Modeling the Effect of Interferences among *N* Collocated Heterogeneous Wireless Networks

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Abstract-- **With the advent of wireless networks, the usage of mobile devices has been rapidly exploded due to their cable-free convenience. The ubiquity and dense population of mobile devices have led several heterogeneous wireless networks to be redundantly deployed as an underlying infrastructure in a given area, allowing mobile users to choose their preferred wireless networks. These co-placed different networks, however, tend to interfere with each other and therefore suffer from severe performance degradation. To estimate this deterioration, this paper proposes an analytic performance model which precisely evaluates both the inter-network interference and intra-network collision effect on a victim network when involved networks run the same backoff algorithm. Differently from a legacy hidden station model, our model requires a set of Markov chains to separately abstract behaviors of both interfered and interfering networks. Simulation validates that our proposed model predicts the interference impairments more accurately than the hidden station model and even the conventional interference model that ignores the backoff behavior in wireless networks.**

Keywords- interferences, IEEE 802.11, performance model of wireless networks.

I. INTRODUCTION

As a tremendous number of different mobile devices have been emerged, various mobile wireless networks have actively built to provide seamless and ubiquitous connections regardless of where users travel around. To maximize the performance of wireless networks under different topological constraints, furthermore, a variety of communication protocols have been actively standardized. IEEE 802.16, IEEE 802.11, and IEEE 802.15.4 protocols also known as WiMAX, WiFi, and Zigbee, for instance, have been redundantly installed to support the Internet access service over the area of cities, buildings, and rooms respectively.

Even though these collocated networks give the freedom of selecting a network for faster data delivery and lower cost, however, these networks tend to hamper each other's communications especially when they occupy the same bandwidth. WLAN and WPAN sharing 2.4GHz ISM (Industrial, Scientific and Medical) band, for example, would incur frequent interferences namely inter-network collisions, resulting in severely degraded performance. Sikora et. al., report that a packet error rate in IEEE 802.15.4 networks increases by more than 90% when they are installed near to IEEE 802.11 networks [1]. Pollin et al. [2] also demonstrate that the performance of IEEE 802.11 networks go down by up-to 60% when it coexists with IEEE 802.15.4 networks. This interference is expected to be exacerbated in future as FCC (Federal Communications Commission) has designated its newly devised IEEE 802.11y and 802.16h [3][4] standards to share 3.6GHz band.

This severe performance deterioration is mainly attributed to two factors such as the intrinsic laziness of BEB (Binary Exponential Backoff) algorithm adopted by almost all IEEE 802 variants for collision avoidance and the lack of mechanisms to discriminate collision-driven failure from interference-driven failure. At first, BEB algorithm unwieldy spends the time to reach the appropriate contention window when heavy congestion lasts for a long period since it always starts from the small contention window regardless of the current network status. It would experience some number of timeouts to settle to a backoff timeout suitable for the number of currently contending stations.

Secondly, BEB algorithm blindly doubles its contention window due to the lack of any explicit feedback on the outgoing transmission status. Without the explicit feedback, precisely it cannot differentiate collisions signaling intra-network interference from corruptions caused by inter-network interference. Under heavy interferences, it is a better way for victim networks to raise their signal strength rather than expand their contention window to prevent throughput from steeply falling down.

Research has been actively conducted to accurately and separately measure either collision or interference effect on performance. One typical research proposes a performance model which aims at calculating performance downfall of 802.11h when it operates in the same cell as 802.16y[5]. The drawback of this approach, however, is to assume that both WLAN and WMAN run the fixed contention window unlike the standards [3][4] which stipulate to employ BEB algorithm.

To influence the behaviors of BEB algorithm on the effect of interference, this paper proposes a performance model which extends a legacy hidden station model [6]. This extension is required since the inter-network interference is asymmetric while intra-collision by hidden stations is symmetric. In other words, in inter-network collision, superior networks can continue to send frames ignoring transmissions of nearby victim networks due to their asymmetric transmission power whereas hidden stations symmetrically suffer collision just like covered stations since the transmission power of stations in a network is assumed to be equivalent.

