# Coexistence Issues in Contention-Based Heterogeneous Wireless Networks

**Eun-Chan Park[1], Minjoong Rim[1], Hwangnam Kim[2], and Kyung-Joon Park[3]**
[1] Department of Information and Communication Engineering, Dongguk University-Seoul, Korea
[e-mail: ecpark|minjoong @dongguk.edu]
[2] School of Electrical Engineering, Korea University, Korea, [e-mail: hnkim@korea.ac.kr]
[3] School of Electrical Engineering, Seoul National University, Korea, [e-mail: kjp@snu.ac.kr]

***Abstract***

This paper deals with coexistence issues among contention-based heterogeneous wireless networks that have different transmission power and/or coverage. We show that the existing carrier sensing multiple access mechanism, which is a prevailing contention-based protocol, results in a significant unfairness of channel sharing. We analyze the reasons of such unfairness by considering the mutual effects of inter-system interference, carrier sensing, contention resolution, and link adaptation mechanisms. Via simulation study, we evaluate and compare the performance of several approaches for fair channel sharing.

**Keywords*:*** coexistence, contention, interference, fairness, spatial reuse

## 1. Introduction

The Internet is continuously growing with many new emerging services and portable devices, and users want to access to the Internet anywhere anytime with any device. To satisfy diverse requirements of these services and users' demands, the wireless communication system evolves to support higher capacity and quality-of-service (QoS), and new advanced communication systems appear. Therefore, the necessity for wide bandwidth is continuously increasing, but the frequency spectrum is essentially a limited resource. Thus, it is imperative to allocate and utilize frequency spectrum efficiently. Recently, FCC (Federal Communications Commission) has released 3.65 GHz spectrum for license-exempt non-exclusive coexistence among heterogeneous wireless networks and mandated contention-based protocol for fair sharing among them. To satisfy these regulatory requirements, IEEE 802.16h [1] and IEEE 802.11y [2] task groups have been developing coexistence mechanisms for wireless metro area networks (WMANs) and wireless local area networks (WLANs), respectively. Also, in the literature of cognitive radio technologies, various schemes for spectrum sensing and access have been proposed to improve spectral efficiency [3].

This paper deals with coexistence issues arising when heterogeneous wireless networks that have different transmission power and/or coverage employ the carrier sensing multiple access (CSMA) mechanism for channel sensing and access. We show that the existing CSMA mechanism results in a significant unfairness of channel sharing. We analyze the reasons of such unfairness from the viewpoints of (*i*) the asymmetry of carrier sensing and (*ii*) the blindness of binary exponential backoff (BEB) mechanism and link adaptation mechanism in

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response to the interference-driven transmission failure.

There have been several approaches to mitigate interference and to improve spatial reuse in contention-based multi-hop WLANs [4]-[7]. These approaches mainly focus on the effect of carrier sensing threshold (CSTH) on the spatial reuse, and derive its optimal value. Also, they have proposed adaptive control mechanism of CSTH, transmission power, and/or transmission data rate. Although they are effective for homogeneous networks consisting of WLANs, this study confirms that these approach are neither desirable nor feasible, to assure fair and efficient channel sharing among contention-based heterogeneous wireless networks.

The rest of the paper is organized as follows. Section 2 identifies the problem and cause of unfair channel sharing among heterogeneous wireless networks. The simulation study in Section 3 investigates the effect of CSTH and compares the performance of several primitive approaches for fair channel sharing. The conclusion follows in Section 4.

## 2. Problem Statement

We consider two different wireless networks, WMAN and WLAN, which coexist and operate in the same frequency band. As illustrated in Fig. 1, the WMANs are deployed as cellular networks with the frequency reuse factor of 1/3 and they have relatively higher transmission power ($P_{tx,1}$)[1] and coverage ($D_{rx,1}$), compared to the WLAN. The `WLAN` is deployed within the coverage of the central WMAN, `WMAN_0`, and the other six WMANs surrounding `WMAN_0`, denoted as `WMAN_i`, are considered as the 1st-tier interfering systems. As the interference from `WMAN_is` is dominant, we neglect the interference from the 2nd-tier or further-away interfering systems. This work considers a general coexistence scenario where both WMAN and WLAN deploy the contention-based MAC protocol without considering any specific frame structure or signaling between them, even though IEEE 802.16h [1] and IEEE 802.11y [2] propose several mechanisms for coexistence of WMAN and WLAN.

