Delay and Throughput Analysis of Prioritized EDCA in Latency-Sensitive Wi-Fi 8 Networks

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***Abstract*—Wi-Fi 8 introduces Prioritized EDCA (P-EDCA) to support latency-critical traffic within which DS-RTS/CTS operates as a two-phase channel access procedure. In this mechanism, stations first compete in a Defer Signal (DS) contention, which determines the number of stations entering RTS/CTS contention, creating a stochastic coupling not captured by existing IEEE 802.11 models. We develop an analytical framework for the performance analysis of DS-RTS/CTS using a 2-D Markov chain to model the RTS backoff process of a tagged station under a variable number of contenders. Using this model, we obtain expressions for head-of-line delay and normalized throughput. We further formulate an optimization problem for adaptive selection of the DS contention window size. Results show that a moderately sized DS contention window achieves a favorable throughput-delay trade-off across network densities.**

***Index Terms*—IEEE 802.11bn, Markov models, Quality of Service, performance analysis**

I. Introduction

Latency-critical applications such as extended reality (XR), industrial control, and immersive communications impose stringent delay and reliability requirements on WLANs. The IEEE 802.11bn (Wi-Fi 8) standard, dubbed Ultra High Reliability (UHR), targets low-latency in dense deployments [1]–[3]. Its predecessors, IEEE 802.11ax (Wi-Fi 6) and 802.11be (Wi-Fi 7), retain the classical Enhanced Distributed Channel Access (EDCA) mechanism. In these networks, increased high-priority traffic load, of voice access category (AC_VO), leads to frequent collisions, increased head-of-line (HOL) delay, and unpredictable channel-access characteristics [4].

To address this, Wi-Fi 8 introduces High Priority EDCA (HiP EDCA), to reduce long-tail latency for delay sensitive traffic [2]. Within HiP EDCA, a station that has experienced repeated AC_VO transmission failures switches to Prioritized EDCA (P-EDCA) mode. Specifically, once a station's short retry count for the voice access category, QSRC[AC_VO], reaches the retry threshold R_{th}, the station switches from standard EDCA to a structured two-phase access procedure [4]. In this P-EDCA mode, the station first broadcasts a Defer Signal (DS) frame during a DS contention phase to establish priority among competing stations, and the subset of DS-winning stations then proceeds to an RTS/CTS reservation phase to secure the channel. By restricting RTS contention to a self-selected subset of stations, the DS-RTS/CTS mechanism aims to mitigate collisions and ensure bounded access delay, complementing other Wi-Fi 8 features such as coordinated spatial reuse [5] and non-primary channel access [6], [7].

Given the latency guarantees of the DS-RTS/CTS mechanism, a detailed performance study is in order. From an analytical standpoint, existing models for IEEE 802.11 MAC, such as [8]–[10], which consider a deterministic set of contenders in the backoff process are rendered inapplicable here. The reason being that the set of stations contending in RTS phase is random, and is governed by the DS contention outcome; a coupling that existing models do not capture. This necessitates a model that accounts for this stochastic interaction, and analysis that characterizes the delay-throughput trade-off and also facilitates an optimal choice of critical P-EDCA parameters.

In this paper, we develop an analytical framework to study the performance of the DS-RTS/CTS mechanism under P-EDCA. Using an appropriate Markov chain model for the RTS backoff process under a random number of contenders, we derive analytical expressions for HOL delay and normalized throughput. We illustrate the use of the framework to select the optimal DS contention window size for given network density and QoS requirements, and propose algorithms for the same.

II. Preliminaries

We consider a single-hop WLAN with n stations, among which $n_p \leq n$ stations have reached the AC_VO retry threshold, and enter the DS contention phase. In this phase, each DS-eligible station $l \leq n_p$ uniformly selects a backoff counter $M_l \sim \mathcal{U}\{0, 1, \ldots, W_{ds}-1\}$. The stations are assumed to be statistically identical and independent. All stations that choose the backoff counter $M = \min_{l \leq n_p}\{M_l\}$ transmit a DS frame and proceed to the RTS contention phase and compete for channel access using the 802.11 RTS/CTS mechanism.

