

University of Wollongong Research Online

Faculty of Informatics - Papers (Archive)

Faculty of Engineering and Information
Sciences

2008

Characterising the interactions between unicast and broadcast in IEEE 802.11 ad hoc networks

Jerry Chun-Ping Wang
University of Wollongong, jerryw@uow.edu.au

D. Franklin
University of Wollongong, danielf@uow.edu.au

Mehran Abolhasan
University of Wollongong, mehran.abolhasan@uts.edu.au

Farzad Safaei
University of Wollongong, farzad@uow.edu.au

Follow this and additional works at: <https://ro.uow.edu.au/infopapers>



Part of the [Physical Sciences and Mathematics Commons](#)

Recommended Citation

Wang, Jerry Chun-Ping; Franklin, D.; Abolhasan, Mehran; and Safaei, Farzad: Characterising the interactions between unicast and broadcast in IEEE 802.11 ad hoc networks 2008, 180-185.
<https://ro.uow.edu.au/infopapers/1407>

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au

Characterising the interactions between unicast and broadcast in IEEE 802.11 ad hoc networks

Abstract

This paper investigates the relative performance of unicast and broadcast traffic traversing a one-hop ad hoc network utilising the 802.11 DCF. An extended Markov model has been developed and validated through computer simulation, which successfully predicts the respective performance of unicast and broadcast in a variety of mixed traffic scenarios. Under heavy network traffic conditions, a significant divergence is seen to develop between the performance of the two traffic classes - in particular, when network becomes saturated, unicast traffic is effectively given higher precedence over broadcast. As a result, the network becomes dominated by unicast frames, leading to poor rates of broadcast frame delivery.

Keywords

Characterising, interactions, between, unicast, broadcast, IEEE, 802, hoc, networks

Disciplines

Physical Sciences and Mathematics

Publication Details

J. Wang, D. R. Franklin, M. Abolhasan & F. Safaei, "Characterising the interactions between unicast and broadcast in IEEE 802.11 ad hoc networks," in Australian Telecommunication Networks and Applications Conference, 2008, pp. 180-185.

Characterising the Interactions Between Unicast and Broadcast in IEEE 802.11 Ad Hoc Networks

Jerry Chun-Ping Wang, Daniel R. Franklin, Mehran Abolhasan, Farzad Safaei
Telecommunication and Information Technology Research Institute
University of Wollongong, Wollongong, Australia
Email: {jcpw942,danielf,mehrana,farzad}@uow.edu.au

Abstract—This paper investigates the relative performance of unicast and broadcast traffic traversing a one-hop ad hoc network utilising the 802.11 DCF. An extended Markov model has been developed and validated through computer simulation, which successfully predicts the respective performance of unicast and broadcast in a variety of mixed traffic scenarios. Under heavy network traffic conditions, a significant divergence is seen to develop between the performance of the two traffic classes - in particular, when network becomes saturated, unicast traffic is effectively given higher precedence over broadcast. As a result, the network becomes dominated by unicast frames, leading to poor rates of broadcast frame delivery.

Index Terms—IEEE 802.11 DCF, Mixed Unicast and Broadcast Performance, Unicast Dominance

I. INTRODUCTION

In an ad hoc network, the stations require both unicast and broadcast transmission for transferring data and critical management information (i.e. neighbourhood discovery and routing) respectively. Although the wireless medium is inherently broadcast in nature, the transmission requirements of unicast and broadcast frames differ in a number of important ways. In particular, the former is destined for a specific recipient whereas the latter targets everyone within the coverage. As a result, the IEEE 802.11 Medium Access Control (MAC) protocol treats two traffic classes rather differently in the protocol specification.

According to the IEEE 802.11 standard [1], unicast traffic adopts a binary exponential backoff mechanism for contention based access, and includes an optional four-way handshaking technique, known as Request-To-Send / Clear-To-Send (RTS/CTS) for channel reservation. By contrast, broadcast traffic is not intended for a single recipient - hence transmissions cannot be acknowledged. Therefore, each broadcast frame exchange simply constitutes a single-frame sequence. Because of this, the 802.11 standard mandates that the backoff window for broadcast traffic is always equal to the initial minimum backoff size (i.e. no binary exponential increase in window size in the event of a collision). Further, there is no option for RTS/CTS handshake for broadcast transmission. Intuitively, broadcast traffic can be said to have a lower service quality than unicast.