[1] For the simplicity of notation, we use subscription "1" and "2" for WMAN and WLAN, respectively.

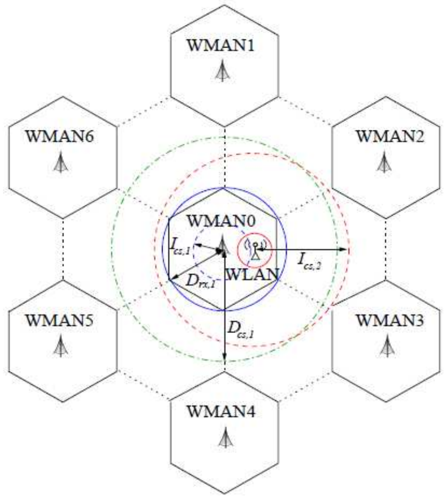



**Fig. 1**. Coexistence scenario of WMANs and WLAN.

### 2.1 Asymmetry of carrier sensing

Consider that `WMAN_0` and `WLAN` have the physical carrier sensing threshold (CSTH), $P_{cs,1}$ and $P_{cs,2}$, respectively, and that they have different transmission powers, $P_{tx,1} > P_{tx,2}$. Note that there are regulatory restrictions on CSTH and transmission power for non-exclusive coexistence. We consider the energy detection approach is used as physical carrier sensing. Let us define $D_{cs}$ and $I_{cs}$, as carrier sensing range within which the transmitter can detect busy channel due to transmission by homogeneous system and heterogeneous system, respectively. Accordingly, $D_{cs}$ and $I_{cs}$ are related to detect the intra-system collision and inter-system interference, respectively. The maximum transmission range with the lowest transmission rate, $D_{rx}$, can be determined by the minimum receiver sensitivity $P_{min}$. Considering the path-loss propagation model with a path-loss exponent of α, these ranges can be represented as

$$D_{cs,1} = \left( \frac{G_1 P_{tx,1}}{P_{cs,1}} \right)^{\frac{1}{\alpha}}, \; I_{cs,1} = \left( \frac{G_2 P_{tx,2}}{P_{cs,1}} \right)^{\frac{1}{\alpha}}, \; D_{rx,1} = \left( \frac{G_1 P_{tx,1}}{P_{\min,1}} \right)^{\frac{1}{\alpha}}. \quad (1)$$

where $G_1$ and $G_2$ are channel gains for WMAN and WLAN systems, respectively. Similarly, $D_{cs,2}$, $I_{cs,2}$, and $D_{rx,2}$ for WLAN can be represented. If $P_{tx,1} > P_{tx,2}$, it can be shown from (1) that

- `WMAN_0`: $D_{cs,1} > I_{cs,1}$
- `WLAN`: $D_{cs,2} < I_{cs,2}$

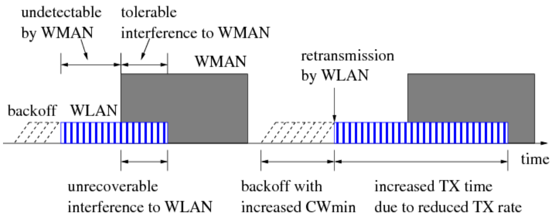



**Fig. 2** Effect of inter-system interference on channel access.

This asymmetry gives favor to `WMAN_0` than `WLAN` in terms of channel access. Depending on the values of $P_{tx}$, $P_{cs}$, and $P_{min}$, it may happen that (*i*) $I_{cs,1}$ is small enough in that it does not cover the transmission range of `WLAN`, i.e., the transmitter of `WMAN_0` fails to detect the channel occupation by `WLAN`, so it tries to access the channel, regardless of whether or not `WLAN` occupies the channel (*`WLAN` becomes a hidden terminal to `WMAN_0`*), (*ii*) $I_{cs,2}$ is large enough to cover the whole transmission range of `WMAN_0`, i.e., the transmitter of `WLAN` defers its transmission whenever `WMAN_0` occupies the channel (*`WMAN_0` becomes an exposed terminal to `WLAN`*). Accordingly, there occurs a severe unfair channel access between `WMAN_0` and `WLAN`. Accordingly, there occurs a severe unfair channel access between `WMAN_0` and `WLAN`.

