Distributed Physical Carrier Sensing Adaptation Scheme in Cooperative MAP WLAN

Yao Hua
Tsinghua National Laboratory for
Information Science and Technology,
Dept. of Electronic Engineering,
Tsinghua University, Beijing China
huay05@mails.tsinghua.edu.cn

Qian Zhang
Dept. of Computer Science, Hong Kong
University of Science and Technology
qianzh@cse.ust.hk

Zhisheng Niu
Tsinghua National Laboratory for
Information Science and Technology,
Dept. of Electronic Engineering,
Tsinghua University, Beijing China
niuzhs@tsinghua.edu.cn

Abstract— **Recently a multiple access point (MAP) architecture is proposed for wireless local area networks (WLAN) to exploit the spatial diversity by permitting each user to associate with multiple APs. Benefited from multiple association, the promising cooperative communication technology can be utilized to further enhance the spatial diversity gain. However, cooperative transmission results in low spatial reuse efficiency with traditional physical carrier sensing (PCS) mechanism. That is because multiple cooperative nodes transmit simultaneously, which causes interference to the adjacent nodes and prevents their transmissions. Therefore the PCS range should be decreased aggressively to support more parallel cooperative transmissions. In this paper, a distributed PCS tuning scheme is proposed to enhance the spatial reuse efficiency in cooperative MAP WLAN. A cooperative node selection scheme is jointly designed to avoid the excessive interference caused by cooperative nodes transmission. Simulation results show that the proposed scheme significantly improves the throughput of cooperative MAP WLAN.**

I. INTRODUCTION

Cooperative communication is an emerging technology to increase spectral and power efficiency, network coverage, and reduce outage probability. Relay-based cooperative transmission has been implemented into wireless local area networks (WLAN) by permitting nodes to relay the overheard data for the users with bad direct link channel quality [1]. Recently, a multiple access point (MAP) WLAN architecture is proposed, where each user can associate with several APs and select one AP with best channel quality for transmission to achieve the spatial diversity [2]. Leveraging the multiple association feature, the more efficient virtual antenna array (VA) based cooperative transmission [3] can be utilized in MAP architecture [10]. In VA-based cooperative transmission, after obtaining the relay data, all of the cooperative nodes (also called VA nodes) transmit simultaneously and their signals are superposed, which remarkably enhances the transmission reliability.

However, introduing cooperative communication in WLAN system brings about the problem of low spatial reuse efficiency. Because of the carrier sensing multiple access (CSMA) mechanism, nodes within the physical carrier sensing (PCS) range of each other share the same spectrum resource. In VA-based cooperative transmission, multiple VA nodes transmit simultaneously which causes interference to the neighboring nodes of each VA node. These nodes have to defer their transmissions to avoid the interference and the spatial reuse efficiency is severely decreased. Consequently, to take advantage of VA-based cooperative transmission in MAP WLAN, the problem of low spatial reuse efficiency must be conquered.[1]

To achieve higher spatial reuse efficiency, PCS adaptation schemes have been widely used in non-cooperative WLAN [5][6]. When the interference level is high, the PCS threshold is decreased so that nodes defer their transmissions more conservatively to avoid the interference. On the other hand, when there are large number of users within the PCS range, the PCS threshold is increased to enhance the spatial reuse efficiency. However, previous PCS adaptation schemes in non-cooperative WLAN cannot be directly adopted in the cooperative WLAN. The reason is that there are multiple candidate VA nodes for each user, and different VA-based cooperative transmissions involve different combination of VA nodes and consequently different PCS settings. What is more, for cooperative transmission, not only the PCS threshold, but also the number of selected VA nodes affects the spatial reuse efficiency. When the PCS threshold is low, more neighboring nodes are deferred by the existing transmission and the spectrum resource is wasted. Therefore, the silenced neighboring nodes should be encouraged to transmit cooperatively to make full use of the wasted bandwidth. In cooperative WLAN, The adaptation of the VA node number and PCS power should be jointly considered.

