A Performance Model for the Effect of Interferences among the Collocated Heterogeneous Wireless Networks

Bilal Khan and Jong-Suk Ahn

Department of Computer Science and Engineering, Dongguk University, Seoul, Korea

Bilalkhan83@hotmail.com and jahn@dgu.edu

Abstract—**As various wireless networks connecting mobile devices have been widely deployed, many researchers are interested in evaluating the effect of interferences among them. It is due to that these heterogeneous collocated wireless networks tend to be asymmetric in terms of transmission power and carrier sense threshold, resulting in unfair channel access and degraded performance of victim networks. This paper proposes an analytical model to evaluate the degree of interferences among collocated wireless networks sharing the same bandwidth and running BEB (Binary Exponential Backoff) algorithm. Furthermore, it introduces a mathematical model to measure the performance improvement by NACK (negative ACK) scheme, which lets senders distinguish inter-network interferences from intra-network ones named collisions. The model predicts that interferences from dominant networks can severely deteriorate the performance of weak networks. It also shows that the NACK technique alone is unable to alleviate the degradation of performance if superior networks continue to deliver data frames.**

Keywords—coexistence; heterogeneous; 802.11; 802.16; interference

I. INTRODUCTION

Recently various wireless networks have been redundantly installed in the same location to network the numerous numbers of wireless mobile devices. WiMAX, Wifi, and Zigbee, each of which is standardized by IEEE 802.16, IEEE 802.11, and IEEE 802.15.4 respectively, for example have been competitively deployed with an aim of providing the Internet access service to mobile phones or internetworking mobile sensor devices.

Even though these collocated networks give the freedom of selecting a network for faster data delivery and low cost, however, these networks tend to hamper each other's communications especially when they share the same bandwidth. WLAN and WPAN sharing 2.4GHz ISM (Industrial, Scientific and Medical) band tend to frequently interfere each other's operation, resulting in severely degrading the performance. Sikora [1] reported that a packet error rate of IEEE 802.15.4 networks could increase by more than 90% when they are co-placed with IEEE 802.11 networks. Pollin et al. [2] also demonstrated that the performance of IEEE 802.11 networks became lowered by up-to 60% when it coexisted with IEEE 802.15.4 devices. It is predicted that this interference problem due to sharing a common channel will be exacerbated in near future since FCC (Federal Communications Commission) has designated 3.6GHz band for its newly devised standards IEEE 802.11y and 802.16h [3][4].

This severe performance deterioration is mainly attributed to two factors such as the intrinsic weakness of BEB algorithm adopted by all IEEE 802 variants for collision avoidance and no mechanism to tell collision from either interference or channel bit errors. At first, the time spent to find the appropriate contention window becomes unwieldy when heavy congestion lasts for a long period since BEB algorithm always starts from the small contention window regardless of the current network status. For instance, an 802.11b network consisting of four saturated stations has collision probability of 14% and this probability approaches 40% when the number of saturated stations grows 40 [5].

Secondly, BEB algorithm blindly doubles its contention window to slow down the transmission speed since BEB algorithm is designed to operate without any explicit feedback on the outgoing frame. It means that BEB cannot differentiate collision signaling congestion from interference happened due to poor channel quality. Under heavy interferences especially suffered by victim networks in collocated networks, the victim networks should raise their signal strength to improve their performance while keeping the contention window as it was rather than increasing the waiting time.

For accurately evaluating the impact of inter-network interferences on the performance of involved networks, this paper introduces a complete analytical model when each network runs its own BEB algorithm. For this, each network behaviors are abstracted by a 2-dimentional Markov model while the interferences from other networks are incorporated by the interference probability. Note that this interference probability is calculated from the performance model of the interfering networks. Furthermore, this paper presents another mathematical model to measure the influence of NACK mechanism when it is employed with the legacy BEB algorithm. It is assumed that the BEB algorithm does not increase the contention window size at the arrival of NACK frames and keeps sending the data frame with the previous contention window.

When WLAN is collocated with WMAN with stronger transmission power, the analytical model predicts that the interference severely degrades the performance of WLAN. It also forecasts that NACK mechanism alone is not enough to improve the performance of WLAN, especially when WMAN constantly sends data frames.

This paper is organized as follows. Section II illustrates some related work. Section III models two Markov chains for WLAN and WMAN when both are collocated and running BEB (Binary Exponential Backoff). In Section IV an analytical model WLAN is built when it adopts the NACK frame mechanism in addition to BEB algorithm. Section V compares the experimental results produced from the analytical models of Section III and IV. Finally Section VI presents the conclusion and future research topics.