In the RTS contention phase, each DS-winning station performs a backoff procedure with retry stages $i \in \{0, \ldots, R_p\}$, where R_p denotes the RTS retry limit. At retry stage i, the station selects a backoff counter as $\mathcal{U}\{0, \ldots, W_i-1\}$ where W_i is the size of the contention window. If an RTS frame collides, i is incremented until either a successful RTS/CTS exchange occurs or $i = R_p$. All stations are assumed to be saturated. Following the decoupling approximation, each station experiences a constant and independent collision probability [8].

Under the DS-RTS/CTS mechanism, contenders in the RTS phase are determined by the DS contention outcome, which depends on the size of the DS contention window W_{ds}. This creates a stochastic coupling, with W_{ds} influencing the contention process and the channel access delay. This central aspect of the DS-RTS/CTS mechanism guides our study.

III. DS Contention Analysis

Among the DS-eligible stations, denote an arbitrarily chosen station as a tagged STA. Suppose that the tagged STA chooses a backoff counter $m \in \{0, 1, \cdots, W_{ds} - 1\}$, it wins DS contention when the rest $n_p - 1$ stations choose a backoff counter $\geq m$. Therefore, the probability that the tagged STA transmits a DS frame in a given slot is

$$P_{tagDS} = \sum_{m=0}^{W_{ds}-1} \frac{1}{W_{ds}} \left(\frac{W_{ds} - m}{W_{ds}} \right)^{n_p - 1}. \tag{1}$$

Of the DS-eligible stations, denote those that win the DS contention by choosing the same given backoff counter m as the DS-winning STAs. Suppose that there are r DS-winning STAs. For this event to occur, the following events must occur: (i) the tagged STA picks m, (ii) exactly $r-1$ of the remaining $n_p - 1$ stations pick m, and (iii) the other $n_p - r$ stations pick a backoff counter greater than m. This probability is given by

$$P_{tag\ m}^{win(r)} = \frac{1}{W_{ds}} \binom{n_p - 1}{r - 1} \left(\frac{1}{W_{ds}} \right)^{r-1} \left(\frac{W_{ds} - m - 1}{W_{ds}} \right)^{n_p - r} \tag{2}$$

Using (1) and (2), we obtain the probability that exactly r stations transmit DS in a given time slot

$$P_{tag}^{exact}(r) = P_{tagDS}^{-1} \sum_{m=0}^{W_{ds}-1} P_{tag\ m}^{win(r)}. \tag{3}$$

IV. RTS Contention Model and Analysis

We model the RTS contention using a two-dimensional Markov chain, similar to the classical model [8]. We then leverage the model to derive the probability that a DS-winning STA attempts to transmit an RTS in a given time slot.

Let the ordered pair (i, k), where $i \in \{0, 1, \dots\}$ represents the retry stage and $k \in \{0, 1, \dots, W_i - 1\}$ represents the backoff counter, denote the state of the Markov chain. Note that in this analytical model the set of retry stages is unbounded, *i.e.*, we may have $i \to \infty$. This allows us to derive steady-state probabilities without imposing a retry limit. However, for numerical evaluation and simulation, we truncate the retry process at a finite stage R_p. In this implementation, the state $i = R_p$ represents all higher retry stages, *i.e.*, once this stage is reached, the process remains in R_p until a successful transmission occurs. The Markov chain model is presented in Fig. 1. The state transitions are governed by P_{idle} which is the probability that an RTS slot is idle, and p_r which represents the RTS reservation-failure probability. The derivation of P_{idle} is deferred until later, while we derive p_r below.

