SPECTRUM SHARING BETWEEN WIFI AND RADIO ASTRONOMY

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ABSTRACT

The proliferation of wireless local area network also known as WiFi system has enabled easy wireless information access for consumers. However, it also causes radio frequency interference (RFI) to passive wireless systems such as radio astronomy systems (RAS), making almost impossible to get useful scientific observations around the WiFi bands. This paper proposes a new paradigm for the coexistence between WiFi and RAS. The proposed approach creates a coexistence access zone (CAZ) around the RAS site within which WiFi and RAS follow a pre-determined time-division spectrum access. Two modified WiFi medium access control (MAC) protocols are developed to embed the time-division coexistence access. Furthermore, traffic statistics based improved spectrum access is developed. Performance evaluation results show that at the cost of slight WiFi throughput reduction, RAS achieves substantial RFI-free spectrum access which were infeasible in the existing paradigm.

***Index Terms*—** Coexistence, WiFi, radio astronomy

1. INTRODUCTION

Wireless services can be divided into active services (e.g., WiFi) and passive services (e.g., RAS). Although passive wireless systems do not cause RFI to active wireless systems, even the very low level spectrum side-lobes of an active wireless system can destroy the measurements of scientific signals. Passive wireless services provide economically and scientifically important observations of Earth's environment, our solar system and the cosmos [1]. Due to their benefits to society, several of the ITU-R recommendations stipulate for protection of them [2–7]. Thus, it is very crucial to develop new spectrum coexistence paradigms between the active wireless communications and the passive remote sensing systems that answer the needs of both types of systems. This paper considers spectrum coexistence scenarios between WiFi and RAS.

The spectrum of interest to RAS covers all available atmospheric windows ranging from 2 MHz to 1000 GHz and above [2]. Some observations in the bands allocated to the active wireless services are essential for RAS [1]. In the past, sporadic spectrum use of active services allows RAS's observations in the active service bands during the unused time intervals. But such opportunities are diminishing as new wireless systems with dynamic spectrum access proliferate. RFI detection is an important task for RAS [8–14] but it is more challenging for such emerging scenarios since commonly used non-Gaussianity test becomes invalid. Furthermore, in view of expansions of human settlements with active wireless services and the need of more RAS measurements and receivers, the existing approach of isolation of RAS receivers in remote locations together with radio protection zones [15, 16] would not be able to answer the future needs of the society. New spectrum coexistence strategies are in great need.

One of the most widely used active wireless systems is WiFi but its deployment has caused 5-6 GHz band close to unusable for RAS (a feedback from a radio astronomer at Arecibo radio observatory) over the past 10 years or so. There are no protected RAS bands there but there are some exciting spectral lines to observe in that band. Thus, this paper develops an approach for spectrum coexistence between WiFi and RAS. Note that WiFi uses distributed MAC. Our work on the shared spectrum access between cellular wireless communications with centralized MAC and RAS is presented in [17].

Our main contribution in this paper is a new paradigm of spectrum coexistence between WiFi and RAS based on time-division-embedded distributed WiFi MAC protocols which enable geographical and spectral coexistence between WiFi and RAS. We present detailed design aspects, proposed MAC protocols, and advanced resource allocation based on WiFi's traffic statistics. Simulation study illustrates that the proposed approach can address the needs of WiFi and RAS and provide substantially enhanced spectrum utilization.

2. COEXISTENCE ACCESS ZONE (CAZ)

An important step in developing the proposed coexistence access paradigm is to define a coexistence access zone (CAZ)

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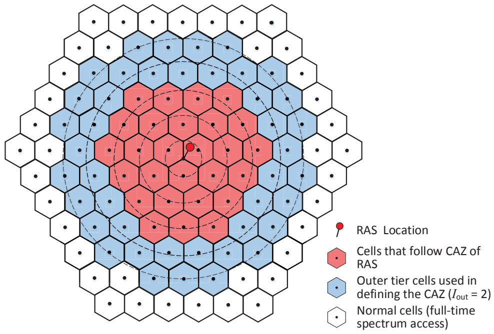


Fig. 1. Tiers of WiFi cell rings around an RAS receiver.

