Collision Reduction in Cognitive Wireless Local Area Network over Fibre

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***Abstract*—Cognitive wireless local area network over fiber (CWLANoF), which employs remote antenna units (RAUs) connected to a central cognitive access point through optical fibres, can provide a cost-effective and efficient architecture for devices to equally share the industrial, scientific, and medical band by taking advantage of cognitive radio capabilities. Based on the CWLANoF architecture, we propose two methods to reduce collisions among stations, with multiple independent channels operating at each RAU, and transmitter and receiver diversity through cooperation of adjacent RAUs. Multi-channel-operation method is enabled by wide-band optical fibres and diversity method is enabled by distributed RAUs in the CWLANoF architecture. Extensive simulations show substantial improvements in Transmission Control Protocol throughput and packet error rate reduction of constant-bit-rate traffic streams, especially under dynamic traffic conditions.**

Keywords- cognitive radio; radio over fibre; WLAN; diversity; capture effect

I. Introduction

Wireless local area networks (WLANs) are widely used for connecting computing equipment in homes and offices to the Internet. Cognitive wireless local area network over fiber (CWLANoF) is a new architecture [1] that applies advanced cognitive radio [2] and broadband radio over fiber (RoF) [3] technologies to infrastructure-based IEEE 802.11 WLAN Extended Service Sets (ESSs) comprised of multiple access points (APs), each forming its own Basic Service Set (BSS). This architecture is intended to provide centralized radio resource management and access control through cooperative spectrum sensing.

Since WLANs share the industrial, scientific, and medical (ISM) band with other independently-operated license-free devices such as Bluetooth radios and microwave ovens, they must tolerate interference from these devices. Cognitive radio techniques have been recently proposed for secondary users to exploit spectrum holes left unused in licensed frequency bands by primary users of the allocated spectrum. In this paper, we exploit cognitive radio techniques in the CWLANoF architecture for equal access in the license-free ISM band to enhance system performance via spectrum sensing, interference avoidance and coexistence.

Successful simultaneous transmissions of multiple WLAN channels over low-cost multi-mode optical fibres [4]-[7] and clarification of WLAN medium access control (MAC) operation in RoF structures [8]-[10] motivate the proposal of CWLANoF as an architecture that offers huge potentials to increase system capacity and improve quality-of-service. The ever-decreasing cost of optical fibers and wavelength-division multiplexing components has resulted in commercial fiber-based indoor wireless networks being deployed to penetrate large buildings such as stadiums [11], hospitals [12], business buildings and shopping malls [13]. It would be expensive to cover these buildings with cable-based networks due to the ever-increasing cable cost. It is also difficult to monitor and manage the radio environment within such large buildings if antennas cannot be efficiently coordinated. The success of these commercial indoor wireless networks further demonstrated potential markets for CWLANoF networks.

In this work, we focus on how to reduce access collisions in a WLAN through methods made possible by the CWLANoF architecture, which would be difficult if not impossible to realize in a conventional WLAN.

In a conventional WLAN, each AP performs carrier sensing independently and only over the channel it operates on. In contrast, CWLANoF applies cognitive radio techniques to enable a WLAN ESS to more efficiently utilize the ISM band. The centralized architecture of CWLANoF systems enables cooperative sensing and consequently reduces the interference detection time while improving the detection accuracy. Moreover, the multi-channel carrying capability of advanced broadband RoF systems can significantly increase available radio resources at each WLAN AP. By implementing dynamic radio resource management based on accurate spectrum sensing, interference avoidance or mitigation can be easily accomplished. Effectively, the CWLANoF architecture enables the new concept of applying cognitive radio techniques for equal spectrum access in the ISM band.

In a conventional WLAN, each AP has an 802.11 radio modem and is digitally bridged to the distribution system, usually an 802.3 Ethernet. In a CWLANoF, radio modems and bridges in the APs are moved to a centralized unit referred as the *cognitive access point* (CogAP); the resulting simplified APs are now named as *remote antenna units* (RAUs). RAUs are connected to the CogAP via analog radio frequency signals transmitted over optical fibers. By centrally processing broadband RF signals received from the RAUs, the CogAP has a complete picture of the radio spectrum usage in the coverage area of the WLAN ESS. The Distributed Coordinated Function of 802.11 MAC employing carrier-sensed multiple access with collision avoidance (CSMA/CA) is carried out at the CogAP instead of at individual APs as in a conventional WLAN. These changes enable a CWLANoF to more effectively combat packet collisions that inevitably occur over a random-access channel. A typical CWLANoF system and the structure of the CogAP are illustrated in Fig. 1.

The paper is organized as follows. In Section II, we review related work on how to improve WLAN system capacity. In Section III, two methods are proposed to reduce collisions among WLAN stations: *load balancing* to reduce collisions caused by heavy traffic, and *transmitter and receiver diversity* to reduce the effects of collisions. The performance of proposed methods is evaluated through extensive Monte-Carlo simulations in Section IV. We conclude by summarizing the paper and discussing future work in Section V.

II. Related Work on WLAN

Much recent research on WLANs aims to increase system capacity of individual WLAN BSSs, and reduce co-channel interference (CCI) and adjacent-channel interference (ACI) among BSSs in WLAN ESSs.

The system capacity of a WLAN BSS can be increased through three methods: enhancing existing MAC protocols by either adjusting parameters or adding new MAC flavors to achieve a higher MAC efficiency, exploiting capture effects, and introducing multiple-input, multiple-output (MIMO) to exploit spatial multiplexing. Enhancing the WLAN MAC protocol usually requires an update of station hardware or firmware. We therefore mainly review recent advances on exploiting capture effects and employing MIMO in WLAN.

The capture effect has been initially studied within the context of an ALOHA network [14]. It refers to the fact that when two packets arrive at one station at the same time, the packet with stronger signal strength will be synchronized and "captured" by the station. Luo and Ephremides [15] showed that with the capture effect, system throughput is maximized when all nodes transmit at maximum power. This conclusion, however, is based on an optimistic assumption that any packet can be successfully received as long as it has the highest power level at the receiver, regardless of how many overlapping packets are being received at lower power levels. After taking interference into account, Hadzi-Velkov and Spasenovski investigated the capture effect and its interaction with RTS/CTS (request to send/clear to send) in 802.11b networks [16]. Kochut *et al*. studied the capture effect by comparing system throughput at the physical and transport layers in 802.11b networks [17]. Their comparisons showed that capture effect is magnified through variations of contention window size in the MAC layer and congestion window size in the Transmission Control Protocol (TCP) layer. Based on Bianchi's model [18], WLAN performance is derived in [19] by considering the capture effect. Capture effect and successive interference cancellation were later studied in a direct sequence spread spectrum (DSSS)-based ZigBee network [20].