II. RELATED WORK

Most of the performance models proposed so far to measure the performance of 802.11 follow the Bianchi [5] technique where packet errors are only due to collisions. Only few studies address the issue of channels errors in addition to packet collisions. For example, Ahn et al. [6] considered transmission failures due to channel errors in their performance model. In addition to performance, their model also analyses the energy consumption of 802.11 with FEC codes when it is deployed over wireless sensor networks. In their proposed model, transmission is successful when there is neither collision nor channel error. In [7], authors propose an analytical framework for analyzing the throughput of 802.11 in the presence of non-ideal transmission channel and capture effects. Moreover, their proposed model is based on unsaturated conditions to reflect the real behavior of network.

As already described in Section I, a substantial number of channel errors arise when heterogeneous networks are collocated [1][2]. Several mechanisms have been proposed for the successful coexistence of heterogeneous networks. Authors in [8] argue that in addition to collisions error prone channel also leads to transmission failure in IEEE 802.11 networks. In order to explicitly inform sender of the channel errors driven transmission failure, they proposed NACK frame mechanism [8]. However, differently from the previous work this paper only accounts for the transmission failure due to inter-network collision caused by the transmission from neighboring networks with higher transmission power and carrier sense threshold.

In [9], authors propose a mechanism to differentiate between loss and collision by using RTS/CTS frames. For instance, according to their approach if the exchange of RTS/CTS is successful then the *ACK timeout* will be considered as the failure due to channel error, whereas the failure of RTS/CTS exchange would be considered as a collision. Based on the information of RTS/CTS exchange failure and *ACK timeout*, the adjustment of the contention is determined. Their approach has a drawback in that it cannot take into account the effect of collision due to heterogeneous networks.

More recently, Park et al. [10] proposed NACK-frame mechanism for WLAN to successfully coexist with WMAN. In [10] it is mentioned that, Inter-network collision happens when PLCP (Physical Layer Convergence Procedure) header is successfully received with the failure to decode MPDU (MAC Protocol Data Unit). On the other hand, failure to receive both PLCP and MPDU is considered intra-network collisions. In case of inter-network collisions a NACK frame would be sent to the sender however, otherwise the receiver would remain silent which marks the occurrence of intra-network collision.

The aforementioned and other newly proposed algorithms are the candidates to be deployed in the future networks with the objective to make the coexistence of heterogeneous networks successful; therefore it is vital to measure the performance of these algorithms before any deployment takes place. This paper presents an analytical model based on Markov chain to precisely measure the performance of BEB when the NACK frame mechanism is adopted.

Although this paper analyses WLAN and WMAN, based on 802.11y and 802.16h respectively, the method of performance analysis could be generalized to any heterogeneous networks which uses BEB mechanism for contention resolution at MAC layer.

III. Performance Model of collocated WLAN and WMAN

This section presents an analytical model for computing the throughput of two co-placed networks sharing the same frequency band such as WLAN and WMAN running over 3.6 GHz band.

Fig. 1(a) and (b) illustrate the 2-dimensional Markov chain models for WLAN and WMAN, respectively, when both networks are collocated. The box with dotted line labeled as $\tau_{L,1}$ in Fig. 1(a) contains the states corresponding to the transmission of a WLAN frame. Similarly, the smaller box with dotted line in Fig. 1 (b) contains the states corresponding to the transmission of a WMAN frame and has been labeled as $\tau_{M,1}$. Furthermore, the bigger box labeled as $\tau_{M,2}$ in Fig. 1(b) describes the vulnerable period and is equal to the transmission delay of a WLAN data frame and its acknowledgement frame in addition to SIFS assuming that all WLAN frames are of same sizes. Both networks use CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) for channel access and the legacy BEB algorithm for contention resolution. WLAN station upon *i-th* transmission failure, either due to inter-network or intra-network collision, increases the size of its contention window according to IEEE 802.11 standard [3] as below

$$W_i = \begin{cases} 2^i W_0\,, & i \le m' \\ 2^{m'} W_0\,, & i > m' \end{cases} \tag{1}$$

Here W_i is the current contention window and $i \in (0, m)$, is backoff stage where m denotes maximum backoff stage. Furthermore W_0 is the minimum contention window can be denoted as CW_{min} at $i = 0$. Contention window reaches maximum, can be denoted as CW_{max} at $i = m'$ and remains there after subsequent transmission failures until it is reset to CW_{min} [11].

