KADIR HAS UNIVERSITY
GRADUATE SCHOOL OF SCIENCE AND ENGINEERING

COEXISTENCE OF COGNITIVE RADIO BASED NETWORKS IN TV WHITE SPACE

MASTER OF SCIENCE

by
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“ I, Onur Karatalay, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis”

Author’s Signature

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ÖZET

BİLİŞSEL RADYO TABANLI AĞLARIN TV BEYAZ BOŞLUĞUNDA BİRLİKTE VAROLMASI

En önemli doğal kaynaklardan biri olan RF tayfı, gelişen kablosuz haberleşmelerdeki artan veri hızları sebebiyle daha da önemli hale gelmiştir. Bu kısıtlı tayfı daha verimli kullanmak ve kıtlık sorununu çözmek için, düzenleyici kurumlar lisanssız ağlara ya da ikincil kullanıcılara (SUs), birincil kullanıcılara zararlı olacak girişim yaratmamaları koşuluyla lisanslı bantlara erişip kablosuz haberleşme yapabilmeleri için onay vermiştir. Bilişsel radyo (CR) teknolojisi aygıtların tayfa fırsatçı bir şekilde erişebilmelerini sağlar. CR tabanlı ağları kullanarak, lisanslı bandlar kablosuz haberleşme için daha verimli bir şekilde kullanılabilinir. TV Beyaz Boşluğu (TVWS) önceden sadece lisanslı karasal TV yayınlarına ayrılmış ve şimdi de düzenlemeler altında ikincil kullanıcıların da kullanımına açılmş tayfı kastetmektedir. Düzenlemeler TVWS'te bulunan lisanslı kullanıcıları zararlı girişimlerden korurken, lisanssız kullanıcılar arasındaki girişimi önleme daha çok üreticilere bırakılmıştır. Bu nedenle, TVWS ağları arasında yeni bir birlikte varolma yaklaşımına ihtiyaç vardır. Birlikte varolma metotlarından biri olan meşgul tonu (BT) yayınımı, TVWS ağları tarafından seçilen frekans bandının dolu olduğunu haber vermek için kullanılabilinir. Bu tezde, TVWS bandında çalışan kablosuz yerel alan ağı (WLAN) (ör: IEEE 802.11af ağı) için meşgul tonu tabanlı bir birlikte varolma algoritması önerilmiş ve kablosuz bölgesel alan ağının (WRAN) (ör: IEEE 802.22 ağı), meşgul tonu yayıncısı olduğu var sayılmıştır. Önerilen algoritma, log-normal gölgeleme etkisini, erişim noktası etrafındaki kullanıcı dağılımlarını ve kullanıcı sayılarını dikkate alarak detaylı bir şekilde analiz edilmiş, girişim yapan paket oranı ve başarılı paket gönderme oranı için kesin ifadeler bulunup, doğrulukları da farklı senaryolarda simülasyonlar ile onaylanmştır. Sonuçlar göstermektedir ki, önerilen birlikte varolma yaklaşımı ile WLAN güvenilir bir şekilde meşgul tonunu fark edip, frekans bandını değiştirebilir ve WRAN'a yapılan girişimi azaltabilir. WLAN için uygun frekans bandı olmasa dahi, WRAN iyileştirilmiş paket gönderim performansını sürdürmeye devam edebilir. Önerilen algoritmanın uygulanması TVWS bandları gibi girişimin düzenlenmediği bilişsel kablosuz bölgesel ve yerel alan ağlarının başarılı bir şekilde birlikte varolabilmeleri için önemlidir.

Anahtar Kelimeler: TV beyaz boşluğu, birlikte varolma, meşgul tonu algoritması, WRAN, IEEE 802.22, WLAN, IEEE 802.11af, bilişsel radyo ağları.

ABSTRACT

COEXISTENCE OF COGNITIVE RADIO BASED NETWORKS IN TV WHITE SPACE

Due to increasing data rates in enhancing wireless communications, RF spectrum, which is one of the most crucial natural sources, has become more valuable. In order to utilize the limited spectrum efficiently and solve the scarcity problem, regulatory agencies granted unlicensed networks or secondary users (SUs) access to licensed bands for wireless communication with the condition that they should not cause harmful interference to primary users (SUs). Cognitive radio (CR) technology enables devices to access the spectrum opportunistically. Using CR based networks, licensed bands can be utilized more effectively for wireless communications. TV White Space (TVWS) refers to portions of the RF spectrum that was reserved only for licensed terrestrial TV broadcasting and is opened to unlicensed use under regulatory conditions. While regulations protect licensed systems in TVWS from harmful interference, interference prevention among unlicensed systems is left mainly to manufacturers. Consequently, there is a need to develop new coexistence approaches between TVWS networks. Busy tone broadcasting is a coexistence method, which can be used by TVWS networks to announce that the selected frequency band is occupied. In this dissertation, a busy tone based coexistence algorithm is proposed for wireless local area networks (WLANs) operating in TVWS (i.e., IEEE 802.11af based networks), where wireless regional area network (WRAN) (i.e., IEEE 802.22 based network) is assumed to be the busy tone broadcaster. The proposed algorithm is analyzed in detail considering the effects of log-normal shadowing, client distribution around the access point and the number of clients, where exact interfering packet rate and successful packet transmission rate expressions are obtained and validated by simulations for different scenarios. The results show that with the proposed coexistence approach, a WLAN can reliably detect the busy tone signal to change its frequency band and can reduce interference to WRAN. Even if there is no available frequency band for the WLAN, the WRAN still maintains its enhanced successful packet transmission performance. The deployment of the proposed algorithm is important for successful coexistence between cognitive wireless regional and local area networks, where interference among networks is not regulated, such as in TVWS bands.

Keywords: TV white space, coexistence, busy tone algorithm, WRAN, IEEE 802.22, WLAN, IEEE 802.11af, cognitive radio networks

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LIST OF SYMBOLS/ABBREVIATIONS

DSA : Dynamic Spectrum Access

CR : Cognitive Radio

TVWS : Television White Space

SU : Secondary User

PU : Primary User

BT : Busy Tone

MAC : Medium Access Control Layer

SDR : Software Defined Radio

TVBD : TV Band Device

WRAN : Wireless Regional Area Network

WLAN : Wireless Local Area Network

WPAN : Wireless Personal Area Network

PHY : Physical Layer

AP : Access Point

CL : Client

BS : Base Station

CPE : Customer Premises Equipment

GLDB : Geo-location Database

SIR : Signal-to-Interference-Ratio

K : Number of IEEE 802.11af Clients

ψ : Traffic Percentage of Downlink in IEEE 802.11af Network

$1-\psi$: Traffic Percentage of Uplink in IEEE 802.11af Network

T_{11af} : IEEE 802.11af Transmit Power level

T_{22} : IEEE 802.22 Transmit Power level

T_{BT} : Busy Tone Transmit Power level

λ_{11af} : IEEE 802.11af Sensing Threshold in dBm

λ_{BT} : Busy Tone Detection Threshold in dBm

λ_{int} : Interference Threshold in dBm

λ_{WLAN} : Tolerable SIR Level in IEEE 802.11af Network in dB

Γ : Total Packets of IEEE 802.22 Network

f : Operating Frequency in MHz

L : Path Loss between Stations

1. Introduction

Demand for wireless communication technologies has dramatically risen over the last decades, which resulted in tremendous traffic growth and higher data rates. Recently, it has been realized that static spectrum allocation leads to inefficient use of the frequency bands and will fail to provide sufficient data rates for faster communication in the future. Since the spectrum is one of the most expensive and limited natural source, efficient utilization of available frequency bands can cope with the excess demand. Although the available spectrum is already allocated to the use of licensed devices, most of the spectrum is underused at any given time and region, which brings the idea of re-using the allocated bands for wireless communications. Thus, new technologies and solutions have been developed, such as dynamic spectrum access (DSA) and cognitive radios (CRs).

Instead of static operation in one frequency band, CR based networks can opportunistically access the spectrum and dynamically select their operating frequency band, which provides better utilization and optimization of the available frequency bands and resolves the scarcity problem in the spectrum. TV White Space (TVWS) refers to one of such licensed bands allocated for terrestrial TV broadcasts and recently regulated for secondary user (SU) access and wireless communications. Although operating in licensed bands as an opportunistic network may provide spectrum usage efficiency and high data rates, mitigating possible interference between those networks and primary users (PUs) (i.e., TV broadcasts) as well as among secondary networks is a challenging problem and should be addressed.

In this dissertation, various methods for preventing interference to PUs caused by opportunistic networks are summarized. Since the main focus of this thesis is the coexistence of cognitive radio based networks in TVWS, detailed interference analysis among such networks operating in TVWS is studied. In order to prevent the interference between SUs, a Busy Tone (BT) based coexistence algorithm is proposed. The performance of this algorithm is analyzed by considering both ideal and realistic environment and channel models. Furthermore, packet traffic analysis among SUs is provided for both cases of BT based algorithm used and not used.

1.1. Motivation for Cognitive Radio

CR technology was first introduced by Joseph Mitola and Gerald Q. Maguire, Jr. in 1999 [1]. It is considered as reconfigurable transceiver of the advanced software-defined radio (SDR), which allows CR based devices to monitor and detect the spectrum and access it dynamically by reconfiguring the necessary parameters (i.e., operating mode or frequency). Due to flexible use of the RF band, packet traffic and data rates can be increased within the network.

CR based devices use intelligent algorithms to adopt the environment and decide what is best for the network. Thus, every cognitive device operates according to the following procedures [2]. First, CR monitors the spectrum and senses the channel activity. Second, a decision is made based on the parameters regarding whether or not the selected channel is suitable for communication. Then, parameters within the network are adjusted accordingly. Finally, CR learns the channel activity from previously visited channel. Based on the selected mode, CR can operate either in *overlay* or *underlay* mode [3]. In the *overlay* mode, CR based devices access the unoccupied spectrum (i.e., white spaces) via spectrum database without any transmit power constraints. On the other hand, if a CR device selects *underlay* mode, transmitted power level must be adjusted according to interference constraint between SUs and PUs.

1.2. Motivation for TV White Space

As a scarce resource, RF spectrum bands can be utilized inefficiently due to the nature of wireless applications and hesitancy to improve the transmission technology to ensure backward compatibility. Technological advancements can create opportunities to improve utilization efficiency. Such an opportunity occurred during the period of analog to digital TV transition in many countries. Due to shift from analog TV to digital TV broadcasting and thanks to the precise windowing and filtering in digital communication, unoccupied channels have become available for cognitive radio access. This vacant spectrum, which is within the 470-790 MHz frequency range, is referred to as TV White Spaces (TVWS).

In order to utilize these under-used channels, Federal Communications Commission (FCC) regulated the spectrum for unlicensed users (i.e., cognitive based network) while protecting the PUs in TVWS [4]. Similar regulations were ruled by regulatory agencies worldwide, where TVWS operation of fixed and mobile devices were allowed [5]-[6]. These unlicensed devices or secondary users (SUs) in this spectrum are called TV Band Devices (TVBDs). Due to favorable characteristics of signal penetration in TVWS, which include wide coverage range of networks and successful penetration through obstacles, many standards have been developed for TVWS access, including IEEE 802.22 wireless regional area network (WRAN) [7], IEEE 802.11af wireless local area network (WLAN) [8], and IEEE 802.15.4m wireless personal area network (WPAN) [9]. When these networks have been deployed in TVWS, they may cause interference to PUs as well as to each other. Thus, peaceful coexistence mechanisms should be addressed for each possible scenario.

1.3. Contribution of the Thesis

Although the interference caused from opportunistic networks to licensed users is strictly prevented by the standards, possible interference among unlicensed devices is likely to occur because of the heterogeneous nature of TVWS networks. Since the coexistence between SUs in TVWS is left to the manufacturers, various coexistence algorithms and interference analysis towards this problem are proposed in the literature. However, they fail to provide realistic client distributions and do not use appropriate environment models in their studies. If the distance between networks or the respective positions of devices change, the analysis of the proposed model needs to be adjusted accordingly. On the other hand, this thesis proposes a unique way to analyze the coexistence problem among SUs by providing

1. the probabilistic client distribution within a network (i.e., IEEE 802.11af client distribution), where the paths between access point and clients experience log-normal shadowing,
2. the interference analysis between two cognitive radio networks (i.e., IEEE 802.11af and IEEE 802.22 networks) according to the obtained realistic distribution with different number of clients, and
3. accurate interfering packet rate and successful packet transmission rate expressions of the proposed approach by using analytical methods considering different distances between networks, number of clients and level of shadowing.

1.4. Dissertation Organization

This dissertation consists of 6 chapters. The literature review for cognitive radio and TV white space is presented and the motivation of the thesis is given in Chapter 1. In Chapter 2, interference caused by SUs to PUs and proposed solutions to protect the PUs are given. Furthermore, possible interference and coexistence scenarios as well as safe distance calculation for SUs are presented. In Chapter 3, a BT based coexistence algorithm is proposed and analysis of this algorithm for deterministic cases is given and validated by simulations. In Chapter 4, considering realistic channel models and client distributions, extended analysis of the proposed algorithm is presented in terms of interfering packet rates followed by numerical and simulation results for different cases. In Chapter 5, successful packet transmission for both non-BT (i.e., no protection) and BT cases are given and validated by simulations. Finally, Chapter 6 concludes the thesis and gives directions for future research.

