Analysis of Extended Busy Tone Performance for Coexistence between WRAN and WLAN TVWS Networks

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***Abstract*—TV White Spaces indicate spectrum bands, which were reserved for licensed terrestrial TV broadcasting and opened to unlicensed use under regulatory conditions. One important regulation which is common in all regulatory domains is no harmful interference is created to licensed devices. On the other hand, interference between unlicensed devices is not regulated. As a result system designers developed new methods to improve coexistence between TVWS networks. Extended busy tone, one of such methods, is designed for coexistence between wireless regional area and wireless local area networks based on IEEE 802.22 and 802.11af standards, respectively. In this paper we analyse the performance of extended busy tone at different range conditions and verify via simulations under realistic conditions. Our results indicate that the method can reduce interference considerably at intermediate distances and enable networks to operate without a significant reduction in throughput.**

Keywords*—*TV White Space, Coexistence, WRAN, WLAN, IEEE 802.22, IEEE 802.11af, Busy Tone.

I. Introduction

As a scarce resource, RF spectrum bands can be utilised 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 utilisation efficiency. Such an opportunity occurred during the period of analog to digital TV conversion for many countries. Regulators auctioned some of the spectrum for more efficient communication systems but more importantly, they started to allow the use of spectrum by secondary unlicensed users, if it is not used by a licensed broadcasting system in a given location in a given time. This spectrum is called TV White Spaces (TVWS). First regulations related to TVWS came from the USA, Federal Communications Commission (FCC) which allowed TVWS operation of both fixed and personal/portable devices [1], followed by OFCOM of the United Kingdom [2] and IDA of Singapore [3].

The unlicensed devices in TVWS are called Secondary Users (SU) or TV Band Devices (TVBD), whereas licensed broadcasters are called primary users (PU). Because of the frequency characteristics, TVWS networks provide better penetration through obstacles and wide coverage range. Many standards are developed for TVWS access, including IEEE 802.22 wireless regional area network (WRAN) [4], IEEE 802.11af wireless local area network (WLAN) [5], and IEEE 802.15.4m wireless personal area network (WPAN) [6]. When these networks have been deployed in TVWS, they can cause interference to PUs as well as to each other. Thus, peaceful coexistence mechanisms should be addressed for all networks.

In order to protect the PUs, TVBDs are required to use a geo-location database (GLDB) approach [7]-[8]. Since these frequency gaps depend on the locations and time, it is expected that all unlicensed devices have the knowledge of the idle bands before they start communication. However, SUs may share a frequency band and interfere each other, which may result in packet losses for both networks. Since these unlicensed networks are heterogenous in terms of both PHY and MAC layers, implementing a coexistence algorithm is challenging. Thus, IEEE 802.19.1 coexistence standard in TVWS for SUs has been developed [9]. In [10], various coexistence approaches have been proposed. These approaches include power control, energy detection and dynamic channel selection. In addition to these techniques, Busy Tone (BT) method is suggested as a simple yet an effective method for SUs coexistence for coexistence between 802.22 and 802.11af networks [11].

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. Although in [11] BT method is simulated, unrealistic indoor path loss model was used instead of outdoor environment and only network coordinator was considered as a BT receiver station. In [12], the BT method is generalised for networks with multiple users and performance of the algorithm is simulated in terms of interfering packet rate (IPR) by generating a realistic rural communication environment. While a simulation based study was conducted for a specific range in [12], this work provides an analytical framework for the extended BT method considering all possible coexistence scenarios.

The rest of this paper is organized as follows. In the next section we provide the system model, including detailed explanation of the interference range calculation and the extended busy tone method. Section III provides the theoretical analysis for performance. Analytical and simulation results are presented in Section IV. Section V concludes the paper.

II. System Model

In this work, it is assumed that IEEE 802.22 WRAN and IEEE 802.11af WLAN based networks are operating in the same frequency band, which is free of PU transmission at all times. As depicted in Fig.1, IEEE 802.22 Base Station

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(BS) at point A is communicating with its Customer Premises Equipment (CPE), which is at point B. When IEEE 802.11af Access Point (AP) at location D initiates communication with its clients, it becomes a hidden terminal for CPE. If the signal power coming from point A to point B is weaker than the signal power caused by the WLAN network, then the quality of communication of the CPE will be deteriorated.