Consider the number of WLAN and WMAN stations is n_L and n_M, respectively thus the total number of stations is $n = n_L + n_M$. Referring to Fig. 1(a), WLAN station accesses the channel in a randomly chosen time slot with probability $\tau_{L,1}$. WLAN ongoing transmission can be interfered by a WMAN transmission only if the backoff window of WMAN reaches 0 before the end of WLAN transmission while all other WLAN stations freeze their backoff process due to the channel being busy. In this case, WLAN transmission is susceptible to inter-network collision from WMAN and the duration in which WLAN frame is susceptible to interference is the vulnerable period or vulnerable window. Hence, the longer the vulnerable period is, the higher would be the probability of WMAN transmission interfering WLAN's transmission.

Referring to Fig. 1 (b), let $\tau_{M,1}$ be the probability that a WMAN station accesses the channel in a randomly chosen time slot. Furthermore, suppose the transmission of this WMAN station falls inside the vulnerable period with the transmission probability denoted as $\tau_{M,2}$. A WLAN station suffers transmission failure either due to another WLAN station transmission with intra-network collision probability of $p_{L,collision}$ or due to transmission of a WMAN station in vulnerable window with inter-network collision probability $p_{L,Inter}$, respectively. Stationary probabilities resorting to Fig. 1(a) are:

$$b_{i,k} = \frac{W_i - k}{W_i}\begin{cases} (1-p_{L,Inter})(1-p_{L,collisioin})\sum_{j=0}^{m} b_{j,0} & i = 0 \\ 1-(1-p_{L,Inter})(1-p_{L,collision})b_{i-1,0} & 0 < i \le m \end{cases} \tag{2}$$

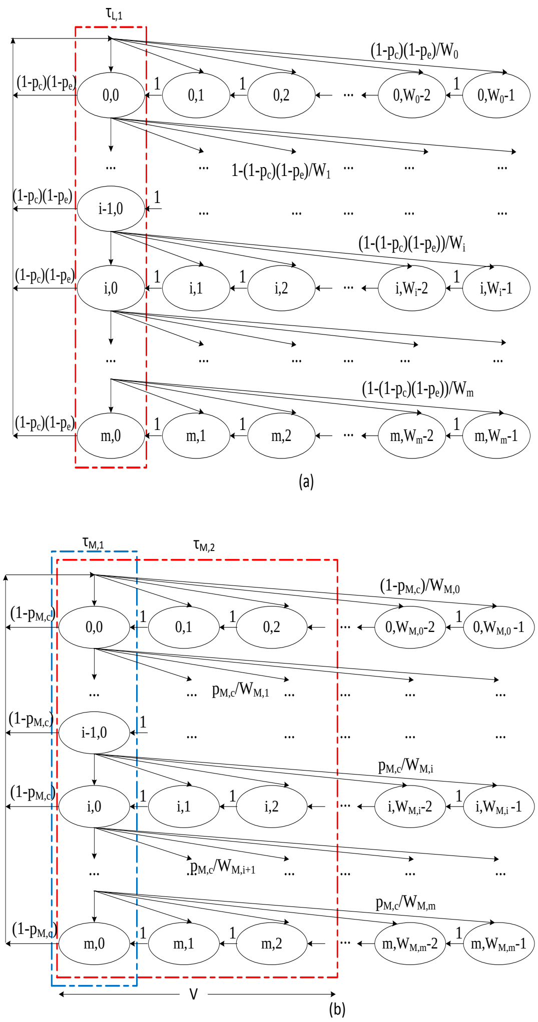

Figure 1. 2-dimensional Markov chain for (a) WLAN and (b) WMAN both running legacy BEB.

Now, using normalization condition for stationary distribution and setting $p = (1-(1-p_{L,collision})(1-p_{L,Inter}))$, we obtain $b_{L,0,0}$ as given in Eq. 3.

$$b_{L,0,0} = \begin{cases} \dfrac{2(1-p)(1-2p)}{W_0(1-p)(1-(2p)^{m+1}) + (1-p^{m+1})(1-2p)} & m \le m' \\ \dfrac{2(1-p)(1-2p)}{W_0(1-p)(1-(2p)^{m'+1}) + (1-p^{m+1})(1-2p) + W_0 2^{m'} p^{m'+1}(1-p^{m-m'})(1-2p)} & m \ge m' \end{cases} \tag{3}$$