In this paper, a distributed PCS adaptation scheme is proposed for downlink VA-based cooperative transmission of MAP WLAN. To our knowledge, this is the first work on PCS adaptation in cooperative WLAN. A simple system model is proposed to investigate the impact of PCS threshold and the number of VA nodes on the system performance. Based on the model, a distributed scheme for joint PCS and number of VA nodes adaptation is proposed. Each AP first individually measures its own packet loss rate and channel busy ratio to predict the network status. The PCS threshold and the number of VA nodes are jointly tuned according to the variation of

---

[1] Under high density environment, although there are limited number of orthogonal channels available in existing WLAN system, frequency reuse cannot completely solve the low spatial reuse efficiency problem [4]

978-1-4244-4148-8/09/$25.00 ©2009

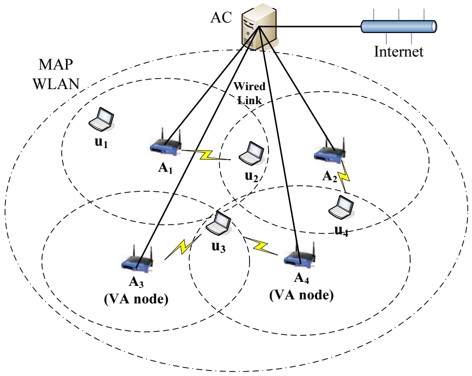

Fig. 1. Multiple-AP architecture.

network status. Finally, a modified MAC protocol based on existing IEEE 802.11 protocol is designed to implement the proposed scheme. Simulation result shows that the system throughput is significantly enhanced by adopting the proposed scheme compared with the non-cooperative WLAN.

The rest of this paper is organized as follows. In Section II, a theoretical model is proposed to illustrate the impact of PCS range and number of VA node on system performance. Based on the model, a distributed PCS adaptation and VA node selection scheme is proposed in Section III. Section IV shows the simulation results. Finally, Section V concludes the paper.

II. IMPACT OF PCS ADAPTATION ON THE SYSTEM PERFORMANCE OF MAP WLAN

A. Multiple-AP Architecture and Virtual Antenna Array (VA) based Cooperation

To exploit the spatial diversity of WLAN system, the MAP architecture was proposed [2]. Fig.1 illustrates the concept. All of the APs are connected to a centralized access point coordinator (AC) via wired line such that all of the APs can coordinate with each other. Leveraging coordination among APs, each user associates with multiple APs and opportunistically selects the one with best channel quality to communicate and the spatial diversity is obtained. The wired line communication can be realized by existing inter-AP communication protocols such as CAPWAP [7].

The multiple association feature of MAP architecture facilitates the implementation of cooperative transmission strategies into WLAN. The general reason is that, each AP is connected to AC and all of the channel state information (CSI) can be aggregated at AC. Based on the CSI, AC decides which APs transmit cooperatively to serve which user to achieve higher system performance. It is also observed that VA-based cooperative transmission is more appropriate for MAP WLAN system, especially for downlink transmission. That is mainly because relay data can be broadcasted to all the VA nodes by wired line transmission, which significantly enhances wireless resource utilization. Another reason is that synchronization among VA nodes can be realized by the coordination of AC.

However, there still exists a fundamental challenge for VA-based cooperative transmission, i.e., the tradeoff between cooperative gain and spatial reuse efficiency. The increase of VA nodes number increases the receiving SINR, while the transmissions of VA nodes incur more interference and reduce the chance of parallel transmissions. Take Fig.1 for example. A_3, A_4 are candidate VA nodes for the transmission of u_3. When only A_3 transmits to u_3, users within the interference range of A_4, e.g. u_4, still have the opportunity to be served simultaneously by other APs, e.g. A_2. If A_4 joins in the VA set, A_2 cannot transmit to u_4 simultaneously. Therefore, A_4 should weigh between the cooperative gain of u_3 and the spatial reuse lost in u_4. To optimize the performance of the VA-based cooperation, the two effects should be jointly considered.