within which WiFi and RAS follow the proposed coexistence spectrum access protocol while WiFi systems outside CAZ can access their spectrum freely but their transmissions do not cause harmful RFI to RAS. For this, we adopt the interference power level threshold as defined in ITU-R RA.769-2 as the maximum RFI level the RAS receiver can tolerate and denote it by $I_{\rm th}$. We consider downlink of WiFi with full load to determine the RFI level at RAS. Suppose the CAZ is with radius $R_{\rm CAZ}$ kilometers centered at the RAS receiver, and the WiFi hexagon cells, each with radius r kilometers, surround the RAS receiver as shown in Fig. 1. In calculating interference power experienced at RAS, we approximate each hexagonal cell by its inscribed circular cell with radius $\sqrt{3}r/2$. This yields closer WiFi access points (APs) to RAS than the hexagon case, thus giving an upper bound on the actual interference power and hence a safer design for RFI protection of RAS. The ith tier cell ring has $K_i \triangleq \lfloor \pi(2i-1) \rfloor$ cells with the same distance $d_i = (2i-1)\sqrt{3}r/2$ between AP and RAS receiver. Denote the AP of cell j at the ith tier cell ring by ${\rm AP}_{i,j}$. Then, the CAZ design can be given by the radius $R_{\rm CAZ}$ of the CAZ which is computed based on $I_{\rm out}$ outer tiers of WiFi cells as

$$R_{\rm CAZ} = \min_{i_0} \{(2i_0-1)\sqrt{3}r/2\}, \quad \text{s.t.} \sum_{i=i_0+1}^{i_0+I_{\rm out}} \frac{K_i P_{\rm AP}}{L_{\rm tot}(d_i)} < I_{\rm th}, \tag{1}$$

where $P_{\rm AP}$ is the transmitted power of WiFi APs, and $L_{\rm tot}(d_i)$ is the total propagation loss at the ith tier. Note that due to terrain constraints, associated path-loss and antenna down-tilting, using a finite $I_{\rm out}$ is justified. Fig. 1 illustrates the tiers of WiFi hexagon cell rings around an RAS receiver, as well as the outer tiers ($I_{\rm out} = 2$ for presentation convenience) used in defining the CAZ. In this illustration, the CAZ is composed of 3 tiers (for presentation convenience) of WiFi cells, and WiFi transmissions in these cells follow the proposed coexistence access protocol. WiFi transmissions in other cells follow their original access protocol.

The total propagation loss is given by

$$L_{\rm tot} = \frac{L_{\rm p}}{G_{\rm WiFi} G_{\rm RAS} L_{\rm s}}, \tag{2}$$

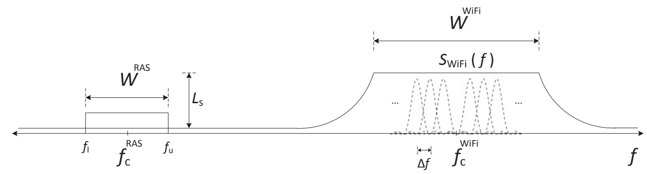


Fig. 2. PSD of WiFi appears at the observation band of RAS.

where $G_{\rm WiFi}$ is the transmit antenna gain of WiFi APs, $G_{\rm RAS}$ is the antenna gain of RAS receivers (for WiFi interferences), that appears in the band of RAS, and $L_{\rm p}$ is the propagation path loss. WiFi adopts orthogonal frequency division multiplexing (OFDM) technology. Suppose the OFDM system has a subcarrier spacing of Δf, an OFDM symbol duration of $1/\Delta f'$ (including cyclic prefix interval; thus $\Delta f' < \Delta f$), $N_{\rm u}$ used subcarriers with their subcarrier index set $\mathcal{I}$, and the carrier frequency of $f_{\rm c}^{\rm WiFi}$. Then the power spectral density (PSD) of the WiFi OFDM signal is given by

$$S_{\rm WiFi}(f) = \sum_{i\in\mathcal{I}} \frac{P_{\rm AP}}{N_{\rm u}\Delta f'} {\rm sinc}^2 \left(\frac{f - f_{\rm c}^{\rm WiFi} - i\Delta f}{\Delta f'} \right) \tag{3}$$