### 2.2 Binary exponential backoff and link adaptation due to interference

The BEB mechanism is helpful to alleviate intra-system collision by doubling the contention window size on detecting transmission failure. However, it deprives WLAN of channel access opportunity when the transmission failure is due to inter-system interference. As shown in Fig. 2, WMAN cannot detect on-going packet transmission by WLAN and starts transmitting its packet. WMAN can tolerate the interference by WLAN and successfully receives the packet since the interference signal strength of WLAN is relatively small. However, the high interference signal of WMAN may corrupt WLAN's packet transmission, resulting in a transmission failure. Then, WLAN will retransmit the packet with a possibly increased backoff time according to the BEB mechanism. Therefore, the BEB mechanism, which cannot distinguish collision-driven failure from interference-driven failure, reduces the channel access opportunity of WLAN and deteriorates fair channel sharing.

Similar to the BEB mechanism, the link adaptation mechanism also worsens the problem. The automatic rate fallback (ARF), the most common link adaptation algorithm, adjusts the transmission rate by estimating the channel condition based on the consecutive numbers of transmission successes and failures. If packet transmission fails consecutively (regardless of the cause of failure, i.e., intra-system collision, inter-system interference, temporary degrade of channel quality), ARF decreases the transmission rate to the next lower one among the available sets to make the transmission more robust to the channel error. Then, the receiver can decode the packet correctly with the higher probability in the presence of noise and interference. In a sense, the link adaptation mechanism is beneficial to interference mitigation; however, it has an adverse effect in the case where WMAN and WLAN coexist with different transmission power. It is important to note that the transmission time required for transmitting a constant-size packet is inversely proportional to the transmission rate. The reduced transmission rate of WLAN increases its transmission time and the probability that WLAN packet transmission is interfered by WMAN increases accordingly (see Fig. 2). In this case, the reduced transmission rate of WLAN makes its transmission more vulnerable to interference by WMAN.

## 3. Performance Evaluation and Analysis

### 3.1 Simulation setup

We perform simulation study to evaluate how serious the problem of unfair channel sharing is. We consider the network configuration shown in Fig. 1. The parameters and their values used in the simulations are listed in Table 1. They are determined considering regulatory restrictions and realistic deployment. The wireless channel is modeled considering path-loss (α=3.7 for urban environment), Rayleigh multi-path fading, and shadowing (log-normal distribution with zero mean and standard deviation of 8 dB). The thermal noise power is set to -100 dBm. The IEEE 802.11a MAC/PHY parameters are used in the simulations.

**Table 1**. Parameters used in the simulation.

| Parameter | Value | |
|---|---|---|
| | WMAN | WLAN |
| transmission power, $P_{tx}$ | 1000 mW | 50 mW |
| minimum receiver sensitivity, $P_{min}$ | -80 dBm | -80 dBm |
| cell radius, $D_{rx}$ | 750 m | 100 m |
| number of users per cell | 10 | 10 |
| path-loss exponent, $\alpha$ | 3.7 | |
| distance between the centers of WMAN_0 and WLAN, $D_{int-sys}$ (m) | 300 m | |
| slot size ($\mu$s) | 9 | |
| minimum contention window (slot) | 15 | |
| packet size (byte) | 1000 | |

**Table 2**. Minimum threshold value of SINR for each data rate.

| Data rate (Mbps) | SINR (dB) | Data rate (Mbps) | SINR (dB) |
|---|---|---|---|
| 54 | 24.56 | 48 | 24.05 |
| 36 | 18.80 | 24 | 17.04 |
| 18 | 10.79 | 12 | 9.03 |
| 9 | 7.78 | 6 | 6.02 |

The SINR-based closed-loop rate control is implemented in the simulation and the corresponding minimum value of SINR for each data rate is given in Table 2. The packet error is modeled according to [8]. Ten users are randomly distributed per cell. For each user, a 1000-byte packet is randomly generated such that its inter-arrival time follows a Poisson distribution with the mean value of 5ms. This packet generation rate is high enough to saturate the network capacity. Users send/receive packets to/from the base station of WMAN and access point of WLAN.