As we have mentioned in Section I, PCS adaptation effectively enhances the spatial reuse efficiency in non-cooperative WLAN. In previous works [5][6], packet loss rate is utilized as the indication of network status. When the packet loss rate of one node is high, its PCS threshold is decreased so that the transmitter is more sensitive to interferers and defers transmission more carefully to avoid interference and vice versa. However, these schemes cannot be directly used in cooperative WLAN. The reason lies in the fact that different VA nodes may have different PCS settings. Apart from that, the number of VA node selection should be jointly considered with the PCS threshold adaptation. As the PCS threshold decreases, more neighboring nodes are deferred. Therefore the number of VA nodes should be increased to make full use of the wasted bandwidth of the deferred neighboring nodes. Therefore a cooperative PCS adaptation scheme is required.

B. System Model

Now a simple model is established to investigate the system throughput performance. Although the optimal parameter settings cannot be derived from the model, the impact of PCS threshold and number of VA nodes on the system performance is observed, which is useful for the parameter tuning.

A multi-cell WLAN system is considered with N APs and M users randomly distributed in a certain area. The MAP architecture is adopted as introduced in Section II-A. Both APs and users are static. The user set and AP set are denoted as $\mathbb{U}$ and $\mathbb{A}$ respectively. Each user can associate with at most n APs for VA transmission. Each combination of the n candidate VA nodes is available for cooperative transmission. We focus on downlink transmission with RTS/CTS mechanism. It is assumed that each device, either AP or user, has only one antenna, but several APs can transmit cooperatively for one user. Essentially each cooperative transmission constitutes a Multiple Input Single Output (MISO) channel with transmitter side CSI. All of the APs have identical transmission power P at reference distance d_0 and work under the same channel. The received signal strength in user u_j from AP A_i is expressed as [8].

$$P_{ij} = GP(\frac{d_0}{d_{ij}})^{\alpha}|h_{ij}|^2 \tag{1}$$

where G is the channel gain constant depending on antenna height and signal frequency. d_{ij} is the distance between AP A_i and user u_j. α is the path loss coefficient. h_{ij} is the channel gain from A_i to u_j. The small scale channel fading is considered and h_{ij} obeys i.i.d. Rayleigh block fading, i.e., h_{ij} keeps constant during each scheme update period T_{up} and vary in different T_{up}.

The higher data rate should be selected when the observed signal to interference plus noise ratio (SINR) is high. However, we cannot simply choose the highest available data rate based on the observed SINR, because RTS/CTS exchange cannot avoid the potential interference from APs out of the communication range of the user. Therefore, a guard power P_h is adopted to combat certain amount of interference. We regulate that the following data rate is selected for the transmission of u_i using the jth VA node combination

$$R_{ij} = W\log\left(1+\frac{\sum_{v\in V_{ij}} P_{vi}}{N_0+P_h}\right),\ \forall i \in \mathbb{U}, \forall j \in V_i \qquad (2)$$

where V_i is set of VA node combinations. The cardinality of V_i is $2^n - 1$. V_{ij} is the set of APs in the jth element of V_i. W is the bandwidth. N_0 is the addictive white Gaussian noise power. By this rate selection, the interference signal weaker than P_h can be overlooked. P_h should be carefully designed because high P_h leads to low data rate while low P_h makes the link vulnerable to interference.

The p-persist model is adopted in the model, which is approved to precisely approximate the MAC behavior of 802.11 WLAN [9]. For analysis simplicity we first assume the user heterogeneity and omit the user suffix in the section. The PCS adaptation scheme proposed in the next section considers the difference of network status for different users. We assume each AP has constant transmission probability p in each slot. P_{cs} is the PCS power threshold of the user. D is the PCS range which satisfies $P_{cs} = GP(\frac{d_0}{D})^{\alpha}|h|^2$. $n_c = \lambda\pi D^2$ represents the number of APs within the range D where λ is the AP density. We assume the ith combination of VA nodes in V has the probability $p_c^{(i)}$ to be selected in any slot. Then the per-user throughput is formulated as follows:

$$S = \sum_{i=1}^{2^n-1} p_c^{(i)} \frac{P_s^{(i)}E[P]}{P_s^{(i)}T_s^{(i)} + T_{busy} + T_{idle}} \qquad (3)$$

