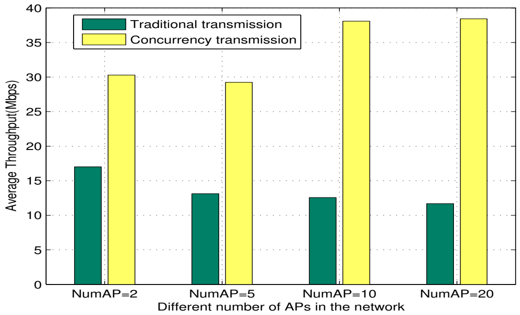


Fig. 6. Average Throughput Comparison with Multiple Concurrent Links.

For a clearer illustration, the average throughput performance is shown in Fig. 6. The throughput gain of the concurrency scheme, defined as the throughput of C^2SMA/CA divided by the throughput of traditional CSMA/CA, is 1.8, 2.2, 3.02 and 3.3 when there are 2, 5, 10 and 20 APs in the network respectively. The improvement becomes less significant when the number of APs increases from 10 to 20. That is because that for a given channel condition, only a limited number of concurrent links can be supported. In a dense network, the number of concurrent links stays stable even when the number of APs increases.

B. Influence of Different Network Densities

The average throughput performance with different network densities is investigated in this subsection. 20 AP nodes are distributed randomly into dense, medium and sparse networks. The network configurations are listed below.

- Dense: 50 m × 50 m, $\gamma = 4$, indoor environments;
- Medium: 200 m × 200 m, $\gamma = 2.6$; semi-open environments;
- Sparse: 1000 m × 1000 m, $\gamma = 2$, outdoor environments.

From the simulation results shown in Fig. 7, it is obvious that the performance of C^2SMA/CA is highly dependent on network scenarios, but outperforms the traditional scheme in all cases. In the dense network scenario, C^2SMA/CA can provide three times as high throughput as CSMA/CA does. However, the benefits of concurrent transmissions are less significant in medium and sparse networks. The reason is that lower probability of concurrent transmissions exists in those networks. The results indicate that C^2SMA/CA works most efficiently in densely distributed environments.

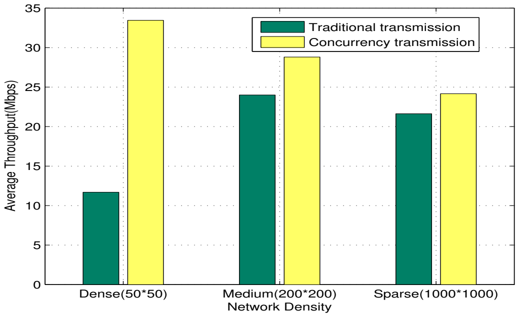


Fig. 7. Average Throughput Comparison with Different Network Densities.

C. Influence of Asymmetric Uplink/Downlink Traffic

The performance of C^2SMA/CA is affected by different ratios of uplink and downlink traffic streams since it only provides concurrency for the new downlink traffic from APs. The simulations are made in a dense network with 20 APs in an area of 50 m × 50 m. As shown in Fig. 8, the average throughput of C^2SMA/CA decreases slowly as the ratio of downlink traffic decreases. In C^2SMA/CA, concurrent transmissions are only decided and initiated at APs where the necessary position and traffic information is available. It is reasonable that the throughput decreases when lighter traffic is initiated from APs with a lower downlink traffic ratio. However, the probability of concurrent transmissions is still considerably high since there are 20 APs in the network. Even with an equal ratio of uplink/downlink traffic, the performance improvement in Fig. 8 is still significant. Therefore, remarkable performance gains are expected with C^2SMA/CA in real-life WLAN scenarios, since the downlink traffic is dominant in most Wi-Fi applications.

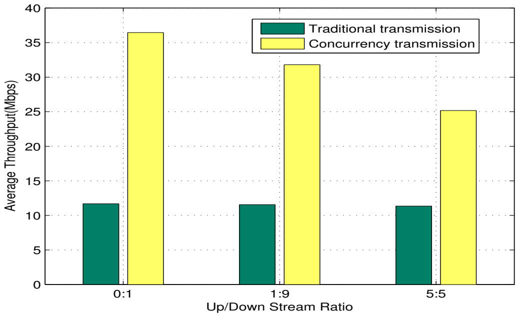


Fig. 8. Average Throughput Comparison with Different Uplink/Downlink Traffic Ratio.

VI. CONCLUSIONS AND FUTURE WORK

In this paper, we have proposed C^2SMA/CA, a concurrency transmission scheme in infrastructure WLANs based on interference estimation using positional information. The simulation results clearly demonstrate the advantage of C^2SMA/CA over its legacy counterpart. Better performance is achieved when more concurrent links are available. In a dense network, three times as high throughput is provided by C^2SMA/CA compared with traditional CSMA/CA, and the benefits are more significant when there is heavier downlink traffic in the network.

In our future work, we will take the impairments from inaccurate position estimations as well as imperfect channel estimation into consideration. Furthermore, the comparison between the proposed scheme and other existing concurrent transmission schemes will also be investigated.

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