Eq. 3. can be verified by replacing p with $(1-(1- p_{L,collision})(1-p_{L,Inter}))$ and setting $p_{L,Inter} = 0$, the resulting equation is equivalent to $b_{0,0}$ in Haitao [11]. Now using Eq. 3, $\tau_{L,1}$ can be computed which is the channel access probability by WLAN in a randomly chosen time slot.

$$\tau_{L,1} = \sum_{i=0}^{m} b_{i,0} = b_{L,0,0}\frac{1-(1-(1-p_{L,collision})(1-p_{L,Inter}))^{m+1}}{1-(1-(1-p_{L,collision})(1-p_{L,Inter}))} \tag{4}$$

Intra-network and inter-network collision probabilities, are denoted by $p_{L,collision}$ and $p_{L,Inter}$, respectively and can be give as

$$p_{L,collision} = 1-(1-\tau_{L,1})^{n_L-1} \tag{5}$$

$$p_{L,Inter} = 1-(1-\tau_{M,2})^{n_M} \tag{6}$$

A. Deriving WMAN transmission probabilities '$\tau_{M,1}$' and '$\tau_{M,2}$'

Unlike in WLAN in Fig. 1(a) where transmission fails due to inter-network and intra-network collisions with probabilities $p_{L,Inter}$ and $p_{L,collision}$, respectively, in WMAN in Fig. 1(b) there exist only collision probability i.e., $p_{M,c}$ which is the probability that more than one WMAN stations transmit in the same time slot with probability $\tau_{M,1}$, therefore, $p_{M,c} = 1-(1-\tau_{M,1})^{n_M-1}$. $p_{M,c}$ causes WMAN station to increase its contention window. Note that $p_{M,c}$ is not affected by the WLAN's transmission due to the latter's low transmission power. Now considering WMAN Markov chain in Fig. 1(b) and using normalization condition for stationary distribution we obtain

$$b_{M,0,0} = \begin{cases} \dfrac{2(1-p_{M,c})(1-2p_{M,c})}{W_{M,0}(1-p_{M,c})(1-(2p_{M,c})^{m+1}) + (1-p_{M,c}^{m+1})(1-2p_{M,c})} & m \le m' \\ \dfrac{2(1-p_{M,c})(1-2p_{M,c})}{W_{M,0}(1-p_{M,c})(1-(2p_{M,c})^{m'+1}) + (1-p_{M,c}^{m+1})(1-2p_{M,c}) + W2^{m'} p_{M,c}^{m+1}(1-p_{M,c}^{m-m'})(1-2p_{M,c})} & m \ge m' \end{cases} \tag{7}$$

Where $W_{M,0}$ is the initial contention window of WMAN station when $i=0$. Now the probability $\tau_{M,1}$ that a WMAN station transmits in a randomly chosen time slot is given by

$$\begin{aligned} \tau_{M,1} &= \sum_{i=0}^{m}\sum_{k=0}^{W_i} b_{M,i,k} \\ &= b_{M,0,0}\frac{1-p_{M,c}^{m+1}}{1-p_{M,c}} \qquad \begin{cases} 0 \le K \le W_i \\ 0 \le i \le m' \end{cases} \end{aligned} \tag{8}$$

In contrast, let $\tau_{M,2}$ denote the probability that the WMAN randomly chosen time slot for transmission is in the vulnerable window V and that eventually leads WLAN transmission being failed. Note that V is the number of time slots elapsed from the start of frame transmission to the reception of ACK frame, i.e. $V=Payload+SIFS+ACK$. $\tau_{M,2}$ can be obtained from Fig. 1(b) as below

$$\tau_{M,2} = \sum_{i=0}^{m}\sum_{k=0}^{V} b_{M,i,k} \qquad \begin{cases} 0 \le K \le V \\ 0 \le i \le m' \end{cases} \tag{9}$$

Where $b_{M,i,k}$ is the probability that the WMAN station is in the *i-th* backoff stage and *k-th* backoff counter. Here V is the vulnerable window and is equal to the size of WLAN frame, ACK frame and interframe space, i.e., *payload+ACK+SIFS*. Now solving Eq. 9 we obtain Eq. 10.

$$\begin{aligned} \tau_{M,2} &= \sum_{i=0}^{m}\sum_{k=0}^{V} b_{M,i,k} = \sum_{i=0}^{m} b_{M,i,0}\sum_{k=0}^{V}\frac{W_{M,i}-k}{W_{M,i}} \\ &= b_{M,0,0}\left((V+1)\frac{1-p_{M,c}^{m+1}}{1-p_{M,c}} - \frac{V(V+1)}{2W_{M,0}}\,\frac{1-\left(\frac{p_{M,c}}{2}\right)^{m+1}}{1-\frac{p_{M,c}}{2}} \right) \begin{cases} 0 \le K \le V \\ 0 \le i \le m' \end{cases} \end{aligned} \tag{10}$$