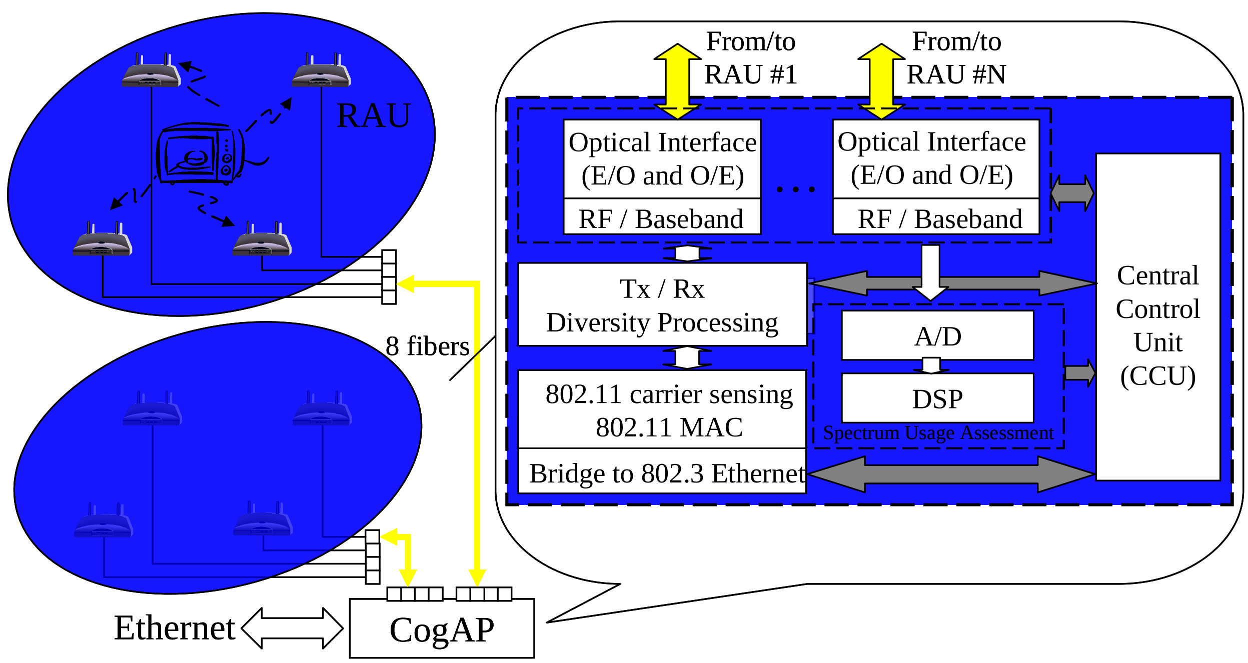


Fig. 1 A typical CWLANoF system and CogAP structure. E/O: electrical-optical converter. O/E: optical-electrical converter.

Capture effect in 802.11a networks was studied in [21][22] through real-world experiments using commercial WLAN devices. It was shown that with an arrival time difference of up to 50 μs, the stronger 802.11a packet can still be captured. Different from previous 802.11b capture effect studies where the stronger frame has to arrive within the preamble time of the weaker frame, this observation suggests that even when the arrival time difference of two packets is larger than the preamble length of the first packet, the stronger packet could still be captured. Such phenomena have been observed in commercial 802.11a/b/g adapters working in either DSSS mode or orthogonal frequency division modulation mode.

The capture effect was further exploited in the form of "message in message" (MIM) to increase system throughput [23][24]. The AP sends the message with smaller channel gain first and the message with larger channel gain later such that the weaker packet's preamble can be successfully locked by one recipient and the stronger packet can also be locked by another recipient. The AP abuses CSMA rule and stations use delayed ACKs. Using MIM requires the AP to update the system interference map periodically.

Exploiting diversity in WLAN is classified into micro-diversity and macro-diversity. The IEEE 802.11n standard is developed to enable micro-diversity in WLANs using MIMO. Previous work on macro-diversity includes the concept of distributed radio bridges proposed in [25] and their subsequent applications in WLAN [26][27].

A WLAN ESS is a multi-cell WLAN system in which the WLAN controller assigns channels and sets maximum AP transmit power to different BSSs to reduce CCI and ACI among them. Sub-optimal radio resource management algorithms have been extensively studied for this purpose. These algorithms address three basic problems: channel allocation across APs [28], user association (or load balancing) [29], and AP transmit power control [30]. The conflict set coloring method jointly optimizes channel allocation and load balancing [31]. Measurement-driven guidelines in [32] provide a heuristic method to jointly address the three basic problems. However, due to the limited number (usually one) of channels that each BSS can support, these algorithms have limited abilities to handle dynamic traffic, and become extremely complicated when channel allocation, load balancing and AP transmit power control are jointly considered. Authors of [33] investigated how to coordinate MAC mechanisms across multiple APs in the ESS by switching from contention-based access to time-slotted access when the ESS is heavily loaded with audio and video streams. The MAC switching reduces packet collisions and thus provides better quality-of-service for multimedia streams. However, the signaling protocol required by the AP coordination was not given in [33].

III. Collision Reduction

A collision happens when two stations access the channel at the same time, or when one station fails to sense an on-going packet transmission due to fading or hidden terminal problem and starts a new transmission. Based on the CWLANoF architecture, in this paper we propose a load-balancing method to reduce collisions caused by heavy traffic, and a transmitter and receiver diversity method to reduce the impact of packet collisions by increasing the chance of successful reception. The two methods used to reduce collisions in CWLANoF are illustrated in Fig. 2.

A. Load Balancing Method

A practical load balancing technique facilitated by the CWLANoF architecture is to distribute the total traffic load in the frequency domain. The broadband RoF connection between each RAU and the CogAP allows more than one channels to be allocated to any RAU. Consider the case of two RAUs covering a given area: RAU1 operates on the channel f_1 and RAU2 operates on f_2. When the collision rate on f_1 is higher than a target threshold, the CogAP can use the "disassociation" process to force some of the stations to be dissociated from this channel, while simultaneously sending beacons on a different channel f_3. Stations dissociated from f_1 will then have two options. If a dissociated station receives beacons on channel f_2 from RAU2, it can request to associate with RAU2 on this channel. This effectively transfers a portion of the traffic load of RAU1 to RAU2, creating a distributed load balancing solution among RAUs. Alternately, a dissociated station will receive beacons on channel f_3 from RAU1, and request to associate with RAU1 over this channel. In this case, load balancing occurs over the frequency domain within the same RAU, where a portion of the traffic at RAU1 is switched from overloaded channel f_1 to channel f_3. The second case is particularly made possible by the broadband RoF connections between RAUs and CogAP. In contrast, conventional WLAN APs are generally not equipped for multi-channel operations.

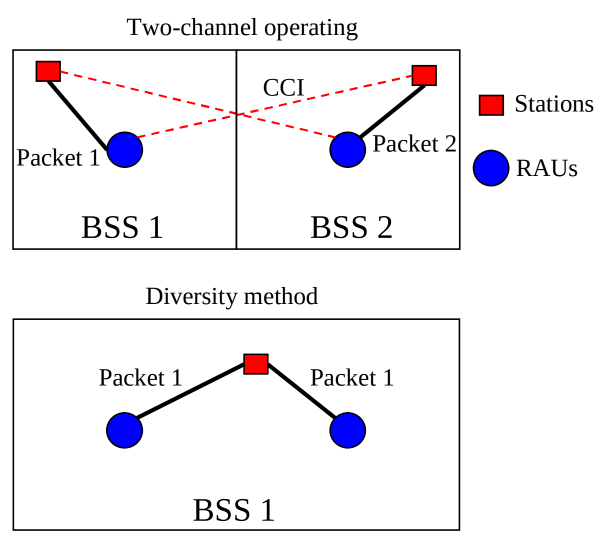


Fig. 2 Collision reduction: diversity and two-channel-operation

The gain in system throughput in the above example is two-fold: one from increased MAC efficiency due to decreased contention among stations accessing the same channel, and another from the use of three channels instead of two. We are more interested in the latter owing to its potential of linearly increasing system throughput. However, to fairly compare a CWLANoF with a conventional WLAN, we investigate the worst case where the new channel assigned to RAU1 is the same as that assigned to RAUs, i.e., f_2. We shall examine the throughput gain that can be achieved in the presence of co-channel-interference on f_2.