This work is partly supported by the Desert Knowledge CRC (DK-CRC) under the joint DK-CRC / University of Wollongong (UoW) project "Sparse Ad hoc Network for Desert (SAND)".

Given the importance of utilizing both unicast and broadcast transmissions throughout an ad hoc network, there is a strong motivation for developing a better understanding of the network performance in presence of both traffic classes. Oliveira *et al.* [2], [3] developed a two-dimensional Markov model which they used to evaluate the performance of network with an arbitrary mix of unicast and broadcast traffic. While their work examines total aggregated performance of the traffic mix, the unicast and traffic transmissions, in general, operate *separately* in different applications and different layers. *i.e.* unicast transmissions are typically used in the data applications, and broadcast transmissions are mostly utilized by the routing protocols. Perhaps, it would be more important to study the performance of the traffic mix on a separate basis.

In this paper, we examine the interactions and relative performance between unicast and broadcast in a one-hop ad hoc network. Specifically, this paper highlights the following merits:

- Building on the model presented in [2], [3], the model is extended and improved by considering the freezing of backoff counter and the non-saturated network load (Section III).
- We verify the accuracy of the model with network simulator and substantiate there exists performance differentiation between unicast and broadcast (Section IV).
- We further explore the interaction between unicast and broadcast in Section V by quantifying the degree of differences over a wide range of traffic loads as well as various mixed traffic scenarios.

Before we evaluate the interactions between unicast and broadcast in detail, the related work is discussed in Section II. Finally, Section VI summarizes the potential impacts of the observations then concludes the paper.

II. RELATED WORK

The Markov chain has been widely recognized as an accurate tool for examining the performance of IEEE 802.11 DCF. In his inspiring paper [4], Bianchi presents a well known two-dimensional discrete-time Markov chain to evaluate the saturation throughput of DCF unicast traffic. Since then, a number of other authors have extended Bianchi's work and further improved the accuracy of the analytical model in several important ways. Wu *et al.* [5] refined Bianchi's model by introducing the retry limits for each station. Ziouva *et al.*

[6], Foh *et al.* [7], and Kim *et al.* [8] improved Bianchi's model by considering backoff counter freeze when the medium become busy. Recently, due to increasing interest in exploring non-saturated behaviour of IEEE 802.11 DCF, various studies have introduced an additional idle state to represents non-transmitting stations [9], [10].

While the past works emphasized on the unicast transmission, Ma and Chen [11] identified that the existing model can not be reduced to a broadcast process as most models assume infinite transmission retry. Hence, they propose one-dimensional Markov chain for broadcast. Oliveira *et al.* further explored DCF saturation throughput [2] and non-saturation delay [3] with mixed unicast and broadcast traffic. This study introduced a new Markov model which combines the unicast model from [5] and the broadcast model from [11]. The model highlights the degradation on total aggregated throughput, however it is not clear whether such degradation is principally due to the unicast or broadcast, or a combination of both. Thus, our model extends the Oliveira's study by further examining the individual behaviour of the unicast and broadcast in the mixed-traffic environment.

III. ANALYTICAL MODEL

The analytical study on an arbitrary mix of unicast and broadcast traffic can be used with the models proposed in [2], [3]. However, the proposed model includes the freezing process from Kim *et al.* [8] to capture the freezing of backoff counters when the channel is sensed busy by a station (depicted by dashed lines in Fig 1), which according to Foh *et al.* [7] is more accurate than the one without the backoff freeze. Further, we adopt the non-saturated process from Xu *et al.* [9] to evaluate the impact of network loads on both unicast and broadcast.

The model assumes a single-hop ad hoc network with n contending stations, with an ideal signal propagation environment, no hidden terminal, and no capture effect. The RTS/CTS access mechanism is switched off. Each station (STA) generates a unicast or broadcast frame according to a uniform probability density function, with probability P_u and $P_b = 1 - P_u$ for unicast and broadcast transmissions respectively. Let CW_{min} and CW_{max} be the minimum and maximum contention window size respectively, and let m be the maximum backoff stage. Each STA uniformly selects a value for the backoff counter over the interval $[0, W_i - 1]$, where

$$W_i = \min(2^i CW_{min}, CW_{max}) \quad i \in [0, m] \quad (1)$$

For a unicast transmission, the size of the contention window in backoff stages grows exponentially upon each transmission failure until it reaches CW_{max} . The contention window then remains at CW_{max} until the packet has either been successfully transmitted or dropped when the maximum backoff stage has been reached. It should be noted that broadcast transmission voluntarily completes at first transmission attempt, therefore the broadcast window size always remains as minimum (ie. CW_{min}). To simplify the analysis, the

model assumes that the maximum window size is reached at maximum backoff stage, i.e. $2^m CW_{min} = CW_{max}$.