$b_{M,0,0}$ derived for $\tau_{M,1}$ can also be used for $\tau_{M,2}$ and is given in Eq. 7. Numerical method is used to solve Eq. 4, Eq. 8 and Eq. 10. Now WLAN throughput TH_L in the presence of WMAN can be given as

$$TH_L = \frac{P_{L,S}L}{P_{L,S}T_S + P_{L,C}T_C + P_{L,I}T_I} \tag{11}$$

Where L is the payload size and $P_{L,I}$, $P_{L,S}$, $P_{L,E}$, $P_{L,C}$ are the probabilities that there is no transmission in the considered time slot, the probability of successful transmission and the probability that the transmission is unsuccessful either due to inter or intra-network collision and can be represented as

$$\begin{cases} p_{L,I} = (1-\tau_{L,1})^{n_L}(1-\tau_{M,1})^{n_M} \\ p_{L,S} = (1-p_{L,collision})(1-p_{L,Inter}) \\ p_{L,C} = 1-(1-p_{L,collision})(1-p_{L,Inter}) \end{cases} \tag{12}$$

Moreover T_S, T_C,T_I in Eq. 10 account for the time intervals for the channel being busy due to successful transmission, the time spent in unsuccessful transmission due to either intra or inter-network collision and the time when the channel was idle, respectively. Knowing the time durations of various inter-frame spaces such as *DIFS* (distributed inter-frame space) and *SIFS* (short inter-frame space), *EIFS* (Extended Inter-Frame Space), *ACK* frames, slot time *(σ)*, data frame length *L*, *PHY* and *MAC* header durations, propagation delay*(δ)*,T_C and T_S can be computed. Note that unlike T_S, T_C and T_E need *EIFS* for another contention period.

IV. Performance Model of WLAN running NACK Mechanism in the Presence of WMAN

In previous section, we derived throughput equation for WLAN when it is collocated with WMAN and runs the legacy BEB algorithm. In order to prevent WLAN station increasing its backoff stage after its transmission is interfered from the collocated WMAN station, NACK-frame mechanism has been proposed by [8]. This section presents the performance analysis of the legacy BEB when it runs NACK frame.

Fig. 2 illustrates Markov chain model for WLAN when it uses BEB along with NACK frame. Note that the Markov model for WMAN remains the same as shown in Fig. 1(b), i.e., WMAN uses the legacy BEB.

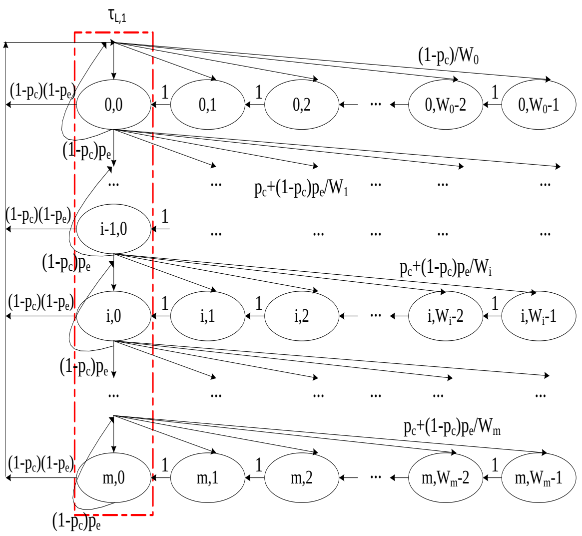

Figure 2. 2-dimensional Markov chain model for IEEE 802.11 using binary exponential backoff with NACK frame.

As discussed earlier, WLAN station suffers two types of collision, inter-network collision with probability $p_{L,Inter}$ and intra-network collision with probability $p_{L,collision}$. However, with NACK-frame being employed only intra-network collision causes WLAN station to increase its backoff window whereas in case of inter-network collision it remains in the same backoff stage. Hence from Fig. 2, $b_{i,0}$ can be obtained as

$$\begin{aligned} b_{i,0} &= b_{i-1,0}p_{L,collision} + b_{i,0}(1-p_{L,collision})p_{L,Inter} \\ &= \left(\frac{p_{L,collision}}{1-p_{L,Inter}(1-p_{L,collision})}\right)^{i} b_{0,0} \quad 0 < i \le m \end{aligned} \tag{13}$$