where ${\rm sinc}(x) \triangleq \sin(\pi x)/(\pi x)$. Note that the existing PSD expression (e.g., in [18]) uses $\Delta f' = \Delta f$ in the above equation which is inaccurate due to the cyclic prefix. Fig. 2 shows how the PSD of WiFi signal appears at the observation band of RAS since both systems operate at frequency bands close to each other, where $f_{\rm c}^{\rm RAS}$ is the RAS observation band center frequency, $W^{\rm RAS}$ is the RAS observation bandwidth, and $W^{\rm WiFi}$ is the bandwidth of WiFi. The normalized interfering WiFi signal power within the RAS bandwidth, denoted by $L_{\rm s}$, is calculated as

$$\begin{aligned} L_{\rm s} &= \int_{f_{\rm l}}^{f_{\rm u}} \frac{S_{\rm WiFi}(f)}{P_{\rm AP}} df < \sum_{i\in\mathcal{I}} \int_{f_{\rm l}}^{f_{\rm u}} \frac{\Delta f'/(N_{\rm u}\pi^2)}{(f - f_{\rm c}^{\rm WiFi} - i\Delta f)^2} df \\ &= \sum_{i\in\mathcal{I}} \frac{\Delta f' \, W^{\rm RAS}/(N_{\rm u}\pi^2)}{(f_{\rm c}^{\rm WiFi} + i\Delta f - f_{\rm l})(f_{\rm c}^{\rm WiFi} + i\Delta f - f_{\rm u})} \end{aligned} \tag{4}$$

where $f_{\rm l} = f_{\rm c}^{\rm RAS} - \frac{W^{\rm RAS}}{2}$ and $f_{\rm u} = f_{\rm c}^{\rm RAS} + \frac{W^{\rm RAS}}{2}$.

Note that $L_{\rm s}$ is evaluated in [18] after applying Maclaurin expansion of the function ${\rm sinc}^2(x)$. Therefore, the expression of $L_{\rm s}$ in [18] is accurate only for any small frequency window inside the WiFi band. Since the two systems are separated in frequency, using the expression of $L_{\rm s}$ in [18] is not valid. That is why we derive an upper bound which is valid for any frequency separation.

As for the propagation path loss $L_{\rm p}$, we adopt the empirical propagation model in [19]. This model is shown to have good fit to actual measurements for large distances in order of tens kilometers [20].

3. COEXISTENCE MAC PROTOCOLS

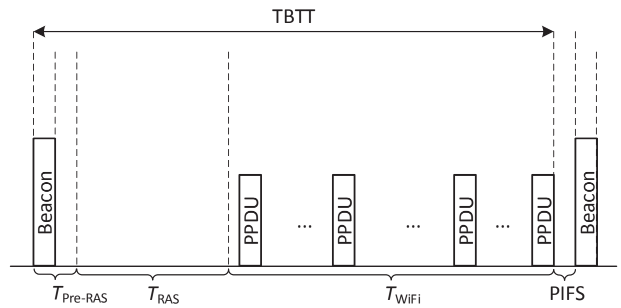
After determining the CSZ, the next step is to show how WiFi MAC protocol can be modified (for WiFi devices within the CAZ) to enable the coexistence between the two systems. The idea is to develop a time-division approach such that all WiFi devices within the CAZ are silent during the time intervals allocated to RAS. Since WiFi systems use distributed medium access control (MAC) protocol, to maintain compatibility with the existing WiFI MAC protocol principle, we propose to embed the time division spectrum access between WiFi and RAS within the distributed MAC framework. We make a brief review on the WiFi access and sensing modes. Then, we present the proposed coexistence schemes.