2. Coexistence of TVWS Networks

In this chapter, implementing TVWS networks and its challenges are investigated in detail. One of the most crucial problems for deploying an opportunistic network and maintaining healthy communication in white spaces is the harmful interference caused to PUs as well as to other SUs. In TVWS, three different types of networks (i.e., IEEE 802.22 WRANs, IEEE 802.11af WLANs and IEEE 802.15.4m WPANs) are planned to be operating. These networks should ensure that their operation in the selected channels is not causing any interference to both PUs and other SUs. However, it is difficult to maintain interference-free communications due to realistic path losses and shadowing effects on to the signals. Thus, IEEE 802.19.1 TVWS coexistence standard has been developed to prevent both PU and SU interference [10].

In the following sections, PU (i.e., TV signals) protection is investigated and proposed mechanisms in the literature are given. Then, interference analysis and safe distance calculation among opportunistic networks are provided by using appropriate environment and path loss models.

2.1. Protection of PUs from SU Interference in TVWS

In order to protect the PUs and prevent possible interference, the FCC has required three different mechanisms as geo-location database (GLDB), transmit power control (TPC) and spectrum sensing mechanisms [11]. In GLDB method, it is expected that all SUs are connected to the data base as depicted in Fig. 2.1 and have the knowledge of the idle bands (i.e., PU-free channels) before they start communication [13]-[14]. In this database, operating frequencies and schedules as well as the location information of licensed users are stored. On the other hand, SUs that cannot access the database, must use spectrum sensing and power control mechanisms. However, due to high transmit power level (i.e., higher than

1W) for fixed devices and strict requirements for spectrum sensing (i.e., any SU must detect the presence of PU with threshold of -107 dBm under 2 seconds and not exceed the 50mW transmit power level) regulated by standards [11], fixed devices cannot operate in those modes. Thus, GLDB mechanism can provide efficient PU protection during SU operation in TVWS.

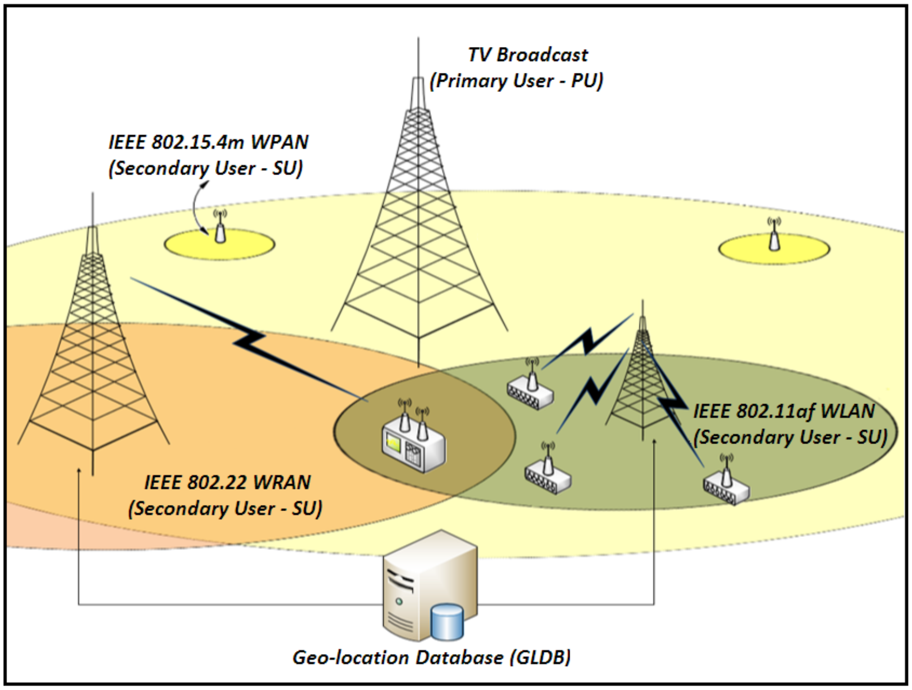

Figure 2.1. Protection of PUs from SU interference using GLDB in TVWS Bands

2.2. Interference-free Distance Calculation between SUs

In this study, it is assumed that two different TVWS networks, namely, IEEE 802.22 and IEEE 802.11af based networks, are operating in the same frequency band and the interference to PUs is prevented by the GLDB. A common interference scenario, e.g., *hidden terminal problem*, is depicted in Fig. 2.2. Accordingly, an IEEE 802.22 Base Station (BS) located at point A is communicating with its Customer Premises Equipment (CPE) at point B and an IEEE 802.11af network consisting of an Access Point (AP) and its Clients (CL)

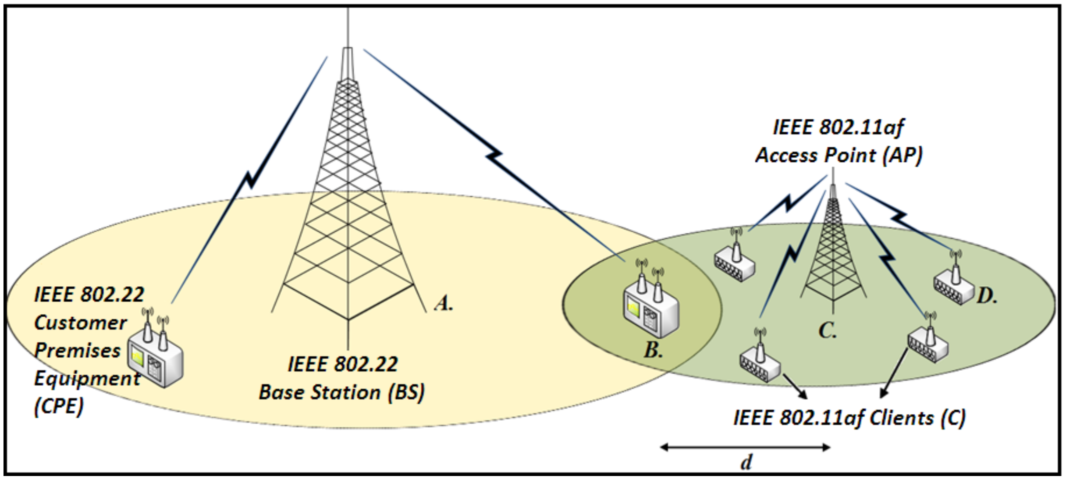

Figure 2.2. Hidden terminal problem between SUs in TVWS Band

are located at C and D, respectively. While the uplink operation of the CPE will not be interfered by the AP and Clients due to the distance between BS and them, the downlink operation is likely to be interfered as the two heterogeneous networks cannot communicate with each other [7]-[8]. Due to close deployment of these networks and wider coverage areas, if the signal power coming from point A to point B is weaker than the signal power due to the WLAN network, then the communication quality of the CPE will be deteriorated. In the hidden terminal problem the interference caused by IEEE 802.11af network to an IEEE 802.22 CPE depends on the distance d between CPE and the AP. Thus, when deploying these networks, a safe distance should be taken into account as follows.

It is assumed that IEEE 802.22 and IEEE 802.11af networks operate at maximum allowed power levels, T_{22} and T_{11af}, respectively [4]. The received signal power under ideal conditions (i.e., no shadowing effect) at point B transmitted by a device at point A as shown in Fig. 2.2 can be calculated as

$$S_{AB} = T_{22} - L_{AB} \tag{2.1}$$

where L_{AB} represents the path loss between point A and B. Furthermore, the instantaneous signal-to-interference-ratio (SIR) at point B due to interference level from each WLAN terminal in Fig. 2.2 (AP or Clients) can be calculated as

$$SIR = S_{AB} - S_{xB} \tag{2.2}$$

where $S_{xB} \in \{S_{CB}, S_{DB}\}$ can be similarly calculated as in (2.1) for the AP and Clients.

Finally, SIR ranges under different interference thresholds are given in Fig. 2.3 considering the rural HATA path loss model [28], where the safe-to-talk distance of AP/Client and CPE changes with respect to the distance between BS and CPE without considering any distortion in the channel (i.e., when the effect of shadowing is neglected). If the distance between BS and CPE or the SIR threshold value increases, any of IEEE 802.11af devices should be located at a further distance than the CPE in order not to cause interference. For example, if BS-CPE distance is 5.71km, then the minimum SIR range should be 1km for 6dB interference threshold. If the SIR value in (2.2) is dropped below a certain threshold defined within the network, packets of IEEE 802.11af network would interfere with the packets of CPE. Thus, these ranges should be strictly obeyed for professional deployments, which is unlikely for the purpose of WLAN systems and wide coverages in TVWS. Otherwise, there must be an algorithm to prevent SU interference.

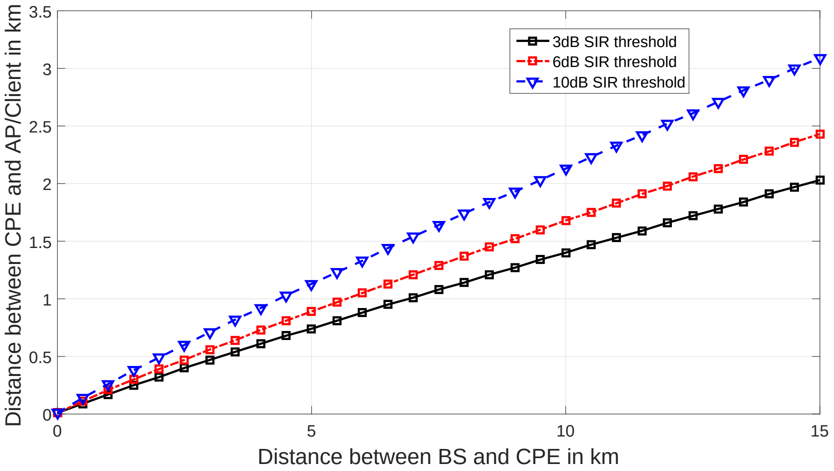

Figure 2.3. SIR ranges between IEEE 802.22 and 802.11af networks under different interference thresholds

3. BT Based Coexistence Algorithm between TVWS networks

If SUs access the same frequency band, packet interferences among those networks become inevitable. Since these unlicensed networks are heterogeneous in terms of both PHY and MAC layers, implementing a coexistence algorithm is challenging. Thus, IEEE 802.19.1 coexistence standard in TVWS has been developed [10] and various coexistence approaches have been proposed in [15]. In the literature, these approaches have been studied in detail including adaptive transmit power control [16], radiated power and range prediction [17], dynamic frequency selection [18] and interfering neighbor discovery [19] algorithms proposed for TVWS. However, according to [10], all SUs are required to be connected to a coexistence server which results in additional costs to networks and under-utilization of CR devices.

In addition to these techniques, a busy tone (BT) based method is suggested as a simple yet an effective method for coexistence between IEEE 802.22 and 802.11af networks [20]. Basic premise of the BT method is that while an IEEE 802.22 network is communicating, network nodes can broadcast BT signals to announce to other networks in the area to indicate that the selected frequency is already occupied. BT broadcast assumes that IEEE 802.22 network devices have simultaneous transmit and receive capability (STAR) [21], which can provide a high level of transmit signal suppression (i.e., self BT interference cancellation).

In [20], BT approach is simulated, where only Access Point (AP) of IEEE 802.11af network can detect BT signal. Therefore, the coexistence performance of the proposed approach had limitations as the Clients in the IEEE 802.11af network could interfere with IEEE 802.22 network. Furthermore, an indoor path loss model was used for the outdoor environment, resulting in unrealistic ranges for network coverage. Although various BT based algorithms (e.g., interference aware BT, dual-tone narrow-band BT, etc.) were suggested in the MAC layer of IEEE 802.11 systems to prevent hidden and exposed terminal problems [22]-[24], there are fewer studies in the literature considering the coexistence of heterogeneous networks using the BT based algorithms. In [25] and [26], BT based algorithms are considered for IEEE 802.11 and 802.15.4 networks in the ISM band for peaceful coexistence among heterogeneous networks. However, these studies did not consider the effect of shadowing and realistic client distributions.

It is difficult to achieve collision-free communication only by fixed professional deployment since the Clients may be mobile and the AP may not know the presence of the CPE. Considering the limitations of mentioned studies, we propose a busy tone based coexistence for IEEE 802.11af networks to enhance the coexistence performance of IEEE 802.22 and IEEE 802.11af networks. The detatils are given in Algorithm 1.