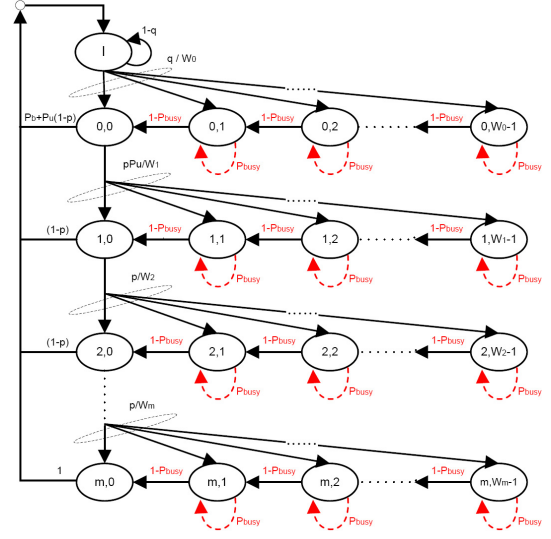


Fig. 1. The state transition diagram for non-saturated mixed traffic Markov model

TABLE I
NOTATIONS USED FOR ANALYTICAL MODEL

Parameters	Explanation
n	Number of Stations
p	Conditional collision probability
P_{busy}	Medium busy probability
q	Packet arrival probability
m	Maximum backoff stage
P_u	Probability of unicast transmission
P_b	Probability of broadcast transmission

Figure 1 shows the state transition diagram used to model the behaviour of a station in a mixed traffic scenario. Table I summarises the notation that will be used in this model. As described by Bianchi [4], we let $b_{i,k}$ ($i \in [0, m]$, $k \in [0, W_i - 1]$) be the stationary distribution of backoff states. We further introduce b_I for the stationary distribution of idle state. Through chain regularity, the following closed-form solutions for the Markov chain can be obtained:

$$b_{i,0} = p^i P_u b_{0,0} \quad (2)$$

$$b_I = \frac{1}{q} b_{0,0} \quad (3)$$

$$b_{0,k} = \frac{W_0 - k}{W_0} \frac{1}{1 - P_{busy}} b_{0,0} \quad k \in [1, W_0 - 1] \quad (4)$$

$$b_{i,k} = \frac{W_i - k}{W_i} \frac{p^i P_u}{1 - P_{busy}} b_{0,0} \quad i \in [1, m], k \in [1, W_i - 1] \quad (5)$$

Imposing the normalised condition results in:

$$b_I + \sum_{k=0}^{W_0-1} b_{0,k} + \sum_{i=1}^m \sum_{k=0}^{W_i-1} b_{i,k} = 1 \quad (6)$$

where the summations can be expanded and represented in form of $b_{0,0}$:

$$\sum_{k=0}^{W_0-1} b_{0,k} = b_{0,0} + \sum_{k=1}^{W_0-1} b_{0,k} = b_{0,0} + \frac{W_0 - 1}{2(1 - P_{busy})} b_{0,0} \quad (7)$$

$$\begin{aligned} \sum_{i=1}^m \sum_{k=0}^{W_i-1} b_{i,k} &= \sum_{i=1}^m b_{i,0} + \sum_{i=1}^m \sum_{k=1}^{W_i-1} b_{i,k} \\ &= P_u b_{0,0} \left[\frac{p - p^{m+1}}{1 - p} + \frac{2p - 2p^{m+1}}{2(1 - P_{busy})(1 - 2p)} W_0 \right. \\ &\quad \left. - \frac{p - p^{m+1}}{2(1 - P_{busy})(1 - p)} \right] \end{aligned} \quad (8)$$