In the RTS phase, a station sends an RTS when its backoff counter is 0. Thus, the RTS attempt probability is derived as

$$\tau = \sum_{i=0}^{R_p} (p_r)^i \left(\sum_{i=0}^{R_p} \frac{W_i + 1}{2} (p_r)^i \right)^{-1}, \tag{4}$$

where the second term on the RHS is the steady-state probability of the state $(0, 0)$. Before deriving the reservation-failure probability p_r, we need to find the probability that

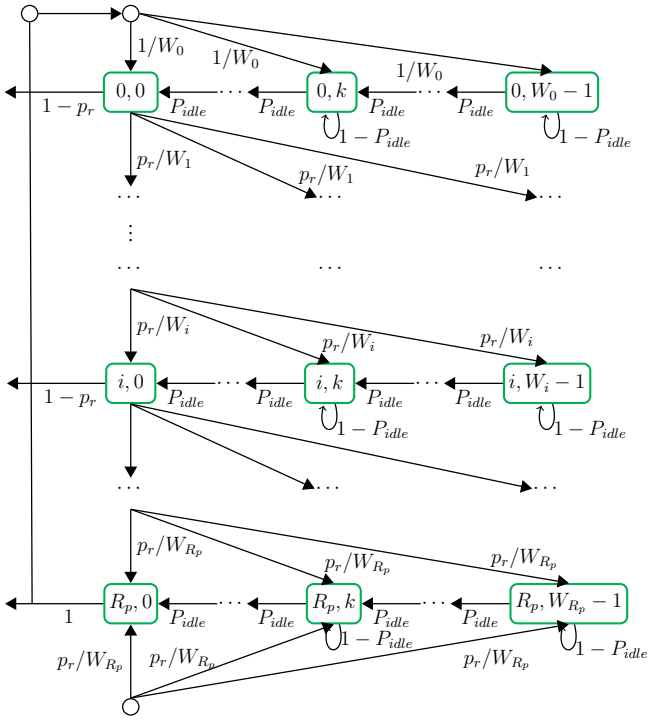

Fig. 1: Two-dimensional Markov chain of RTS backoff under DS-RTS/CTS. Each state represents the backoff stage and backoff counter as an ordered pair (i, k). At the retry limit R_p, the backoff stage wraps back into itself.

a transmitted RTS experiences collision, which causes reservation failure. Let $P_c(r)$ denote the conditional probability that a transmitted RTS packet experiences a collision when r stations are contending in the RTS phase. Following [8], a collision occurs whenever at least one of the remaining $r - 1$ stations transmits an RTS in the same slot. Given the independence of the stations, the conditional collision probability is $P_c(r) = 1 - (1 - \tau)^{r-1}$. The number of DS-winning STAs r is random, and the tagged STA contends with $r - 1$ stations with probability $P_{tag}^{exact}(r)$. Thus, the RTS reservation-failure probability is

$$p_r = \sum_{r=1}^{n_p} P_{tag}^{exact}(r)\, P_c(r). \tag{5}$$

Note that the probabilities τ and p_r are coupled through a nonlinear fixed-point relation. Specifically, p_r depends on τ via the conditional collision probability, while τ depends on p_r through the stationary distribution of the Markov chain. One may obtain the solution numerically via fixed-point iteration.

V. Delay and Throughput Analysis

Recall that the DS-eligible stations contend to transmit a DS, and this results in a set of r DS-winning stations. These stations then participate in the RTS phase, where contention continues until a successful RTS/CTS/DATA/ACK exchange occurs. Let us define a DS cycle as consisting of a DS contention, DS transmission and the RTS contention. Of these,

the DS transmission duration is deterministic, and the rest are random. Therefore, the expected duration of each DS cycle is

$$T_{cycle} = \mathbb{E}[T_{DS-cont}] + T_{DS} + \mathbb{E}[T^{sys}_{RTS-phase}], \quad (6)$$

where the expectations correspond to DS and RTS contention process. We now derive each of these expectations.