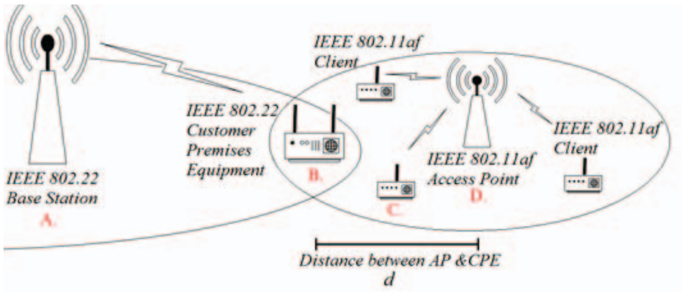

Fig. 1. Hidden terminal problem among secondary users

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 or networks must be protected with a coexistence mechanism.

A. Interference Range Calculation

According to the FCC regulations [1], the maximum power levels are $P_{CPE} = 4W$ (36dBm) for IEEE 802.22 and $P_{AP} = 100mW$ (20dBm) for IEEE 802.11af networks, respectively. Sensing thresholds are modulation dependent. For QPSK modulation with R=1/2 coding rate for both networks, sensing thresholds are -91.3 dBm and -85 dBm, respectively for the IEEE 802.22 and IEEE 802.11af networks [4]-[5]. As for antenna heights, the antenna for BS is assumed to be at 30m, whereas the antenna for CPE is at 10m. Furthermore, AP and all Clients are assumed to be at 1m height. Considering these parameters, the received signal powers can be calculated. For example, received signal power at point B due to point A can be calculated as

$$S_{A-B} = P_{BS} - L_{A-B} \tag{1}$$

and at point B due to point D as

$$S_{D-B} = P_{AP} - L_{D-B} \tag{2}$$

where L is the path loss from the desired point. Unlike [11] considering an indoor pathloss model for an outdoor environment, we considered a rural environment for the network locations and used $HATA_{rural}$ path loss model [13] as follows:

$$L = L^{'} - 4.78(\log_{10}(f))^2 + 18.33\log_{10}(f) - K_L \tag{3}$$

$$L^{'} = 69.55 + 26.16\log_{10}(f) - 13.82\log_{10}(h_t) - a(h_r) + (44.9 - 6.55\log_{10}(h_t))\log_{10}(d) \tag{4}$$

$$a(h_r) = 3.2(\log_{10}(11.75h_r))^2 - 4.97 \tag{5}$$

where h_t and h_r are the transmitter and receiver antenna heights and f is the carrier frequency which is selected as 600 MHz in this work. K_L is defined for the rural environment as 35.94 in [13]. Finally, SINR value for point B can be written as

$$SINR = S_{A-B} - S_{D-B}. \tag{6}$$

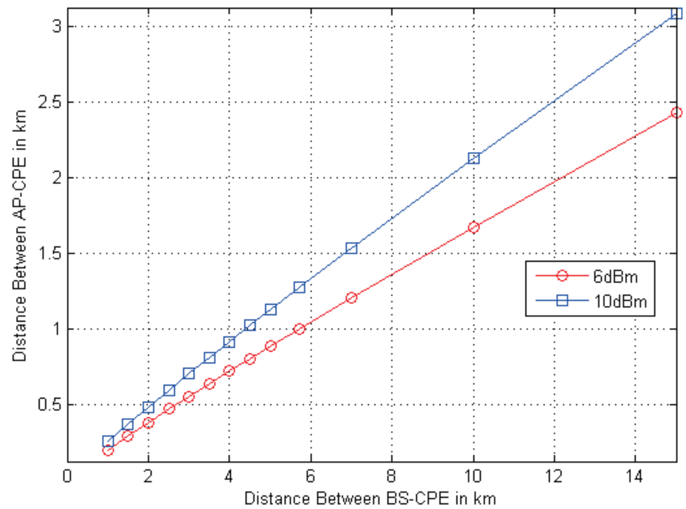

Fig. 2. 6dBm and 10dBm interference thresholds

In Fig. 2, for 6dBm and 10dBm SINR thresholds are calculated with respect to the distance d between BS and CPE. For example, if BS-CPE distance is 5.71km, then the minimum SINR range should be 1km for 6dBm interference threshold. This is the tolerable interference range for CPE. When there is an IEEE 802.11af AP or Client closer than that range, packet losses cannot be prevented. In order to maintain reliable communications within IEEE 802.22 and IEEE 802.11af networks, these ranges should be considered as minimum distances, if there is no coexistence mechanism.