To appreciate this asymmetric aspect of *N* collocated heterogeneous wireless networks, the proposed model distinctly abstracts the behavior of each interacting network to evaluate its interior interactions and at the same time the degree of interference on other networks. Note that the traditional hidden station model requires only one Markov chain regardless of the number of hidden stations. As a result, for *N* collocated heterogeneous wireless networks our model requires *N* separate Markov chains to which the effect of interference from superior networks is added. ns-2 simulations validate our proposed model with only less than 10% deviation that both the conventional model [5] and the hidden station model [6] underestimate by around 85% the effect of interference in heterogeneous wireless networks on the achievable throughput of victim networks.

The remainder of this paper is organized as follows. Section II illustrates some related work. Section III presents our proposed model for *N* collocated networks. Section IV describes the ns-2 module for differentiating interferences from collisions. Section V explains the simulation results and compares them with the results obtained from the analytic model. Finally Section VI presents the conclusion and future research issues.

II. RELATED WORK

As wireless mobile networks have become popular, huge literatures has been published about the impact of interferences among coexistent heterogeneous wireless networks. To accurately evaluate the degree of interferences, various analytical models have been proposed. One of them predicts the interference effect on WLAN's throughput without explicitly assuming the presence of nearby wireless networks [7]. It abstracts interactions of co-placed wireless networks by channel errors measured by bit-error-rate without analyzing behavioral details of the intervening networks. It, furthermore, evaluates the performance improvement by employing FEC (Forward Error Correction) codes as a way to overcome this interference problem in WLAN.

In [8], authors introduce an analytic model for the performance analysis of WLAN taking into account the NACK (Negative ACK) frame as a solution when transmissions fail due to channel errors. Like [7], the model in [8] is also unable to include the impact of interference caused by the collocated networks.

A hybrid Markov chain model is introduced in [9] for the performance evaluation of hybrid IEEE 802.11b and IEEE 802.11g networks. Their targeted hybrid networks, however, are not a truly heterogeneous network since transmission failures in their hybrid networks are solely due to collisions whereas transmissions in heterogeneous networks are aborted by either collisions or interferences. In addition to the lack of evaluating the effect of interference in heterogeneous wireless networks, the applicability of their model is restricted to the two specific types of networks.

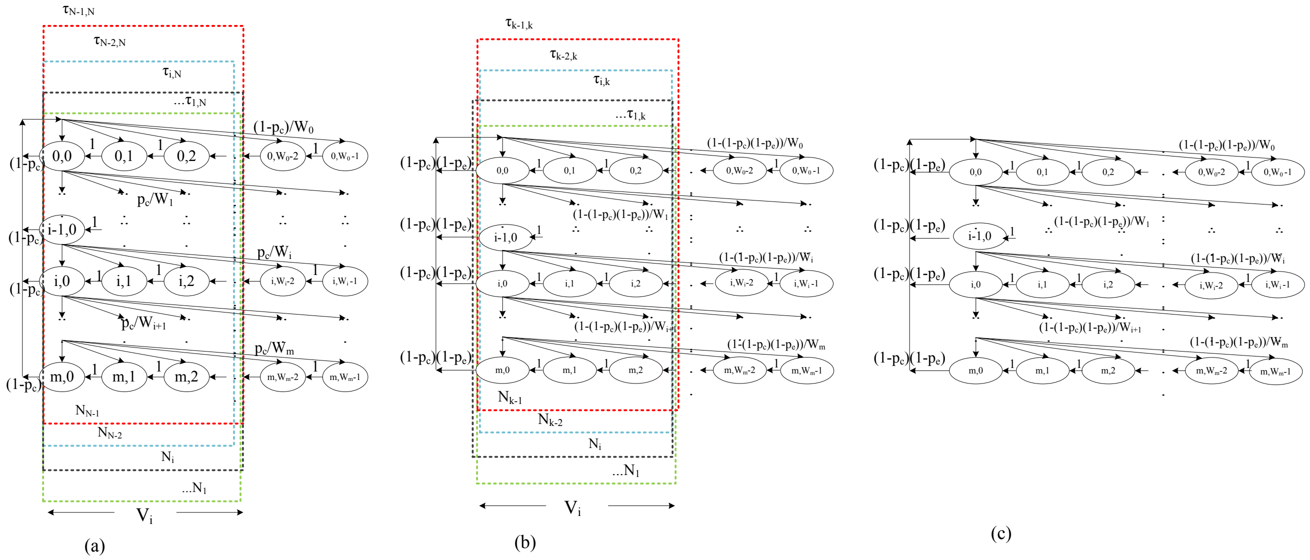
Authors in [5] describe an advanced analytic model to address the issue of transmission failure in collocated heterogeneous wireless networks. In contrast to our model, however, their analytic model assumes the constant size of contention windows for all the participant heterogeneous networks for the convenience of analysis even though most real MAC protocols employ BEB. Similar to [9], moreover, the analytic model in [5] falls short for the performance evaluation of more than two heterogeneous networks.