where $T_{idle} = (1-p)n_c\sigma$ is the average channel idle period for each transmission. $T_{busy} = (1-(1-p)^{n_c-1})T_c \approx n_c p T_c$ is the average channel busy period for each transmission and $P_s^{(i)} = p(1-p)^{n_c-1}(1-P_L^{(i)})$ is the success probability for the ith combination of VA nodes, $T_s^{(i)}$ and $P_L^{(i)}$ are the transmission time and packet loss rate conditioned that the ith VA node combination is used. $T_c, \sigma, E[P]$ are the duration for one failed transmission, one time slot and one packet length respectively.

It is illustrated from Eq. (3) that, the adaptation of P_{cs}, i.e., the adaptation of D, should weigh between the two parameters P_L and n_c. If P_{CS} decreases, P_L decreases and the value of P_s is increased. On the other hand, n_c increases with the decrease of P_{CS}, which leads to higher T_{busy}. Generally, when P_L is high, the decrease of P_s will be the bottleneck and P_{cs} should be decreased to reduce high packet loss rate. Conversely, the high T_{busy} effects the throughput performance more significantly if P_L is not very high, consequently P_{cs} should be increased to support more parallel transmissions.

The number of VA nodes n should also be carefully designed. Once maximum VA nodes number n increases, the achievable data rate is enhanced and T_s is shortened. On the other hand, the increase of n leads to higher p and consequently longer T_{busy} for their neighboring nodes. The two aspects should be jointly considered for tuning n. This impact can be investigated by observing channel busy ratio for each user. If channel busy ratio of one user is low, the channel resource is not fully utilized and the number of VA nodes should be encouraged to increase and vice versa.

Since the AP density is not evenly distributed in real-world environment, the theoretical optimal settings of PCS threshold and number of VA nodes are difficult to achieve. Therefore, each user should tune its P_{cs} and n in the distributed manner.

III. ALGORITHM DESCRIPTION AND PROTOCOL DESIGN

A. A Dynamic PCS Adaptation Scheme

As we have discussed the impact of PCS threshold and number of VA nodes on the system performance, in this section we focus on how to adjust the two parameters to achieve high spatial reuse efficiency. We should first investigate which metrics can be used to indicate the tuning of PCS adaptation and number of VA nodes. As we have mentioned above, the following two metrics are good candidates to demonstrate the status of each node.

Packet Loss Rate: packet loss rate (P_L) is generally used for PCS adaptation. When P_L is high, the interference level is high and the PCS threshold should be reduced such that the transmitter is more sensitive to interference to prevent the potential packet loss. If P_L is low, the PCS threshold should be increased since the number of parallel transmissions is increased without incurring too much packet loss.

Busy Ratio: busy ratio (T_b) is defined as the proportion of time that a transmitter is deferred by the transmission of its neighboring nodes. The busy ratio is generally used for the adaptation of n. If T_b is low, the traffic load in the vicinity of the transmitter is low. Therefore the idle neighbors are more encouraged to transmit cooperatively with the transmitter and the number of VA nodes n should be increased and vice versa.

P_L should be considered for the choice of the number of VA nodes n. If P_L is high, the node should increase n to encourage the interfering nodes to join in the VA node set and vice versa. Notice that the intensives to increase n are different for high P_L and low T_b, therefore the conditions should be logic OR. On the other hand, if T_b is high, the traffic load in the neighboring nodes is high, and n should be decreased to avoid capturing the resource of the busy neighboring nodes. However, if P_L is already very high at the same time, the cooperative transmission is not reliable and n should not be encouraged to decrease. The two conditions should be satisfied simultaneously.