Let $b_{i,k}$ be the stationary distribution of the WLAN Markov chain from Fig.1 and can be given as Eq. 14.

$$b_{i,k} = \frac{W_i - k}{W_i} \begin{cases} (1-p_{L,Inter})(1-p_{L,collision})\sum_{j=0}^{m} b_{j,0} + (1-p_{L,collision})b_{0,0} & i = 0 \\ b_{i-1,0}p_{L,collision} + b_{i,0}(1-p_{L,collision})p_{L,Inter} & 0 < i \le m \end{cases} \tag{14}$$

Setting $p_L = p_{L,collision} / (1-p_{L,Inter}(1-p_{L,collision})$ and using normalization condition for stationary distribution we obtain $b_{L,0,0}$ for WLAN running NACK frame and is given as

$$b_{L,0,0} = \begin{cases} \dfrac{2(1-p_L)(1-2p_L)}{W_0(1-p_L)(1-(2p_L)^{m+1}) + (1-p_L^{m+1})(1-2p_L)} & m \le m' \\ \dfrac{2(1-p_L)(1-2p_L)}{W_0(1-p_L)(1-(2p_L)^{m'+1}) + (1-p_L^{m+1})(1-2p_L) + W_0 2^{m'} p_L^{m+1}(1-p_L^{m-m'})(1-2p_L)} & m \ge m' \end{cases} \tag{15}$$

Eq.15 can be verified by replacing p_L with $p_{L,collision} / (1-p_{L,Inter}(1-p_{L,collision})$ and setting $p_{L,Inter} = 0$, the resulting equations correspond to the $b_{0,0}$ in Haitao [11]. Now the transmission probability $\tau_{L,1}$ of a WLAN station in a randomly chosen time slot can be given as

$$\tau_{L,1} = \frac{1-p_L^{m+1}}{1-p_L} b_{L,0,0} \tag{16}$$

Now we replace p_L with $p_{L,collision} / (1-p_{L,Inter}(1-p_{L,collision})$ in the above equation and put the resulting $\tau_{L,1}$ in Eq. 11 that will give us $p_{L,collision}$, $p_{L,Inter}$ and $p_{L,I}$ in terms of the newly derived $\tau_{L,1}$. Whereas the transmission probabilities of a WMAN station in a randomly chosen time slot and in vulnerable window remain same as $\tau_{M,1}$ and $\tau_{M,2}$, respectively, as given in Eq. 8 and Eq. 10. Moreover, the throughput equation described in Section III can also be used for measuring the throughput of WLAN when it uses BEB along with NACK frame mechanism.

In the next section we perform some experiments and compare the performance difference between the legacy BEB and NACK frame based BEB.

V. Experiments

In order to assess whether the performance difference exist between the legacy BEB and NACK frame based BEB, we calculate the throughput of WLAN using MATLAB based on the analytical models described in Section III and Section IV. All the parameters used in the experiments are given in Table 1. We plot performance graphs for WLAN that uses BEB mechanism in the presence of WMAN stations as depicted in Figure 3.

TABLE 1. Parameters For Experiments.

Channel Data Rate	11 Mbps
Control Rate	2 Mbps
PHY header	192 bits
MAC header	224bits
ACK	112 bits + PHY header
DIFS	50 μs
SIFS	10 μs
Slot Time (σ)	20 μs
Propagation Delay (δ)	1μs
CW_{min}	31
CW_{max}	1023

WLAN performs well when there is no WMAN present in the proximity. It can be seen from Fig. 3 that the presence of WMAN station severely degrades WLAN throughput. This loss in performance is almost 75% when only one WMAN is collocated and is even more when the number of WMANs increases.

In addition to the number of WMAN stations, the payload size of WLAN is another cause that degrades the performance of WLAN. Figure 4 illustrates WLAN throughput for two different WLAN frame sizes. It shows the longer the size of WLAN frame, the higher would be the probability that the frame is interfered by the WMAN transmission resulting in lower throughput. As shown in Fig. 4 the throughput for a data frame size of 2000 bits is higher than that for 3000 bits. Therefore, the length of WLAN frame coupled with number of WMAN stations decrease WLAN throughput when WLAN runs BEB algorithm.