III. PERFORMANCE MODEL OF N COLLOCATED NETWORKS

This section explains an analytic model for computing the throughput of a network that shares the same frequency band with *N-1* other collocated networks under the assumption of all networks' running the same BEB algorithm. We believe that even though this assumption is not enough general to cover all types of wireless networks, it is still reasonable since the most common wireless networks such as Wifi and Zigbee belong to this category.

For our model, these *N* networks are indexed in an increasing order of transmission power like N_1, N_2,...,N_N. Namely network N_k radiates weaker signals than *N-k* networks ranging from N_{k+1} to N_N whereas it dominates the other remaining networks N_1, N_2, ..., N_{k-1} that refrain themselves from transmitting their frames whenever N_k occupies the channel. Note that the subscript *N* and *k* correspond to any positive integer and an integer lying between *1* and *N* respectively.

Figure 1 shows three Markov chains belonging to the strongest network N_N, to an intermediate network N_k, and to the weakest network N_1, respectively. Markov chain in Figure 1(a), at first, depicts a model for network N_N in which transmission is not affected by any other network, therefore, the success and failure of a transmission is only determined by the probability of collision, denoted as p_c like the one presented in [10]. *N-1* dotted boxes in Figure 1(a) represent transmissions of *N-1* weaker networks that are vulnerable to the network N_N. Transmissions of these *N-1* weaker networks are interfered when the transmission of network N_N falls inside one of the states in its corresponding box. In other words, in a vulnerable period the transmission time of network N_N is overlapped with that of a weaker network.



(a) (b) (c)

Figure 1. 2-Dimensional Markov Chains, (a) for N-th Network N_N (b) for k-th Network N_k (c) for 1-st Network N_1

Two symbols, $\tau_{i,N}$ and V_i around the dotted box N_i in Figure 1(a) represent the probability with which network N_i is interfered by network N_N and the vulnerable interval of network N_i. In $\tau_{i,N}$, first and second subscript represent the interfered or victim network and the interfering or superior network, respectively. Vulnerable interval of network N_i is set to the transmission delay of one frame of network N_i which is assumed to be fixed in our model. The vulnerable interval excludes transmission time of ACK since ACK frame is assumed to be not interfered due to its comparatively higher transmission power, i.e., 24.5dBm [3].

In contrast, Figure 1(b) describes the Markov chain for network N_k which is either superior or inferior to other collocated networks in terms of transmission power. Like Figure 1(a), *k-1* dotted boxes in Figure 1(b) represent vulnerable periods of weaker networks ranging from N_1 to N_{k-1}. The transmission of a weaker network, for example N_i, is interfered with probability $\tau_{i,k}$ that network N_k stays inside one of dotted boxes labeled N_i when network N_i has already initiated its transmission.