The procedure of the proposed PCS adaptation scheme.

```
1:  Initialize: $P_{min}$, $P_{max}$, $B_{max}$, $B_{min}$, $\triangle_{CS}$, $T_{up}$ ,$\delta$
2:  $T$=$T_{up}$;
3:  Measure $P_L^{(i)}$ and $T_b^{(i)}$ for each node $i$
4:  if $T \neq 0$ then
5:      $T = T - 1$;
6:  else
7:      for $i = 1; i \leq N; i = i + 1$ do
8:          if $P_L^{(i)} \geq P_{max}$ then
9:              $P_{cs}^{(i)} = P_{cs}^{(i)} - \triangle_{CS}$
10:         else if $P_L^{(i)} \leq P_{min}$ then
11:             $P_{cs}^{(i)} = P_{cs}^{(i)} + \triangle_{CS}$
12:         end if
13:         if $T_b^{(i)} \geq B_{max}$ && $P_L^{(i)} \leq P_{min}$ then
14:             $n_i = \max(1, n_i - 1)$
                $P_{cs}^{(i)} = P_{cs}^{(i)} + \delta\triangle_{CS}$
15:         else if $T_b^{(i)} \leq B_{min}$ | | $P_L^{(i)} \geq P_{max}$ then
16:             $n_i = \min(\mathrm{V}_{\max}, n_i + 1)$
                $P_{cs}^{(i)} = P_{cs}^{(i)} - \delta\triangle_{CS}$
17:         end if
18:     end for
19:     Return to 2;
20: end if
21: Return to 4;
```

Last, if n increases, the transmission of the user incurs more interference. Consequently its PCS threshold is decreased to avoid interference to neighboring links and vice versa.

To implement the scheme, we first set the upper and lower thresholds of packet loss and busy ratio for future PCS tuning. If the measured metrics are below or above the thresholds, the corresponding PCS and VA node adaptation is triggered. The algorithm should be done by each AP periodically in each update period T_{up}. T_{up} should be less than the channel coherence time such that the adaptation of parameters n and P_{CS} can keep up with the variation of wireless environment. Then a distributed joint PCS and VA node adaptation scheme is proposed as the following table shows, where P_{min}, P_{max}, B_{max}, B_{min} are the tuning thresholds of P_L and T_b respectively. $\triangle_{CS}$ is the PCS threshold tuning granularity. $\delta\triangle_{CS}$ is the tuning granularity of PCS threshold when varying n. The parameters are trained to achieve high performance and rapid convergence process. Take P_{min} for example, an 8-AP topology is adopted. All the other parameters are fixed. By varying the value of P_{min}, the value of P_{min} to achieve optimal system performance is obtained. The rest of the parameters are optimized sequentially (although we cannot guarantee the global optimization of parameter setting by this manner). The trained values of the thresholds are listed in Table I. An appropriate value of maximum number of VA nodes $\mathrm{V}_{\max}$ is 3, the reason of which refers to [10].

B. MAC Protocol Design

In this section a MAC protocol is designed based on the modification of existing IEEE 802.11 protocol to implement the proposed schemes. The MAC protocol is divided into the following four stages: association process, cooperation decision, cooperation preparation and cooperative transmission. The MAC process is illustrated in Fig.2.

Association Process: AC first utilizes the scheme proposed in Section III to update the parameters n and P_{CS} based on the metrics value in the last update period. The tuned parameters are broadcasted to the APs in the system. Each user measures the signal strength of beacon packets from all of the APs and informs the CSI to AC. AC selects n APs with strongest signal strength to associate with the user. Then each AP maintains the association table to record the associated users that can be served for VA-based cooperative transmission.

Cooperation Decision: cooperation decision is made for each packet. When one downlink packet arrives, the MAC goes into the contention state which is regulated by distributed coordination function (DCF) [11]. Once the packet captures the transmission opportunity, the system automatically decides which of the associated APs play as VA nodes. First, AC selects the AP with best channel quality to initiate the RTS packet. When the CTS packet is sent back successfully from the user, each candidate VA node receiving the CTS packet notifies AC its idle state and the measured channel gain by VA request signalling. Then, all of the idle candidate VA nodes become VA nodes and transmit cooperatively with the data rate calculated by Eq.(2).