### 3.2 Effect of carrier sensing threshold

We compare the performance for the following four cases that have different values of CSTH;

- CASE1: ($P_{cs,1}$, $P_{cs,i}$, $P_{cs,2}$)= (-90, -90, -90) dBm,
- CASE2: ($P_{cs,1}$, $P_{cs,i}$, $P_{cs,2}$)= (-100, -90, -90) dBm,
- CASE3: ($P_{cs,1}$, $P_{cs,i}$, $P_{cs,2}$)= (-100, -100, -90) dBm,
- CASE4: ($P_{cs,1}$, $P_{cs,i}$, $P_{cs,2}$)= (-100, -100, -100) dBm.

Here, $P_{cs,i}$ is the CSTH of WMAN_i.

Figure 3 shows per-system throughput and total network capacity for these four cases. Here, the throughput of WMAN_is is represented as their average value while the total network capacity is calculated as the sum of throughputs of WMAN_0, WLAN, and six WMAN_is.

The CASE1 is set as a baseline scenario to evaluate the degree of unfairness. In this case, $D_{cs,1}$ (=$I_{cs,2}$) and $D_{cs,2}$ (=$I_{cs,1}$) are approximately 1400 m and 186 m, respectively, and there occurs the severe unfairness problem due to the reasons addressed in Section 2. The throughput of

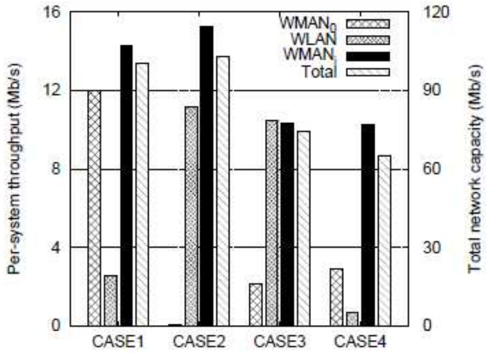



**Fig. 3**. Per-system throughput and aggregate network capacity for four cases with different carrier sensing threshold.

WMAN_0 is higher than that of WLAN by about 5 times. As a naive solution to this problem, we consider the CASE2 where $P_{cs,1}$ is decreased to detect the channel occupation by WLAN, i.e., $P_{cs,1}$ (= -100 dBm) < $(G_2 P_{tx,2} / D_{int-sys})^{1/\alpha}$, where $D_{int-sys}$ is the distance between the centers of WMAN_0 and WLAN. Note that $P_{cs}$ cannot be decreased to an arbitrary small value because of hardware limitation and detection accuracy. In the CASE2, $I_{cs,1}$ (=347m) > $D_{int-sys}$ (=300m) and the transmitter of WMAN_0 can detect busy channel due to WLAN transmission with a reasonable non-zero probability[2]. Here, $P_{cs,i}$ and $P_{cs,2}$ are not changed from -90 dBm. Fig. 3 shows that this naive approach cannot improve fairness of channel sharing at all; the throughput of WMAN_0 becomes almost zero while that of WLAN is increased to about 11 Mb/s. The reason is as follows; the decrease of $P_{cs,1}$ increases $D_{cs,1}$ (=2600m) as well as $I_{cs,1}$, then WMAN_0 is likely to defer transmission when WMAN_is are transmitting packets.