B. Coexistence with Busy Tone Algorithm

Since IEEE 802.22 uses time divison multiple access (TDMA) and IEEE 802.11af uses carrier sense multiple access with collision avoidance (CSMA-CA) as MAC layers [4]-[5], they cannot identify each others' existence. Thus, a coexistence mechanism is needed for throughput protection. IEEE 802.22 CPEs may use a second antenna for sensing the PU transmissions. This second antenna can be used to broadcast Busy Tone (BT) signals with power 100mW (20dBm). In this paper, a BT based algorithm supported by a mesh topology as seen in Fig. 3 is considered [12]. Accordingly, IEEE 802.11af network listens to the spectrum by setting Clear Channel Assessment (CCA) threshold at -68dBm before initiating a transmission. Using this sensing threshold and (3), the maximum detectable BT distance r_1 is calculated as 300m for the rural environment. Considering the distance d in (3)-(6), tolerable interference distance can be represented as r_3. Also, r_2 is the radius of the communication range of IEEE 802.11af network.

In IEEE 802.11af network, it is assumed that AP generates α of the total packets P, where $0 < \alpha < 1$. On the other hand,

TABLE I. BUSY TONE COEXISTENCE ALGORITHM

Algorithm 1: Coexistence with Busy Tone Algorithm and Determination of Interfered Packets in IEEE 802.22 Networks.

```
while BT=true
  if AP heard BT
    Measure SINR from AP to CPE;
    if Threshold_AP=true
      No Packet Interfered and AP searches new frequency;
    else
      1 Packet Interfered and AP searches new frequency;
    end if
  else Client heard BT
    Measure SINR from Client to CPE and Client informs AP that BT is present on the channel;
      if Threshold_Client=true
        No Packet Interfered;
        if Threshold_AP=true
          No Packet Interfered;
        else
          1 more Packet Interfered due to AP;
        end if
      else
        1 Packet Interfered;
        if Threshold_AP=true
          No Packet Interfered;
        else
          1 more Packet Interfered due to AP;
        end if
      end if
  end if
end while
```

assuming there are K Clients with similar traffic patterns, one Client generates $\frac{1-\alpha}{K}$ of the total packets. If there is no BT, the CPE may lose α of its packets due to AP and up to $(1-\alpha)$ of the packets due to Clients depending on their possible existence in the SINR range. In order to prevent such high packet losses for the CPE, BT algorithm serves as a coexistence mechanism given in Table I. Accordingly, if AP is located within the BT and SINR ranges at the same time, then CPE will lose only one packet since AP instructs its Clients to stay slient during the BT signal. If at least one of its Clients can hear the BT signal but not the AP itself, then Client tells the AP that BT signal is present and AP relays this message to its clients which may not be aware of the BT signal. In that case, only two packets will be lost. Considering this idea as presented in Table I, we analyze in detail the interfering packet rate in terms of BT range, SINR range, IEEE 802.11af communication range and the distance between CPE and AP.

III. SYSTEM ANALYSIS

As seen in Fig. 4, 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 Areas A, B and C can be computed by calculating the shaded areas on the circles. To calculate the area of the shaded zones, integration of the circle equation with respect to the intersection of points on x-axis is used as

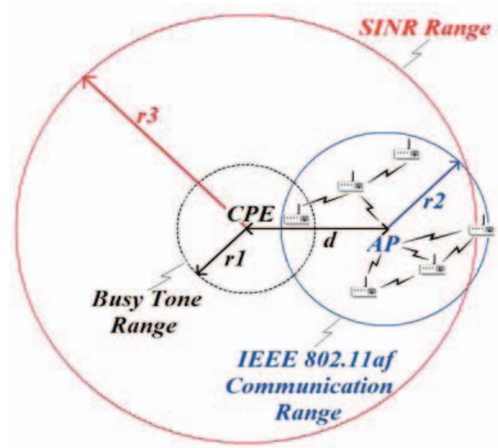

Fig. 3. Increasing BT range with mesh topology

$$y^2 + x^2 = r^2 \tag{7}$$

where r is the the radius of selected circle.

