Supporting Throughput Fairness in IEEE 802.11ac Dynamic Bandwidth Channel Access: A Hybrid Approach

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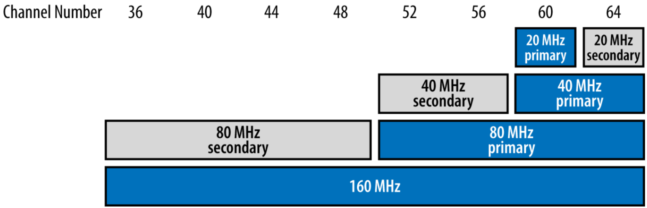
Objective

To develop a hybrid adaptive resource reservation mechanism for supporting fair channel access in IEEE 802.11ac dynamic bandwidth channel access

Preface – Channel Bonding in IEEE 802.11ac

- High throughput wireless access networks like IEEE 802.11ac supports advanced channel bonding feature
- Channel bonding combines multiple 20 MHz channels to construct wider channels like 40 MHz, 80 MHz or 160 MHz
- A station acquires a 20, 40 or 80 MHz channel as the **primary channel**
- In the consecutive space, another extension of the same channel width is considered as the **secondary channel**



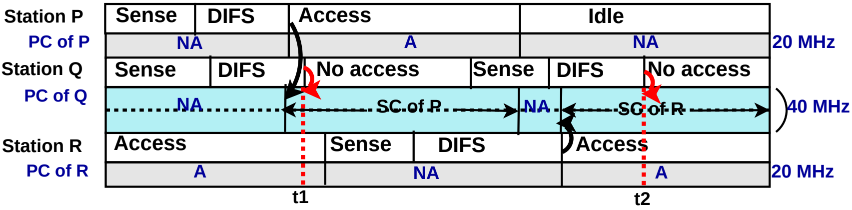
Dynamic Bandwidth Channel Access

- **Dynamic Bandwidth Channel Access (DBCA):** Extends the primary channel for data transmission, if other secondary channels are free during the time of communication
- DBCA is an extension of IEEE 802.11 Distributed Coordination Function (DCF) to handle both primary and secondary channels

Dynamic Bandwidth Channel Access

- After getting the access to the primary channel, the station attempts for a transmission after waiting for a time interval – Distributed Inter-Frame Spacing (DIFS)
- If the secondary channel is free, the station transmits data in both the primary and the secondary channels
- If the secondary channel is sensed as busy, it initiates transmission only at the primary channel
- A station follows an instantaneous access to the secondary channel based on its availability at the time of access of the primary channel

DBCA – Performance Impact on a Dense Network



PC - Primary channel
SC - Secondary channel

A - Acquired
NA - Not Acquired

- **Primary channels for one station may also be used as secondary channels which are acquired by some other stations at that time**
- The opportunistic nature of access of secondary channels blocks primary channels of some stations

Solution for this Problem – HA-DBCA

- Design an adaptive resource reservation mechanism for supporting fair channel access in DBCA – **Hybrid Adaptive DBCA (HA-DBCA)**
- HA-DBCA is a polling based online learning mechanism that avoids starvation of primary channel users

Motivation: How Does DBCA Impact Short Term Fairness?

- We show that DBCA results in severe unfairness in channel access, as we increase secondary channel users in the network
- The analysis has been done over a IEEE 802.11ac testbed developed at the department of CSE, IIT Kharagpur
- 1 IEEE 802.11ac supported wireless routers, and 25 IEEE 802.11ac wireless stations to setup the testbed
- ASUS RT3200-AC routers which use Broadcom BCM43602 IEEE 802.11ac chipset to transmit data at 5 GHz channel
- Open source `asus-wrt merlin` firmware along with `brcmfmac` driver
- The firmware release rt-7.14 has been used with Linux kernel version 2.6

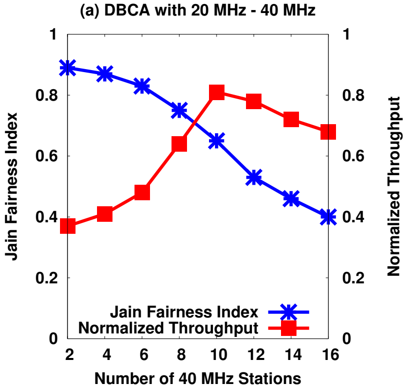
Motivation: How Does DBCA Impact Short Term Fairness?