Cooperation Preparation: as cooperation decision has been made, three crucial works should be finished to prepare for the VA-based cooperative transmission, i.e., relay data dissemination, VA nodes synchronization and channel reservation. In MAP architecture, the relay data is transmitted to each of the VA nodes via wired line. After relay data dissemination, AC broadcasts a specific synchronization signaling to all the VA nodes to indicate the start transmission time for synchronization. The format and the functionality of the synchronization signalling should refer to [10] due to space limitation. The channel reservation is realized by the PCS mechanism. When any AP is in the idle state, it goes into busy state as long as the measured signal strength is above its own P_{CS}.

Cooperative Transmission: once cooperation preparation has been operated, all of the informed VA nodes start cooperative transmission simultaneously at the time regulated by synchronization signaling with the date rate computed by Eq.(2). After successful reception, the user returns an unicast acknowledge packet back to the AP with best channel quality.

IV. PERFORMANCE EVALUATION

In the section we adopt discrete time event simulation to verify the effectiveness of the proposed PCS adaptation and VA node selection scheme.

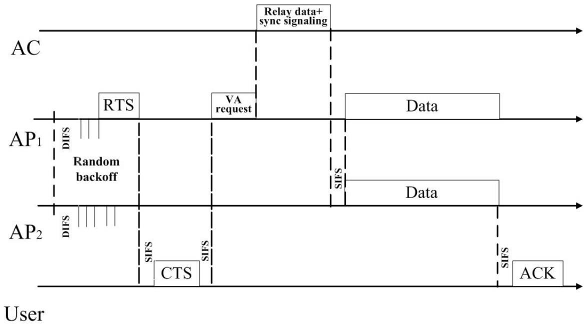

Fig. 2. MAC procedure.

TABLE I
SIMULATION PARAMETERS.

parameters	value	units
P	100	mW
N_0	0.0001	mW
P_{min}	0.2	
P_{max}	0.6	
B_{min}	0.2	
B_{max}	0.5	
δ	0.95	
$\triangle_{CS}$	1.2	
Packet size	1000	Bytes

A. System Setup

Our simulation is based on random topology, where all the APs and users are randomly distributed in a 100 × 100 meter square area. Each end user is assumed to have saturated traffic demand. IEEE 802.11a protocol is adopted [11]. The simulation parameters are listed in Table.I. The default value of α is four and T_{up} is 100 milliseconds, which are the typical value for indoor environment [8].

We compare the proposed scheme with the standard 802.11 DCF function [11]. The cooperative scheme is also divided into two parts, the first one with only PCS adaptation and the second one with both PCS and number of VA nodes adaptation. The simulation result is averaged for 10 different topologies and each topology with 40 update periods.

We first testify the convergence of the proposed distributed scheme in Section III to guarantee the scalability. Then the setting of the parameter P_h is determined. The system performance versus AP density and the traffic load are given to observe the performance gain of the proposed schemes in different wireless environment.

B. Simulation Results

We first verify the convergence of the proposed distributed algorithm. A 20-AP topology is adopted. We run the two schemes iteratively and calculate the average PCS power threshold in each step to demonstrate the variation of the PCS thresholds. It is clearly shown from Fig.3 that the proposed adaptive PCS tuning scheme quickly converges to the stable PCS threshold without much fluctuation. The result demonstrates that the distributed scheme can converge to the stable operation point which guarantees the system scalability.

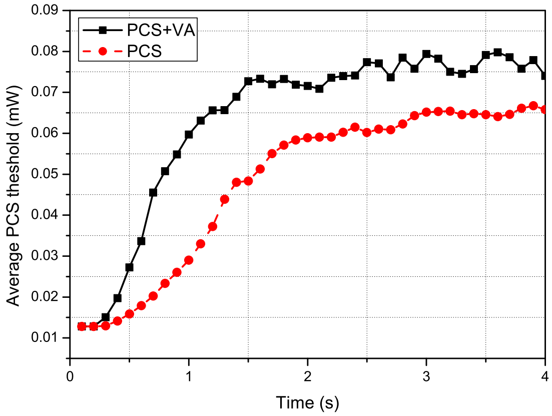

Fig. 3. Iteration convergence of PCS adaptation.