During the DS contention phase, each of the n_p DS-eligible stations picks a backoff counter from $\{0, \ldots, W_{ds} - 1\}$. Let M denote a discrete random variable which represents the minimum of the backoff counters picked by r stations. The probability mass function of M is

$$\Pr(M = m) = \left(\frac{W_{ds} - m}{W_{ds}}\right)^{n_p} - \left(\frac{W_{ds} - m - 1}{W_{ds}}\right)^{n_p}. \quad (7)$$

Using (7), we find $\mathbb{E}[M]$. Now, the expected DS contention duration is

$$\mathbb{E}[T_{DS-cont}] = T_{slot}\,\mathbb{E}[M]. \quad (8)$$

When r DS-winning STAs contend to transmit an RTS frame, the probabilities that an RTS slot is idle, contains a successful transmission, or results in a collision are

$$P_{idle}(r) = (1-\tau)^r, \quad P_{succ}(r) = r\tau(1-\tau)^{r-1},$$
$$P_{coll}(r) = 1 - P_{idle}(r) - P_{succ}(r).$$

A successful slot comprises the transmission of RTS/CTS/DATA/ACK frames sequentially, separated by SIFS duration, followed by a DIFS; and thus has a duration

$$T_s^{RTS} = T_{RTS} + T_{CTS} + T_{DATA} + T_{ACK} + 3T_{SIFS} + T_{DIFS}.$$

Likewise, a slot that results in a collision has a duration of

$$T_c^{RTS} = T_{RTS} + T_{DIFS}.$$

Thus, the average RTS slot duration is

$$T^{RTS}_{slot}(r) = P_{idle}(r)T_{slot} + P_{succ}(r)T_s^{RTS} + P_{coll}(r)T_c^{RTS}. \quad (9)$$

Let r denote the number of stations that select the minimum DS backoff slot M. The system-level distribution of the number of DS-winning STAs is

$$P^{sys}(r) = \sum_{m=0}^{W_{ds}-1} \binom{n_p}{r} \left(\frac{1}{W_{ds}}\right)^r \left(\frac{W_{ds} - m - 1}{W_{ds}}\right)^{n_p - r}. \quad (10)$$

Averaging over $P^{sys}(r)$, probability of an idle RTS slot is

$$P_{idle} = \sum_{r=1}^{n_p} P^{sys}(r)\, P_{idle}(r). \quad (11)$$

If the tagged station loses the DS contention, the number of winners among the remaining stations follows a distribution, say $P^{sys}_{-tag}(r)$, given by the RHS of (10) with n_p replaced by $n_p - 1$. Suppose that the number of RTS slots to successful transmission of RTS follows a geometric distribution, in expectation it would take $1/P_{succ}(r)$ slots to success. In this case, the expected duration of the RTS phase is given by

$$\mathbb{E}[T^{sys}_{RTS-phase}] = \sum_{r=1}^{n_p-1} P^{sys}_{-tag}(r) \frac{T^{RTS}_{slot}(r)}{P_{succ}(r)}. \quad (12)$$

TABLE I: System Parameters

Parameter	Value	Parameter	Value
Slot time T_{slot}	$9\,\mu s$	SIFS	$16\,\mu s$
DIFS	$34\,\mu s$	Legacy preamble	$20\,\mu s$
Basic rate	6 Mbps	RTS/CTS size	160/112 b
Retry limit R_p	1000	Payload/ACK size	1400 B/240 b

Substituting (8) and (12) in (6) yields the expected duration of each DS cycle. Further, since each DS cycle culminates in exactly one successful transmission and the n_p DS-eligible stations are statistically identical, by symmetry the tagged STA is served once every n_p cycles. Hence the expected number of cycles until its successful transmission is n_p, and the expected delay incurred in the preceding unsuccessful cycles is

$$\mathbb{E}[D^{pre}_{DS}] = (n_p - 1)T_{cycle}. \quad (13)$$

Similarly, we derive the expected RTS contention delay, after the tagged STA wins DS as

$$\mathbb{E}[D_{RTS,tag}] = \sum_{r=1}^{n_p} P^{exact}_{tag}(r) \frac{T^{RTS}_{slot}(r)}{\tau(1-\tau)^{r-1}}, \quad (14)$$

where $P^{exact}_{tag}(r)$ is given by (3).

The HOL delay consists of the DS delay incurred before the tagged station transmits DS, followed by the DS contention time and DS frame transmission in the winning cycle, and the tagged RTS contention delay which includes the final successful exchange. The expected HOL delay is given by

$$D_{HOL} = \mathbb{E}[D^{pre}_{DS}] + \mathbb{E}[T_{DS-cont}] + T_{DS} + \mathbb{E}[D_{RTS,tag}]. \quad (15)$$

Finally, the normalized system throughput, the fraction of time used to successfully transmit payload bits, is obtained as

$$S = \frac{\mathbb{E}[P]}{T_{cycle}}, \quad (16)$$

where $\mathbb{E}[P]$ denotes the average payload size.