WLAN operations on f_1 and f_2 can be independent and as such we refer to this load-balancing method as *multiple-independent-channel-operation*. Let us compare a two-AP conventional WLAN, where AP1 operates on f_1 and AP2 operates on f_2, with a two-RAU CWLANoF, where RAU1 operates on f_1 and f_2 and RAU2 operates on f_2. We can certainly focus on the throughput on f_2. It is clear that the CWLANoF provides the worst throughput on f_2 when the spatial frequency re-use is impossible, i.e., when all stations associated on f_2 can perfectly hear each other. We now argue that even in such a situation, the CWLANoF could provide a higher throughout than a conventional WLAN. For simplicity, we only consider downlink traffic. In the conventional WLAN, AP2 can only send one data packet at a time. In the CWLANoF with RAU1 and RAU2 independently operated, they might simultaneously send two data packets on f_2. Owing to capture effects, the two packets may both survive from the collision, thus generating a throughput gain.

B. Transmiter and Receiver Diversity Method

Besides operating channels independently, the CogAP can also manage channels to exploit macro-diversity since signals received from widely separated RAUs tend to be uncorrelated. If each RAU is also equipped with multiple antennas, we can further implement micro-diversity in conjunction with macro-diversity. However, if we keep the number of fibers between each RAU and the CogAP the same, i.e., one to transmit and one to receive, wavelength division multiplexing would then be required to deliver RF signals from/to different antennas attached to the same RAU. Here we focus on macro-diversity enabled by distributed RAUs.

1) Receiver Diversity

Consider an area covered with two RAUs, using the same set of frequencies to serve a group of stations. If maximum-ratio combining (MRC) is used at the CogAP for uplink signals, not only do we achieve an array gain of 3 dB due to the increased receive antenna gain, but also obtain a diversity gain if the two paths from the station to the two RAUs experience independent fading. Both gains will help reduce the effects of packet collisions, resulting in increased throughput and reduced packet error rate (PER). When the number of RAUs increases to four, we expect a higher performance improvement due to 3 dB more in array gain and a higher diversity gain.

An immediate effect of receiver diversity is an improvement in sensing capability at the CogAP, and hence a reduction in WLAN packet collisions between downlink packets and uplink packets. Another effect of diversity gain is to reduce unfairness among stations in terms of their chances to access the channel due to their different distances from the RAUs.

2) Transmitter Diversity

For the downlink, we can use transmitter diversity to improve signal-to-noise-ratio (SNR) at the stations without requiring them to have additional capabilities. Multiple copies of each packet are distributed to RAUs and then to the destination such that when some copies are largely attenuated due to poor channel conditions, other copies can still reach the destination; hence, transmitter diversity. By reciprocity of the channel, transmitter diversity at the CogAP through multiple RAUs achieves the same SNR gain as receiver diversity, subject to a total transmit power constraint on all RAUs.

We investigate equal-gain combing (EGC) and MRC using transmitter diversity. In EGC scheme, each RAU is subject to a given per-RAU transmit power constraint, which reduces distortions due to nonlinearity at optical-electrical converters of RAUs. In MRC scheme, RAUs are only subject to a total transmission power constraint, and therefore have a larger freedom on transmission power allocation across RAUs, providing a larger SNR gain than EGC.

Both EGC and MRC require that signals from different RAUs can be added coherently at the receiving station. Therefore, the CogAP must have exact channel state information (CSI) from all participating RAUs to the receiving station right before a packet is sent, such that signal phases can be properly shifted at the different RAUs. This makes CSI estimation for transmitter diversity more difficult than receiver diversity, where the CogAP can always rely on the physical-layer header of WLAN packets to estimate CSI.

IV. Performance Evaluations

We utilize the NS-2.33 simulator [34] with its dei80211mr WLAN rate adapter package [35] to evaluate the performance of the proposed methods. The interference-recorded channel model incorporated in this package greatly enhances the accuracy of simulations involving channel capturing.

A. Simulation Model

The simulation model includes two RAUs connected to one CogAP, which is then connected to a fixed host computer. Stations are either uniformly or non-uniformly placed in a 30-by-60 m^2 area. When no diversity is used, the CogAP communicates with stations through their closest RAUs. Traffic streams only flow between stations and the fixed host. The wireless propagation model is a simplified pathloss model [36] with shadowing and Rayleigh fading.

The WLAN uses 802.11g and two non-overlapping channels are used. Each AP in the baseline conventional

WLAN operates on one channel only, while the CogAP in CWLANoF operates on both channels through the two RAUs either co-operatively for macro-diversity or independently. Data mode used by each station and the CogAP is determined by the signal-to-noise-ratio-based dynamic rate adaptor in dei80211mr package. No RTS/CTS is used. Perfect CSI is assumed to be available at the CogAP.

The frequency plan used in the simulations is shown in Fig. 3 and simulation parameters are listed in Table 1. The synchronization interval (SI) is used to model the capturing process. When the arrival times of two packets are within the SI, it is assumed that the receiver is able to synchronize to the packet with the stronger receive power.

The simulations employ two types of traffic that represent increasingly popular Internet applications: File Transfer Protocol (FTP) over TCP in downlink representing traffic from file downloading applications, and constant bit-rate (CBR) traffic in both uplink and downlink representing Voice over Internet Protocol (VoIP) and IP television (IPTV). FTP over TCP traffic is saturated, i.e., stations always have packets to send. VoIP and IPTV, as multimedia traffic, have the same fixed packet interval yet different packet length due to different amount of information contained in their packets. We are mainly interested in file downloading speed and voice and video quality; thus, TCP downlink throughput and CBR PER are chosen as our main performance evaluation criteria. To evaluate proposed methods for file sharing applications, we also evaluate TCP uplink throughput in some simulation scenarios.

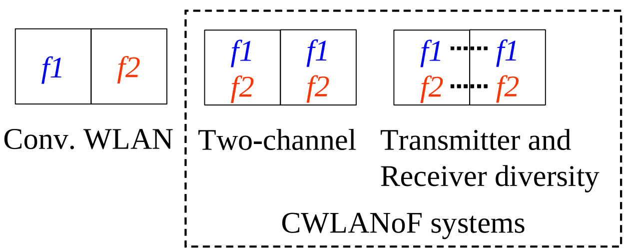


Fig. 3 Frequency plan in simulations

TABLE 1. SIMULATION PARAMETERS

Propagation	Pathloss exponent = 2.5
	Reference distance, d_0 = 2 m
	Standard deviation of shadowing = 3.5 dB
PHY	Transmission power, P_t = 10 mW
	Carrier-sensing threshold = -70 dBm
MAC	Synchronization interval = 5 µs
	aSlotTime = 20 µs
	CWMin/Max = 31 / 1023
FTP traffic	TCP/Reno. Packet size = 1000 bytes.
CBR traffic	Packet interval 20 ms. 1000-byte packets for IPTV; 40-byte packets for VoIP.