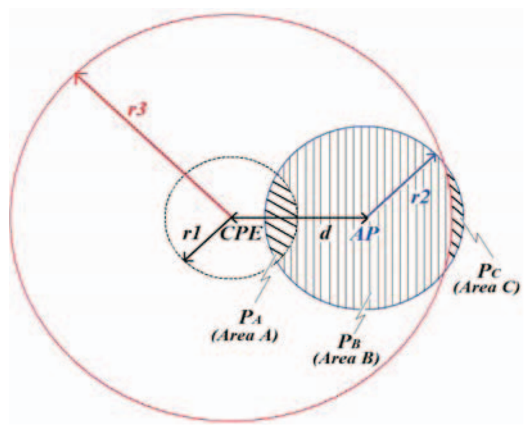

Fig. 4. Overlapping regions

We assumed that the centers of the circles lay on the x-axis. We can obtain the intersection points 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

$$P_A = \frac{2 \times \left(\int_x^{r_1} y_1 \; dx + \int_{d-r_2}^{x} y_2 \; dx \right)}{\pi {r_2}^2}. \tag{8}$$

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

$$P_C = \frac{2 \times \left(\int_x^{d+r_2} y_2 \, dx - \int_x^{r_3} y_3 \, dx \right)}{\pi {r_2}^2}. \quad (9)$$

Finally, P_B can be obtained as

$$P_B = 1 - (P_A + P_C). \quad (10)$$

For uniform distribution of IEEE 802.11af Clients in the communication range, the distance d between CPE and AP, and various conditions of r_1, r_2 and r_3, interfering packet rate (IPR) will be analyze in the absence of a BT signal and when the proposed BT algorithm is applied. Here, IPR is the ratio of number of collisions caused by IEEE 802.11af AP and/or its Clients to all transmitted packets.

A. IPR Calculation without Busy Tone Signal

In the case when there is no BT signal transmitted by CPE, Area A does not occur. Thus, IPR only depends on r_2, r_3 and d. If SINR range is greater than IEEE 802.11af communication range as seen in Fig. 5, IPR can be calculated as follows.

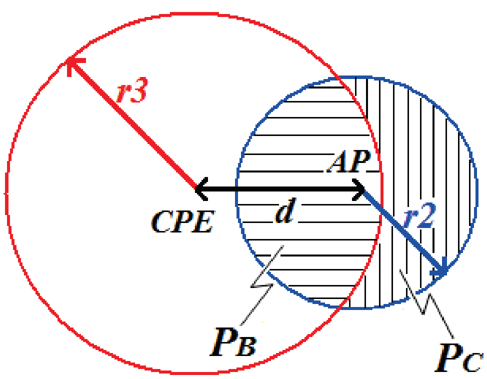

Fig. 5. WLAN communication range and SINR range w/o BT signal

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

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

$$IPR = 1 \quad (11)$$

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

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

$$IPR = \sum_{k=1}^{K} \binom{K}{k} p(B)^k p(C)^{K-k} \left(\frac{k + \alpha P}{P} \right) \quad (12)$$

where K is the number of IEEE 802.11af Clients and P is the total packets of IEEE 802.11af network. Here α is the coefficient of packet traffic for AP. In this interval, AP is in the interference region and it is assumed that it controls half of the total packets in the network. In that case $\alpha = \frac{1}{2}$, which means that half of the packets will collide due to AP.

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

$$IPR = \sum_{k=1}^{K} \binom{K}{k} p(B)^k p(C)^{K-k} \left(\frac{k}{P} \right) \quad (13)$$

And finally,

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

$$IPR = 0 \quad (14)$$

On the other hand, SINR 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 (12) is valid because AP will be present in SINR range during this interval. Thus, it affects the total packet collisions proportional to αP.

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

Equation (13) is valid since AP is not in the SINR range.

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

There is no interference between networks in that range. Hence, IPR is given as in (14).