Therefore, the solution for $b_{0,0}$ can be derived with three unknown variables (p, P_{busy}, q):

$$\begin{aligned} b_{0,0} &= \left(\frac{1}{q} + 1 + \frac{W_0 - 1}{2(1 - P_{busy})} + P_u \left[\frac{p - p^{m+1}}{1 - p} W_0 \right. \right. \\ &\quad \left. \left. + \frac{2p - 2p^{m+1}}{2(1 - P_{busy})(1 - 2p)} - \frac{p - p^{m+1}}{2(1 - P_{busy})(1 - p)} \right] \right)^{-1} \end{aligned} \quad (9)$$

Let τ_u and τ_b be the probabilities that a station transmits a unicast or broadcast frame at a given time. A STA is permitted to transmit only when the backoff counter reaches zero, regardless of the type of transmission (unicast or broadcast) and the backoff stage. Therefore, τ_u and τ_b may be defined as:

$$\tau_u = P_u b_{0,0} + \sum_{i=1}^m b_{i,0} = \frac{1 - p^{m+1}}{1 - p} P_u b_{0,0} \quad (10)$$

$$\tau_b = P_b b_{0,0} \quad (11)$$

To evaluate the value of conditional collision probability p , it should be noted that a collision occurs when one station transmits on the channel, and at least one of the remaining $n-1$ stations also transmits on the same channel at same time, regardless of the type of transmission. Similarly, the channel is occupied (busy) when there is at least one STA transmitting during a given slot time. Therefore, the conditional collision probability p and channel busy probability P_{busy} can be expressed as

$$p = 1 - (1 - (\tau_u + \tau_b))^{n-1} \quad (12)$$

$$P_{busy} = 1 - (1 - (\tau_u + \tau_b))^n \quad (13)$$

Let P_{us} , P_{bs} , and P_{ns} be the probability of successful unicast transmission, successful broadcast transmission and no transmission respectively. Since a packet can only be successfully transmitted when there is exactly one station transmitting on the channel, and given the value of τ_u and τ_b , the successful transmission probability P_{us} , P_{bs} , and P_{ns}

can be derived as follows

$$P_{us} = n\tau_u(1 - (\tau_u + \tau_b))^{n-1} \quad (14)$$

$$P_{bs} = n\tau_b(1 - (\tau_u + \tau_b))^{n-1} \quad (15)$$

$$P_{ns} = (1 - (\tau_u + \tau_b))^n \quad (16)$$

Similarly, let P_{uc} and P_{bc} be the collision probability for collisions involving only unicast and only broadcast frame respectively. These may now be defined as

$$P_{uc} = (1 - \tau_b)^n - P_{ns} - P_{us} \quad (17)$$

$$P_{bc} = (1 - \tau_u)^n - P_{ns} - P_{bs} \quad (18)$$

Given the value of P_{uc} and P_{bc} , the probability of collisions involving both unicast and broadcast frames, P_{mc} , can be derived:

$$P_{mc} = 1 - P_{us} - P_{bs} - P_{uc} - P_{bc} - P_{ns} \quad (19)$$

In the Markov state machine, the interval between two consecutive back-off states is represented by a single timeslot period. The timeslot includes either an empty slot, a collision or a successful transmission, and its average length is equal to

$$\begin{aligned} TimeSlot &= P_{ns}\sigma + P_{us}T_{us} + P_{bs}T_{bs} + \\ &\quad P_{uc}T_{uc} + P_{bc}T_{bc} + P_{mc}T_{mc} \end{aligned} \quad (20)$$

where σ represents the duration of an empty slot. T_{us} and T_{uc} are the time required for successful and unsuccessful unicast transmissions respectively, while T_{bs} and T_{bc} are the times required for successful and unsuccessful broadcast transmissions respectively. T_{mc} is the temporal cost of collisions involving both unicast and broadcast.

The packet arrival probability q determines the offered load that a STA can inject into the network. The model assumes the packets arrive in a Poisson arrival process, with an a mean arrival rate of λ . The packet arrival probability q can now be expressed as:

$$q = 1 - \exp^{-\lambda SlotTime} \quad (21)$$

Eq. (10), (11), (12), (13), and (21) form a non-linear system with five unknown variables τ_u , τ_b , p , P_{busy} and q . This system of equations can be solved numerically through non-linear optimisation techniques.