VI. Performance Evaluation

We now present some computations conducted using the above analysis. Specifically, we compute the HOL delay and the normalized system throughput by varying: (i) the number of DS stations n_p, and (ii) the DS contention window size W_{ds}. Varying n_p enables us to quantify the system performance for varying levels of network density, while understanding the impact of W_{ds} allows us to explore the possibility of better decision making regarding DS contention by the stations.

For these computations, the number of DS stations is varied as $n_p \in \{2, 4, 6, 8, 10, 20, 30, 40, 50\}$, and the DS contention window size as $W_{ds} \in \{2, 4, 8, 16, 32, 64, 128, 512, 1024\}$. We vary one parameter at a time while keeping the other fixed. The PHY and MAC parameters, chosen in accordance with existing studies on WiFi 8 [6], are listed in Table I. For each configuration, the metrics are computed using equations (6)–(16).

The normalized throughput, expected HOL delay, expected minimum slot picked by the DS-winning STAs, $\mathbb{E}[M]$, are presented in Fig. 2. We also calculated the reservation failure probability, p_r, using equation (5) by varying n_p, for various

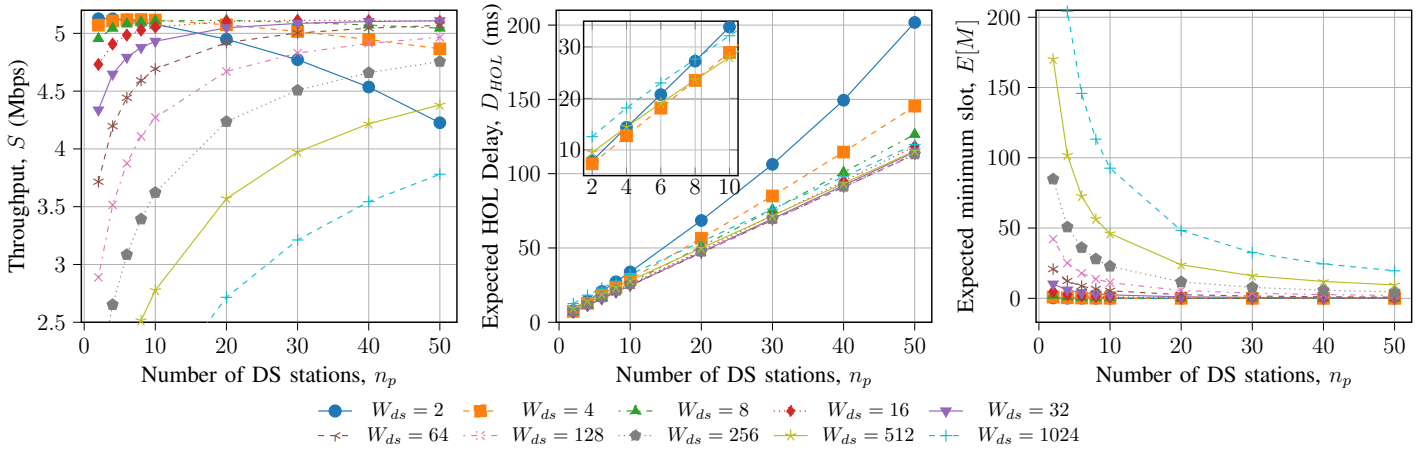

Fig. 2: Impact of number of DS stations on (left) throughput, (center) HOL delay for different W_{ds}, and expected value of the backoff counter selected by the DS-winning STAs (right).