B. IPR Calculation with Busy Tone Signal

BT signal is generated by CPE and can be heard by AP and/or Clients within the radius r_1. As shown in Fig. 4, Area A should be included in the IPR calculations according to the distance d. Since SINR 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) $0 \leq d < r_3$:

$$IPR = \frac{1}{P} \quad (15)$$

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) $r_3 \leq d \leq r_1$:

$$IPR = 0 \quad (16)$$

In this interval, AP can hear the BT signal and tell its Clients to stay silent. Since the AP is not in the SINR region, there is no interference between the networks. If all IEEE 802.11af Clients are outside the SINR range as AP, then throuhput of IEEE 802.11af network will decrease to zero. This is another important research problem and will be considered in future studies.

iii) $d > r_1$:

Case 1: If $P_A \neq 0$

As shown in Fig. 6, Clients which are in the Area A cause interference, but also they are the ones which can hear the BT signal. If at least one Client is located in the Area A, it will relay the BT signal information to the AP and will interfere

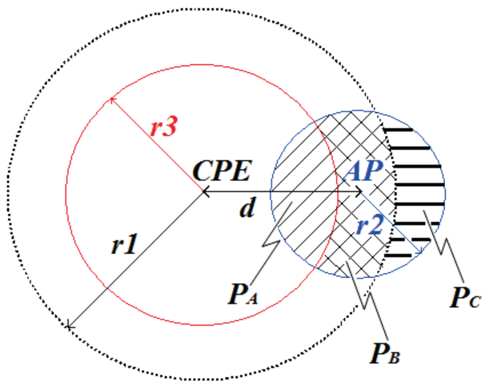

Fig. 6. Busy Tone range greater than SINR range

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:

$$IPR = \left(1 - (P_B + P_C)^K\right)\frac{1}{P} \tag{17}$$

Case 2: If $P_A = 0$

$$IPR = 0 \tag{18}$$

Even if BT signal is used, in this interval due to r_2, Area A may not occur. This means there is not any 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 throuphput.

On the other hand, the SINR range may be greater than the BT range as shown in Fig. 4. Accordingly, if $r_3 > r_1$, depending on d, there will be four regions:

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

$$IPR = \frac{1}{P} \tag{19}$$

Because of the distance d, AP always hears the BT signal by itself.

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.

Case 1: If $P_A \neq 0$ and $P_C \neq 0$

$$IPR = \sum_{k=1}^{K}\left[\binom{K}{k}\sum_{m=0}^{K-k}{P_A}^k{P_B}^m{P_C}^{K-k-m}\right]\left(\frac{2}{P}\right) + \sum_{k=0}^{K}\binom{K}{k}{P_B}^k{P_C}^{K-k}\left(\frac{k+\alpha P}{P}\right) \tag{20}$$

Case 2: If $P_A \neq 0$ and $P_C = 0$

$$IPR = \sum_{k=1}^{K}\binom{K}{k}{P_A}^k{P_B}^{K-k}\left(\frac{2}{P}\right) + {P_B}^K \tag{21}$$

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

$$IPR = \sum_{k=0}^{K}\binom{K}{k}{P_B}^k{P_C}^{K-k}\left(\frac{k+\alpha P}{P}\right) \tag{22}$$

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

$$IPR = 1 \tag{23}$$

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 $P_A \neq 0$

$$IPR = \sum_{k=1}^{K}\left[\binom{K}{k}\sum_{m=0}^{K-k}{P_A}^k{P_B}^m{P_C}^{K-k-m}\right]\left(\frac{2}{P}\right) + \sum_{k=0}^{K}\binom{K}{k}{P_B}^k{P_C}^{K-k}\left(\frac{k+\alpha P}{P}\right) \tag{24}$$

Case 2: If $P_A = 0$

$$IPR = \sum_{k=1}^{K}\binom{K}{k}{P_B}^k{P_C}^{K-k}\left(\frac{k}{P}\right) \tag{25}$$

Only Clients which are within the SINR region cause packet collisions.

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

$$IPR = 0 \tag{26}$$

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

IV. System Performance

Since analytical IPR calculations depend on different combinations of r_1, r_2 and r_3 values, we considered two different cases, where $r_1 < r_2 < r_3$ and $r_3 < r_1 < r_2$, to verify the analysis by simulation results. To determine the IEEE 802.11af communication range r_2, received power level and sensing threshold determined by QPSK R=1/2 modulation is used and calculated as $r_2 = 450m$ for both cases. For the first case where $r_1 < r_2 < r_3$, SINR range, r_3 is decided by placing the IEEE 802.22 CPE 5.71km away from the BS. Accordingly, the safe interference range $r_3 = 1km$. Previously, in Section II.B, the BT range was calculated as $r_1 = 300m$. For the second case where $r_3 < r_1 < r_2$, we arranged the distance between IEEE 802.22 BS and CPE as 1.26km. Accordingly SINR range r_3 becomes 250m which is smaller than the BT range r_1. Considering these assumptions, the only variable is the distance d between CPE and the AP. By using Monte Carlo simulations, we studied the IPR performance for different number of IEEE 802.11af Clients. Also, the improving effect of BT algorithm is compared with the non-BT case, where the total packets is equal to $P = 1000$.