B. *Effects of Receiver Diversity*

We first investigate the effect of receiver diversity, i.e., receiving packets transmitted from one station using more than one RAU. Assuming the channel gain of each path is Rayleigh distributed, we know that the received signal power at a given RAU$_i$, $P_r^i(x,y)$, is an exponentially distributed random variable with the probability density function (p.d.f.)

$$f_{i,x,y}(P_r^i) = 1/P_{avg}^i(x,y)\cdot e^{-P_r^i/P_{avg}^i(x,y)}, \qquad \textbf{(1)}$$

where $P_{avg}^i(x,y)$ is the averaged power of signals received by RAU$_i$ from a station located at (x,y) and reflects the pathloss between them. Thus, at the CogAP that receives the signals from both RAU$_i$ and RAU$_k$, the p.d.f. of the total received signal power is given by

$$f_{cap,x,y}(P_r^{cap}) = \frac{(e^{-\frac{P_r^{cap}}{P_{avg}^i(x,y)}} - e^{-\frac{P_r^{cap}}{P_{avg}^k(x,y)}})}{P_{avg}^i(x,y) - P_{avg}^k(x,y)}, \qquad \textbf{(2)}$$

where P_r^{cap} is the power of the combined signal at the CogAP (by combining signals from RAU$_i$ and RAU$_k$) and the notation $f_{cap,x,y}(P_r^{cap})$ implies the p.d.f. of P_r^{cap} is a function of (*x*,*y*), the geographical coordinate of the transmitter. When the station has the same average pathloss to the two RAUs, $f_{cap,x,y}(P_r^{cap})$ becomes an Erlang distribution with the shape factor *N*=2. Given different locations of stations, the CogAP and individual RAUs exhibit different outage probabilities Prob($P_r \leq$ threshold) over the whole area, as shown in Fig. 4. Fig. 5 shows the reduction on the outage probability when MRC or EGC is used, compared to the case where diversity is not employed. In both figures the blue surfaces correspond to EGC and the red ones correspond to MRC. The black surface corresponds to conventional WLAN in Fig. 4 and serves as the zero-reference plane in Fig. 5. Results are based on simulations using parameters in Table 1. Two RAUs (or APs in the conventional WLAN) are fixed at locations (15, 15) and (15, 45) in units of meters.

We observe that MRC always reduce outage probabilities more than EGC, especially for stations at corner areas where the pathlosses to the two RAUs largely differ. From Fig. 4, we also observe that compared with EGC, MRC has a flatter distribution of outage probabilities across the area, so that stations located farther away from the RAUs will still be heard by the CogAP. Therefore, their uplink packets will less likely collide with downlink packets, and consequently their contention windows will not suffer as much from exponential increases. With receiver diversity at the CogAP, stations farther away from the RAUs still have good chances to access the channel compared with those closer to the RAUs.

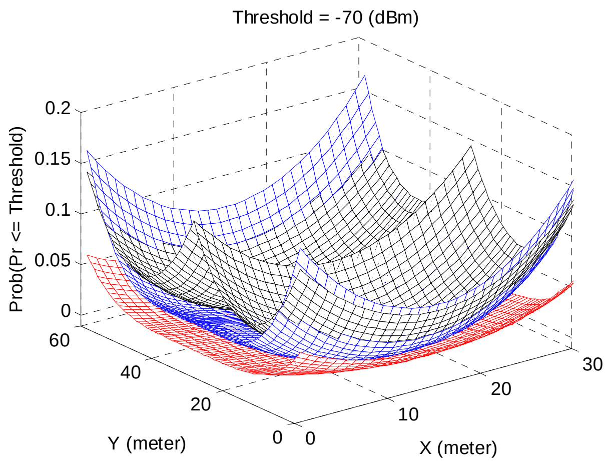


Fig. 4 Outage probabilities across a WLAN ESS

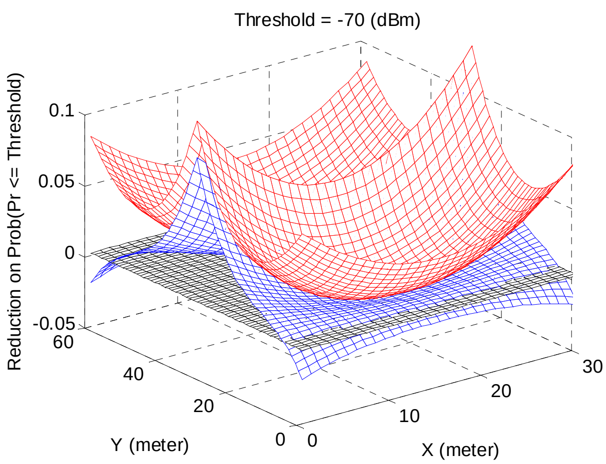


Fig. 5 Reduction in outage probability with MRC and EGC

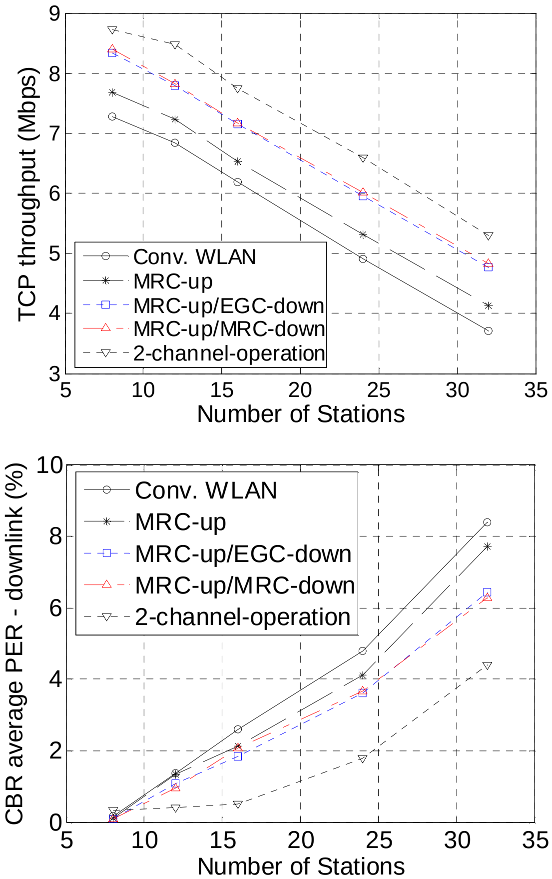


Fig. 6 TCP throughput and CBR PER vs. Number of stations. Traffic: VoIP uplink/downlink + FTP downlink. MRC-up: MRC is used for uplink diversity. EGC-down: EGC is used for downlink diversity.