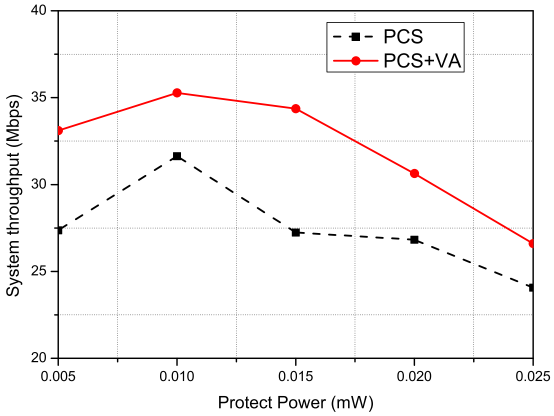

Fig. 4. The impact of guard power value.

We also notice that, for the scheme with number of VA nodes selection, the converged PCS threshold is higher than that without VA node selection. That is mainly because the smart VA node selection guarantees the transmission robustness and consequently provides more aggressive spatial reuse.

The setting of guard power P_h significantly affects the system performance. We still adopt the 20-AP topology to observe the variation of overall throughput with different P_h. It is demonstrated from Fig.4 that the highest system performance is achieved when P_h is 0.01mW for both two cooperative schemes. Too high and too low guard power can cause pessimistic or optimistic estimation of interference. In the rest of the simulation P_h adopts the optimal value we get during the simulation.

The impact of AP density on the proposed PCS and number of VA nodes tuning scheme is discussed. The number of APs in the system varies from 12 to 36. The aggregate throughput of the three schemes are compared in Fig.5. It is shown from the figure that, the traditional 802.11 DCF mechanism always has poor performance compared with the two proposed schemes. That is mainly because the default PCS threshold is very low and all of the APs have to share the same spectrum resource. The PCS adaptation in the proposed schemes effectively increases the number of concurrent transmissions and conse-

978-1-4244-4148-8/09/$25.00 ©2009
This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE "GLOBECOM" 2009 proceedings.

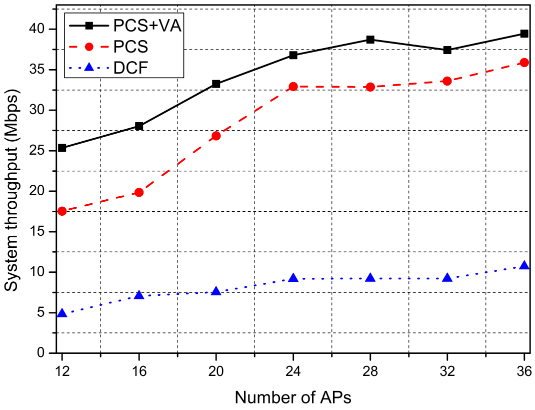

Fig. 5. Aggregate throughout versus user density.

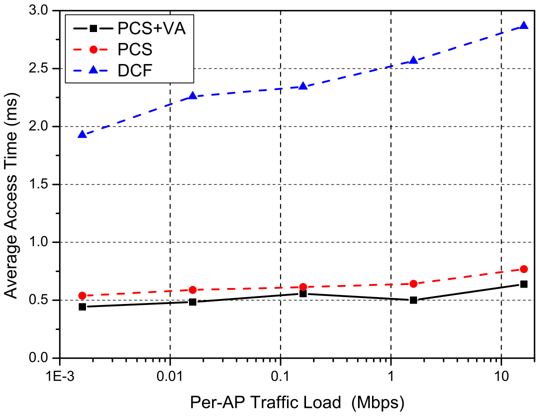

Fig. 6. Aggregate throughout versus traffic load.

quently enhances the spatial reuse efficiency. The utilization of the number of VA nodes tuning can further improve 20% throughput performance compared with that without VA node selection. That is mainly because the adaptive VA number selection can either avoid the excessive interference induced by large number of VA nodes or take full use of the wasted bandwidth of deferred APs.