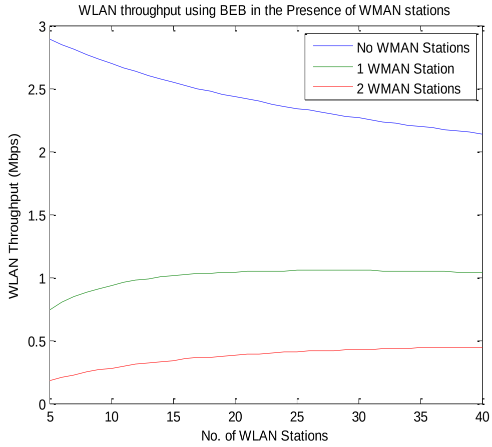

Figure 3. WLAN Throughput versus number of WLAN stations using BEB in the presence of WMAN.

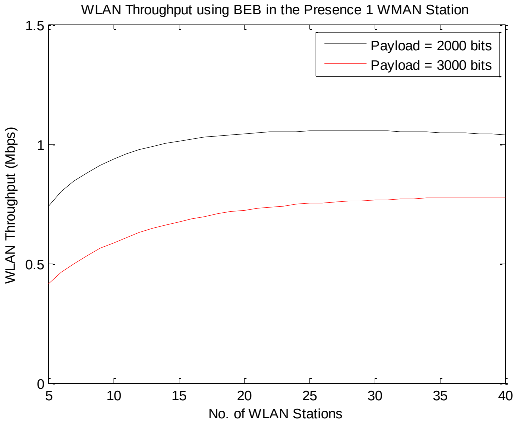

Figure 4. Effect of payload size on the WLAN throughput in the presence of a WMAN station.

With the use of NACK frame WLAN station is prevented from increasing its contention window in case of interference-driven transmission failure to protect the wastage of bandwidth. Based on the analytical model described in Section IV some experiments are performed here in order to analyze the performance difference of legacy BEB and the BEB that runs NACK frame. Figure 5 illustrates the throughput of WLAN in the presence of one WMAN station when it runs BEB while using NACK frame for reporting interference-driven failure and is further compared with the throughput obtained from the legacy BEB. BEB that adopts NACK frame was supposed to perform better than the legacy BEB in heterogeneous environment instead degrades WLAN performance as depicted in Fig. 5. The performance of BEB while using NACK frame is 50% less than that of the legacy BEB in the presence of only one WMAN station. Performance is further degraded when the number of collocated WMAN stations increases when WLAN runs NACK frame based BEB.

In contrast to legacy BEB, WLAN remains in the same backoff stage when it runs NACK frame in case of interference-driven transmission failure, therefore causes more contention among the WLAN stations. Hence, intra-network collision becomes the dominant factor in deteriorating WLAN throughput.

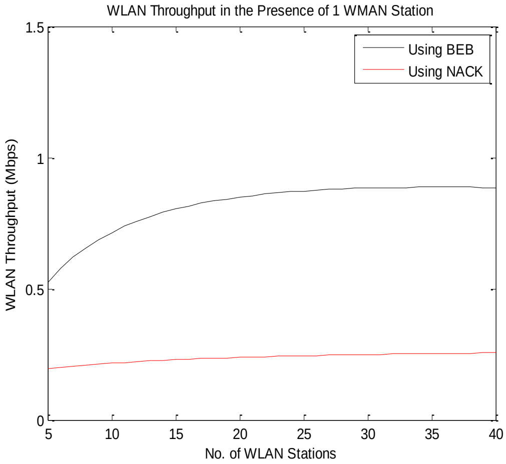

Figure 5. Performance comparison of legacy BEB and NACK in the presence of WMAN stations.

In order to analyze effect of WLAN frame size and the number of WMAN stations on the probability of inter-network collision a graph is plotted as shown in Fig. 6. First, it can be seen that inter-network collision probability increases with the increase in the payload size that in turn increases the vulnerable period causing WLAN frame more vulnerable to WMAN's interference. Second, the probability of inter-network collision is higher when two WMAN stations are present as compared to the case when only one WMAN station is present thus giving less opportunity of channel access to WLAN stations.

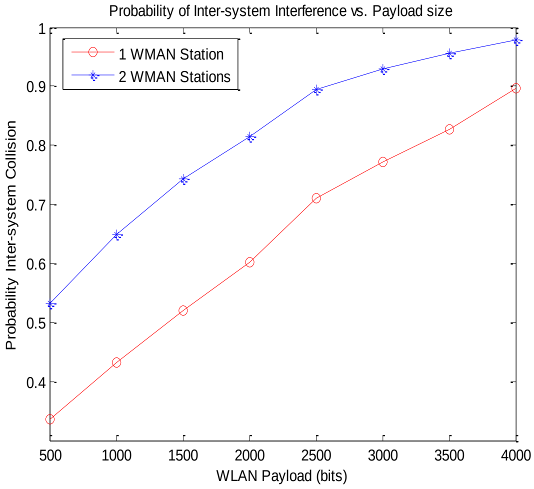

Figure 6. Effect of WLAN payload size and WMAN stations on the inter-network collision probability.