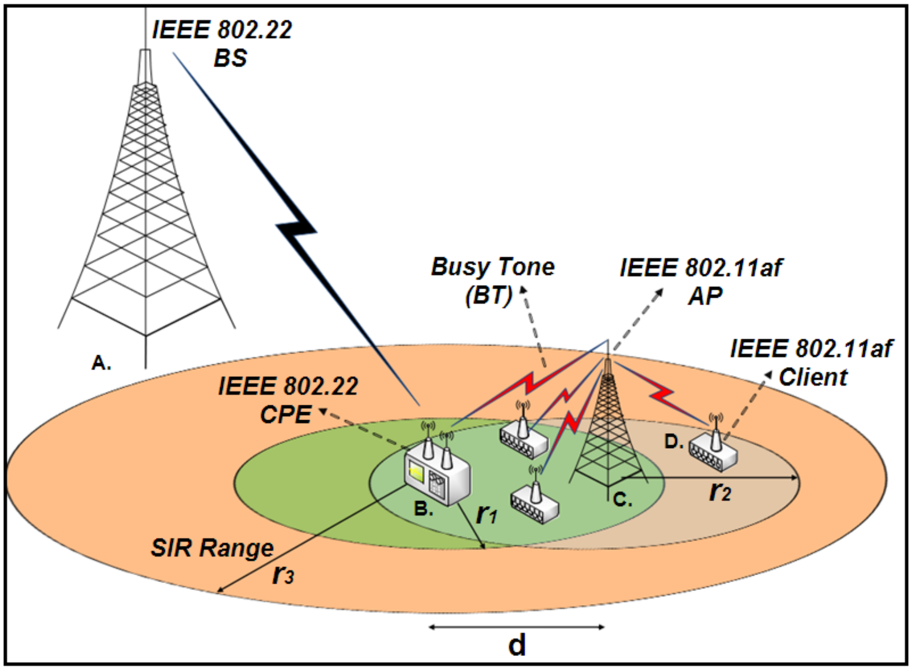

Figure 3.1. Hidden terminal problem and Busy Tone protection in TVWS Band

To prevent interference among these networks, IEEE 802.22 CPE can send a constant BT signal to inform other SUs around it, where the received BT signal power can be calculated similar to (2.1). If IEEE 802.11af devices are located in BT detection range as shown with radius r_1 in Fig. 3.1, then data transmission in the WLAN communication range, which is depicted with radius r_2, should be stopped or moved to an available frequency band to prevent possible interference to WRAN. According to the algorithm, not only IEEE 802.11af AP but also its Clients listen to the spectrum to detect the presence of BT signal.

Algorithm 1 Coexistence with Busy Tone Algorithm & Resulting Interference to WRAN Packets

```
while $BT = True$ do
    if $BT_{AP} \geq \lambda_{BT}$ then %AP detected BT
        Measure SIR between CPE and AP;
        if $SIR_{CPE-AP} \geq \lambda_{int}$ then
            No Packet is interfered and
              AP initiates the protocol for operation in another TVWS band;
        else
            1 Packet is lost due to interference from AP and
              AP initiates the protocol for operation in another TVWS band;
        endif
    else if $BT_{CL} \geq \lambda_{BT}$ then %Client detected BT
        Measure SIR between CPE and Client;
        if $SIR_{CPE-Client} \geq \lambda_{int}$ then
            No Packet is interfered and
              Client informs AP about the presence of BT signal;
        else
            1 Packet is lost due to interference from Client and
              Client informs AP about the presence of BT signal;
        endif
            %AP is informed about the presence of a BT signal ;
        Measure SIR again between CPE and AP;
        if $SIR_{CPE-AP} \geq \lambda_{int}$ then
            No Packet is interfered and
              AP initiates the protocol for operation in another TVWS band;
        else
            1 More Packet is lost due to interference from AP and
              AP initiates the protocol for operation in another TVWS band;
        endif
    endif
endwhile
```

As denoted in the algorithm, λ_{BT} refers to the BT signal detection threshold and λ_{int} is the SIR threshold. If AP cannot detect the BT signal, then it is adequate that at least one of the Clients becomes aware of the BT signal and informs AP. Meanwhile, if the SIR level at CPE is smaller than the interference threshold λ_{int}, loss of packets due to interference will be inevitable. Assuming the shadowing effect is negligible, interference analysis among IEEE 802.22 and IEEE 802.11af can be given as follows.

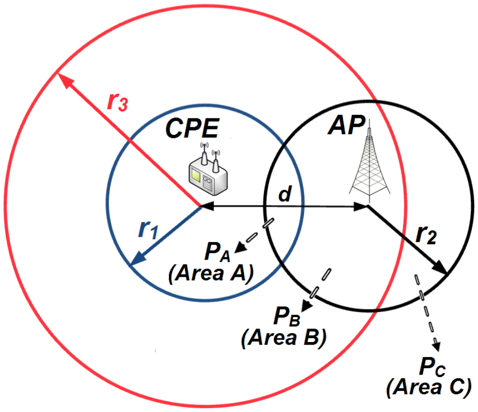

Figure 3.2. Overlapping regions

As seen in Fig. 3.2, r_1, r_2, r_3 and distance d determine the overlapping regions. In the IEEE 802.11af network, we assumed that the Clients are randomly distributed within the communication range r_2. Hence, Clients may be present in different regions and their possible distribution in Area A (i.e., BT detecting region), Area B (i.e., SIR region) and Area C (i.e., no interference region) can be computed by calculating overlapping areas on the circles. To calculate the desired areas, integration of the circle equation with respect to the intersection of points on x-axis is used as

$$y^2 + x^2 = r^2 \tag{3.1}$$

where r is the the radius of selected circle.

Without loss of generality, we assumed that the centers of the circles lay on the x-axis and the intersection points can be obtained on x-axis by solving their equations jointly.

Then, the probability of a Client being in Area A can be calculated by integrating the circle equations in the form of y_1 and y_2 from intersection point x to the area boundaries bounded by r_1 and $(d-r_2)$. Thus, P_A, the ratio of Area A to the area of IEEE 802.11af communication range is calculated as

$$P_A = \frac{2 \times \left(\int_x^{r_1} y_1 \; dx + \int_{d-r_2}^{x} y_2 \; dx \right)}{\pi {r_2}^2}. \tag{3.2}$$

For Area C, y_2 and y_3 need to be solved jointly in order to find their intersection points. Then, P_C can be calculated as

$$P_C = \frac{2 \times \left(\int_x^{d+r_2} y_2 \; dx - \int_x^{r_3} y_3 \; dx \right)}{\pi {r_2}^2}. \tag{3.3}$$

Finally, P_B can be obtained as

$$P_B = 1 - (P_A + P_C). \tag{3.4}$$

For uniform distribution of IEEE 802.11af Clients in the communication range r_2, the distance d between CPE and AP, and various conditions of r_1, r_2 and r_3, interfering packet rate (IPR) is analyzed in the following sections with the absence of a BT signal and when the proposed BT algorithm is applied. Here, IPR is the ratio of packet interferences caused by IEEE 802.11af AP and/or its Clients to all transmitted packets in IEEE 802.22 network, specifically the packets of CPE.

3.1. IPR w/o BT algorithm

In the case when there is no BT signal transmitted by CPE, Area A does not occur as depicted in Fig. 3.3. Thus, IPR only depends on r_2, r_3 and d which can be calculated as follows.

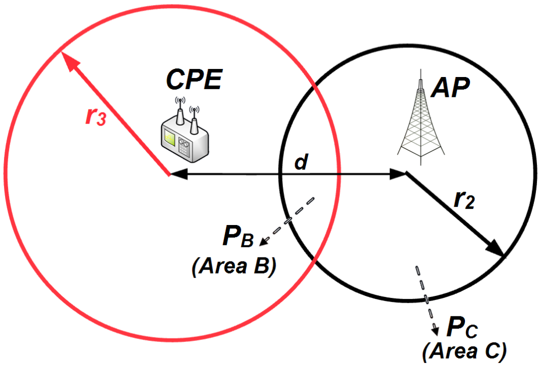

Figure 3.3. WLAN communication range and SIR range w/o BT signal

If $r_3 > r_2$, then depending on d, there will be four regions:

i) $0 \leq d \leq (r_3 - r_2)$:

$$IPR = 1 \tag{3.5}$$

In this range all packets of IEEE 802.11af network will interfere with CPE transmission.

ii) $(r_3 - r_2) < d < r_3$:

$$IPR = \sum_{k=1}^{K} \binom{K}{k} {P_B}^{k} {P_C}^{(K-k)} \cdot \frac{k(1-\psi)}{K} + \psi \tag{3.6}$$

where K is the number of IEEE 802.11af Clients and ψ is the packet traffic percentage of downlink. In this interval, AP is in the interference region and it is assumed that it controls half of the total packets in the network.

iii) $r_3 \leq d < (r_2 + r_3)$:

$$IPR = \sum_{k=1}^{K} \binom{K}{k} {P_B}^{k} {P_C}^{(K-k)} \cdot \frac{k}{K} \cdot (1 - \psi) \tag{3.7}$$

where $(1 - \psi)$ represents the packet traffic percentage of IEEE 802.11af uplink.

iv) $d \geq (r_2 + r_3)$:

$$IPR = 0 \ . \tag{3.8}$$

On the other hand, SIR range may be smaller than the communication range. Then, IPR can be calculated as follows.

If $r_3 \leq r_2$, then depending on d, there will be three regions:

i) $0 \leq d \leq r_2$:

In this case (3.6) is valid because AP will be present in SIR range during this interval. Thus, it affects the total packet collisions proportional to $(\psi \cdot \Gamma)$, where Γ represents the total packets in IEEE 802.22 system.

ii) $r_2 < d < (r_2 + r_3)$:

Equation (3.7) is valid since AP is not in the SIR range but the Clients are.

iii) $d \geq (r_2 + r_3)$:

There is no interference between networks in that range. Hence, IPR equals to zero.

3.2. IPR w/ BT algorithm

BT signal is generated by CPE and can be detected by AP and/or Clients within the radius r_1. As shown in Fig. 3.2, Area A (i.e., BT region) should be included in the IPR calculations according to the distance d. Since SIR range r_3 depends on the distances between BS-CPE and CPE-AP, the relationship between r_3 and r_1 must be taken into account when calculating the IPR.

If $r_3 \leq r_1$ then, depending on d, there will be three regions:
i) $0 \leq d < r_3$:

$$IPR = \frac{1}{\Gamma} \tag{3.9}$$

AP is in the interference region but it can always hear the BT signal and relay this message within the network. Hence, only one packet will collide.

ii) $r_3 \leq d \leq r_1$:

$$IPR = 0 \tag{3.10}$$

In this interval, AP can hear the BT signal and tell its Clients to stay silent. Since the AP is not in the SIR region, there is no interference between the networks while relaying the BT information.

iii) $d > r_1$:

Due to IEEE 802.11af communication region, r_2, different regions such as BT or SIR, may not be formed and it has to be taken into account as follows.

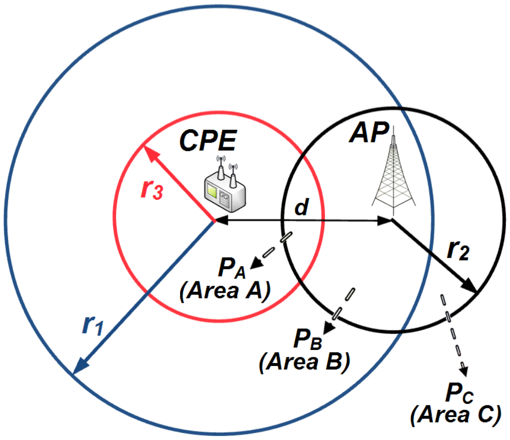

Figure 3.4. Busy Tone range greater than SIR range

Case 1: If $P_A \neq 0$

As shown in Fig. 3.4, Clients which are in the Area A cause interference, but also they are the ones which can detect the BT signal. If at least one Client is located in the Area A, it will relay the BT information to the AP and will interfere with CPE. Thus, only that Client causes packet lost. When calculating the IPR, Area B and Area C can be treated as a single region and the probabilities are added together:

$$IPR = \left(1 - (P_B + P_C)^K\right) \cdot \frac{1}{\Gamma} \tag{3.11}$$

Case 2: If $P_A = 0$

$$IPR = 0 \tag{3.12}$$

Even if BT signal is used, in this interval due to r_2, Area A may not occur. This means there is no interference among the networks, hence, IPR equals zero. However, depending on the Client locations, IEEE 802.11af network could stay silent because of the BT range, which will affect its throughput.

On the other hand, the SIR range may be greater than the BT range as shown in Fig.

3.2. Accordingly, if $r_3 > r_1$, depending on d, there will be four regions:

i) $0 \leq d \leq r_1$:

$$IPR = \frac{1}{\Gamma} \tag{3.13}$$

Because of the distance d, AP always hears the BT signal by itself and relays to its Clients.

ii) $r_1 < d < r_3$:

In this interval, due to the possible variations of IEEE 802.11af communication range r_2, different situations may occur and they should be considered seperately.

<u>Case 1:</u> If $P_A \neq 0$ and $P_C \neq 0$

$$\begin{aligned} IPR = &\sum_{k=1}^{K} \left[\binom{K}{k} \sum_{m=0}^{K-k} {P_A}^k {P_B}^m {P_C}^{(K-k-m)} \right] \cdot \frac{2}{\Gamma} \\ &+ \sum_{k=0}^{K} \binom{K}{k} {P_B}^k {P_C}^{(K-k)} \cdot \frac{k}{K} \cdot (1-\psi) + \psi \end{aligned} \tag{3.14}$$

<u>Case 2:</u> If $P_A \neq 0$ and $P_C = 0$

$$IPR = \sum_{k=1}^{K} \binom{K}{k} {P_A}^k {P_B}^{(K-k)} \cdot \frac{2}{\Gamma} + {P_B}^K \tag{3.15}$$

Case 3: If $P_A = 0$ and $P_C \neq 0$

$$IPR = \sum_{k=0}^{K} \binom{K}{k} {P_B}^k {P_C}^{(K-k)} \cdot \frac{k}{K} \cdot (1-\psi) + \psi \tag{3.16}$$

Case 4: If $P_A = 0$ and $P_C = 0$

$$IPR = 1 \tag{3.17}$$

iii) $r_3 < d < (r_2 + r_3)$:

As for this region, depending on P_A, there will be two different cases.