Finally the impact of traffic load on the channel access time is observed. The number of AP is again fixed to 20. Then we vary the traffic load of each AP from 1.6Kbps to 16Mbps. It is illustrated in Fig.6 that both PCS and number of VA nodes tuning schemes have far shorter access delay than the DCF function. The reason is two-folded. When the traffic load is light, the interference is low and the cooperative network can invite more idle neighbors to enhance cooperative gain in cooperative transmission. Therefore the access delay is significantly decreased compared with the non-cooperative scheme. As traffic load goes up, the access delay does not increase obviously in the two proposed schemes neither, which is due to the interference cancelation by the PCS adaptation.

V. CONCLUSION

The VA-based cooperative transmission is utilized in MAP architecture to enhance the spatial diversity gain in WLAN. However, the severe spatial reuse inefficiency constrains the system performance. In this paper, a distributed PCS threshold tuning scheme combined with cooperative node selection has been proposed to enhance the spatial reuse efficiency. Simulation results show that by joint PCS and VA nodes number tuning, the aggregate throughput can be improved over 100% compared with non-cooperative WLAN. Also, the distributed scheme is proved to converge quickly to the optimal value so that the system scalability is guaranteed.

VI. ACKNOWLEDGMENT

The research was supported in part by grants from RGC under the contracts CERG 622508 and N_HKUST609/07, by grant from HKUST under the contract RPC06/07.EG05, by grant from ITC HK ITP/023/08LP, the grant from Huawei-HKUST joint lab, the NSFC oversea Young Investigator grant under Grant No. 60629203, the Foundation of Scientific and Technological Planning Project of Nansha District, Guangzhou, China, the National Basic Research Program of China (973 Program: 2007CB310607), NSFC-RGC joint program(60731160631) and the International ST Cooperation Program of China (ISCP) (No. 2008DFA12100).

REFERENCES

[1] P.Liu et. al., "CoopMAC:A Cooperative MAC for Wireless LANs," *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 2, Feb. 2007.

[2] Y. Zhu, Z. Zhou, B. Tan, Z. Niu, Q. Zhang and J. Zhu, "Leveraging Multi-AP Diversity for Transmission Resilience in Wireless Networks: Architecture and Performance Analysis", to appear in *IEEE Transactions on Wireless Comminications*, 2009

[3] G. Jakllari, S. Krishnamurthy, M. Faloutsos, al. " A Framework for Distributed Spatio-Temporal Communications in Mobile Ad hoc Networks",*Proc. IEEE INFOCOM*, April. 2006.

[4] A.Akella, G. Judd, S. Seshan, and P.Steenkiste, "Self-Management in Chaotic Wireless Deployments," *Proc. ACM MobiCom'05*, August 28-September 2, 2005.

[5] Y. Zhu, Q. Zhang, Z. Niu, and J. Zhu, "On Optimal Physical Carrier Sensing: Theoretical Analysis and Protocol Design", *Proc. IEEE INFOCOM mini synpotum*, April. 2007.

[6] J. Zhu, B. Metzler, X. Guo, and Y. Liu, "Adaptive CSMA for Scalable Network Capacity in High-Density WLAN: a Hardware Prototyping Approach", *Proc. IEEE INFOCOM 2006*, April, 2006.

[7] IETF draft, *"CAPWAP Protocol Binding for IEEE 802.11"*, draft-ieft-capwap-protocol-binding-ieee80211-06.

[8] T. Rappaport, *Wireless Communications: Principles and Practice*, Upper Saddle River, N.J. : Prentice Hall PTR, 1996.

[9] G. Bianchi, "Performance analysis of the IEEE 802.11 Distributed Coordination Function", *IEEE Journal on Selected Areas in Communications*, vol. 18, pp. 535-547, Mar. 2000.

[10] Y. Hua, Q. Zhang and Z. Niu, A Cooperative MAC Protocol with virtual-antenna array Support in Multi-AP WLAN System, to appear in *IEEE Transactions on Wireless Comminications*, 2009

[11] Wireless LAN medium access control (MAC) and physical layer (PHY) specifications: high-speed physical layer in the 5 GHZ band,*IEEE,* 1999.