In this section, various plots have been drawn to observe the effect of different parameters, i.e., number of WLANs, number of WMANs and payload size, on the performance of WLAN when it runs and does not run NACK frame. These plots confirm the accuracy of the analytical model. However, one important aspect is the validation of our proposed model. The task of validating the analytical model using simulation has been left for the future work.

VI. CONCLUSIONS

Inherent drawbacks of CSMA coupled with the asymmetric nature of wireless heterogeneous networks are the causes that degrade the performance of WLAN running BEB. A mechanism based on NACK (negative ACK) frame has been proposed by various researches to prevent WLAN increasing its contention window due to interference-driven failure, thus to maximally attain the spectral efficiency. In this paper, we proposed an analytical model to accurately measure the performance of WLAN when it does not adopt NACK frame and when it adopts NACK frame. In both situations, WLAN is collocated with WMAN whiles both networks running legacy BEB. Finally, the performance of WLAN when it adopts NACK frame and does not adopt NACK frame technique is compared by performing several experiments using MATLAB. It was found that NACK frame mechanism alone is insufficient to improve the performance of WLAN when it runs BEB. In our future research we will analyze the performance of WLAN running NACK frame mechanism while WMAN running a different backoff mechanism with the aim to give a fair channel access opportunity to the WLAN station. In addition, validating our proposed analytical model using simulation is also included in our future research.

ACKNOWLEDGMENT

This research is supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (No. 2012-2020051).

REFERENCES

[1] A. Sikora and V.F. Groza, “Coexistence of IEEE 802.15.4 with other systems in the 2.4GHz ISM band,” Proceedings of the IEEE Instrumentation and Measurement Technology Conference, IMTC’ 05, pp. 1786-1791.

[2] S. Pollin, I. Tan, B. Hodge, C. Chun, and A. Bahai, “Harmful coexistence, between 802.15.4 and 802.11: a measurement based study,” Proceedings of the 3rd International Conference on Cognitive Radio Oriented Wireless Networks and Communications, CrownCom ’08

[3] *IEEE Std. 802.11y-2008(2008) IEEE Standard for Local and Metropolitan Area Networks – Specific Requirements, Par 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 3: 3650-3700 MHz Operation in USA*. IEEE, New York.

[4] *IEEE Std. 802.16h (2010) IEEE Standard for Local and Metropolitan Area Networks Part 16: Air Interface for Fixed Broadband Wireless Access Systems Amendment 2: Improved Coexistence Mechanisms for License-Exempt Operation*. IEEE, New York.

[5] G.Bianchi “Performance Analysis of 802.11 Distributed Coordination Function”, *IEEE Journal on Selected Areas in Communication.* V18, N3, March 2000.

[6] Jong-Suk Ahn, Jong-Hyuk Yoon, and Kang-Woo Lee, “Perfromance and Energy Consumption Analysis of 802.11 with FEC Codes over Wireless Sensor Networks”, *Journal of Communications and Networks*, Vol. 9, No., 3, September 2007.

[7] F. Daneshgaran, M. Laddomada, F. Mesiti, and M. Mondin, “Unsaturated Throughput Analysis of IEEE 802.11 in Presence of Non Ideal Transmission Channel and Capture Effects”, *IEEE Transactions on Wireless Communications*, Vol. 7, Issue 4, April 2008.

[8]Q. Pang, C. M. L. Victor, S. C. Liew, “Improvement of WLAN Contention Resolution by Loss Differentiation*”, IEEE Transactions on wireless communications*, Vol. 5, No. 12, December 2006

[9]A. Ksentini, A. Gueroui, M. Naimi, “Enhancing the DCF mechanism in noisy environment”, Vehicular Tech. Conference, pp. 650-654, Sept., 2005.

[10] Eun-Chan Park and Minjoong Rim, “Fair Coexistence MAC Protocol for Contention-Based Heterogeneous Networks”, *The Computer Journal, 2011.*

[11] W. Haitao, Yong Peng, Keping Long, Shiduan Cheng, Jian Ma, “Performance of Reliable Transport Protocol over IEEE 802.11 Wireless LAN: Analysis and Enhancement”, IEEE INFOCOM 2002.