C. *Spatially Uniformly Distributed Traffic*

Stations are uniformly placed over the whole area to represent spatially uniformly distributed traffic. For a given number of active stations, 20 different station locations are randomly generated. Simulated results under these scenarios are then averaged for evaluations. From Fig. 6 and Fig. 7, we observe that under two types of spatially uniformly distributed traffic, operating two channels in both RAUs increases TCP throughput by 14%~18% when only 8 stations are active. When the number of active stations increases, the TCP throughput gain also increases, reaching 36% for VoIP uplink/downlink plus FTP downlink traffic and 20% for IPTV downlink plus FTP downlink traffic when the number of active stations is 32. Downlink PER for CBR traffic is also reduced by 50%. Uplink PER for CBR is zero and thus not presented here. The reason is that uplink is not heavily loaded without presence of saturated FTP over TCP traffic. The performance gain of two-channel-operating can be attributed to channel capturing effects on downlink data packets in CWLANoF (see Section III.A).

Note that we use the number of stations to indicate the intensity of traffic since all of stations have always-on CBR and FTP/TCP traffic.

The confidence interval of obtained average PERs can be estimated by *berconfint* function in MATLAB, provided that the number of packet errors follows binomial distribution. Each simulation run lasts 120 seconds with 20 ms packet interval. Therefore, in 12-station case, 36,000 downlink and 36,000 uplink packets are generated, resulting a 95% confidence interval [0.93%, 1.08%] at 1% average PER, and [0.08%, 0.13%] at 0.1% average PER. A higher number of stations or a higher average PER generates a tighter confidence interval. To avoid clutter, we do not superpose the confidence intervals on PER figures.

Comparing the diversity methods we have investigated, using only MRC for uplink diversity slightly increases TCP throughput and reduces downlink PER for CBR traffic, while engaging additionally downlink EGC or MRC transmit diversity further improves performance by providing a higher TCP throughput gain and lower PER for CBR traffic. The results also show that two-channel-operation always outperforms the diversity methods in either TCP throughout or downlink PER for CBR traffic. The advantage of multi-channel operation originates from additional operation channels, which can linearly increase system capacity (assuming no CCI), while diversity methods we investigate here only logarithmically increase system capacity. When the always-on VoIP traffic is not present, our simulation results showed similar TCP throughput gains from both multi-channel operation and diversity methods. The results are not presented here to avoid repetition.

As shown in Fig. 8, heavy traffic streams like VoIP uplink/downlink and FTP uplink/downlink largely increase CBR PER. We observe that diversity methods still consistently improve TCP throughput when the number of active stations changes. CBR PER, however, is only slightly affected, and we regard the small difference of CBR PER between conventional WLAN and diversity methods as random effects in the simulations. In fact, our simulations show little difference among diversity methods; therefore, only MRC-uplink/MRC-downlink method is plotted in the CBR PER figure to avoid clutter. The two-channel-operation method improves TCP throughput and outperforms diversity methods when the number of active stations is less than 10. When the network contains more than 10 active stations, TCP throughput of two-channel-operation method decreases and even becomes worse than conventional WLAN when there are 24 active stations.

To identify the reason of TCP throughput degradation of two-channel-operation, we plotted the TCP uplink and downlink throughput separately in Fig. 9. We observe that two-channel-operation generates the highest TCP downlink throughput but the lowest TCP uplink throughput, which taken together causes the lowest total TCP throughput. To explain the reason of TCP uplink throughput degradation, we notice that when two-channel-operation method is used, stations being served in one channel are found in areas twice as large as those in the conventional WLAN, and therefore suffer more packet collisions due to the hidden terminal problem. The above observation suggests that when there are too many active stations in the CWLANoF ESS, enough number of channels should be operated to ensure proper file sharing efficiency.

Compared with diversity methods and conventional WLAN, the two-channel-operation method generates the highest CBR PER when the number of active stations is less than 12, and the lowest CBR PER when the number of active stations is larger than 12. This phenomenon is not easy to see in scenarios under VoIP traffic. To see it more clearly, observe scenarios under IPTV downlink and FTP downlink traffic, enlarged in Fig. 10. When two-channel-operation method is used in lightly loaded networks, CBR PER is increased because capturing a new packet causes a loss of

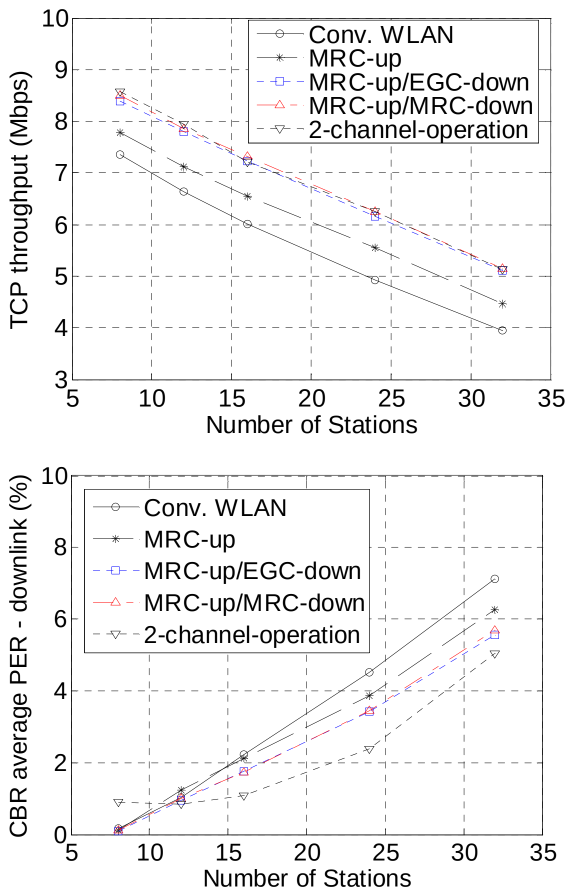


Fig. 7 TCP throughput and CBR PER vs. Number of stations. Traffic: IPTV downlink + FTP downlink.

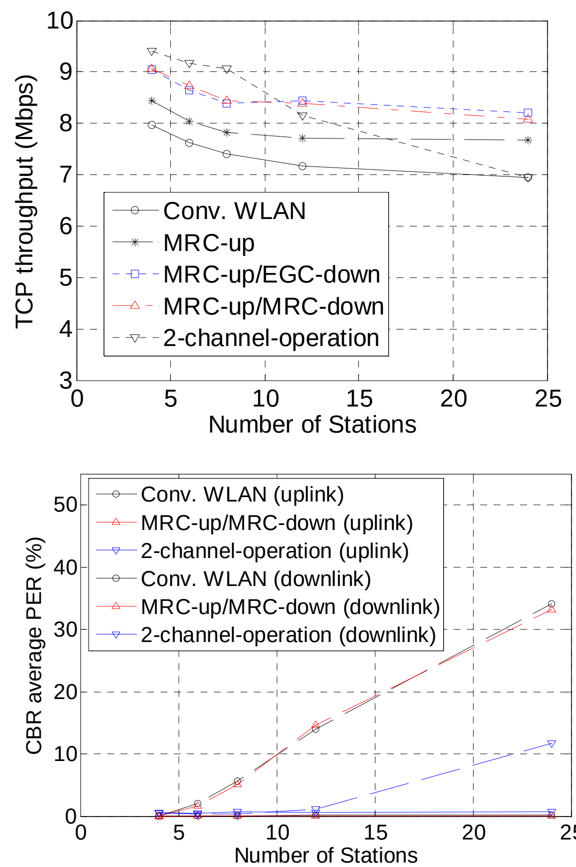


Fig. 8 TCP throughput and CBR PER vs. Number of stations. Traffic: VoIP uplink/downlink + FTP uplink/downlink.

previously being received packet; in heavily loaded networks, however, the reduced packet collisions due to extra channels outweighs the disadvantage of CBR packet loss due to channel capturing, causing lower overall CBR PER than diversity methods and conventional WLAN. Although two-channel-operation caused a bit higher CBR PER for uplink packets, CBR PER in downlink is largely decreased. For VoIP application, such balanced CBR PERs provided by two-channel-operation would be very useful.