The normalized throughput is defined the ratio of amount of successful unicast/broadcast payload bits transmitted over the average slot time ($SlotTime$). Let $E[PU]$ and $E[PB]$ be the average unicast and broadcast payload size. The normalised throughput for unicast S_u and broadcast S_b becomes

$$S_u = \frac{P_{us}E[PU]}{SlotTime} \quad S_b = \frac{P_{bs}E[PB]}{SlotTime} \quad (22)$$

Finally, it is necessary to determine appropriate values for T_{us} , T_{uc} , T_{bs} , T_{bc} and T_{mc} . Let $H = \text{MAChdr} + \text{PHYhdr}$ be the size of the packet header, H the time taken to deliver the header, and ACK is the size of acknowledgement packet. $DIFS$ and $SIFS$ are the distributed and short inter-frame spacing respectively. Assuming the system has transmission

rate R and the propagation delay σ , the values for T_{us} and T_{uc} are given by:

$$\begin{cases} T_{us} = \frac{H+E[PU]}{R} + SIFS + \sigma + \frac{ACK}{R} + DIFS + \sigma \\ T_{uc} = \frac{H+E[PU]}{R} + SIFS + \sigma \end{cases} \quad (23)$$

Broadcast transmissions consist of a single frame sequence, and no RTS/CTS access method may be used. Therefore, T_{bs} and T_{bc} are defined as:

$$T_{bs} = T_{bc} = \frac{H + E[PB]}{R} + DIFS + \sigma \quad (24)$$

T_{mc} is dependent upon the probability of broadcast and unicast transmissions, as well as T_{uc} and T_{bc} :

$$T_{mc} = P_u T_{uc} + P_b T_{bc} \quad (25)$$

IV. MODEL VALIDATION

To validate the analytical model, a series of simulations have been conducted using a network simulator (Qualnet version 4.0). The simulation environment consisted of $n + 1$ stations randomly distributed across a square, flat region of $100m \times 100m$. Each STA equipped with an IEEE 802.11b radio interface and an omni-directional antenna positioned 1.5 m above the ground. The RF channel is modelled using a simple *Free-Space* propagation model, and the maximum data bit-rate is set at 1 Mbps. In this scenario, each STA has a maximum range of approximately 1400m, thus ensuring that all nodes are within one hop of each other in the simulation environment. Qualnet's *MACDot11* library is used as the MAC protocol. Table II summarises the MAC parameters that are used to obtain analytical and simulation results.

TABLE II
SIMULATION AND ANALYTICAL PARAMETERS

Parameters	Values
Data payload ($E[PU]$, $E[PB]$)	8184 bits
MAC Header	272 bits
PHY Header	128 bits
ACK	112 bits + PHY header
RTS	160 bits + PHY header
CTS	112 bits + PHY header
Channel Bit Rate	1 Mbps
Propagation Delay (δ)	1 μ s
Slot Time (σ)	20 μ s
SIFS	10 μ s
DIFS	50 μ s
Maximum Backoff Stage (m)	5
Minimum Window Size (W_0)	32

Traffic is generated by Qualnet's traffic generator (Traffic-Gen) which transmits frames with a fixed payload size (8184 bits) using a Poisson arrival model with mean arrival rate λ . The traffic generator has been modified to allow broadcast and unicast frames to be generated in accordance to the unicast/broadcast transmission probability P_u/P_b . There are n stations, each acts a source for one UDP unicast flow and one broadcast UDP flow. We also include an additional station to serve as the sink for all unicast and broadcast transmissions. The data representing the simulation results are those collected

from the sink node. Each simulation was run for 300 seconds, and all simulation results shown have been obtained from the average of at least 15 independent runs, with more than 95% of results being within 1% of the average value for all simulation results.