Case 1: If $P_A \neq 0$

$$\begin{aligned} IPR = \sum_{k=1}^{K} \left[\binom{K}{k} \sum_{m=0}^{K-k} {P_A}^k {P_B}^m {P_C}^{(K-k-m)} \right] \cdot \frac{1}{\Gamma} \\ + \sum_{k=0}^{K} \binom{K}{k} {P_B}^k {P_C}^{(K-k)} \cdot \frac{k}{K} \cdot (1-\psi) \end{aligned} \tag{3.18}$$

Case 2: If $P_A = 0$

Only Clients which are within the SIR region cause packet collisions. Thus, (3.7) is valid in this region.

iv) $d \geq (r_2 + r_3)$:

In this range, there is no packet collision between the networks, i.e.,

$$IPR = 0 \tag{3.19}$$

3.3. System Performance and Results

In order to calculate the IPR for various scenarios, it is assumed that both networks are operating at maximum allowed transmit powers levels, $T_{22} = 4\text{W}$ and $T_{11af} = 100\text{mW}$ for IEEE 802.22 and 802.11af networks, respectively. The values of transmit powers are chosen according to FCC regulations [4]. Furthermore, BT signal power is set to $T_{BT} = 100\text{mW}$ [27] and $\lambda_{BT} = -68\text{dBm}$ is selected according to the IEEE 802.11af Clear Channel Assessment (CCA) sensitivity level for 6 MHz channel [8]. Since modulation and coding type determines the communication thresholds, QPSK modulation with R=1/2 coding rate for IEEE 802.11af network is assumed and threshold is determined as $\lambda_{11af} = -91.3\text{dBm}$ [8]. Also, SIR threshold value in the system is assumed to be 6dB and rural HATA path loss model [28] is used to determine the path loss between devices as

$$\begin{aligned}
L &= L^{'} - 4.78(\log_{10}(f))^2 + 18.33\log_{10}(f) - 35.94 && (3.20)\\
L^{'} &= 69.55 + 26.16\log_{10}(f) - 13.82\log_{10}(h_t) - a(h_r) \\
&\qquad + (44.9 - 6.55\log_{10}(h_t))\log_{10}(d) && (3.21)\\
a(h_r) &= 3.2(\log_{10}(11.75h_r))^2 - 4.97 && (3.22)
\end{aligned}$$

where d is the distance between devices in km, f is the operating frequency which is selected as 600 MHz, and h_t and h_r are the transmitter and receiver antenna heights. For antenna heights, it is assumed that IEEE 802.22 BS is at 30m and CPE is at 10m, whereas IEEE 802.11af AP and Clients are at 1m.

Since analytical IPR calculations depend on different combinations of r_1, r_2 and r_3 values, two different cases, where $r_1 < r_2 < r_3$ and $r_3 < r_1 < r_2$, are considered. For BT detection range r_1 and IEEE 802.11af communication range r_2, using transmitted power level and sensing threshold, they are calculated as $r_1 = 300\text{m}$ and $r_2 = 450\text{m}$, respectively. Also, for the first case where $r_1 < r_2 < r_3$, SIR range, r_3 is decided by placing the IEEE 802.22 CPE 5.71km away from the BS. Accordingly, the safe interference range $r_3 = 1\text{km}$. For the

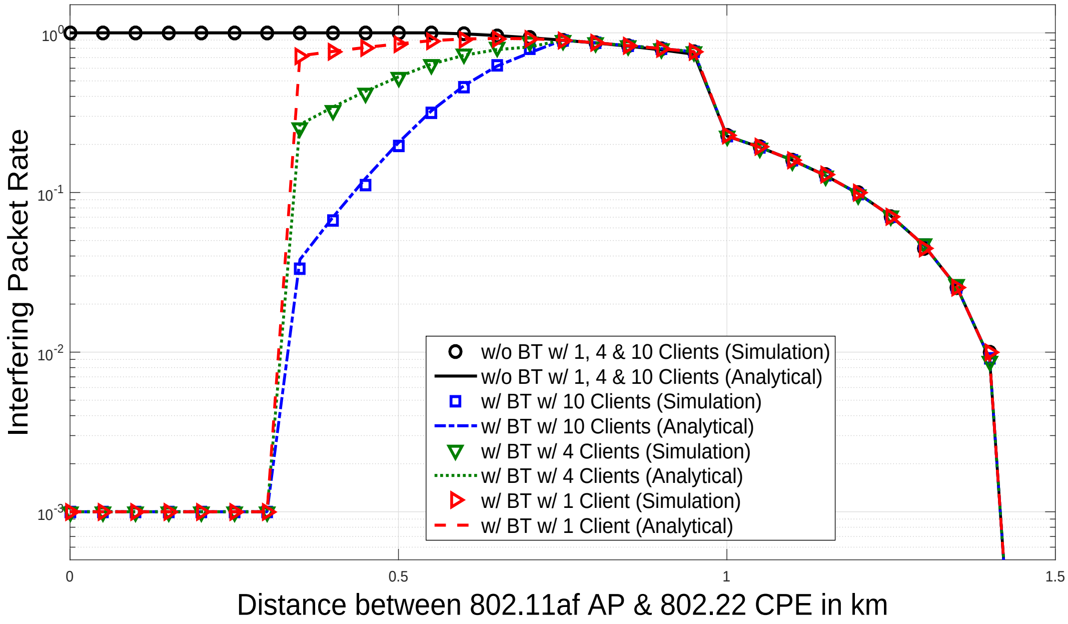

Figure 3.5. Analytical vs simulation results when $r_1 < r_2 < r_3$

second case where $r_3 < r_1 < r_2$, we arranged the distance between IEEE 802.22 BS and CPE as 1.26km. Accordingly SIR range r_3 becomes 250m which is smaller than the BT range r_1. Note that different SIR ranges can be determined simply from Fig. 2.3. Considering these assumptions and changing the distance d between CPE and the AP and number of IEEE 802.11af Clients, IPR performance, where the total packets set to $\Gamma = 1000$, is validated by using Monte Carlo simulation as shown in Figs. 3.5 and 3.6.

It can be observed that simulation results are in well correspondence with IPR calculations, confirming the validity of the analysis. In Fig. 3.5, where $r_1 < r_3$, the AP can hear the BT up to $r_1 = 300m$ and the Clients can hear the BT up to $750m$. Hence, the BT algorithm performance outperforms the non-BT case in these regions. Furthermore, in the [300,750]m range, the increase in the number of Clients reduce the IPR as it will be more likely that at least one of the Clients will hear the BT. After 750m, the BT algorithm and the non-BT case perform the same.

In Fig. 3.6, where $r_3 > r_1$, the AP can hear the BT up to 300m. Since the safe SIR range is $r_3 = 250m$, only one packet of IEEE 802.11af network is interfering with the

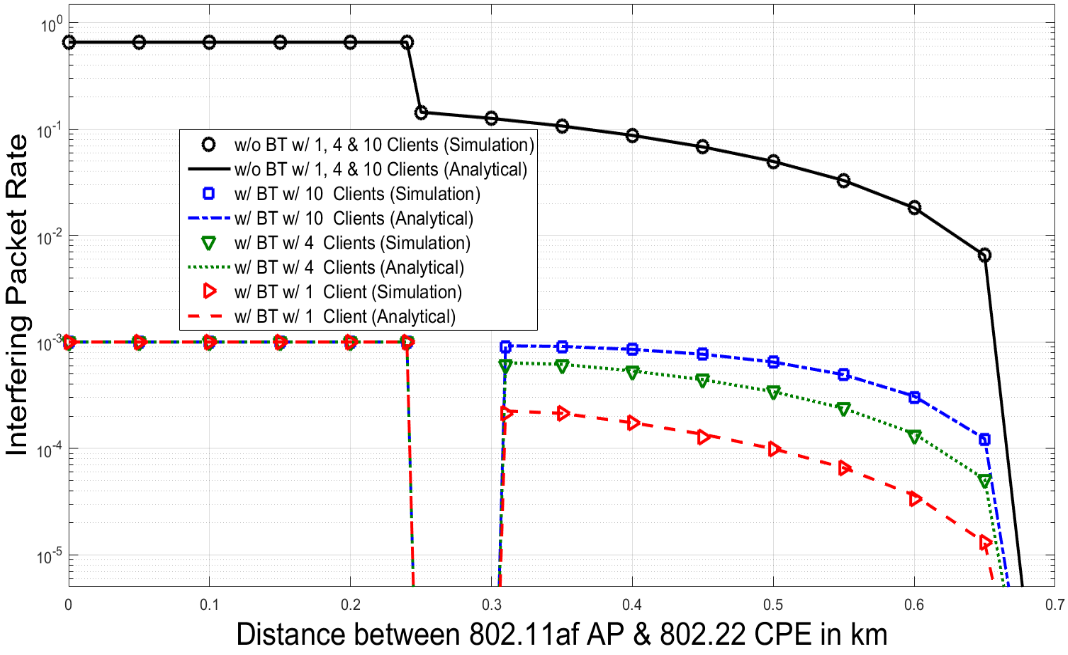

Figure 3.6. Analytical vs simulation results when $r_3 < r_1 < r_2$

CPE up to 250m. In the [250,300]m range, the AP can still hear the BT, but does not cause interference to CPE since it is outside the SIR region. After 300m, there may be one or more Clients hearing and possibly interfering because of the SIR range. Hence, the interfering packet rate performance is at most $IPR = 10^{-3}$. For this case, the BT algorithm outperforms the non-BT case for all distance ranges.

Although our analysis is validated by simulations, case-dependent solution of the analysis, unrealistic client distributions and deterministic channel assumptions (i.e., no shadowing) make it difficult to apply the analysis in real life applications. Thus, in the next section, by considering more realistic assumptions, the IPR calculation is given for both BT and non-BT cases.

4. Analysis of Proposed BT Algorithm under Realistic Conditions

In this chapter, realistic channel models with probabilistic client distributions including shadowing effect are considered and a simplified analysis for IPR calculations is provided. Including the effect of shadowing on the channel[1], the received signal power at point B transmitted by a device at point A as shown in Fig. 3.1 can be calculated as

$$S_{AB} = T_{22} - L_{AB} + \eta \tag{4.1}$$

where η represents log-normal shadowing with $\eta \sim N(0, \sigma^2)$ and L_{AB} represents the path loss between points A and B. Also, SIR value between two stations can be found similarly as in (2.2). Accordingly, the probability of interference among SUs as well as probability of BT detection can be calculated as follows.

4.1. Analysis of Interference to WRAN Packets

In this section, we define the probability of interference between the two networks followed by interfering packet rate calculations. The probability of interference caused by AP to a CPE at distance d can be calculated as

$$P_{INT}^{AP}(d) = Q\left(\frac{\lambda_{int} - (T_{11af} - L(d))}{\sigma}\right) \tag{4.2}$$

where $Q(x) = \dfrac{1}{\sqrt{2\pi}} \int\limits_{x}^{\infty} e^{-t^2/2} dt$, $L(d)$ is the path loss between IEEE 802.11af AP and 802.22 CPE, λ_{int} is the interference threshold in dBm and σ is the standard deviation of shadowing

---

[1] It is assumed that the signal-to-noise-ratio (SNR) level is sufficient enough to neglect the noise for interference calculation and the system performance is dominated by shadowing.

effect. Similarly, the probability of BT signal detection by AP at distance d can be calculated as

$$P_{BT}^{AP}(d) = Q\left(\frac{\lambda_{BT} - (T_{BT} - L(d))}{\sigma}\right) \tag{4.3}$$

where T_{BT} is the BT signal power transmitted from IEEE 802.22 CPE and λ_{BT} is the threshold to detect BT.

Since Clients may cause interference to the CPE, the Client distribution around AP should be determined. Although the positions of Clients are assumed to be uniformly distributed around AP, shadowing affects their connection probability. The probability of a successful Client-AP connection under log-normal shadowing, $P_C(r)$, can be obtained by replacing λ_{int} with IEEE 802.11af communication threshold λ_{11af} as

$$P_C(r) = Q\left(\frac{\lambda_{11af} - (T_{11af} - L(r))}{\sigma}\right) \tag{4.4}$$

where r is the distance between Client and AP in km as shown in Fig. 4.1.

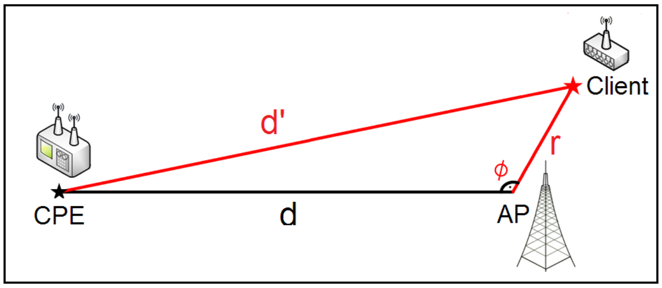

Figure 4.1. Determining locations of AP and a Client with respect to CPE

Subsequently, a Client near AP will connect to the AP with a very high probability, whereas with distance r increasing connection probability will be less. Assuming that all Clients are subject to same conditions, the probability of a connected Client being at a specific location at that instant (i.e., Client distribution) can be obtained by normalizing

$P_{_C}(r)$ by the volume obtained by rotating (4.4) with respect to $\phi \in [0, 2\pi]$ as

$$P^{cl}_{dist}(r) = \frac{Q\left(\dfrac{\lambda_{11af} - (T_{11af} - L(r))}{\sigma}\right)}{2\pi \int\limits_0^\infty P_{_C}(r) r dr} \tag{4.5}$$

where $P^{cl}_{dist}(r)$ is the probability of a Client being at distance r from AP and is independent from ϕ. This is illustrated in Fig. 4.2 for Client distribution around AP under 10dB shadowing variance, where the Client distribution has a three-dimensional probability density function (PDF).