In Fig. 7 and Fig. 8, it can be observed that simulation results are in well correspondence with numerical calculations, confirming the validity of the analysis. In Fig. 7, 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 extended BT algorithm performance outperforms the non-BT case in these

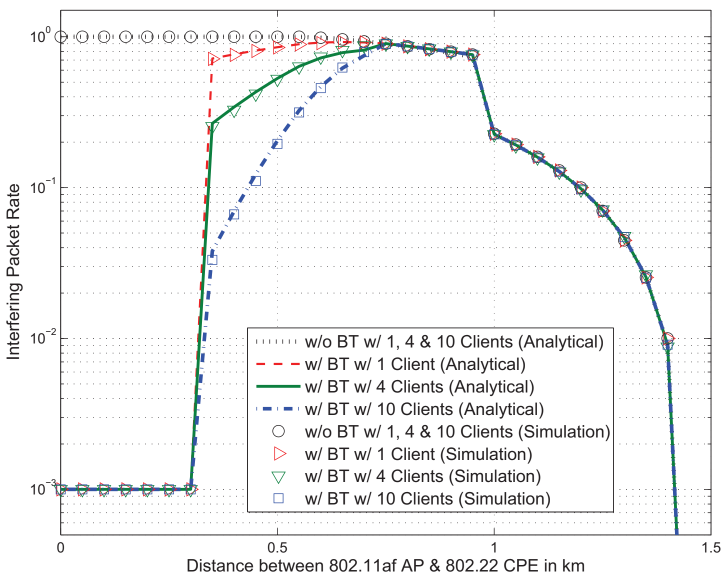

Fig. 7. Analytical vs simulation results ($r_1 < r_2 < r_3$)

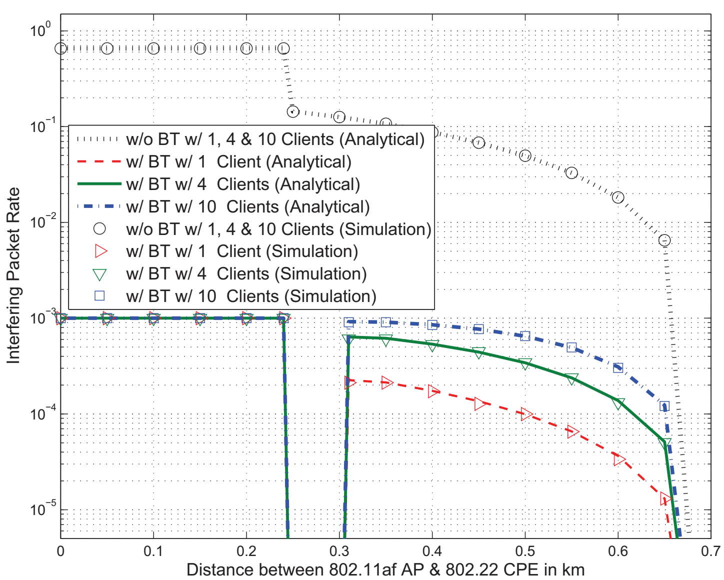

Fig. 8. Analytical vs simulation results ($r_3 < r_1 < r_2$)

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. 8, where $r_3 > r_1$, the AP can hear the BT up to 300m. Since the safe SINR range is $r_3 = 250m$, there is one packet interfering with the CPE. 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 SINR region. After 300m, there may be one or more Clients hearing the BT while it is in the SINR 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.

V. Conclusion

In this paper, coexistence between secondary users in TVWS was investigated. A BT based algorithm that reduces the interference to IEEE 802.22 networks has been considered. The performance is evaluated in terms of interfering packet rate when the BT algorithm and the non-BT case are considered. For both considerations, numerical analysis is performed considering the BT range, SINR range, IEEE 802.11af communication range and the distance between CPE-AP. The numerical results that are confirmed with simulations show the superiority of the BT based coexistence mechanism for various scenarios considered. Hence, such a coexistence mechanism is important to implement for peaceful coexistence of secondary networks.

Acknowledgment

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