- We have added a driver hook in router to switch on and switch off DBCA mode in the `brcmfmac` source that follows `cfg80211` driver framework for IEEE 802.11
- At the client side, we use ASUS USB-AC56 IEEE 802.11ac dongle that uses Realtek RTL8812AU chipset to support IEEE 802.11ac in station mode
- Open source `rtl8812au` driver for configuring the chipset in wireless station mode
- Experiments in two modes – (a) $20 - 40$ mode, where 10 wireless stations use 20 MHz primary channel for communication
- Then we increase the 40 MHz stations (20 MHz primary, 20 MHz secondary) to check the impact of secondary channel access

Motivation: How Does DBCA Impact Short Term Fairness?

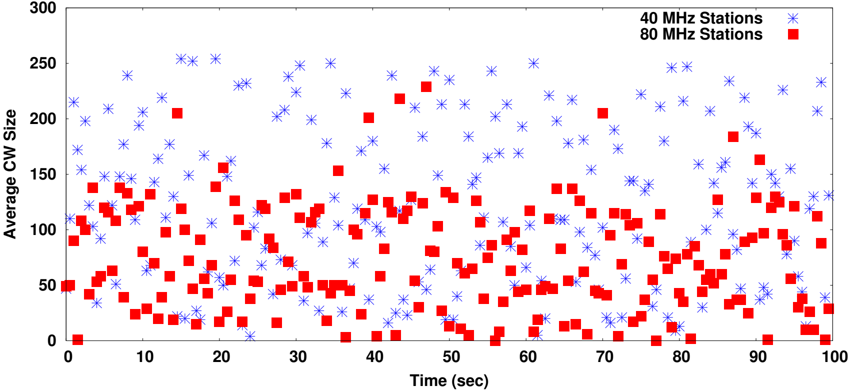
- (b) 40 – 80 mode, where 10 wireless stations use 40 MHz primary channel for communication
- Then we increase the number of 80 MHz stations (40 MHz primary and 40 MHz secondary bandwidth) to analyze the impact of secondary channel
- Linux tool `iperf` to generate traffic at the wireless stations
- We keep the stations at fixed position so that mobility does not impact performance
- Constant bit-rate traffic (CBR) at a rate of 5 Mbps at every station, so that the application traffic remains saturate
- We measure the performance at the MAC layer

Motivation: How Does DBCA Impact Short Term Fairness?



Impact of Secondary Channel Access over Network Fairness and Normalized Throughput

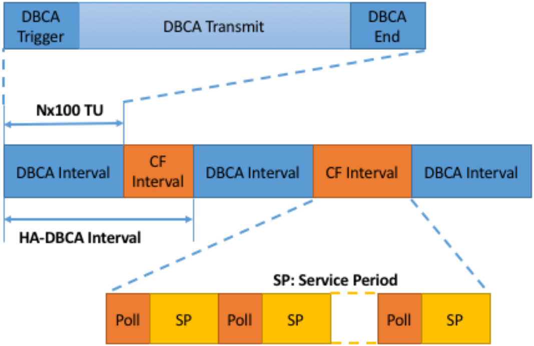
Motivation: How Does DBCA Impact Short Term Fairness?



CW Evolution for 40 MHz and 80 MHz Stations ($N_{40} = 10$ and $N_{80} = 10$)

HA-DBCA: Frame Structure

- Divide the time into periodic HA-DBCA intervals, where every HA-DBCA interval has two sub-intervals – **DBCA interval** and **contention free (CF) interval**
- DBCA interval has two components – DBCA trigger and DBCA transmit.