Finally, Figure 1(c) shows the Markov chain for the weakest network N_1. Due to its low transmission power network N_1 does not pose any threat to the collocated networks.

A. Collision and Interference Probability of Network N_k

This subsection calculates p_c and p_e in Figure 1(b) representing the collision and interference probability of network N_k, respectively, as a function of the number of collocated networks and number of stations in each network. Once p_c and p_e are calculated, (1) solves the probability of failure p_f that is the complement of the probability of success p_s. Note that, in addition to collisions, interferences also contribute to the probability of failure p_f, unlike the hidden station model [6] which ignores the effect of interference.

$$p_f = 1 - p_s = 1 - (1 - p_e)(1 - p_c) \qquad (1)$$

p_e is described in (2) where n_j and $\tau_{k,j}$ represent the number of stations in network N_j and the probability of interference caused by network N_j , respectively. In other words, $\tau_{k,j}$ is the probability of transmission by a station in network N_j that is superior to network N_k while the latter has already initiated a transmission. The second term in (2) describes the probability that any network superior to network N_k does not initiate transmission when the latter has already occupied the channel. These superior networks range from N_{k+1} to N_N.

$$p_e = 1 - \prod_{j=k+1}^{N} \left((1-\tau_{k,j})^{n_j} \right)^j \qquad (2)$$

p_c is described in (3) where n_k and ζ_k represent the number of stations in network N_k and the probability of transmission of a station of network N_k, respectively. The second term in (3) describes the probability that n_k *-1* stations in network N_k do not transmit any frame, when one station of network N_k has occupied the channel.

$$p_c = 1 - (1 - \zeta_k)^{n_k - 1} \qquad (3)$$

After p_f is found, $b_{0,0}$ is calculated from (4). Here m, m' and W specify the maximum number of allowable retransmission, the maximum number of contention window's backoffs, and the minimum contention window size. For more details, please refer to [11][12].

$$b_{0,0} = \begin{cases} \dfrac{2(1-p_f)(1-2p_f)}{W(1-p_f)(1-(2p_f)^{m+1}) + (1-p_f^{m+1})(1-2p_f)} & \text{when } m \le m' \\ \dfrac{2(1-p_f)(1-2p_f)}{W(1-p_f)(1-(2p_f)^{m'+1}) + (1-p_f^{m+1})(1-2p_f) + W2^{m'}p_f^{m'+1}(1-p_f^{m-m'})(1-2p_f)} & \text{when } m > m' \end{cases} \qquad (4)$$

$$\tau_{k,j} = \sum_{s=0}^{m}\sum_{c=0}^{V_k} b_{s,c}$$

$$= \begin{cases} b_{0,0}\cdot\left(\left(\frac{W}{2}\right)\frac{1-(2p_f)^X}{1-2p_f} + \left(\frac{1}{2}\right)\frac{1-p_f^X}{1-p_f} + (V_k+1)\frac{p_f^X - p_f^{m+1}}{1-p_f} - \frac{V_k(V_k+1)}{2W}\frac{\left(\frac{p_f}{2}\right)^X - \left(\frac{p_f}{2}\right)^{m+1}}{1-\frac{p_f}{2}} \right) & \text{when } 0 \le V_k \le W_{m'} \text{ and } 0 \le X \le m' \\ 1 & \text{when } V_k > W_{m'} \end{cases} \tag{6}$$

B. Transmission Probability of Network N_k and Interference Probability of Its Superior Networks

The probability of transmission ζ_k of a station in network N_k is the sum of the state probabilities in the first column in Figure 1(b) as shown in (5). Here, s the first subscript in $b_{s,0}$ indicates the number of backoffs or the level of row in Figure 1(b).