values of W_{ds}, as presented in Fig. 3. For small W_{ds} (≤ 8), the throughput starts high and is seen to decrease as n_p increases. This aligns with the rapid increase in p_r with n_p, for small W_{ds} (see Fig. 3). As the number of DS stations grows, more stations are likely to win the DS contention, which increases the number of contenders in the RTS phase and the probability of RTS collisions, causing more reservation failures and decrease in throughput. For moderate W_{ds} (e.g., $16, 32$), throughput increases rapidly with n_p. This is because the increasing number of contenders reduces $\mathbb{E}[M]$ and shortens the otherwise longer DS phase. For large W_{ds} ($\geq$ 128), a longer DS contention phase causes significantly lower throughput for small n_p. Although throughput increases with n_p due to a substantially small p_r, it remains considerably low compared to that obtained for smaller values of W_{ds} throughout the range of n_p considered. The HOL delay increases with n_p, for all W_{ds}. Moreover, the ordering across W_{ds} appears to reverse as n_p increases; see the crossover of the curves for $W_{ds} = \{2, 4\}$ in the inset shown in Fig. 2. At low n_p, large W_{ds} incurs the highest delay owing to the long DS contention phase (and large $\mathbb{E}[M]$). At high n_p, small W_{ds} causes larger HOL delay, due to longer T_{cycle}. These trends follow directly from $\mathbb{E}[M]$, *i.e.*, increasing n_p reduces $\mathbb{E}[M]$, shortening DS contention but raising the tie probability, while increasing W_{ds} increases $\mathbb{E}[M]$ and suppresses ties. Moderate W_{ds} balances these effects, achieving the best throughput-delay tradeoff across network densities. These results collectively highlight that the choice of W_{ds} is central to system performance. Further, this choice governs the deterioration (or lack thereof) in system performance as the network density increases.

VII. Mechanism for Adaptive DS Contention

Motivated by the influence of the DS contention window size W_{ds} on system performance, we propose a mechanism for stations participating in DS contention to dynamically select W_{ds} based on network conditions. Towards this, we formulate the selection of W_{ds} as a constrained optimization problem.

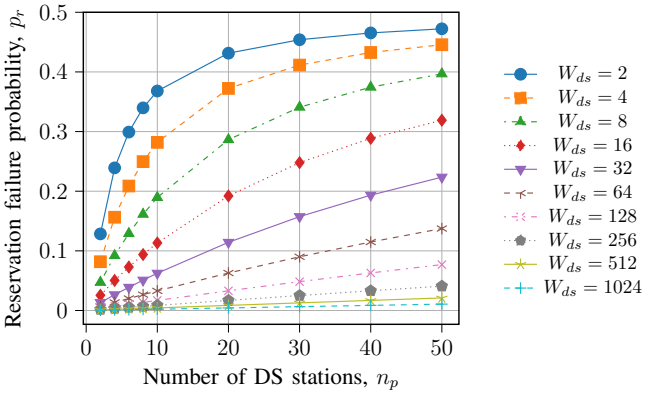

Fig. 3: RTS reservation failure probability p_r as a function of the number of DS stations n_p for different W_{ds}. Smaller W_{ds} leads to rapid growth in p_r due to increased RTS contention, while larger W_{ds} significantly reduces reservation failures.

Consider the objective function

$$\mathcal{G}(W_{ds}) = \alpha \cdot \frac{S(W_{ds})}{R_{PHY}} - \beta \cdot \frac{D_{HOL}(W_{ds})}{D_{ref}}, \qquad (17)$$

where $S(W_{ds})$ is the system throughput given by (16), $D_{HOL}(W_{ds})$ is the HOL delay given by (15) denoted as functions of the optimization variable W_{ds}; R_{PHY} is the data rate and $\alpha, \beta \geq 0$ are weighting coefficients. Further, D_{ref} is a normalization parameter that represents a tolerable delay of the latency-sensitive application hosted by the station. Each STA can select D_{ref} based on its QoS requirements, enabling heterogeneous latency sensitivity within the network. The normalization ensures that both throughput and delay contribute comparably to the objective function. Note that $\mathcal{G}(W_{ds})$ is an increasing function in $S(W_{ds})$, and a decreasing function in $D_{HOL}(W_{ds})$. Each station may choose α, β to achieve the desired throughput-delay balance.