3.1. An overview on WiFi access and sensing modes

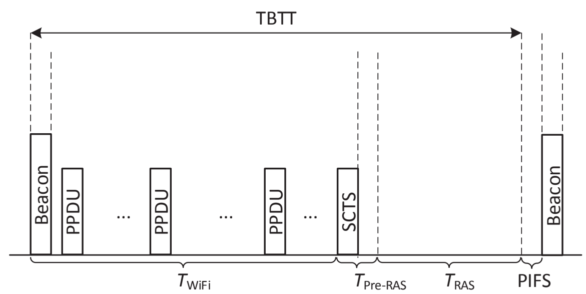
The MAC layer of WiFi networks is based on carrier sense multiple access with collision avoidance (CSMA/CA). The fundamental mechanism is called distributed coordination function (DCF) which is a random access scheme based on CSMA/CA. DCF has two access modes for packet transmission. The first one is the basic two-way hand shaking mode called basic access. If the channel is sensed idle for a time duration equal to a distributed interframe space (DIFS), the WiFi node can transmit. If the channel is sensed busy, the node monitors the channel until it is measured idle for a DIFS, and then it generates a random backoff interval before transmission. The successful transmission is identified by the reception of an immediate acknowledgment after a time duration called short interframe space (SIFS). Note that the basic access mode applies physical carrier sensing. The second access mode is the four way hand shaking mode called request-to-send/clear-to-send (RTS/CTS). After the channel is sensed idle or after the random backoff time, the sender WiFi STA reserves the channel by sending an RTS frame. The receiver sends a CTS frame to acknowledge the reception of RTS. The RTS and CTS frames include information about the length of the packet to be transmitted and hence the time duration needed for transmission. Other WiFi nodes apply virtual carrier sensing by decoding the CTS frame and setting an internal counter called network allocation vector (NAV) equal to the time duration needed for transmission. During this duration, they do not sense or access the medium. Similarly, the successful transmission is identified by the reception of an immediate acknowledgment after a SIFS.

3.2. Proposed coexistence MAC protocols

We consider beacon transmission based WiFi association [21]. WiFi AP transmits a beacon frame periodically, and WiFi STAs connect to that WiFi AP if the beacon frame is received properly. The beacon frame is transmitted every target beacon transmission time (TBTT), denoted by T_{TBTT}, after a time duration defined by the point coordination function interframe space (PIFS) to ensure the medium is free.



(a) Beacon based coexistence MAC protocol



(b) CTS based coexistence MAC protocol

Fig. 3. Proposed coexistence MAC protocols for beacon transmission based WiFi association.

The proposed coexistence schemes are shown in Fig. 3. Across time, we divide every TBTT into three phases, namely, WiFi only phase, Pre-RAS phase, and RAS only phase with time durations of T_{WiFi}, $T_{\mathrm{Pre-RAS}}$, and T_{RAS} respectively. The duration of the three phases can be time-dependent and different from TBTT to another TBTT. During the WiFi only phase, WiFi nodes can transmit physical protocol data units (PPDUs) but RAS does not collect data as it is heavily corrupted by RFI from WiFi devices. In fact, during such time intervals, RAS switches off its external scientific data measurement but it can measure its reference noise power level (as used in VLA telescopes of NRAO). The Pre-RAS phase consists of either a beacon frame or a special clear-to-send (SCTS) frame (depending on the WiFi access mode) followed by a guard time T_{G} to absorb the propagation delays of different WiFi devices. T_{G} can be designed as

$$T_{\mathrm{G}} = \kappa\sigma \left\lceil \frac{R_{\mathrm{CAZ}}/\left(3\times 10^5\right)}{\sigma} \right\rceil \tag{5}$$

where σ is the WiFi time-slot duration, and $\kappa \geq 1$ (e.g., $\kappa = 2$) is to accommodate propagation model mismatches. During the RAS only phase, there is no WiFi transmission within the CAZ. Thus, RAS is free from WiFi-induced RFI. RAS conducts reliable data collection during this phase.

Time-division-embedded beacon-based distributed MAC: The proposed beacon based coexistence protocol is based on

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a modified basic WiFi MAC access mode as shown in Fig. 3(a). The beacon transmission based WiFi association is modified to act as follows. After the reception of the beacon frame, WiFi nodes keep silent for a time duration equal to $T_{\rm G} + T_{\rm RAS}$. Note that $T_{\rm Pre-RAS} = T_{\rm B} + T_{\rm G}$, where T_B is the time duration of the beacon frame. The remaining time of $T_{\rm TBTT}$ is left for WiFi only phase. For practical deployment, this proposed protocol needs to be included in the WiFi access modes as a new WiFi access mode for coexistence. Moreover, the RAS observation time should be known and updated for all WiFi nodes within the CAZ.