HA-DBCA: Frame Structure

- During DBCA trigger, AP broadcasts a *DBCA Initiation Packet* (DIP) that indicates the start of a DBCA interval
- Once the stations receive the DIP packet, they starts accessing the channel based on DBCA
- At the end of DBCA interval, the AP again broadcasts a *DBCA End Packet* (DEP). Then the stations stop transmitting data using DBCA
- On receiving the DEP, a station applies an online learning based estimation mechanism to compute whether it is in starvation

Detection of Stations under Starvation

- A station may not transmit data either because (i) it does not have sufficient data to transmit, or (ii) it is not able to get access to the channel due to channel blockage by the secondary channel users
- Therefore, the AP cannot detect independently whether a station has starved or not
- Station can not decide independently whether it is starved because of the uneven access of the channel or network saturation due to high traffic load
- Need to develop a methodology based on coordination between the AP and wireless stations
- Develop an online learning, **Multi Armed Bandit (MAB)**, based estimation mechanism to identify whether a station is under starvation

Upper Confidence Bound (UCB)

- Incorporate **Upper Confidence Bound (UCB)** model of MAB in the contention-free slots
- To select stations which can transmit their data during the contention free access and reset their contention window to break the starvation
- The index is the summation of two terms – (i) the present average reward and (ii) confidence interval for the average reward
- **UCB algorithm:** At each time step, for each arm j, calculate confidence bound, $conf_j = \sqrt{\frac{2 \ln n}{n_j}}$, where n_j denotes the number of times arm j has been selected and played so far and n is the total number of plays. Choose the arm that maximizes $\hat{\mu}_j + conf_j$, where $\hat{\mu}_j$ is the average reward of arm j

Starvation Resilience using UCB

- An arm represent a station which is contending for accessing the channel
- For station j, let n denote the total number of attempts taken by it to access the channel. Let j have accessed the channel n_j number of times
- Following UCB, the confidence bound is $conf_j = \sqrt{\frac{2 \ln n}{n_j}}$
- If μ_j specifies Head-of-Line (HOL) delay for j, we define α as the *confidence factor* and $\alpha_j = \mu_j + conf_j$
- Let $\mathcal{T}$ denote the probability of transmission and it is defined as

$$\mathcal{T} = (1 - \frac{1}{\alpha}) \times \text{access channel} + \frac{1}{\alpha} \times \text{not access channel} \quad (1)$$

Starvation Resilience using UCB

- At the end of DBCA period, all the stations calculate their confidence factors
- After that, each station computes its probability of data transmission by applying Eq. (1)
- It can be observed that the probability of accessing channel increases as α gets high
- For any station j, as it enters into starvation, $(n - n_j)$ increases. Consequently, $conf_j$ is also increased
- μ_j also grows up in this situation. As a result, $\mathcal{T}$ increases.
- Hence, the stations which are in starvation get higher opportunities to acquire the channel in the contention-free period

Theoretical Modeling of HA-DBCA

- HA-DBCA interval (HDI) (T_{HDI}) is variable depending on the number of IEEE 802.11ac stations getting starved in the DBCA interval
- Consider N numbers of IEEE 802.11ac stations that are attached to an IEEE 802.11ac AP
- Assume that the data packets are of fixed length L (measured in terms of seconds based on the data rate of the corresponding channel bonding level used by the station)
- Data are generated at each station following a Poisson process with mean arrival rate λ
- Assume that the stations have serial IDs from 1 to N. Let the CF period be divided into N number of Poll intervals of length L_p
- Assume that the SP durations are multiple of L for a given station, and we consider it to be L_m.

Delay Experienced in the HA-DBCA Where the Target Packet is Transmitted at the CF Interval

- A CF interval has the length $N \times L_p + M \times L_m$, where M is the number of starved stations in the DBCA interval
- Let $\mathcal{J}$ denote the number of stations having reservation other than the N^{th} station in the CF interval in which the target packet is being transmitted
- There are $N - 1$ number of stations that get an opportunity to transmit before the N^{th} station
- $\mathcal{J}$ follows a binomial distribution with parameters $N - 1$ and ρ, where ρ denotes the probability of a station having reservation in the CF interval

Delay Experienced in the HA-DBCA Where the Target Packet is Transmitted at the CF Interval