$$\zeta_k = \sum_{s=0}^{m} b_{s,0} = b_{0,0}\frac{1-p_f^{m+1}}{1-p_f} \tag{5}$$

(6) determines the probability $\tau_{k,j}$ with which network N_k is interfered by superior network N_j. In other words $\tau_{k,j}$ is the sum of all the state probabilities of states contained within the box labeled with N_k within the Markov chain of network N_j where j ranges from $k+1$ to N. Note that c the second subscript in $b_{s,c}$, in (6) is the number of time slots in the vulnerable interval ranging from 0 to V_k. X is the minimum backoff stage for which the contention window of superior network N_j is greater than the vulnerable interval V_k of network N_k. For example, if $W_1<V_k\le W_2$, then use $X=2$ in (6).

C. Throughput of Network N_k

Throughput TH of network N_k is calculated in (7) where L is the payload size and p_I, p_S, p_f are the probabilities that there is no transmission in the considered fraction of time, the probability of successful transmission of network N_k and the probability, which is computed in (1), that the transmission of network N_k is unsuccessful due to either collision or interference.

$$TH = \frac{p_S L}{p_S T_S + p_f T_f + p_I T_I} \quad \text{where} \quad p_I = 1 - p_S - p_f \tag{7}$$

Moreover T_S, T_f and T_I in (7) account for the time intervals for the channel being busy due to successful transmission, the time spent in unsuccessful transmission due to either collision or interference and the time when the channel was idle, respectively.

IV. A MODULE FOR INTERFERENCES IN ns-2

To differentiate inter-network collision from intra-network collision, we add some number of steps as shown in Figure 2 since the current version of ns-2 [13] can only simulate the interaction of wireless networks of the same type. According to the module we added when another frame denoted as the 2nd frame arrives while a frame named as the 1st frame is being received, the receiver checks which part of the 1st frame is being received.

A frame is successfully received when a receiver receives both PLCP and MPDU. The execution of different steps can be summarized as below:

- An inter-network collision is declared when a 2nd frame arrives while MPDU of the first frame is being received of the 1st frame. This is due to the fact PLCP of the 1st frame has been already received before the arrival of the 2nd frame.
- When a 2nd frame arrives with receiving power ratio, labeled as Power ($PLCP_2$)/Power ($PLCP_1$), higher than a certain threshold denoted as CP_{TH} while PLCP of the 1st frame is being received [14]. In this case, the 1st frame is dropped due to interference and interference is declared.
- In contrast, an intra-network collision is declared when a 2nd frame arrives during the PLCP reception of the 1st frame and fails the PLCP reception power ratio check. In this case receiver fails to successfully receive PLCP header and MPDU [5] and therefore both frames are discarded.

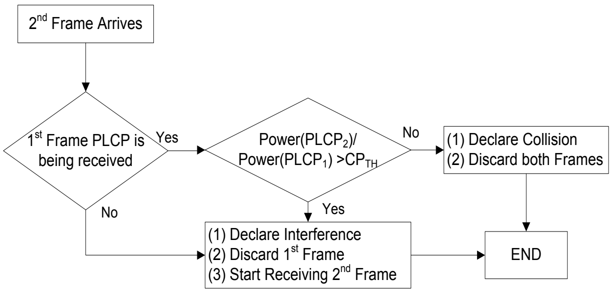


Figure 2. A Module for Telling Collision from Interference in ns-2

TABLE 1
PARAMETERS USED IN SIMULATION AND MATHEMATICAL ANALYSIS

Parameters	Values	Parameters	Values
Data Rate	11 Mbps	DIFS	50 µs
Control Rate	2 Mbps	SIFS	10 µs
PHY Header	120 bits	Slot Time (σ)	20 µs
MAC Header	272 bits	CW_{min}	31
Transmission Power	10 dBm (WLAN)	CW_{max}	1023
	30 dBm (WMAN)	Retransmission Limit (m)	5
ACK Frame	112 bits	Maximum Backoffs (m')	5