Time-division-embedded CTS-based distributed MAC: Fig. 3(b) shows the proposed CTS-based coexistence scheme, where we assume that DCF applies RTS/CTS access mode in order to exploit the virtual carrier sensing. During the Pre-RAS phase, WiFi APs broadcast a special CTS (SCTS) frame having a value in the packet length field long enough for the RAS observation time which is equal to the remaining time in that TBTT. After receiving this SCTS frame, WiFi STAs keep silent until the next TBTT. The SCTS frame is followed by the guard time $T_{\rm G}$. Note that $T_{\rm Pre-RAS} = T_{\rm CTS} + T_{\rm G}$, where $T_{\rm CTS}$ is the time duration of the CTS frame. It is worth mentioning that one SCTS can make WiFi devices silent for a time duration between 1ms and approximately 32ms with 1ms step. A typical value for $T_{\rm TBTT}$ is 100ms. Thus if the required RAS observation time is more than 32ms per each TBTT, multiple SCST are sent to satisfy this requirement. Note that for the proposed CTS based coexistence scheme, WiFi APs should know the required RAS observation time, while WiFi STAs do not need this information. Therefore, any new WiFi STA with CTS access mode entering the CAZ will follow automatically the proposed CTS based coexistence scheme. For practical deployment, only WiFi APs will need a modified protocol to transmit SCTS frames for reserving RAS spectrum access times.

Note that synchronization is required between WiFi backbone network and RAS for the proposed coexistence schemes.

4. RESOURCE ADAPTATION

WiFi wireless traffics show specific temporal usage characteristics. Utilizing such traffic statistics, we propose to enhance the resource allocation through adaptation across time. Under the constraint that RAS must have a minimum resource amount in each frame and the ratio of the total resource amounts per day between WiFi and RAS is maintained, we optimize the resource allocation across time to maximize WiFi traffic support.

The average per-user WiFi throughput at hour k (denoted by ρ_k) is given by

$$\rho_k = R_{\rm PPDU}\tilde{\rho_k}\frac{T_{{\rm WiFi},k}}{T_{\rm TBTT}} \tag{6}$$

where $R_{\rm PPDU}$ is the physical data rate and $\tilde{\rho_k}$ is the normalized WiFi throughput at hour k provided that WiFi utilizes the whole TBTT [22]. $\tilde{\rho_k}$ is a function of the packet arrival rate λ_k at hour k, and hence it can be different for a different k.[1]

Suppose WiFi and RAS require minimum time durations $T_{\rm WiFi,min}$ and $T_{\rm RAS,min}$ in each TBTT respectively, and the ratio of resource amounts per day between WiFi and RAS during the WiFi only and RAS only phases is γ. Then our resource allocation problem becomes designing the time-dependent TBTT structure to maximize the WiFi average throughput as

$$\{T_{{\rm WiFi},k}\} = \arg\max_{\{T_{{\rm WiFi},k}\}} \left(\frac{1}{24}\sum_{k=1}^{24}\rho_k^{\upsilon}\right)^{\frac{1}{\upsilon}}, \tag{7}$$

$$\text{s.t.}\quad {\rm C1}: \sum_{k=1}^{24} T_{{\rm WiFi},k} \le T_{\rm WiFi},$$

$$\qquad {\rm C2}: T_{\rm WiFi,min} \le T_{{\rm WiFi},k} \le T_{\rm WiFi,max} \qquad \forall k,$$