- The probability mass function of $\mathcal{J}$ is

$$P\{\mathcal{J} = j\} = \binom{N-1}{j} \rho^j (1-\rho)^{N-1-j} \tag{2}$$

- The expected value of $\mathcal{J}$, $E[\mathcal{J}]$ is $E[j] = (N-1)\rho$
- The amount of delay that the target packet experiences in the CF interval can be given as $D_F = B + N \times L_p + j \times L_m$
- B is the duration of the DBCA interval, $N \times L_p$ is the total duration of the poll intervals in the CF interval
- Averaging over j, the expected delay $E[D_F]$ is

$$E[D_F] = B + N \times L_p + (N-1) \times \rho \times L_m \tag{3}$$

M/G/1 Model for Computing the Value of ρ

- Define a queuing system (M/G/1 queue) that models the behavior of a packet in HA-DBCA
- A packet can be scheduled only when the station can get access to the channel, either in the DBCA interval, or in the CF interval
- The average service time ($E[s]$) for that packet can be given as

$$E(s) = (L_T + 2L_T + ... + NL_T)/N = L_T(N+1)/2 \tag{4}$$

where $L_T = L_p + L_m$. Based on this, we can compute ρ as

$$\rho = E(s) \times \lambda = (L_T(N+1)\lambda)/2 \tag{5}$$

Effect of Heterogeneous Data Arrival Rates at the Wireless Stations

- Let the arrivals of packets at the i^{th} station follow Poisson distribution with rate λ_i
- Using the M/G/1 queuing model for each station, the utilization factor for the i^{th} station (ρ_i) is $\rho_i = (L_T(N+1)\lambda_i)/2$
- Let S_k denote the set of stations (apart from the N^{th} station) having reservation in the current CF interval, and S'_k denote the complement of the above set
- Let $|S_k| = \beta$ be the number of stations having SP allocation in the CF interval before the N^{th} node
- The expected delay in the CF interval in which the target packet is transmitted is

$$E[D_F] = B + NL_p + E[j]L_m \tag{6}$$

Effect of Heterogeneous Data Arrival Rates at the Wireless Stations

- Let $E[\beta]$ be the expected number of stations that use a SP in the CF interval to transmit data
- ρ_i is the probability that the station i has a packet to transmit at the CF interval
- Let $\mathcal{E}$ be the event that a station j transmits before the N^{th} node

$$P[\mathcal{E}] = \sum_{|S_k|=0}^{N-1} \sum_{k=1}^{\binom{N-1}{|S_k|}} \prod_{r \in S_k} \rho_r \prod_{r \in S'_k} (1 - \rho_r) \qquad (7)$$

- The average of β is $E[\beta] = \sum_{i=1}^{N-1} \rho_i$
- Therefore, the delay in the last CF interval for the heterogeneous traffic arrival is $E[D_F] = B + NL_p + \left(\sum_{i=1}^{N-1} \rho_i\right) L_m$

Effect of Random Ordering of SP Allocation

- The probability of r nodes (not including the target node) having SP allocated in the CF interval, denoted by an event $\mathcal{Z}_r$, is

$$P[\mathcal{Z}_r] = \binom{N-1}{r}\rho^r(1-\rho)^{N-1-r}; \quad \forall r \in [0, N-1] \tag{8}$$

- The target packet can occupy any slot out of the $r+1$ SP slots uniformly with a probability $\frac{1}{r+1}$.
- Thus, the probability of target packet being at i^{th} position is

$$P[\mathcal{P}_i] = \binom{N-1}{r}\rho^{r+1}\rho^{N-1-r}.\frac{1}{r+1}; \qquad \forall i \in [1, r+1], \forall r \in [0, N-1] \tag{9}$$

- Therefore, $E[\mathcal{P}_i] = \frac{r+2}{2}\binom{N-1}{r}\rho^r(1-\rho)^{N-1-r}$