V. SIMULATION STUDY

This section performs simulation using ns-2 to evaluate the effect of interference when the arbitrary number of networks *N* is set to 2, equivalent to a situation where one WLAN and one WMAN competes for the same wireless channel. Table 1 lists the values assigned to PHY/MAC parameters of 802.11b that is assumed to be employed by both WLAN and WMAN. It is worth mentioning that Park et. al., in [5] also assumes that WLAN and WMAN run 802.11a for the convenience of analysis. Furthermore, we use 400 bytes of payload size for both WLAN and WMAN for all experiments.

A. Evaluating the Accuracy of the Proposed Model

Figure 3 illustrates WLAN throughput versus the number of WLAN nodes when there is no WMAN station present in the vicinity. At first, Figure 3 proves that the throughput obtained using analytic model is different only by 5~10% from that obtained using simulations for various number of WLAN stations.

Secondly when collocated with only one WMAN station WLAN suffers severe reduction in its performance as shown in Figure 3. This reduction in WLAN throughput is over 99% when there is less number of WLAN stations, e.g., 2~10, but decreases when the number of stations in WLAN increases. The slight improvement in WLAN performance when there are many WLAN stations is due to the availability of a station to transmit in the idle time between the two consecutive WMAN transmissions.

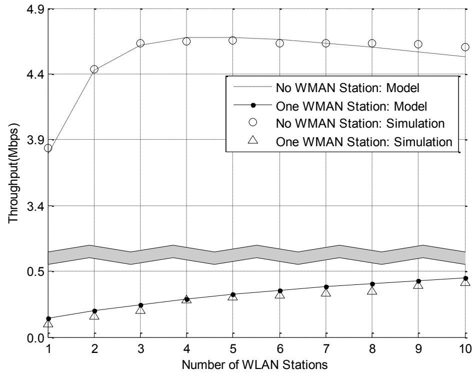


Figure 3. WLAN Throughput in Absence and Presence of WMAN

B. Comparing the Proposed Model with the Conventional Model

This sub-section compares our model with the conventional model proposed in [5] as shown in Figure 4. One WMAN station is present in the vicinity of WLAN with the number of stations varying. Note that our proposed model assumes that WLAN and WMAN run BEB algorithm with the initial size of CW set to 31, whereas the model of Park et. al., [5] sets CW constant 31 for both WLAN and WMAN.

Figure 4 verifies the validity of our proposed model after the results obtained from it is matched with those obtained from the simulation. We see in Figure 4 that conventional model overestimates WLAN throughput in the presence of one WMAN station. The gap between the throughputs obtained from the two models starts decreasing after the number of WLAN stations reaches 5. Unlike the IEEE standards [3][4] that state the use of binary exponential backoff for the contention resolution, [5] uses constant backoff contention window in its proposed model, thereby deviating from the results obtained from the simulation which uses binary exponential backoff. Finally, [5] determines throughput using probabilistic approximations of the transmission attempts of WLAN stations and WMAN stations unlike our proposed approach that is based upon calculating the collision and interference probability.

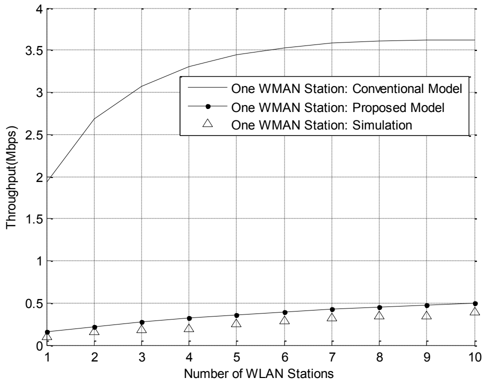


Figure 4. Comparison of Throughput between Proposed and Conventional Model

C. Differentiating the Proposed Model from the Hidden Station Model

We argued earlier that the presence of one or more stations of heterogeneous type affects the performance of WLAN differently than the presence of a hidden station and therefore their affects shall be analyzed using separate models. Figure 5 shows the comparison between the performances of WLAN in the presence of a hidden station [6] to the performance of WLAN when it is collocated with a WMAN station.