1) Explanations on the performance improvement

TCP throughput gain and CBR PER reductions of diversity-based CWLANoF systems come from independent channel fading and more antennas involved at the receiver or transmitter. Gains of two-channel-operating CWLANoF systems come from channel capturing and channel fading effects. We now further explain where these gains come from.

Suppose a conventional WLAN ESS serves 10 stations on channel 1 of AP1 and another 10 stations on channel 2 of AP2. Assume these stations are associated to the AP closer to them. Two-channel-operating actually splits the 20 stations into 4 groups, each assigned to one channel through one RAU. The resulting CWLANoF system can be viewed as four independently-operated conventional BSSs. Although CCIs exist between these BSSs, we still gain system capacity due to the linearly increased bandwidth while the signal-to-interference-noise ratio is only logarithmically degraded. On the other hand, a diversity-based CWLANoF controls RAUs and forms BSSs with distributed antennas, serving stations that spread out in the whole area.

An intuitive example can observed from Fig. 2: apparently stations located in the middle of the area will favor diversity technique since they have similar average pathlosses to the two RAUs, while stations at corner areas will favor multiple-independent-channel-operating method since there will be less CCIs between corners. This observation reminds us that when the location information of stations is available at the CogAP, advanced location-aware channel management techniques can provide even higher system capacity. How to achieve a balance between multiple-independent-channel-operating method and diversity techniques to better serve stations with dynamic traffic would be our next research topic.

It should be noted that when uplink or downlink diversity is used, if two or more packets collide, we discard both of them in simulations. Therefore, the performance shown is the lower bound of MRC or EGC performance in practice. And once multi-user reception techniques such as sequential interference cancellation are applied, diversity could obtain higher TCP throughput and decrease the CBR PER more. However, in multi-user access, the MAC layer needs a careful joint-design with sophisticated signal processing at the physical layer.

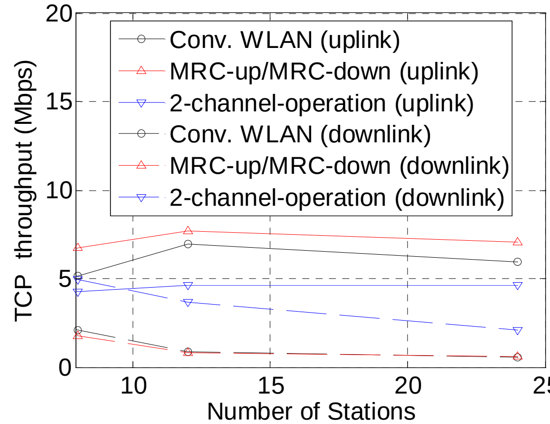


Fig. 9 TCP throughput degradation of two-channel-operation method in heavily loaded networks. Traffic: VoIP uplink/downlink + FTP uplink/downlink.

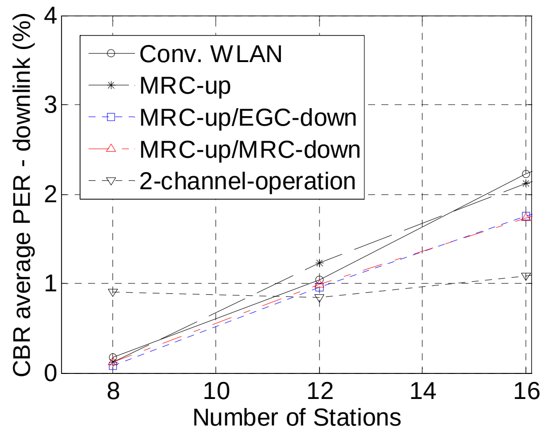
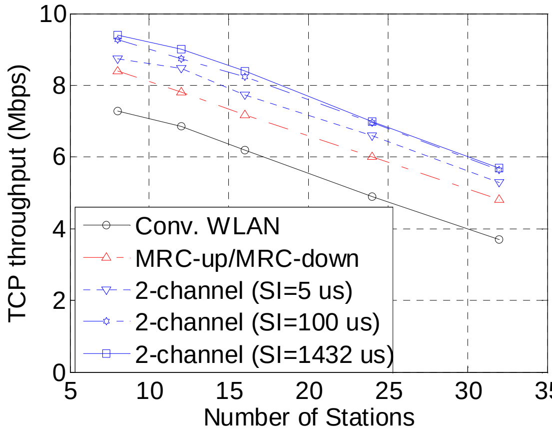


Fig. 10 CBR PER degradation of two-channel-operation in lightly loaded networks. Traffic: IPTV downlink + FTP downlink.

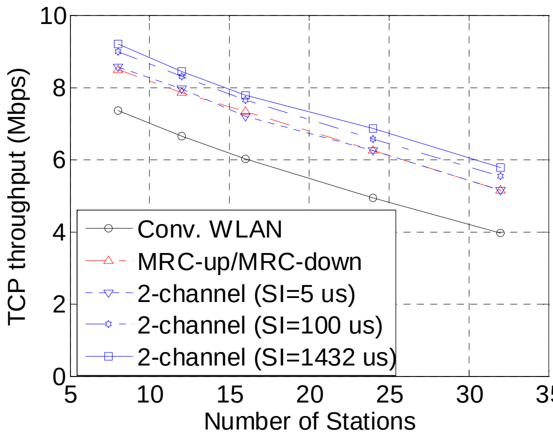
2) Effects of SI values

Results in [1] only showed scenarios using SI = 5 μs. We examine effects of different SI values on TCP throughput under three types of traffic, as shown in Fig. 11. Effects of SI on CBR PER is very small and thus omitted. Since different SI values only affect two-channel-operation; only one diversity method (MRC in uplink and downlink) is plotted for comparison purpose.

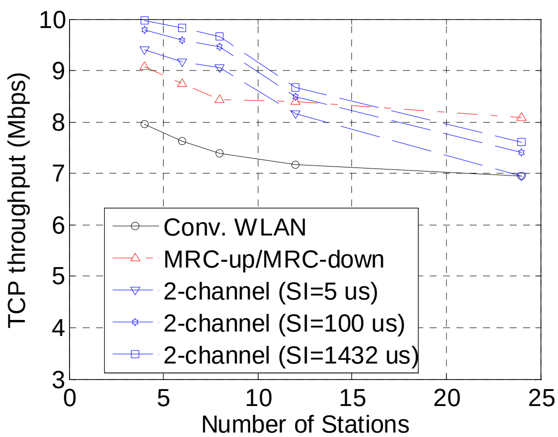
We observe that by using SI = 1432 μs, TCP throughput can be increased by 5.6%~10% when compared with SI = 5 μs, owning to the fact that larger SI values cause more packet capturing than smaller SI values. However, we also notice that there is little difference between SI = 1432 μs and SI = 100 μs, indicating that by only looking for the strongest signal during SI = 100 μs, a WLAN receiver can achieve most of throughput gain due to capture effect. For the rest of this work, 100 μs is used as SI value.