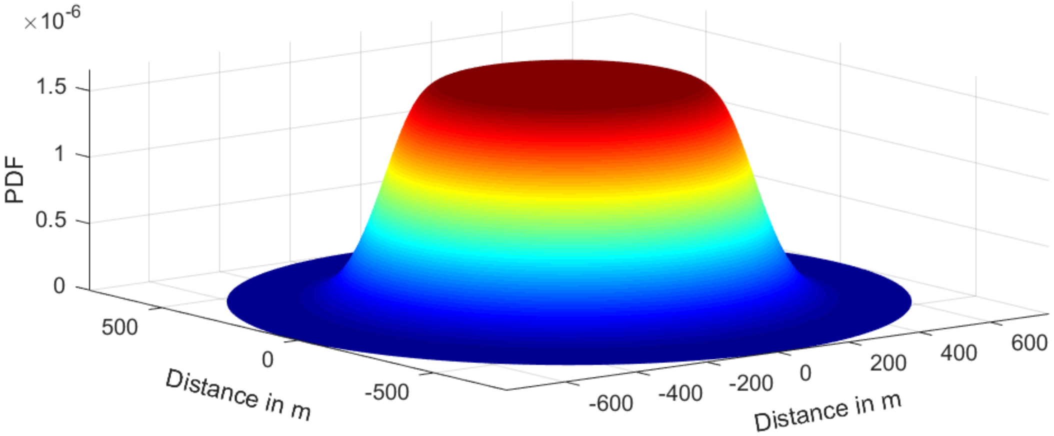

Figure 4.2. PDF of connected Client distribution around AP under 10dB shadowing variance

Given that a Client is at distance r from AP making an angle ϕ as shown in Fig. 4.1, the probability of interference caused by a Client at distance d', which is calculated from the cosine theorem, equals to

$$P^{cl}_{int}(d|r,\phi) = Q\left(\frac{\lambda_{int} - (T_{11af} - L(d'))}{\sigma}\right) \tag{4.6}$$

and the probability of BT signal detection by the Client at distance d' is

$$P_{bt}^{cl}(d|r,\phi) = Q\left(\frac{\lambda_{BT} - (T_{BT} - L(d'))}{\sigma}\right) \tag{4.7}$$

where $P_{int}^{cl}(d|r,\phi)$ and $P_{bt}^{cl}(d|r,\phi)$ refer to the probabilities at that specific instants and locations. To determine the overall probabilities for interference and BT signal detection of a Client, location dependent probabilities (4.6) and (4.7) should be considered together with the probability of Client distribution around AP as given in (4.5). Hence, the probabilities of a Client causing interference to CPE and detecting the BT when the Client is connected to the AP under log-normal shadowing at distance d from CPE can be provided respectively as

$$P_{INT}^{CL}(d) = \int_0^{2\pi}\int_0^{\infty} P_{int}^{cl}(d|r,\phi)P_{dist}^{cl}(r)rdrd\phi \tag{4.8}$$

$$P_{BT}^{CL}(d) = \int_0^{2\pi}\int_0^{\infty} P_{bt}^{cl}(d|r,\phi)P_{dist}^{cl}(r)rdrd\phi\ . \tag{4.9}$$

Probability expressions obtained in (4.2)-(4.3) and (4.8)-(4.9) can be used in the calculation of packet interferences of IEEE 802.11af network to IEEE 802.22 CPE. Note that the IPR expression obtained in the following is algorithm-dependent and will be detailed accordingly.

4.2. IPR Calculations

IPR depends on packet traffic percentage of IEEE 802.11af downlink and uplink. Accordingly, IPR when BT signal is not present in the spectrum, can be calculated as

$$IPR(d) = P_{INT}^{AP}(d)\cdot\psi + \sum_{k=1}^{K}\left[\binom{K}{k}\left(P_{INT}^{CL}(d)\right)^{k}\left(1 - P_{INT}^{CL}(d)\right)^{(K-k)}\frac{k}{K}\right]\cdot(1-\psi) \tag{4.10}$$

where d is the distance between AP and CPE in km, K is the number of Clients, ψ and $(1-\psi)$ are the packet traffic percentage of downlink and uplink, respectively. For any value of K, it can be shown that (4.10) can be simplified as

$$IPR(d) = P_{INT}^{AP}(d) \cdot \psi + P_{INT}^{CL}(d) \cdot (1-\psi) \tag{4.11}$$

which indicates that IPR is independent of number of Clients and the total number of packets transmitted by IEEE 802.22 CPE when BT signal is not available in the channel.

On the other hand, when BT signal is present in the channel, all possible interference and BT detection probabilities should be calculated together. According to the positions of AP, CPE and Clients, interference and BT detection cases shown in Fig. 4.3 may occur,

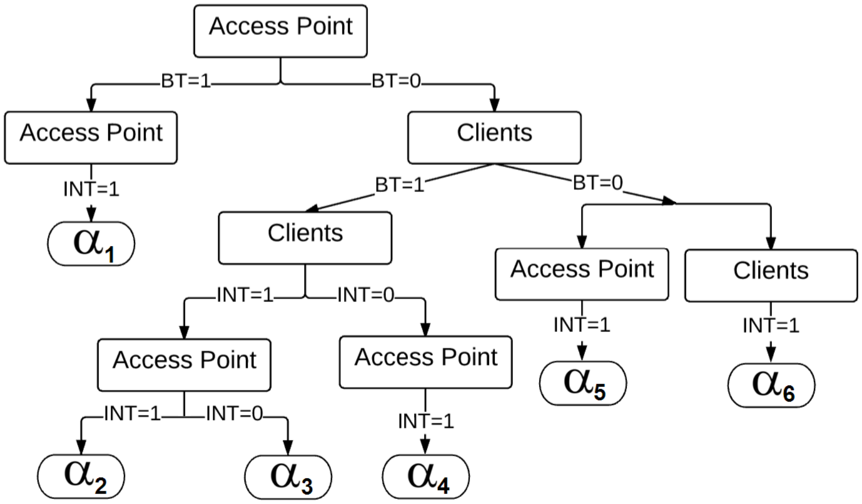

Figure 4.3. Probabilistic interference cases of Busy Tone algorithm

where BT=1 indicates BT detection by AP or Client and INT=1 indicates harmful interference to CPE from any IEEE 802.11af device. In the first case (α_1), AP detects the BT and informs the Clients, which results in one packet loss in the IEEE 802.22 system. If AP cannot detect the BT, then Clients may detect the BT and inform AP about presence of BT signal. In that case both AP and a Client may interfere with IEEE 802.22 CPE and cause packet losses (α_2), or either a Client (α_3) or AP (α_4) may cause a packet loss. Otherwise, if the Clients cannot detect the BT either, AP and/or Clients may cause interference (α_5, α_6). These cases are represented mathematically in (4.12)-(4.17) as

$$
\begin{aligned}
\alpha_1 &= P^{AP}_{BT^1,INT^1} \cdot \frac{1}{\Gamma} && (4.12)\\
\alpha_2 &= P^{AP}_{BT^0,INT^1} \cdot \left(P^{CL}_{BT^1,INT^1}\right)^K \cdot \frac{2}{\Gamma} && (4.13)\\
\alpha_3 &= \left(1 - P^{AP}_{BT}\right) \cdot \left[1 - \left(1 - P^{CL}_{BT^1,INT^1}\right)^K\right] \cdot \frac{1}{\Gamma} && (4.14)\\
\alpha_4 &= P^{AP}_{BT^0,INT^1} \cdot \left[1 - \left(1 - P^{CL}_{BT}\right)^K\right] \cdot \frac{1}{\Gamma} && (4.15)\\
\alpha_5 &= P^{AP}_{BT^0,INT^1} \cdot \left(1 - P^{CL}_{BT}\right)^K \cdot \psi && (4.16)\\
\alpha_6 &= \left(1 - P^{AP}_{BT}\right) \cdot \sum_{k=1}^{K} \left[\binom{K}{k} \left(P^{CL}_{BT^0,INT^1}\right)^k \left(P^{CL}_{BT^0,INT^0}\right)^{(K-k)} \frac{k}{K}\right] \cdot (1 - \psi) && (4.17)
\end{aligned}
$$

where K is the number of IEEE 802.11af Clients, Γ is the total packets of IEEE 802.22 network and $P^{AP/CL}_{BT,INT}$ refers to the joint probability of BT detection and interference to CPE caused by any WLAN device (i.e., $P^{AP}_{BT,INT}$ for AP and $P^{CL}_{BT,INT}$ for Clients).

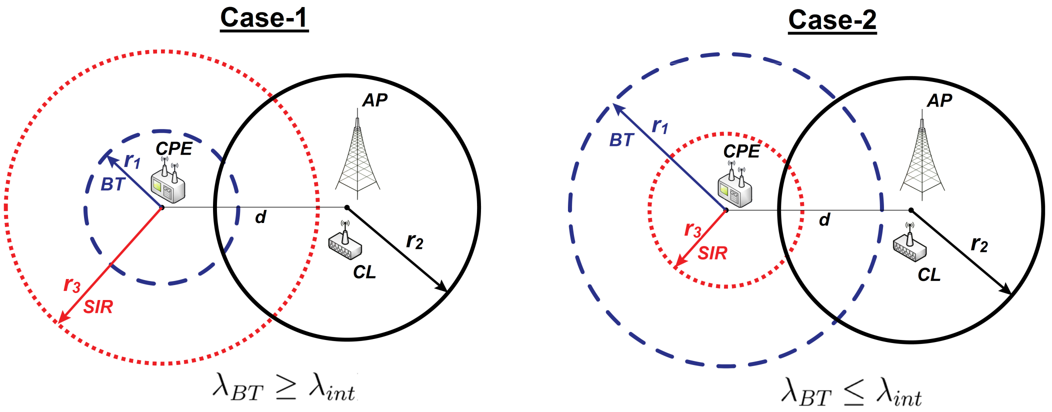

Figure 4.4. BT and interference regions due to different thresholds: Case-1 where BT range is smaller than the interference range, Case-2 where the BT range is larger than the interference range

The joint probabilities depend on the BT detection and SIR thresholds, which define the corresponding ranges. For better illustration, two different cases between WRAN CPE and a WLAN device under no shadowing case are depicted in Fig. 4.4, where r_1 is the BT range, r_2 is the IEEE 802.11af TVBD communication range and r_3 represents the SIR range. Thus, the joint probabilities can be calculated according to the intersection of the desired regions as:

Case-1: If $r_3 \geq r_1$ (i.e., $\lambda_{BT} \geq \lambda_{int}$):

$$P_{BT^0,INT^0}^{AP/CL} = \left(1 - P_{INT}^{AP/CL}\right) \tag{4.18}$$

$$P_{BT^0,INT^1}^{AP/CL} = \left(1 - P_{BT}^{AP/CL}\right) - \left(1 - P_{INT}^{AP/CL}\right) \tag{4.19}$$

$$P_{BT^1,INT^0}^{AP/CL} = 0 \tag{4.20}$$

$$P_{BT^1,INT^1}^{AP/CL} = P_{BT}^{AP/CL} \tag{4.21}$$

Case-2: If $r_3 \leq r_1$ (i.e., $\lambda_{BT} \leq \lambda_{int}$):

$$P_{BT^0,INT^0}^{AP/CL} = \left(1 - P_{BT}^{AP/CL}\right) \tag{4.22}$$

$$P_{BT^0,INT^1}^{AP/CL} = 0 \tag{4.23}$$

$$P_{BT^1,INT^0}^{AP/CL} = \left(1 - P_{INT}^{AP/CL}\right) - \left(1 - P_{BT}^{AP/CL}\right) \tag{4.24}$$

$$P_{BT^1,INT^1}^{AP/CL} = P_{INT}^{AP/CL} \tag{4.25}$$

As can be seen from the intersecting regions when $r_1 = r_3$, equations for both cases give the same result and can be used accordingly. Finally, IPR with BT algorithm can be written as the summation of all α branches in Fig. 4.3 as

$$IPR_{BT}(d) = \sum_{i=1}^{6} \alpha_i \ . \tag{4.26}$$

4.3. System Performance and Results

In order to validate the IPR expressions by simulations, two possible cases, i.e., when SIR range is greater (Case-1) or smaller (Case-2) than the BT range, at various distances, for different number of Clients and various log-normal shadowing values are considered. Similar to the previous assumptions made in Chapter 3, for all scenarios, it is assumed that transmit powers are $T_{22} = 4$W, $T_{11af} = 100$mW, $T_{BT} = 100$mW and sensing thresholds are $\lambda_{11af} = -91.3$dBm, $\lambda_{BT} = -68$dBm. Also, downlink packet traffic for IEEE 802.11af is assumed as $\psi = 0.5$ and path loss between devices is determined according to the rural HATA path loss model as in (3.20).