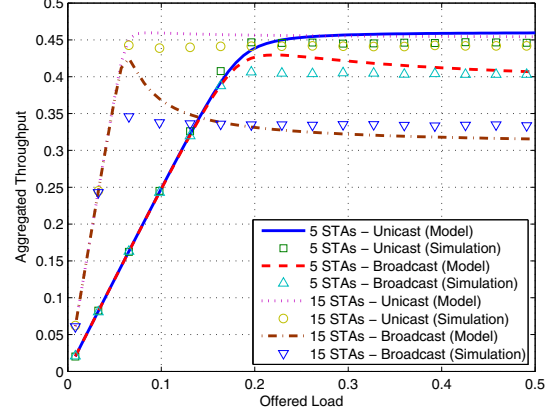


Fig. 2. Model validation with basic access method

Figure 2 shows the results obtained from both analytical model and simulation. The scenario in the simulations/analyses consists of a network of 5 and 15 stations, in which the probability of generating unicast and broadcast frames is equal. Figure 2 evaluates the throughput performance with the basic access mechanism enabled, the figure shows that the analytical results closely match with simulation results over a wide range of traffic load levels. Therefore, the proposed analytical model is accurate in modelling IEEE 802.11 DCF with mixed unicast and broadcast traffic. Both analytical and simulation results have proven that the unicast outperforms the broadcast in the mixed traffic environment. The performance of broadcast drops as number of station increases whereas the unicast performance remains less affected. This highlights an important fact that the throughput degradation is principally due to the loss of broadcast packets rather than the unicast packets.

V. TRANSMISSION ANALYSIS

The Markov model presented in Section III provides a convenient analytical tool to evaluate the successful transmission probability of unicast and broadcast traffic in a mixed traffic scenario. The transmission success probability for each traffic class is defined as the number of successful unicast or broadcast transmissions divided by the corresponding number of transmission attempts. Based on the Markov model, the transmission success probability for unicast traffic TSP_u and broadcast traffic TSP_b are given by:

$$TSP_u = \frac{P_{us}}{1 - P_{ns} - P_{bs} - P_{bc}} \quad (26)$$

$$TSP_b = \frac{P_{bs}}{1 - P_{ns} - P_{us} - P_{uc}} \quad (27)$$

A. Non-Saturation Condition

In this section, three different scenarios have been modelled, illustrating the transmission success probability under non-saturated broadcast-dominated, balanced (equal broadcast-unicast load) and unicast-dominated scenarios. The model follows the parameters in Table II, and employs basic access mechanism for unicast transmission. Unless otherwise specified, the solid lines in the figures represent unicast transmission while the dashed lines represent broadcast transmission.

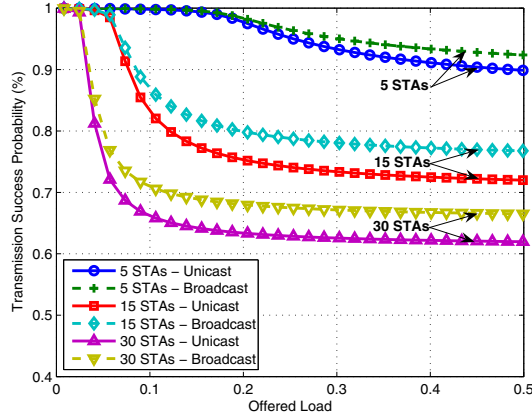


Fig. 3. Transmission success probability in broadcast-dominated scenario

Figure 3 shows the transmission success probability in a broadcast-dominated scenario with a unicast/broadcast ratio of 1:3 ($P_u = 0.25$, $P_b = 0.75$). From Figure 3, it can be seen that both unicast and broadcast traffic will have similar transmission success probability when the offered load is low. As the offered load increases, both traffic classes experience a significant reduction in the transmission success probability. The reduction is more significant when the number of contending stations is higher. Once the network become saturated, there is a clear difference in transmission success probability between unicast and broadcast frames.

Due to the fixed broadcast backoff window and the higher probability of broadcast transmissions, the majority of backoff windows fall within the range of $[0, CW_{min}]$. The dominance of broadcast traffic within CW_{min} results in a high probability that unicast transmission will collide with broadcast transmissions. Although the unicast traffic can exponentially increase its contention window size, once the contention window countdown reaches CW_{min} , unicast traffic still experiences a higher probability of collision. As a result, broadcast maintains higher transmission success probability than unicast traffic in a broadcast-dominated scenario.