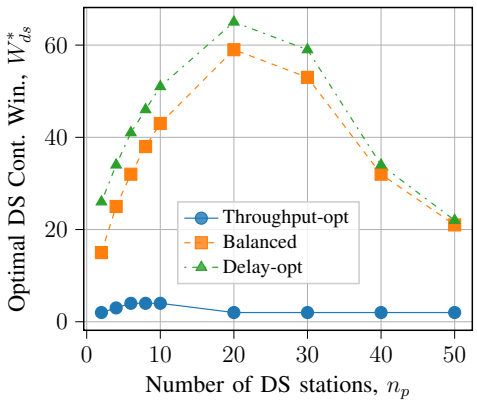

Fig. 4: Optimal DS contention window W^*_{ds} as a function of the number of DS stations n_p under various objectives.

Now, the optimal DS contention window size is obtained as

$$W^*_{ds} = \arg\max_{W_{ds}} \quad \mathcal{G}(W_{ds}), \tag{18}$$

$$\text{s.t.} \qquad (1)\text{–}(16) \text{ and } W_{ds} \in \mathbb{Z}_{\geq 2}. \qquad \text{(C1-C2)}$$

Since the function $\mathcal{G}(W_{ds})$ does not admit a closed-form solution, each station must solve the above optimization problem numerically. This requires the value of n_p, and the DS contention window size, W_{ds}, used by all other stations (see equation (10)). Suppose that the AP broadcasts an estimate of n_p, and a recommendation, say $\overline{W}_{ds}$, in a DS-Control frame. Then, each station can evaluate (10) using $\overline{W}_{ds}$ for the remaining $n_p - 1$ stations while optimizing its own W_{ds}.

The numerically obtained W^*_{ds}, for varying n_p, and three cases: (i) Throughput-oriented $(\alpha = 1, \beta = 0)$, (ii) delay-oriented $(\alpha = 0, \beta = 1)$ and (iii) balanced optimization $(\alpha = \beta = 1)$ is presented in Fig. 4. Here, we set the AP's recommendation of DS contention window size as $\overline{W}_{ds} = 4$, and used $R_{PHY} = 6$ Mbps and $D_{ref} = 10$ ms. Finding the W^*_{ds} required identifying a search upper bound, say $W_{\max}$, by exponentially increasing W_{ds} until $\mathcal{G}(W_{ds})$ decreases, and then searching over $W_{ds} \in [2, W_{\max}]$, which culminated with local refinement. Observe that delay-oriented optimization favors larger W_{ds} to reduce DS collisions and RTS contention, while throughput-oriented optimization prefers smaller W_{ds} to minimize DS contention delay. In the former, W^*_{ds} increases with n_p reaching a maximum before reducing. While the increase reflects the need to mitigate increased contention in dense networks, it remains to see what causes the reduction in W^*_{ds} as networks get denser. In the following, we present self-explanatory algorithms that can be implemented in the AP and STAs for selecting the optimal W^*_{ds} as described above.

VIII. Conclusion

Analytical framework for DS–RTS/CTS operation has been developed. The analysis characterizes the influence of network density and DS contention window size on the HOL delay and normalized throughput. Algorithms for dynamic selection of optimal DS contention window size are presented.

Algorithm 1 AP-Side DS Coordination

Parameters: n_{th} ▷ min. no. STAs for DS-RTS/CTS
Inputs: DS_requests, active_flows
while AP is operational **do**
  DS_reqs ← count of DS requests from STAs
  active_flows ← number of active AC_VO flows
  n_p ← no of unique MAC ID (DS_reqs, active_flows)
  if $n_p \geq n_{th}$ **then**
    Broadcast DS-Control frame:
      include estimated n_p
      include recommended $\overline{W}_{ds}$
      indicate start of DS contention period
  end if
end while
return DS-Control frame

Algorithm 2 STA-Side DS Optimization

Inputs: DS-Control frame
if DS-Control frame received from AP **then**
  Extract n_p and $\overline{W}_{ds}$ from DS-Control frame
  W^*_{ds} ← Solve (18) s.t. (C1-C2)
end if
return W^*_{ds}

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