(a) Traffic: VoIP uplink/downlink + FTP downlink



(b) Traffic: IPTV downlink + FTP downlink



(c) Traffic: VoIP uplink/downlink + FTP uplink/downlink

Fig. 11 Effects of SI values

D. *Spatially Non-uniformly Distributed Traffic*

When a hotspot area has much larger traffic demand than other areas, we face a spatially non-uniformly distributed traffic. We split the 30-by-60 m^2 area into 3-by-6 sub-areas and place the hotspot into one of these sub-areas to simulate non-uniformly distributed traffic. Totally 8 stations are used for background traffic and 4 other stations are placed in certain hotspot location, as shown in Fig. 12. By geometric symmetry, we only need study hotspot locations from 1 to 6. To concentrate on studying the effects of dynamic traffic, we fix the locations of background-traffic stations at the centers of sub-areas 2, 4, 6, etc. Stations that generate hotspot traffic are also fixed in the center part of their respective sub-area. Only one set of station locations is used for simulations followed.

As shown in Fig. 13 and Fig. 14, compared with conventional WLAN, diversity methods in CWLANoF achieve 10%~62% higher TCP throughput and two-channel-operation achieves 17%~48% higher TCP throughput, whereas only 14%~36% gain is achieved when the traffic is spatially uniformly distributed (comparing Fig. 6 to Fig. 8). CBR downlink PER is also largely reduced. This demonstrates CWLANoF's enhanced capability to handle dynamic traffic.

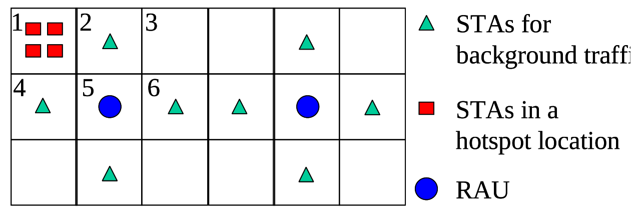


Fig. 12 Spatially non-uniformly distributed traffic. Hotspot locations are numbered from 1 to 6.

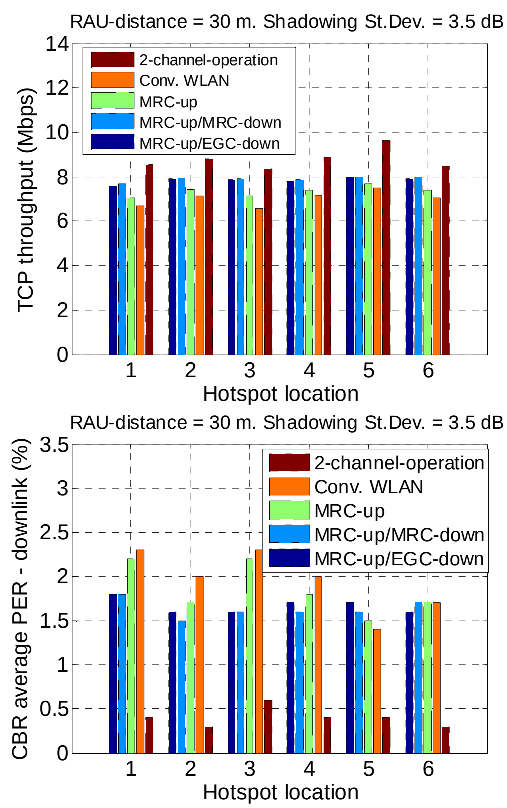


Fig. 13 TCP throughput and CBR PER vs. Hotspot location. (VoIP uplink/downlink + FTP downlink). RAU-distance = 30 m. Shadowing St.Dev. = 3.5 dB.

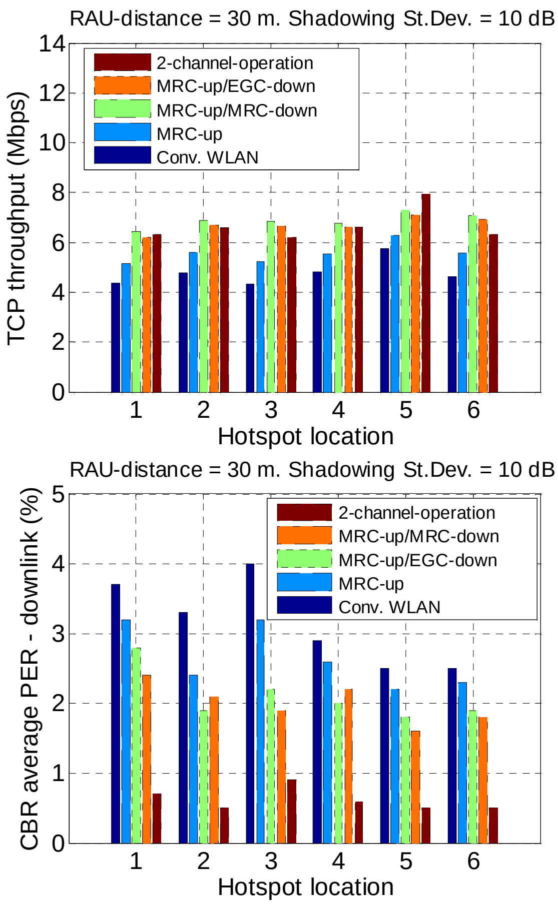


Fig. 14 TCP throughput and CBR PER vs. Hotspot location. (VoIP uplink/downlink + FTP downlink). RAU-distance = 30 m. Shadowing St.Dev. = 10 dB.

Not surprisingly, two-channel-operating achieves a larger throughput gain when the hotspot is in the corners (e.g., location 1), while diversity methods achieve larger gains when the hotspot is in the overlapping area of RAU1 and RAU2 (e.g., location 3 and 6). In fact in such areas, MRC in both uplink and downlink achieves higher TCP throughput than two-channel-operating when the standard deviation of shadowing increases to 10 dB.

When the hotspot moves to location 5, stations at the hotspot are closer to RAU1. Therefore, CCI from stations in BSS2 to those in BSS1 is less likely due to the capture effect. Thus, we observe a larger TCP throughput gain in the tow-channel-operation method, as shown in Fig. 13 and Fig. 14.

Focusing on spatially non-uniformly distributed traffic, we further study the effects of RAU-distance (i.e., the size of BSS) and the maximum transmission power of cooperating RAUs.

1) Effects of RAU-distance

The RAU-distance is also the physical size of a BSS in our simulations. Comparing Fig. 15 with Fig. 14, we observe that both diversity and two-channel-operation methods provide larger TCP throughput gains when the RAU-distance is increased to 45 or 60 meters. SNR gains generated by diversity methods have larger effects on throughput due to increased RAU-distance and consequently increased pathloss. Two-channel-operation method provides higher throughput gains due to increased RAU-distance and consequently reduced CCI, especially at hotspot location 5 where stations are less susceptible to CCIs from stations being served by the neighboring RAU.

2) Effects of total transmission power constraint of cooperating RAUs

In previous simulations, the maximum transmission power of each conventional AP is 10 mW. When MRC or EGC is employed at an RAU, the maximum transmission power of each RAU is set as 5 mW for a fair comparison with conventional WLAN. However, an RAU is covering the same area as a conventional AP. Therefore, an RAU can transmit at 10 mW without causing excessive interference to other ISM devices or health concerns on human bodies.