Figure 4 compares transmission success probability of broadcast and unicast where the traffic load is equally divided between the broadcast and unicast. In this scenario, it is clear that the difference in transmission success probability between the two traffic classes becomes greater as the number of contending stations increases. In comparison to the broadcast-dominated scenario in Figure 4, it can be seen that broadcast

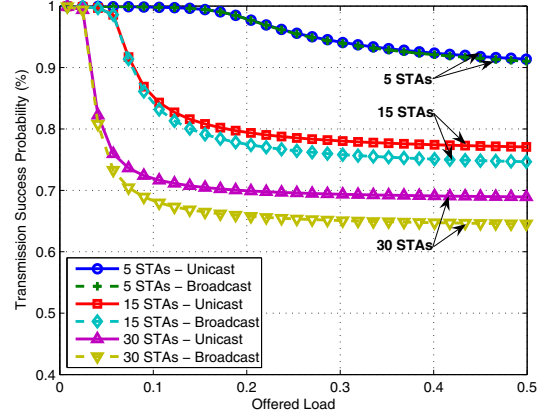


Fig. 4. Transmission success probability in balanced scenario

performance is not significantly different to the previous case. However, unicast packets have a significantly higher probability of successful transmission. This result highlights the fact that the broadcast contention resolution scheme (i.e., with a fixed contention window) copes poorly with contention in comparison with the exponential backoff scheme employed by unicast traffic. Therefore, when the network becomes saturated, unicast traffic has higher transmission success probability than broadcast.

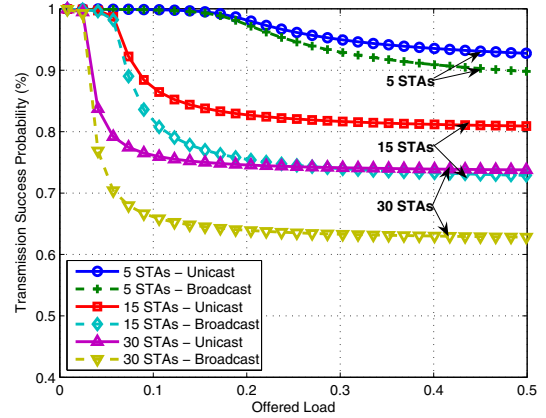


Fig. 5. Transmission success probability in unicast-dominated scenario

Figure 5 shows transmission success probability for unicast and broadcast traffic in a unicast-dominated scenario, where the ratio between unicast and broadcast traffic is 3:1 ($P_u = 0.75$, $P_b = 0.25$). As unicast transmissions dominate, under high levels of contention, the average unicast contention window becomes larger due to the increased need for binary exponential backoff. On the other hand, broadcast remains within the minimum contention window, it has comparatively less opportunity for successful transmission. Hence, unicast traffic has a much higher transmission success probability than broadcast as the contention level increases.

In summary, it is observed that the transmission success

probability of broadcast frames is relatively unaffected by the traffic mix; however for unicast traffic, the probability of successful transmission is higher when the proportion of unicast traffic is higher.

B. Saturation Condition

From the previous section, it is clear that the divergence between unicast and broadcast becomes more significant under the saturated condition. To further investigate the differences between both traffic classes with various unicast and broadcast transmission probabilities, we determine the amount of broadcast traffic needed in order to match the performance of the unicast. Let $q \rightarrow 1$, such that there will be always a packet ready to send upon completion of any network transmission. Given that the broadcast and the unicast can only be equivalent when $\tau_b = \tau_u$. Hence, assuming P_u and P_b are unknown variables, by combining the Eq. (10), (11), (12), (13) along with condition $q \rightarrow 1$, $\tau_b = \tau_u$ and $P_u + P_b = 1$, we can obtain the solution for P_u and P_b through non-linear optimization.

TABLE III
APPROXIMATED INTERSECTING VALUE OF P_u AND P_b

n	10	20	30	40	50
P_u	42.36%	38.56%	36.24%	34.58%	33.30%
P_b	57.64%	61.44%	63.76%	65.42%	66.70%

Table III shows the approximated portion of unicast (P_u) and broadcast (P_b) transmissions in which both traffic classes achieve same transmission success probability. From the table, the stations require to transmit more broadcast data as the number of stations increases in order to match the performance of unicast transmission. This indicates the network capacity is not fairly divided between unicast and broadcast. When network becomes saturated and the network experiences higher contention, unicast is taking much higher precedence over broadcast in the mixed traffic scenario.

VI. CONCLUSIONS

In this paper, we extended the model presented by Oliveira *et al.* [2], [3] to quantitatively evaluate the relative performance of unicast and broadcast traffic in various mixed-traffic scenarios. Analytical and simulation results suggest that the binary exponential backoff mechanism employed by unicast is responsible for a large part of such performance differences, with the result that under heavy network load, unicast traffic is effectively given higher precedence than its broadcast counterpart.