where υ is the generalized mean exponent ($-\infty < \upsilon \le 1$) representing the fairness between different ρ_k (e.g., $\upsilon = 1$ represents the arithmetic mean), $T_{\rm WiFi} = 24(T_{\rm TBTT} - T_{\rm Pre-RAS})\gamma/(1+\gamma)$ and $T_{\rm WiFi,max} = T_{\rm TBTT} - T_{\rm Pre-RAS} - T_{\rm RAS,min}$. Note that $T_{{\rm RAS},k} = T_{\rm TBTT} - T_{\rm Pre-RAS} - T_{{\rm WiFi},k}$. Moreover, we should have $\gamma_{\min} \le \gamma \le \gamma_{\max}$, where $\gamma_{\max} = T_{\rm WiFi,max}/T_{\rm RAS,min}$ and $\gamma_{\min} = T_{\rm WiFi,min}/(T_{\rm TBTT} - T_{\rm Pre-RAS} - T_{\rm WiFi,min})$. In other words, $\gamma_{\max}$ and $\gamma_{\min}$ are the maximum and minimum achievable ratios of resource amounts respectively, otherwise the optimization problem will be infeasible. The optimization problem in (7) is convex since the objective function and the constraints are concave and convex respectively. Therefore, it can be solved by convex programming techniques such as interior point methods [23]. For $\upsilon = 1$ (arithmetic average throughput), it can be easily shown that the optimization problem becomes a linear programming problem. Hence, it can be solved as follows. First, we set $T_{{\rm WiFi},k} = T_{\rm WiFi,min}\ \forall k$. $T_{\rm WiFi}$ is updated as $T_{\rm WiFi} = T_{\rm WiFi} - 24T_{\rm WiFi,min}$. Then, $T_{\rm WiFi}$ is distributed over as many elements of $\{T_{{\rm WiFi},k}\}$ according to the descending order of $\{\tilde{\rho_k}\}$ such that $T_{{\rm WiFi},k} \le T_{\rm WiFi,max}\ \forall k$.

5. PERFORMANCE EVALUATION

In this section, we provide numerical results to analyze the proposed coexistence access paradigm between WiFi and RAS. The simulation parameters are listed in Table 1. The WiFi parameters are based on IEEE 802.11a standard [24] while the RAS parameters are based on ITU-R RA.769-2. Wireless traffic load statistics within a day is shown in Fig. 4 [25] which will be used in our performance evaluation.

Fig. 5 shows the received interference power at RAS. As an upper bound for the interference power experienced at the RAS receiver and hence a safer design, $I_{\rm out}$ is set to ∞ in calculating (1). According to Fig. 5, the coexistence access zone

[1] Detail of the calculation of $\tilde{\rho_k}$ is referred to [22].

Table 1. Simulation parameters

Parameter	Value
WiFi carrier frequency $\left(f_c^{\mathrm{WiFi}}\right)$	5.18 GHz
WiFi bandwidth (W^{WiFi})	20 MHz
Subcarrier spacing (Δf)	312.5 kHz
Index set of used subcarriers $(\mathcal{I})$	$\{-26, \ldots, -1, 1, \ldots, 26\}$
AP transmit power (P_{AP})	40 dBm
AP antenna gain (G_{WiFi})	6 dB
WiFi cell radius (r)	100m
AP antenna height (h_1)	10m
RAS observing center frequency $\left(f_c^{\mathrm{RAS}}\right)$	4.995 GHz
RAS observing bandwidth (W^{RAS})	10 MHz
RAS receive antenna gain for WiFi (G_{RAS})	-12 dB
RAS antenna height (h_2)	30m
Outer tiers used to define CAZ (I_{out})	∞
RAS interference threshold (I_{th})	-207 dBW
RAS minimum time per TBTT $\left(T_{\mathrm{min,RAS}}\right)$	10ms
WiFi minimum time per TBTT $\left(T_{\mathrm{min,WiFi}}\right)$	30ms
WiFi / RAS resource amounts ratio (γ)	3
Generalized mean exponent (υ)	0.5

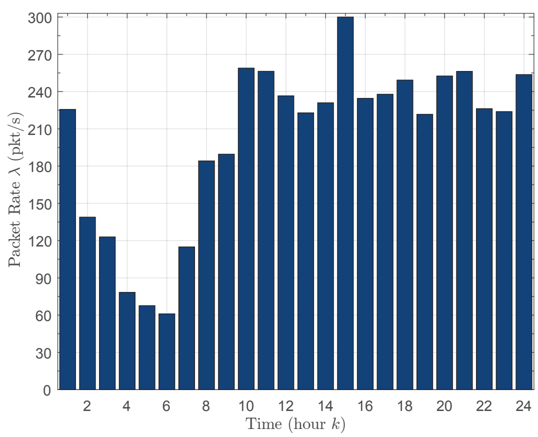

Fig. 4. Typical average traffic load within a day.