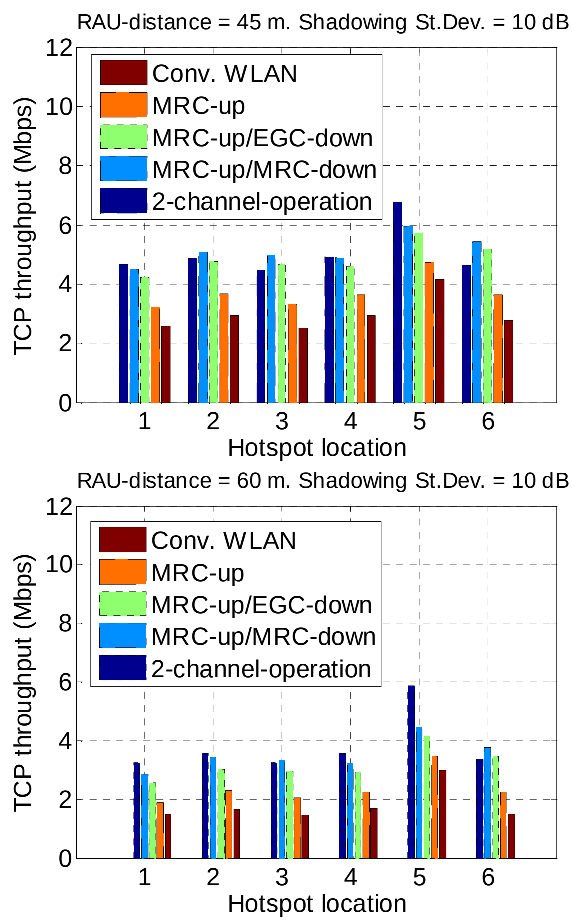


Fig. 15 Effects of RAU-distance. Traffic: VoIP uplink/downlink + FTP downlink. RAU-distance = 45 m or 60 m. Shadowing St.Dev. = 10 dB.

Effects of RAU-distance and RAU transmission power constraints should be examined jointly since both parameters affect system performance by changing SNR at receiver. Our results in Fig. 16 indicate that for usual office WLAN deployment (RAU-distance = 30~60 meters), both proposed methods improve TCP throughput. Compared with diversity methods subject to normal transmission power constraint, when the RAU-distance is small, increasing RAU transmission power constraint has negligible effects on TCP throughput.

V. CONCLUSION AND FUTURE WORK

CWLANoF systems can provide a cost-effective and efficient method for devices to equally share the ISM band by taking advantage of cognitive radio capabilities. In this paper, we have proposed two methods that utilize the specialized capabilities of the CWLANoF architecture to improve system capacity by reducing packet collisions through load balancing and employing diversity to reduce the effects of packet collisions. By exploiting the wideband RoF connections between RAUs and the CogAP in a CWLANoF, multiple-impendent-channel-operation at each RAU has been proposed to reduce the collision probability in each channel by moving stations to different channels. By configuring RAUs as distributed antennas in a CWLANoF, we have demonstrated the use of macro-diversity to increase the sensing capability of the CogAP. Simulation results show that both methods can achieve 14%~18% TCP throughput gain and 10%~50% CBR PER reductions for spatially uniform traffic in an IEEE 802.11g network, and up to 62% TCP throughput gain when hotspots exist. We also studied effects of different SI values, RAU-distance, and total transmission power constraint of cooperating RAUs. Similar TCP throughput gain and CBR PER reduction are observed in all scenarios.

While the CWLANoF architecture raises a rich set of research problems, there is one promising direction to further reduce WLAN packet collisions, using location-aware radio resource management at the CogAP while employing collision reduction among stations. By taking advantage of its centralized signal processing capability, the CogAP can determine the locations of the stations. Obviously, heavy traffic from stations located in the overlapping area of RAUs are better served by applying diversity methods, whereas stations that do not benefit much from diversity can be off-loaded to new channels. This strategy is a simple example of how to dynamically exploit the performance gains between macro-diversity and multiple-independent-channel-operation. Further research is needed to jointly design signal processing techniques in physical layer and the MAC in CWLANoF systems such that multiple collided packets can be successfully received and acknowledged in time.

ACKNOWLEDGMENT

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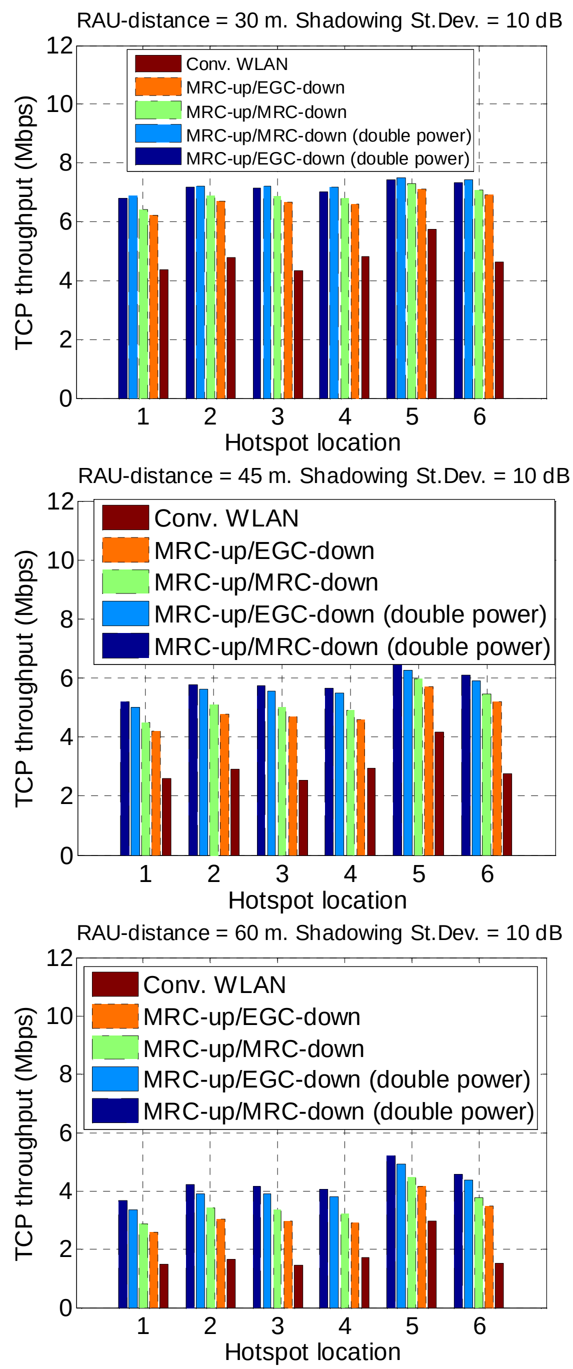

Fig. 16 Effects of total transmission power constraint of cooperating RAUs. Traffic: VoIP uplink/downlink + FTP downlink. RAU-distance = 30 m, 45 m or 60 m. Shadowing St.Dev. = 10 dB. Double power: the total transmission power constraint of cooperating RAUs is 20 mW.

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