Based on the analytical model, the binary exponential backoff is shown to be very effective in managing network contention. However, it appears the benefits of the binary exponential backoff will only be enjoyed by unicast traffic; broadcast traffic suffers in comparison. Thus for a given traffic load, the probability of successful packet delivery is significantly higher for unicast traffic than for broadcast traffic - particularly as traffic load increases.

The differential performance of unicast and broadcast traffic under heavy load conditions effectively results in an unfair

division of available capacity. This is particularly significant in a multi-hop ad-hoc or mesh network, since critical network management information (such as routing table updates) is sent via the broadcast mechanism. In a network in which the topology is variable (for example, where some nodes are mobile or operating intermittently) and/or a proactive routing protocol (such as OLSR) is used, any degradation in throughput for such traffic will have a detrimental effect on network routing stability - which may seriously degrade multi-hop unicast throughput.

In conclusion, the current IEEE 802.11 DCF specification does not provide sufficient broadcast supports for ad hoc networks, and may need to be augmented to improve the reliability of broadcast traffic. As for the future works, we intend to consider the possible solutions which include the introduction of a priority-based backoff mechanism, such as the IEEE 802.11e Enhanced Distributed Coordination Function (EDCF) or an adaptive broadcast backoff scheme. For situations where broadcast traffic must be delivered with maximum reliability, we may consider to provide a separate radio channel for broadcast traffic (such as routing information) which will result in much higher network stability as shown in [12].

REFERENCES

- [1] IEEE, *IEEE Std. 802.11-2007, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications*, IEEE std. 802.11-2007 ed., 2007.
- [2] R. Oliveira, L. Bernardo, and P. Pinto, "Performance analysis of the IEEE 802.11 distributed coordination function with unicast and broadcast traffic," in *Proceedings of IEEE PIMRC 2006*, September 2006, pp. 1-5.
- [3] —, "Modelling delay on IEEE 802.11 MAC protocol for unicast and broadcast nonsaturated traffic," in *IEEE WCNC 2007*, March 2007, pp. 463-467.
- [4] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, pp. 535-547, March 2000.
- [5] H. Wu, Y. Peng, K. Long, S. Cheng, and J. Ma, "Performance of reliable transport protocol over IEEE 802.11 wireless LAN: analysis and enhancement," in *Proceedings of IEEE INFOCOM 2002*, vol. 2, 2002, pp. 599-607.
- [6] E. Ziouva and T. Antonakopoulos, "CSMA/CA performance under high traffic conditions: throughput and delay analysis," *Computer Communications*, vol. 25, no. 3, pp. 313-321, February 2002.
- [7] C. H. Foh and J. W. Tantra, "Comments on IEEE 802.11 saturation throughput analysis with freezing of backoff counters," *IEEE Communications Letters*, vol. 9, no. 2, pp. 130-132, February 2005.
- [8] S. J. Kim, H. Y. Hwang, J. K. Kwon, and D. K. Sung, "Saturation performance analysis of IEEE 802.11 WLAN under the assumption of no consecutive transmissions," *IEICE Transactions on Communications*, vol. E90-B, no. 3, pp. 700-703, March 2007.
- [9] C. Xu and Z. Yang, "Non-saturated throughput analysis of IEEE 802.11 ad hoc networks," *IEICE Transactions on Information and Systems*, vol. E89-D, no. 5, pp. 1676-1678, May 2006.
- [10] D. Malone, K. Duffy, and D. Leith, "Modeling the 802.11 distributed coordination function in nonsaturated heterogeneous conditions," *IEEE/ACM Transactions on Networking*, vol. 15, no. 1, pp. 159-172, 2007.
- [11] X. Ma and X. Chen, "Saturation performance of IEEE 802.11 broadcast networks," *IEEE Communications Letters*, vol. 11, no. 8, pp. 686-688, 2007.
- [12] J. C.-P. Wang, M. Abolhasan, D. R. Franklin, F. Safaei, and J. Lipman, "On separating route control and data flows in multi-radio multi-hop ad hoc network," in *Proceedings of IEEE ICON 2007*, November 2007, pp. 19-24.