There are two points worth noticing. First, WMAN severely affects the performance of WLAN as compared to the effect of a hidden station. Secondly, the model for the performance evaluation of the effect of the hidden station cannot be applied to the situation when WLAN is affected by the presence of WMAN, thereby justifying the extension we made to the hidden station model.

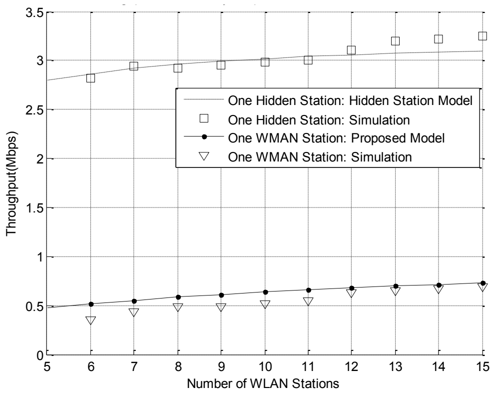


Figure 5. Throughput Difference between Proposed Model and Hidden Station Model

D. Analyzing the Effect of Contention Window of WMAN on the Performance of WLAN

The purpose of this experiment is to observe the ability of our proposed model in assessing the effect of tuning the initial size of CW of WMAN on the performance of WLAN. In addition, this experiment gives us a hint on tuning one of several parameters to improve the performance of WLAN when it is collocated with a network having higher transmission power.

In this experiment we set the total number of WLAN stations 10 with the number of WMAN stations varying from one to two. Figure 6 shows the performance of WLAN when the size of its initial CW is 31 while that of WMAN is varied from 31 to 1023. We see that WLAN throughput is very low when the size of WMAN initial CW is small even when there is only one WMAN station. It shows WMAN with small CW gives less transmission opportunity to WLAN. As WMAN sets the size of initial CW to 63 or further increases its CW, we observe improvement in the performance of WLAN even when there are two WMAN Stations. The throughput of WLAN reaches maximum when the initial size of the CW of WMAN is set to maximum, i.e., 1023. In general, the higher the size of WMAN initial contention window, the better the WLAN performs.

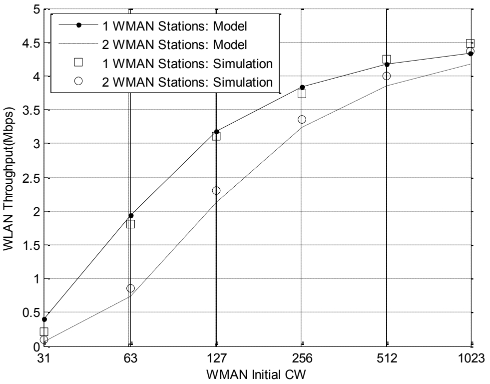


Figure 6. WLAN Throughput as a Function of Contention Window of WMAN

VI. CONCLUSIONS AND FUTURE RESEARCH

Inherent drawbacks of the BEB algorithm coupled with the asymmetric nature of heterogeneous wireless networks are a main cause that degrades the performance of WLAN. This study proposes a performance model that consists of a per-system Markov chain to analyze the effect of superior networks on the collocated victim networks by taking into account both the intra-network and inter-network collisions. Simulation results verify that the proposed model can evaluate the interference effect accurately than a conventional model.

For our future research, we will continue to expand our model to evaluate various variables affecting the degree of interferences such as transmission power, frames size and contention window etc. We will also analyze the affect of already proposed solutions such as NACK with MAC header CRC (Cyclic Redundancy Check) to estimate the performance improvement of the victim network.

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