For Case-1 ($r_3 \geq r_1$), the distance between IEEE 802.22 BS and CPE is assumed to be 5.71km so that the safe distance around CPE becomes $r_3 = 1$km for 6dB threshold, which is greater than the $r_1 = 300$m BT range calculated according to the given T_{BT} and λ_{BT}. For Case-2 ($r_3 \leq r_1$), the distance between BS and CPE is assumed to be 465m, so that the SIR range becomes $r_3 = 100$m, which is smaller than the $r_1 = 300$m BT range. Also, IEEE 802.11af AP-Client communication range is calculated as $r_2 = 425$m considering transmit power T_{11af} and threshold λ_{11af}.

In Figs. 4.5 and 4.6, IPR performance is calculated for Case-1 under 2dB and 10dB shadowing variances, respectively. It can be observed that simulation results are in well correspondence with numerical calculations, confirming the validity of the analysis. While the BT range is $r_1 = 300$m, AP can detect up to 250m and 200m, respectively, due to the effect of shadowing and causes one packet loss while relaying the channel-busy information. As the distance between CPE and AP increases, the IEEE 802.11af network (Client and AP) detects the BT signal to reduce the IPR compared to the non-BT case. After 800m, neither AP nor Clients can detect the BT and the IPR performances of BT and non-BT cases become the same. For further increased CPE-AP distance, it can be observed that the 10dB variance shadowing case has higher IPR values compared to the 2dB variance shadowing case, due to increased shadowing effect.

In order to investigate the effect of number of Clients under different shadowing conditions in Case-1, IPR performance is investigated at $d = 450$m in Fig. 4.7. While for small number of Clients an increase in shadowing variance slightly improves the IPR performance, with the increase in number of Clients the effect of variance diminishes and the IPR approaches zero. This is mainly due to the increase in the probability of at least one of the Clients detecting the BT.

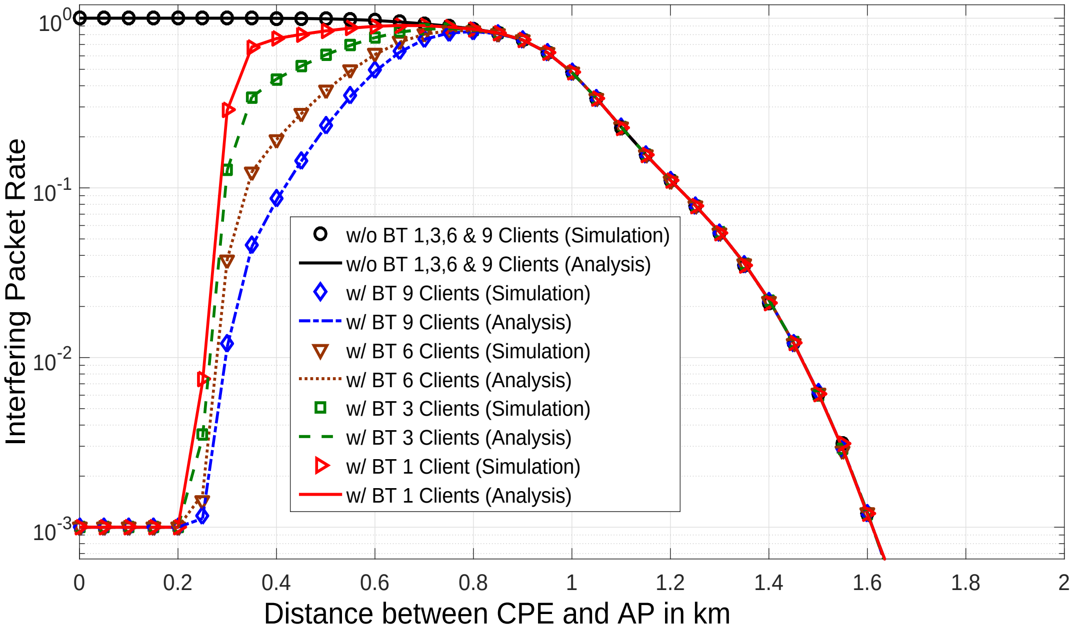

Figure 4.5. IPR performance for Case-1 under 2dB shadowing variance when $r_1 = 300\text{m}, r_2 = 425\text{m}$ and $r_3 = 1\text{km}$

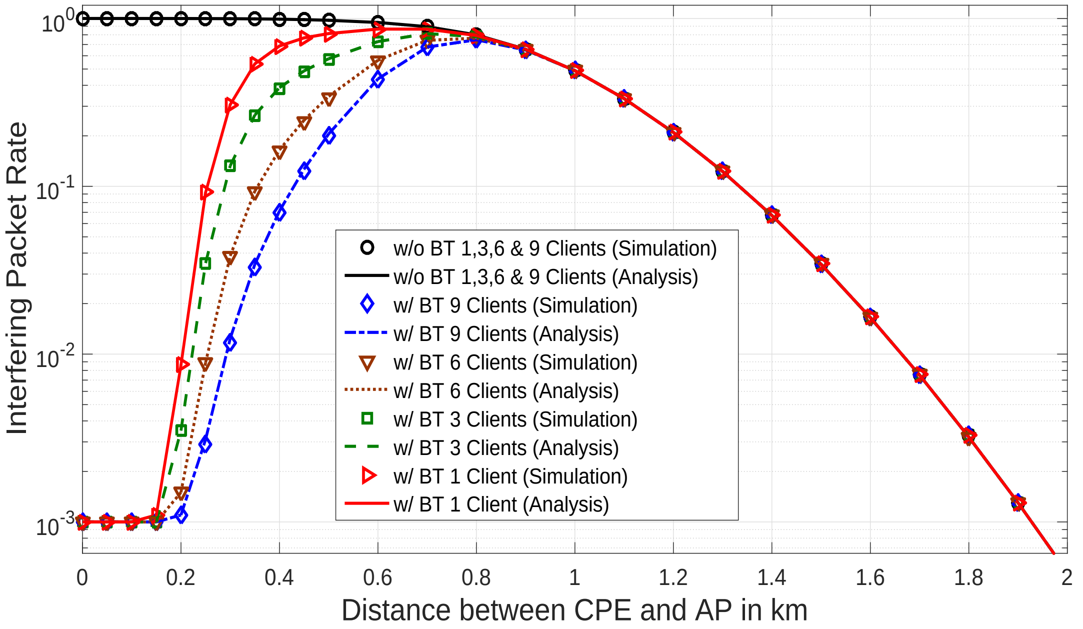

Figure 4.6. IPR performance for Case-1 under 10dB shadowing variance when $r_1 = 300\text{m}, r_2 = 425\text{m}$ and $r_3 = 1\text{km}$

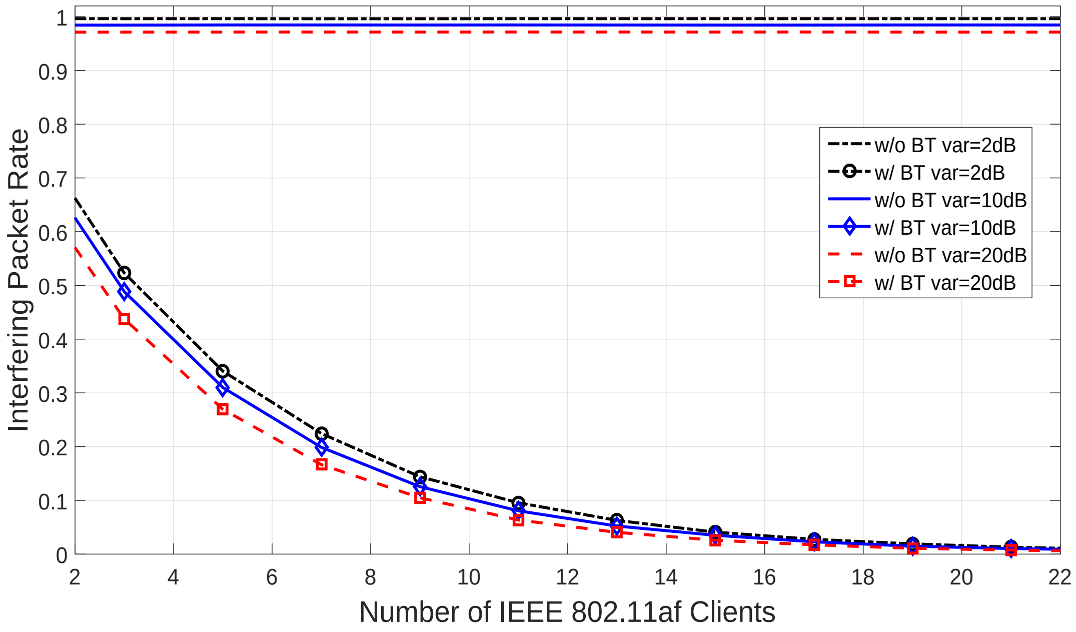

Figure 4.7. IPR performance for Case-1 under various shadowing variance values and number of Clients when $d = 450\text{m}$, $r_1 = 300\text{m}, r_2 = 425\text{m}$ and $r_3 = 1\text{km}$

In Figs. 4.8 and 4.9, IPR performance is considered for Case-2 under 2dB and 10dB shadowing variances, respectively, where the simulation and numerical results are in well correspondence. Since the SIR range is $r_3 = 100$m, the IPR is about 0.5 due to 50% downlink traffic when the distance between CPE and AP is less than 100m for the non-BT case. For the BT case, since the AP is likely to detect the BT signal, there will be only one packet loss, i.e., IPR $= 1/\Gamma$. When $d > r_3$, the AP is likely not to interfere with CPE resulting in sudden IPR decrease, whereas the Clients around AP may interfere for the non-BT case. For the BT case, since the BT range is $r_1 = 300$m, AP or Clients will detect the BT when $d < r_1$ resulting in low or zero IPR depending on the shadowing variance (cf. Figs. 4.8 and 4.9). After 300m, it is less likely that AP or Clients generate interference to CPE for both BT and non-BT cases, yet for the BT case Clients around AP are likely to detect the BT and inform the network resulting in lower IPR.

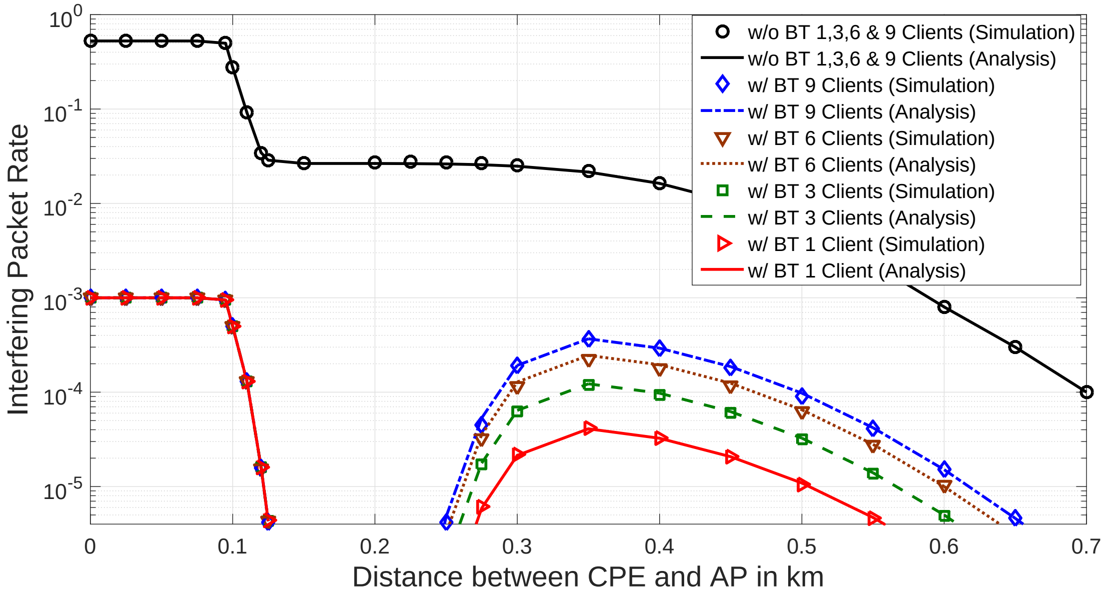

Figure 4.8. IPR performance for Case-2 under 2dB shadowing variance when $r_1 = 300\text{m}, r_2 = 425\text{m}$ and $r_3 = 100\text{m}$

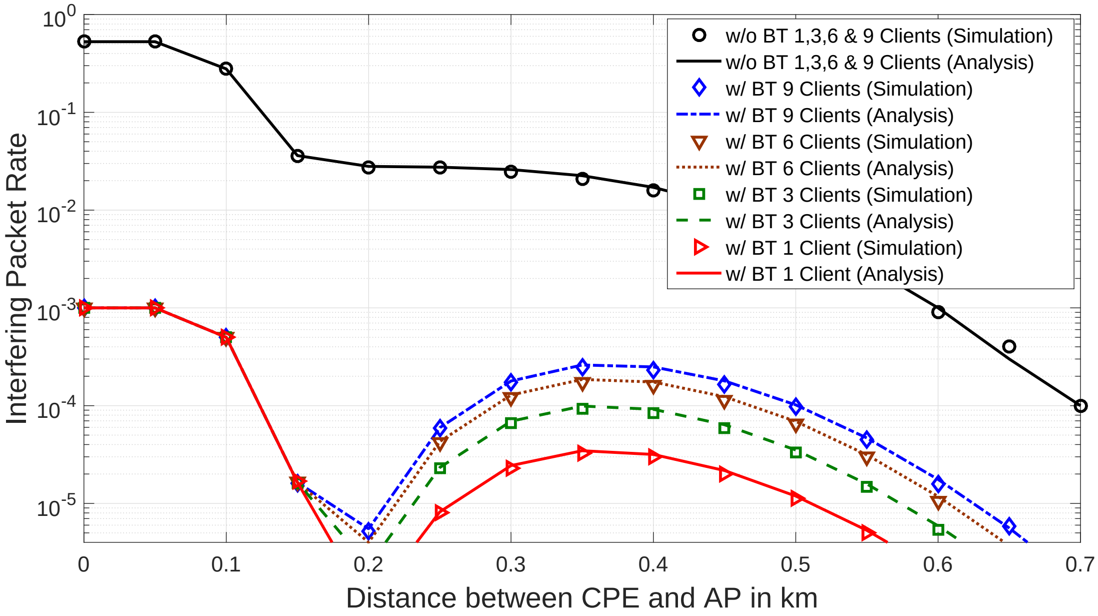

Figure 4.9. IPR performance for Case-2 under 10dB shadowing variance when $r_1 = 300\text{m}, r_2 = 425\text{m}$ and $r_3 = 100\text{m}$