To remedy this, we consider the CASE3 where $P_{cs,1} = P_{cs,i}$ = -100 dBm for all WMANs but $P_{cs,2}$ for WLAN remains unchanged from -90 dBm. This setting still gives the favor to WLAN; the throughput of WLAN is higher than that of WMAN_0 by about 5 times. The unfair channel sharing between WMAN_0 and WLAN appears in the reverse aspect, compared to the CASE1. Meanwhile, the decrease of $P_{cs,i}$ makes another problem; the total network capacity is reduced by about 25% compared to the CASE1 and CASE2,

[2] Even in this case, the transmitters of WMAN_0 cannot completely detect WLAN's packet transmission. The detection probability strictly depends on the locations of WMAN_0 and WLAN transmitters.

because the spatial reuse cannot be fully employed. Lastly in the CASE4, $P_{cs}$ for all the systems are set to -100 dBm. As shown in Fig. 3, the total capacity is further decreased (more than 35% reduction compared to the CASE1 and CASE2), the throughput of `WLAN` is less than that of `WMAN_0` by more than 4 times, and the cell where both `WMAN_0` and `WLAN` coexist has the lower capacity by about 4 times compared to the CASE1. None of these four cases achieves the fair channel sharing and spatial reuse, and the performance is quite sensitive to the value of CSTH.

### 3.3 Feasibility of carrier sensing threshold control

In order to achieve fair and efficient channel sharing, the value of $P_{cs,1}$ should satisfy two requirements of *mutual detection* and *spatial reuse*; (*i*) it should be small enough for `WMAN_0` to detect transmission of `WLAN`, at the same time, (*ii*) it should be large so that `WMAN_0` does not defer its channel access during the transmission of `WMAN_i`. Let us define $d_{tx1-tx2}$ and $d_{tx1-txi}$ as the distance between transmitters of `WMAN_0` and `WLAN` and the distance between transmitters of `WMAN_0` and `WMAN_i`, respectively, and define $K_1$ and $K_2$ as the relative distances of $d_{tx1-tx2}$ and $d_{tx1-txi}$ normalized by $D_{rx,1}$, i.e.,

$$K_1 = \frac{d_{tx1-tx2}}{D_{rx,1}}, \quad K_2 = \frac{d_{tx1-txi}}{D_{rx,1}}. \tag{2}$$

Note that $0 \le K_1 \le 2$ under the condition of overlapping deployment of `WMAN_0` and `WLAN` and $1 \le K_2 \le 5$ considering the deployment of WMANs with the frequency reuse factor of 1/3. These requirements can be represented in terms of $I_{cs,1}$ and $D_{cs,1}$ using (2) as

$$\begin{aligned} I_{cs,1} &> K_1 D_{rx,1} \\ D_{cs,1} &< K_2 D_{rx,1}. \end{aligned} \tag{3}$$

Assuming $P_{min,1} = P_{min,2}$, we can derive the upper and lower bounds on $P_{cs,1}$ from (1) and (3);

$$\begin{aligned} P_{cs,1}(\text{dBm}) &< P_{\min,1}(\text{dBm}) - 10\alpha \log_{10}(K_1/\gamma_{asym}), \\ P_{cs,1}(\text{dBm}) &> P_{\min,1}(\text{dBm}) - 10\alpha \log_{10}(K_2) \end{aligned} \tag{4}$$

where $\gamma_{asym} = D_{rx,2}/ D_{rx,1}$. It is worthwhile to note that $P_{cs,1}$ satisfying (4) does not always exist but it only exists if the following condition on $K_1$, $K_2$, and $\gamma_{asym}$ is satisfied;

$$\frac{K_1}{K_2} < \gamma_{asym} = \frac{D_{rx,2}}{D_{rx,1}} \tag{5}$$

This analysis means that the proper range of CSTH depends on the channel model, node placement, and cell deployment; and thus, it is not always possible to find the proper range of CSTH achieving both mutual detection and spatial reuse.

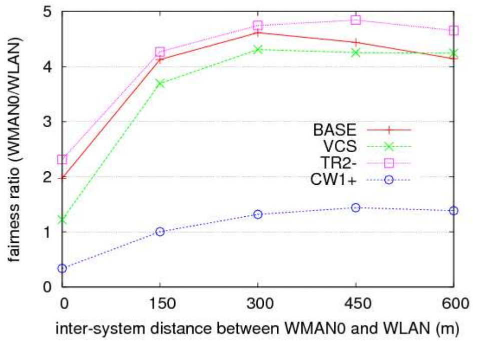
### 3.4 Performance Comparison for Several Approaches

Instead of controlling CSTH, we consider the following primitive approaches to improve fair channel sharing;