Effect of Random Ordering of SP Allocation

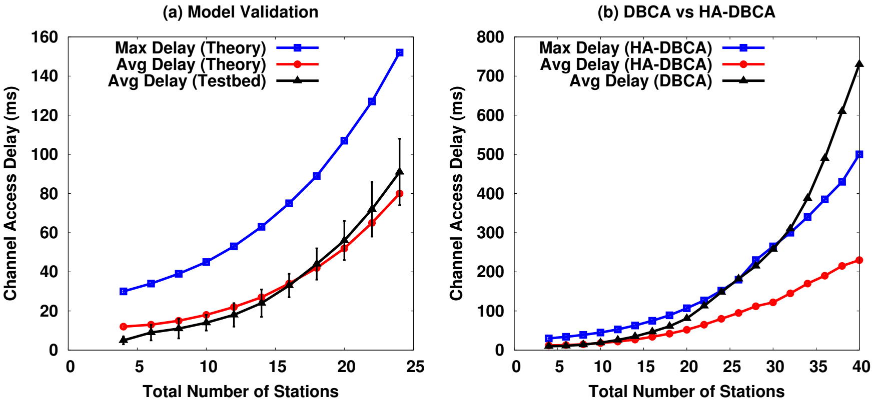
- Similarly,

$$E[\mathcal{Z}_r] = \frac{\rho^2(N-1)}{2}[(N-2)\rho + 3] \tag{10}$$

- The delay in the last CF interval ($E[D_F]$) is

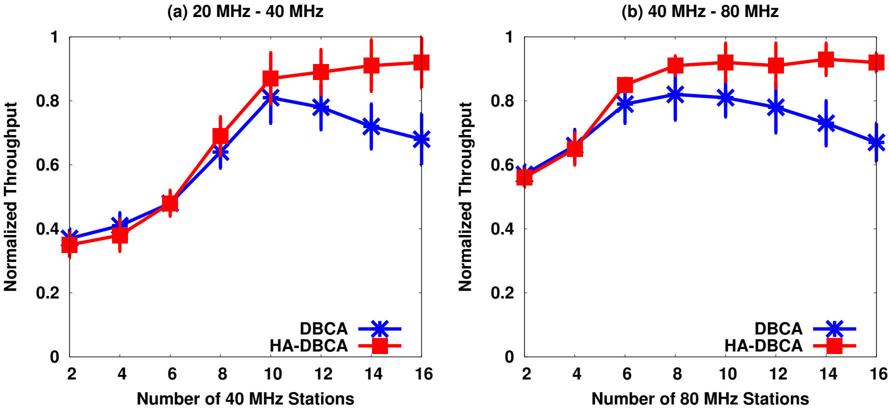
$$E[D_F] = B + NL_p + \frac{\rho^2(N-1)}{2}[(N-2)\rho + 3]L_m \tag{11}$$

Numerical Analysis

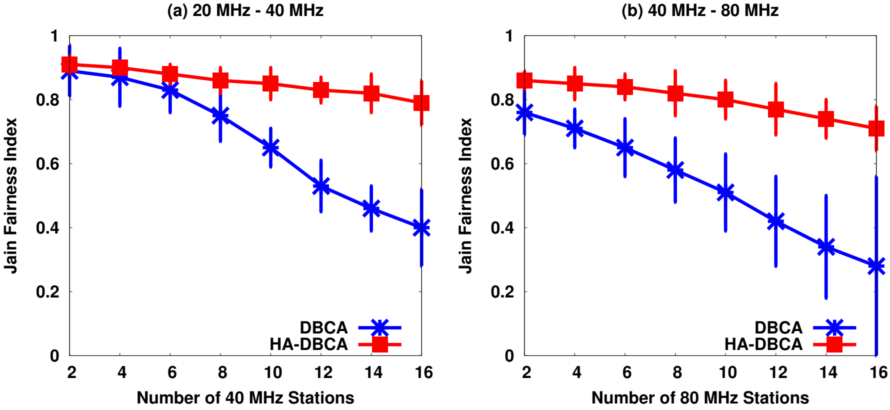


- We observe that the average channel access delay from the theory and from the experiment follows similar trend, which validates the proposed model

Performance Evaluation from Testbed: Normalized Throughput



Performance Evaluation from Testbed: Fairness Index



Conclusion and Future Direction

- Address the issue of unfairness in IEEE 802.11ac DBCA, and design a hybrid adaptive resource reservation mechanism, **HA-DBCA**
- HA-DBCA utilizes contention based resource reservation for implementing DBCA
- Additionally, a polling based **online learning mechanism**, UCB, to avoid starvation of primary channel users
- We have developed a theoretical model, as well as implemented HA-DBCA in IEEE 802.11ac testbed
- Testbed results show that HA-DBCA provides a significant better performance compared to DBCA along with fairness
- *Future work* – thorough investigation of HA-DBCA under dense WiFi scenarios in the presence of legacy wireless technologies

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