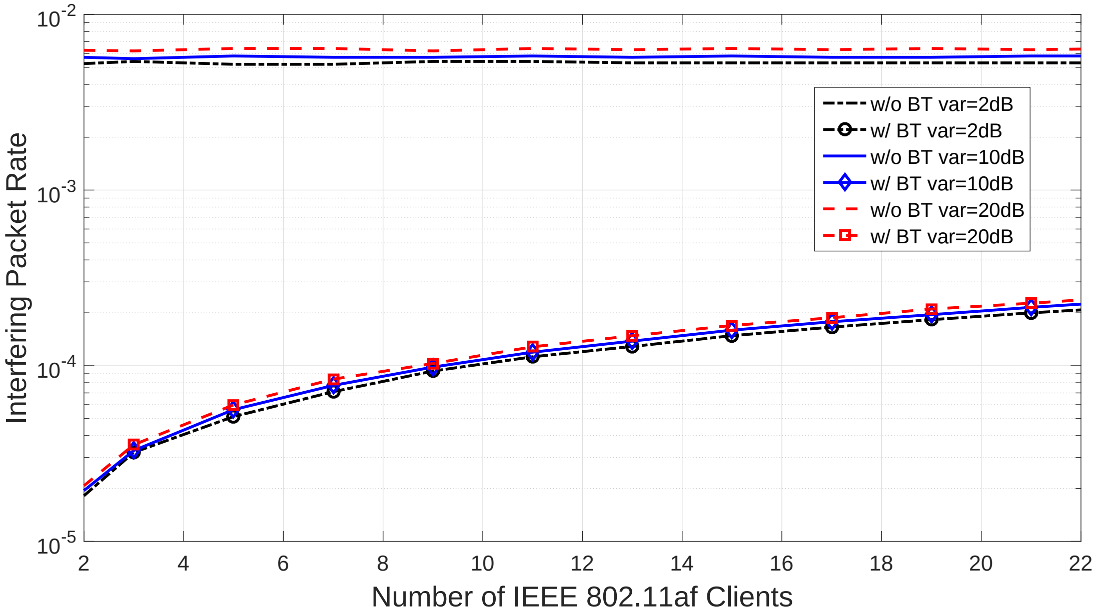

Figure 4.10. IPR performance for Case-2 under various shadowing variance values and number of Clients when $d = 500\text{m}$, $r_1 = 300\text{m}, r_2 = 425\text{m}$ and $r_3 = 100\text{m}$

In Fig. 4.10, the effect of number of Clients under different shadowing conditions is investigated for Case-2 at $d = 500$m. While the effect of shadowing on IPR is negligible due to $d > r_1 > r_3$, with the increase in number of Clients, IPR becomes worse as there may be more Clients causing interference to the CPE. All in all, IPR with BT case is much smaller that the non-BT case when the BT range is larger than the SIR range. While a very low IPR may be achieved to the benefit of the IEEE 802.22 network, in case the IEEE 802.11af network cannot move to an available frequency band, the throughput of WLAN will be reduced.

5. Analysis of Packet Transmission between SUs

In the previous chapter, analysis of packet interference to IEEE 802.22 CPE was provided for both without BT (i.e., no protection) and with BT algorithm cases, assuming IEEE 802.11af network does not cause any harmful interference to IEEE 802.22 BS, which is located outside the interference range of IEEE 802.11af network. As a result, instantaneous successful packet transmission rate (PTR) of the CPE for both BT and non-BT cases can be expressed as

$$PTR_{_{WRAN}}(d) = 1 - IPR(d) \tag{5.1}$$

$$PTR^{^{BT}}_{_{WRAN}}(d) = 1 - IPR_{BT}(d) \ . \tag{5.2}$$

On the other hand, analysis of packet transmission for IEEE 802.11af network requires more analysis and will be detailed in this chapter. In the MAC layer of IEEE 802.11af, Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol is used to prevent packet interference within the network by sending request-to-send (RTS), clear-to-send (CTS) and acknowledgment (ACK) protocol messages [8]. Thus, data packets in the uplink and downlink signals are protected and reliable communication can be sustained. However, these protocol messages may often collide with another protocol message in the same network, or as in our case, they may interfere with the packets of IEEE 802.22 CPE. In this study, only the uplink signal of CPE is considered as interference to data packets and ACK messages in IEEE 802.11af network and collisions with RTS and CTS protocol messages are disregarded. In the following, analysis of successful packet transmission in WLAN is provided for both BT and non-BT cases in detail.

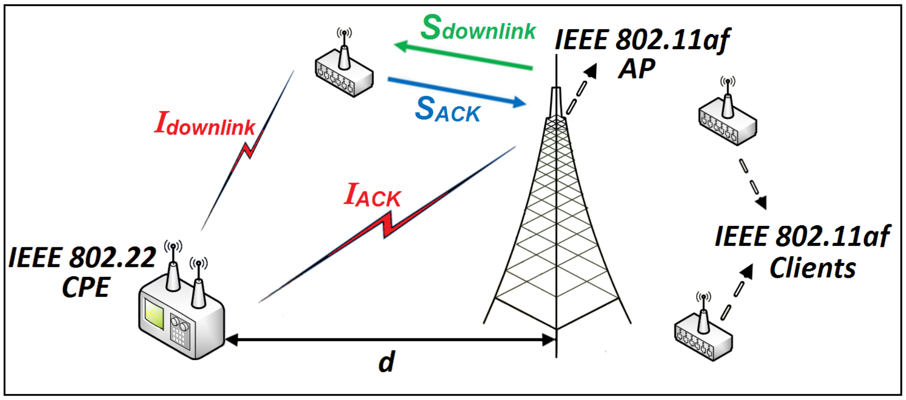

Figure 5.1. IEEE 802.11af packet transmission under WRAN interference

5.1. Successful Packet Transmission without Busy Tone Signal for WLAN

When IEEE 802.22 CPE communicates with its BS, the uplink signal of CPE interferes with IEEE 802.11af network as depicted in Fig. 5.1. In the figure, only the downlink communication is shown to be interfered, however, uplink communication will also be interfered but not drawn for clarity of the figure. Depending on the distance d and shadowing effect, downlink and uplink data and/or ACK signals of AP or Clients are likely to be interfered with the uplink signal of CPE. For successful uplink and downlink transmission in the IEEE 802.11af network, both data and ACK packets must be received and interpreted correctly at the receiver side. In other words, the received signal powers must be above the desired threshold levels at the same time. Thus, successful downlink data transmission in WLAN with a single Client at a known location (cf. Fig. 4.1) can be calculated as

$$SIR_{dw}(d|r,\phi) = S_{downlink} - I_{downlink} \tag{5.3}$$

$$SIR_{dw}^{ACK}(d|r,\phi) = S_{ACK} - I_{ACK} \tag{5.4}$$

where $S_{downlink}$ and S_{ACK} are the downlink data signal power and the associated ACK message signal power between desired points calculated as in (4.1). Also, $I_{downlink}$ and I_{ACK}

represent the interference signal power coming from IEEE 802.22 CPE to downlink data and ACK signal. Using SIR values for the downlink signal, the probability of successful downlink data and ACK signal transmission with a single Client at a known location (i.e., depending on d, r, ϕ) can be calculated, respectively, as

$$P_{dw}(d|r,\phi) = Q\left(\frac{\lambda_{WLAN} - SIR_{dw}(d|r,\phi)}{\sigma}\right) \tag{5.5}$$

$$P_{dw}^{ACK}(d|r,\phi) = Q\left(\frac{\lambda_{WLAN} - SIR_{dw}^{ACK}(d|r,\phi)}{\sigma}\right) \tag{5.6}$$

where λ_{WLAN} is the tolerable SIR threshold among the IEEE 802.11af network to interpret the packets at the receiver side.

Since log-normal shadowing determines the Client locations around AP, using probability of Client distribution calculated in (4.5) and the location-specific successful signal transmission probabilities obtained in (5.5) and (5.6), the probability of successful downlink transmission of IEEE 802.11af network can be calculated as

$$P_{DW}(d) = \int_0^{2\pi} \int_0^{\infty} P_{dw}(d|r,\phi) P_{dw}^{ACK}(d|r,\phi) P_{dist}^{cl}(r) r dr d\phi \ . \tag{5.7}$$

For the uplink part of IEEE 802.11af network data traffic, considering (5.3)-(5.6), the successful uplink transmission can be calculated similarly as

$$P_{UP}(d) = \int_0^{2\pi} \int_0^{\infty} P_{up}(d|r,\phi) P_{up}^{ACK}(d|r,\phi) P_{dist}^{cl}(r) r dr d\phi \ . \tag{5.8}$$

Finally, the overall probability of successful packet transmission rate within the WLAN system equals to

$$PTR_{WLAN}(d) = P_{DW}(d) \cdot \psi + P_{UP}(d) \cdot (1 - \psi) \ . \tag{5.9}$$

5.2. Successful Packet Transmission with Busy Tone Algorithm for WLAN

When BT signal is detected by AP or Clients, the IEEE 802.11af network stops its communication in the interfering band and switches its operating frequency, if available. However, there may not be a vacant frequency band at that time and region. For that case, the data transmission in IEEE 802.11af network starts if and only if AP and any of the Clients cannot detect the BT signal. For the probability of data transmission in the network when BT signal is present, the probability of not detecting the BT signal should be calculated. Since BT signal detection of AP at distance d and a Client at distance d' are calculated by using (4.3) and (4.7), respectively, taking the complement of the maximum probability gives the transmission probability in the network in the presence of BT signal as

$$P_{trans}(d) = \left(1 - \max\left(P_{BT}^{AP}(d), P_{bt}^{cl}(d|r,\phi)\right)\right) \ . \tag{5.10}$$

By multiplying (5.10) with successful downlink data transmission in the non-BT case found in (5.5) and (5.6) gives the BT case equivalent for one Client at a specific location. Considering the Client distribution, the probability of successful downlink transmission of IEEE 802.11af can be obtained as

$$P_{DW}^{BT}(d) = \int_0^{2\pi}\int_0^{\infty} P_{dw}(d|r,\phi)P_{dw}^{ACK}(d|r,\phi)P_{trans}(d)P_{dist}^{cl}(r)rdrd\phi \ . \tag{5.11}$$

Similar to downlink data transmission calculation, the probability of successful uplink transmission can be calculated as

$$P_{UP}^{BT}(d) = \int_0^{2\pi}\int_0^{\infty} P_{up}(d|r,\phi)P_{up}^{ACK}(d|r,\phi)P_{trans}(d)P_{dist}^{cl}(r)rdrd\phi \ . \tag{5.12}$$

After calculating the downlink and uplink successful packet transmission in IEEE 802.11af network for one Client, the effect of other Clients and AP on BT detection, which stops radio transmission in the network and decreases the probability of packet transmission, results in the overall successful packet transmission rate for the BT case as

$$PTR^{BT}_{WLAN}(d) = \left[P^{BT}_{DW}(d) \cdot \psi + P^{BT}_{UP}(d) \cdot (1-\psi)\right] \cdot \left(1 - P^{AP}_{BT}(d)\right) \left(1 - P^{CL}_{BT}(d)\right)^{K-1} \quad .(5.13)$$

5.3. System Performance and Results

In order to calculate successful packet transmission in both networks, tolerable SIR threshold λ_{WLAN} within the IEEE 802.11af network is assumed as 3dB, where both data and ACK signal powers must be above the threshold at the same time at the receiver side. For successful packet transmission of WRAN, (5.1) and (5.2) give the non-interfered packets of IEEE 802.22 network for non-BT and BT cases, respectively. Upon successful execution of the BT algorithm, if the IEEE 802.11af network is able to move to an available frequency band, the packet transmission will not be interfered by the IEEE 802.22 network. Otherwise, PTR expressions in (5.9) and (5.13) will be valid.

In Figs. 5.2 and 5.3, PTR performance is considered for both networks under 10dB shadowing variance for Case-1 according to the assumptions given in Chapter 4.3. Simulation results confirm the analytical results for both BT and non-BT cases. As seen in Fig. 5.2, the PTR of the IEEE 802.11af network is low for both BT and non-BT cases due to high interference level from the CPE. Although it is not shown in Fig. 5.2, an interference free communication for IEEE 802.11af network occurs if the distance d is greater than 7km.