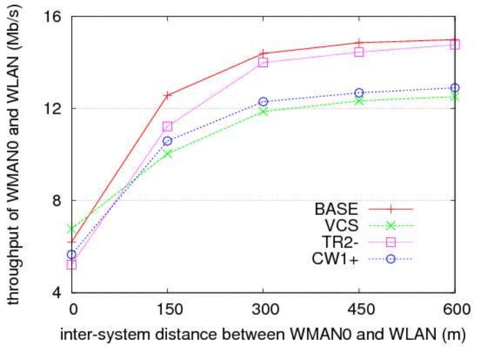
- `BASE`: This is the baseline scheme without any coexistence mechanisms (CASE1 in Section 3.2).
- `VCS`: The virtual carrier sensing mechanism based on ready-to-send/clear-to-send (RTS/CTS) messages is implemented for both `WMAN_0` and `WLAN` to supplement the physical carrier sensing so that `WMAN_0` can detect `WLAN`'s packet transmission with the increased probability.
- `TR2-`: This approach disables the link adaptation mechanism of `WLAN` and uses the most robust transmission rate (6Mb/s) for `WLAN` to overcome the interference from `WMAN_0`.
- `CW1+`: The minimum values of contention window of `WMAN_0` and `WLAN` are set to 1024 and 16, respectively, to give more channel access opportunity to `WLAN`.

We investigate the performance of these schemes for various values of the distance between the centers of `WMAN_0` and `WLAN` ($D_{int-sys}$), which determines the degree of overlapping deployment of WMAN and WLAN and is one of the most important factors affecting performance.

Figure 4(a) shows *fairness ratio* ($\gamma_{\text{fair}}$), defined as the ratio of the throughput achieved by `WMAN_0` to that achieved by `WLAN`, with respect to $D_{int-sys}$. Except for the case of $D_{int-sys} = 0$, there is no significant difference among the values of $\gamma_{\text{fair}}$ for `BASE`, `VCS`, and `TR2-`, and they range between 3.7 and 4.8. These results imply that `VCS` and `TR2-` are not effective to improve fairness. On the other hand, `CW1+` outperforms the other approaches in terms of fairness; $\gamma_{\text{fair}}$ ranges between 0.34 and 1.46 for the entire range of $D_{int-sys}$.




(a) Fairness ratio ($\gamma_{\text{fair}}$)




(b) Coexistence efficiency ($\eta_{\text{coex}}$)

**Fig. 4**. Performance comparison for several approaches in terms of fairness and efficiency.

Next, we observe *coexistence efficiency* ($\eta_{\text{coex}}$), defined as the sum of throughputs of `WMAN_0` and `WLAN`, from Fig. 4(b). The value of $\eta_{\text{coex}}$ of `VCS` is relatively lower than the other approaches due to the overhead of RTS/CTS messages. Also, `CW1+` has lower value of $\eta_{\text{coex}}$ than `BASE` and `TR2-` because the average backoff time of `WMAN_0` is increased. From the results in Fig. 4, we can make the following conclusions;

(*i*) the approach of virtual carrier sensing (`VCS`) is effective to improve fairness only when WLAN is deployed close to the base station of WMAN, and its efficiency is inevitably debased due to the overhead for control messages;

(*ii*) the approach of using robust modulation and coding schme for WLAN (`TR2-`) improves neither fairness nor efficiency;

(*iii*) the approach of controlling contention window (`CW1+`) improves fairness at the cost of efficiency. It is expected that the trade-off between fairness and efficiency can be controlled by the contention window size.

## 4. Conclusion

In this study, we have addressed the coexistence issues arising when WMAN and WLAN with different transmission power coexist according to the contention-based MAC protocol. We have showed that the existing CSMA mechanism fails to assure fair channel sharing and we have identify its causes from the view points of carrier sensing, contention resolution and link adaptation mechanisms. Through simulation study, we have compared the performance of several approaches for fair channel sharing and have found a clue to solving this problem. In our future work, we will develop an adaptive coexistence mechanism that controls contention window size to assure fair channel sharing while mitigating interference and attaining spatial reuse.

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