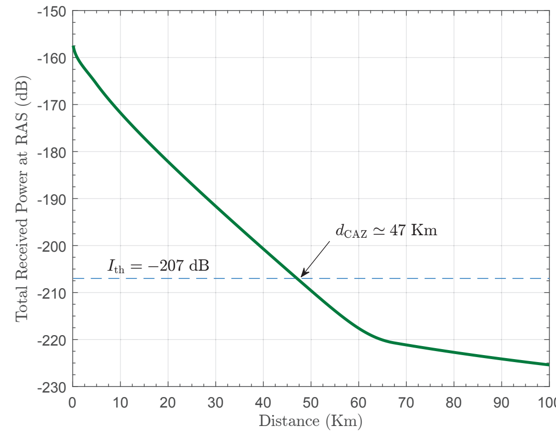

Fig. 5. Received interference power at RAS.

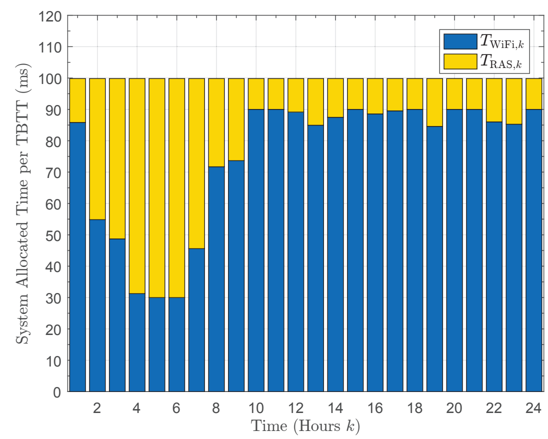

Fig. 6. Adaptive resource allocation

is defined by 47Km surrounding the RAS receiver. This distance requires a time duration of 162μs out of TBTT (0.162% overhead) to absorb the propagation delays of different WiFi APs within the CAZ. Note that WiFi cells outside the CAZ access the spectrum freely.

As for maximizing the average WiFi throughput, Fig. 6 shows the resource allocation during each hour. The time resource amounts allocated to WiFi approximately follow WiFi average traffic load. At the hours with high traffic load, the time resource amounts allocated to WiFi are limited by $T_{\mathrm{WiFi,max}}$ to satisfy the RAS minimum observation time $T_{\mathrm{RAS,min}}$. On the other hand, at the hours with low traffic load, the time resource amounts allocated to WiFi are set to $T_{\mathrm{WiFi,min}}$. Consequently, as shown in Fig. 7, WiFi experiences reduced throughput due to the portion of the time allocated to RAS.

The resource allocation in Fig. 6 and the WiFi throughputs in Fig. 7 can be adjusted through different settings of the minimum time per TBTT for RAS and WiFi and the resource amount ratio between WiFi and RAS. Also note that during the time intervals allocated to WiFi, RAS could do other internal processing which is not connected to the antenna output, for example, measuring noise power from an internal noise source as used in the old VLA of NRAO.

6. CONCLUSION

We have proposed a new paradigm for the coexistence between WiFi and RAS by means of the time-division coexistence access strategy. Coexistence access zone (CAZ) is established around each RAS site. WiFi systems within the zones follow either one of the two proposed time-division-embedded distributed MAC protocols while those outside CAZ have full spectrum access. Average traffic pattern based resource allocation is further developed. The simulation results show that WiFi systems within CAZ experience slight throughput reduction but RAS achieves substantial RFI-free spectrum access which were infeasible in the existing paradigm, thus illustrating high potentials of the proposed paradigm.

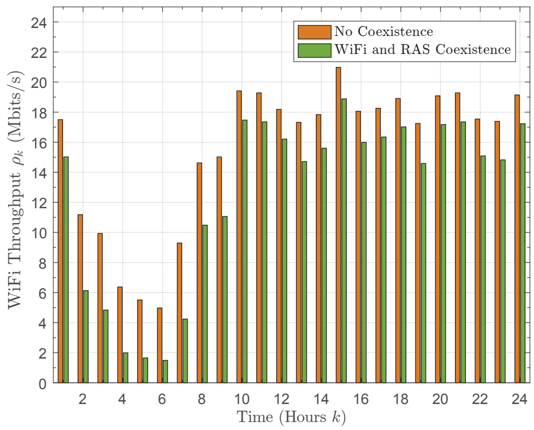

Fig. 7. WiFi average throughput comparison between the WiFi only (no coexistence) and the coexistence schemes.

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