On the other hand, BT signal reduces the performance of IEEE 802.11af network compared to the non-BT case depending on the distance and total number of Clients in the network. An increase in the number of Clients results in PTR performance degradation. The PTR performance of IEEE 802.22 network for the same scenario is provided in Fig. 5.3. The results indicate that BT signal provides full protection of PTR performance up to 200m (i.e., no packets are lost due to interference) and partial protection up to 900m. Increase in the number of IEEE 802.11af Clients improves the PTR performance of BT case.

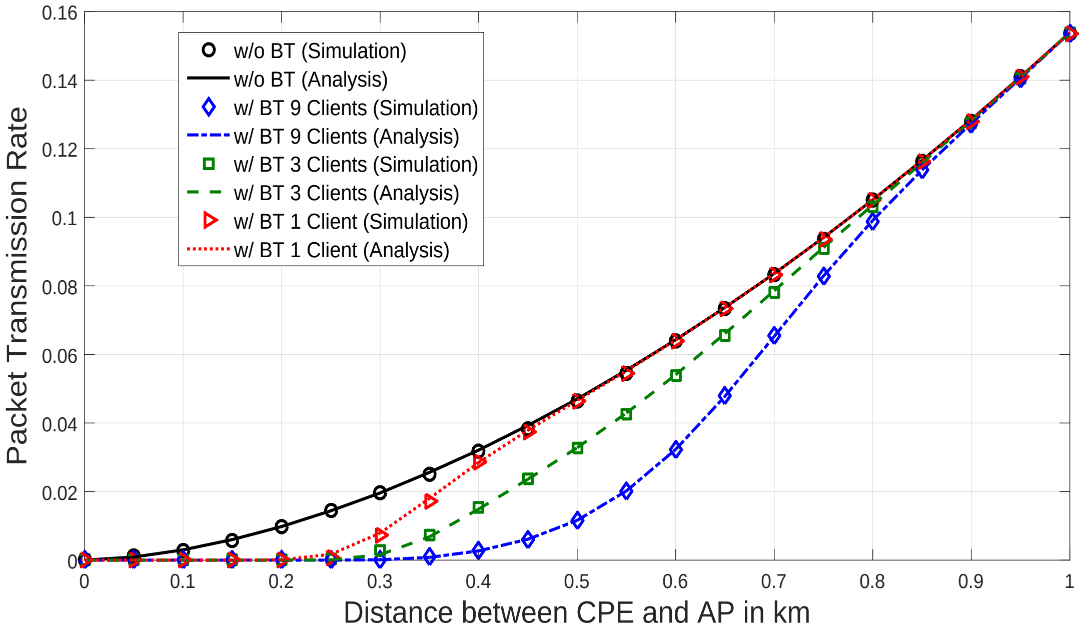

Figure 5.2. PTR performance of IEEE 802.11af for Case-1 under 10dB shadowing variance

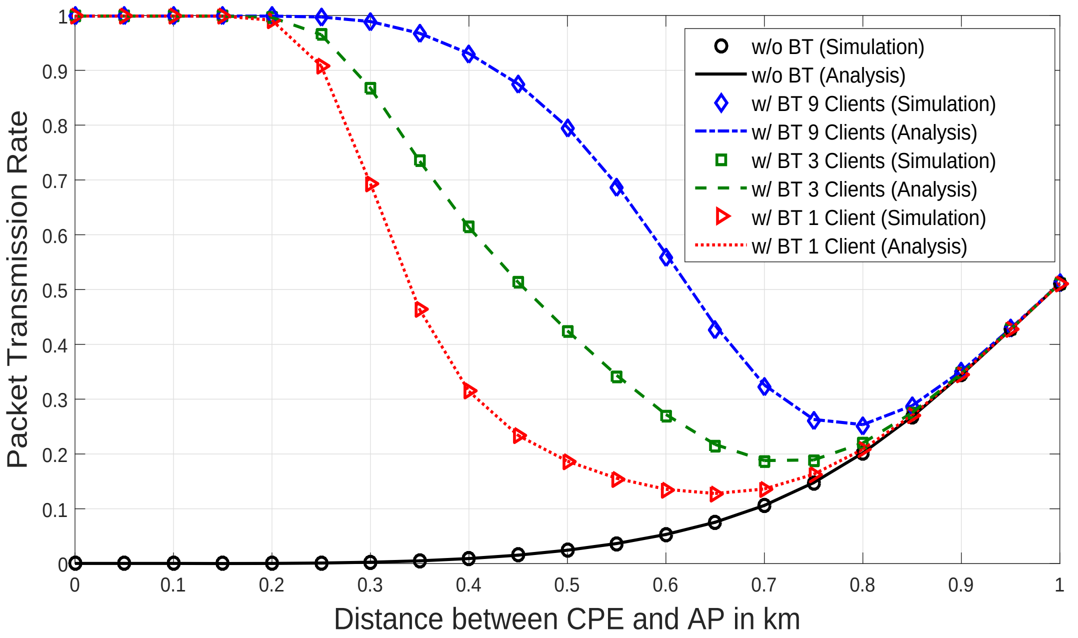

Figure 5.3. PTR performance of IEEE 802.22 for Case-1 under 10dB shadowing variance

6. Conclusions and Future Research

6.1. Conclusions

In this thesis, a busy tone based coexistence algorithm is proposed in order to limit the interference among cognitive radio based IEEE 802.11af and IEEE 802.22 networks operating in TVWS. The proposed algorithm is analyzed in detail

i) under no shadowing and uniform Client distribution
ii) considering the effects of log-normal shadowing and realistic Client distribution.

For both considerations, interfering packet rate and successful packet rate expressions are obtained and verified by simulations. Whether the BT range is greater than the SIR range or not, the proposed approach significantly improves operation of the IEEE 802.22 network. Similarly, by detecting the BT signal the IEEE 802.11af network may switch to an available frequency band for reliable communication, otherwise, stays silent for the duration of the busy tone. In addition, successful packet rate expressions are obtained for the realistic considerations and the trade-off between packet transmission rates of IEEE 802.11af and IEEE 802.22 networks are presented. The deployment of the proposed algorithm is important for TVWS coexistence considerations and it can be extended to coexistence of other cognitive radio based networks.

6.2. Future Research

This thesis focused on BT based coexistence among SUs. However, according to our algorithm, BT signal is blindly transmitted in the spectrum and results show that when interference range is smaller than the BT range, neighboring networks silence their communication even if there is no harmful interference. Thus, future work may include interfering neighbor discovery and adaptive power control algorithms for better utilization of both networks.

REFERENCES

1. A. B. MacKenzie et al., “Cognitive Radio and Networking Research at Virginia Tech,” Proceedings of the IEEE, vol. 97, no. 4, pp. 660-688, Apr. 2009.

2. Y. Tawk, J. Costantine and C. G. Christodoulou, ”Cognitive-radio and antenna functionalities: A tutorial [Wireless Corner],” in IEEE Antennas and Propagation Magazine, vol. 56, no. 1, pp. 231-243, Feb. 2014.

3. M. M. Alam, S. Bhattarai, L. Hong and S. Shetty, ”Robust cooperative beamforming against steering vector uncertainty in cognitive radio networks,” *Proc. IEEE CCNC*, pp. 656-661, Jan. 2016.

4. Federal Communications Commission, Third Memorandum and Order, Apr. 2012.

5. Ofcom, Statement Implementing TV White Spaces, Feb. 2015.

6. iDA, Proposed Regulatory Framework for TV White Space Operations in UHF/VHF Bands, Jun. 2014.

7. IEEE Std 802.22, IEEE Standard for local and metropolitan area networks - Specific requirements - Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Policies and procedures for operation in the TV Bands, 2011.

8. IEEE Std 802.11af, IEEE Standard for information technology – Telecommunications and information exchange between systems - Local and metropolitan area networks - Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 5: Television White Spaces (TVWS) Operation, 2013.

9. IEEE Std 802.15.4m, IEEE Standard for information technology – Telecommunications and information exchange between systems - Local and metropolitan area networks - Specific requirements - Part 15.4: Low Rate Wireless Personal Area Networks (LR-WPANs) Amendment: TV White Space Between 54 MHz and 862 MHz Physical Layer, 2014.

10. IEEE Std 802.19.1, IEEE Standard for information technology–Telecommunications and information exchange between systems – Local and metropolitan area networks – Specific requirements – Part 19: TV White Space Coexistence Methods, 2014.

11. T. Baykas, M. Kasslin, M. Cummings, H. Kang, J. Kwak, R. Paine, A. Reznik, R. Saeed, and S.J. Shellhammer, "Developing a standard for TV white space coexistence: technical challenges and solution approaches," *IEEE Wireless Commun.*, vol. 19, pp. 10-22, Feb. 2012.

12. Xin Tao, Zhifeng Zhao and Honggang Zhang, "Location information based interference control for cognitive radio network in TV white spaces," *Proc. IEEE WCNC*, pp. 3614-3619, Apr. 2013.

13. C.H. Sun, G.P. Villardi, Z. Lan, Y.D. Alemseged, H.N. Tran, and H. Harada, "Coexistence of secondary user networks under primary user constraints in TV white space," *Proc. IEEE WCNC*, pp. 2146–2150, Apr. 2012.

14. S.W. Oh and C.C. Chai, "Geo-location database with support of quality of service for TV white space," *Proc. IEEE PIMRC*, pp. 3428–3433, Sep. 2013.

15. S. Filin, T. Baykaş, H. Harada, F. Kojima, and H. Yano, "IEEE standard 802.19.1 for TV white space coexistence" *IEEE Commun. Mag.*, vol. 54, pp. 22-26, Mar. 2016.

16. K. Mizutani and H. Harada, "Adaptive time-domain windowing based transmit power control for TVWS-WLAN systems," *Proc. IEEE WCNC*, pp. 259–263, Apr. 2014.

17. G. P. Villardi, C. Sun, Y. D. Alemseged, and H. Harada, "Coexistence of TV white space enabled cognitive wireless access points," *Proc. IEEE WCNCW*, pp. 18–23, Apr. 2012.

18. G. P. Villardi, C. S. Sum, C. Sun, Y. Alemseged, Z. Lan, and H. Harada, "Efficiency of dynamic frequency selection based coexistence mechanisms for TV white space enabled cognitive wireless access points," *IEEE Wireless Commun.*, vol. 19, no. 6, pp. 69–75, Dec. 2012.

19. J. Wang, S. Filin, T. Baykaş, M. A. Rahman, C. Song, and H. Harada, "A feasible neighbor discovery algorithm for coexistence control system over TVWS," *Proc. IEEE WCNC*, pp. 3244–3248, Apr. 2012.

20. X. Feng, Q. Zhang, and B. Li, "Enabling co-channel coexistence of 802.22 and 802.11af systems in TV white spaces," *Proc. IEEE ICC*, pp. 6040–6044, Jun. 2013.

21. K. E. Kolodziej and B. T. Perry, "Simultaneous transmit and receive (STAR) mobile testbed," *Proc. IEEE RWS*, pp. 66-69, Jan. 2016.

22. Y. Li, M. Li, and M. Y. Wu, "An interference-aware busy tone based MAC protocol," *Proc. IEEE VTC*, pp. 36–40, Apr. 2007.

23. Z. J. Haas and Jing Deng, "Dual busy tone multiple access (DBTMA)-a multiple access control scheme for ad hoc networks," *IEEE Trans. Commun.*, vol. 50, no. 6, pp. 975–985, Jun. 2002.

24. P. Wang, H. Jiang, and W. Zhuang, "A dual busy-tone MAC scheme supporting voice/data traffic in wireless ad hoc networks," *Proc. IEEE Globecom*, pp. 1–5, Nov. 2006.

25. X. Zhang and K. G. Shin, “Cooperative carrier signaling: harmonizing coexisting WPAN and WLAN devices,” *IEEE/ACM Trans. on Network.*, vol. 21, no. 2, pp. 426–439, Apr. 2013.

26. J. Ock, Y. J. Choi, and S. Bahk, “Performance analysis of periodic busy tones protecting a ZigBee network from Wi-Fi interruption,” *Proc. IEEE VTC*, pp. 1–5, May 2014.

27. O. Karatalay, S. Erküçük, and T. Baykaş, “Analysis of extended busy tone performance for coexistence between WRAN and WLAN TVWS networks,” *Proc. IEEE PIRMC*, pp. 1957–1962, Aug. 2015.

28. A. Goldsmith, Wireless Communications, Cambridge University Press, 2005.

6.3. *Curriculum Vitae

Onur Karatalay was born on 2 March 1991, in Istanbul. He received his B.Sc. degree in Electronics Engineering in 2014 from Kadir Has University. Then, he continued his M.Sc. degree in Electronics Engineering at Kadir Has University, where he worked as a research and a teaching assistant at the Department of Electrical-Electronics Engineering from 2014 to 2016. His research interests include signal processing and wireless communication.

Publications:

*O. Karatalay, S. Erküçük, and T. Baykaş, "Busy tone implementation for coexistence of IEEE 802.22 and 802.11af systems," *Proc. IEEE SIU*, pp. 1845-1848, May 2015.

*O. Karatalay, S. Erküçük, and T. Baykaş, "Analysis of extended busy tone performance for coexistence between WRAN and WLAN TVWS networks," *Proc. IEEE PIRMC*, pp. 1957–1962, Aug. 2015.

A. Yeşilkaya, *O. Karatalay, A. S. Öğrenci and E. Panayırcı, "Channel estimation for visible light communications using neural networks," *Proc. IEEE WCCI*, Jul. 2016. (Accepted)