Minimizing the Age of Information for Monitoring over a WiFi Network

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Abstract—**In this paper, we study how to minimize the age of information (AoI) for remote monitoring over a WiFi network, where a tagged node under study needs to deliver the sampling messages to the monitoring application installed at the access point (AP). We consider a very challenging practical scenario where multiple background nodes might incorporate heterogeneous and generic traffic models; all the nodes contend for the transmission channel through the practical IEEE 802.11 based medium access control (MAC) protocol. The existing AoI analyses over distributed MAC protocol are not sufficient for our problem, which are limited to simplified MAC modeling or homogeneous traffic modeling. We propose an AoI optimization algorithm that integrates the AoI queueing analysis with the 802.11 MAC performance analysis. Specifically, we develop an innovative method to address the impact of the MAC channel attention on the message service time of the tagged node and compute the minimal AoI iteratively. Simulation results demonstrate that our algorithm is very accurate and robust crossing a variety of networking scenarios. Moreover, our methods require only local computation and slight probing of the conditional collision probability, making them suitable for practical use.**

Index Terms—**Age of information, WiFi, queueing systems, medium access control, optimization.**

I. INTRODUCTION

Modern life has massively changed with significant improvements in network technologies and the vast increment of portable devices. Mobile devices' pervasive connectivity and advancement prosper real-time applications such as remote monitoring, attracting focus on time-sensitive information updates. Consequently, a crucial metric measuring the freshness of information called the age of information (AoI) has recently been proposed [1], which defines the period elapsed since the latest update. It is worth noting that we should distinguish the concept of minimizing the AoI from maximizing the system utilization and minimizing the delay of updates. Since widespread internet-of-things (IoT) devices access the Internet via WiFi, it is worth studying the AoI minimization problem for remote monitoring over a WiFi network.

Nevertheless, this problem is challenging as the stations contending for the wireless channel might incorporate heterogeneous and generic traffic models. Prior research studies have investigated the AoI-minimizing update rate by queue analysis [1]–[6]. Existing research works targeting AoI optimization in random access networks such as Slotted-ALOHA networks and CSMA networks are considered in [7]–[10]. Particularly, the authors of [7] propose an ALOHA-like stationary random access to reduce the network-wide AoI. Each IoT device is assigned a fixed channel access probability, which is not practical in most scenarios. The authors of [10] leverage Stochastic Hybrid Systems (SHS) to model a CSMA environment and aim to minimize the total average AoI of the whole network. AoI minimization in centralized multiple access mechanisms can be witnessed in [11], [12]. However, these studies enable the limited capability for practical implementation since the analyses are either based on a symmetric setting where the background nodes contend to the wireless channel with a homogeneous traffic arrival rate or simplified with strong assumptions. Therefore, it is of supreme importance to investigate a cost-efficient way for a portable device to act rationally for optimal AoI in an arbitrary network setting.

This paper is interested in the AoI optimization problem for remote monitoring over a WiFi network with arbitrary and heterogeneous network deployment. In particular, we investigate the strategy for a single device in a WiFi network to determine its optimal update rate based on its own observation at a low cost. Since the complex interplay among the network devices contending the channel makes it challenging for decision making, we thus propose an iterative method to quickly adjust the update rate for the offered load of the MAC queue approaching optimum. We also introduce a bounded successful transmission probability to approximate the service rate in a network with heavy traffic. Our simulation results demonstrate the universality and effectiveness of our method in a WiFi network with an arbitrary number of heterogeneous nodes. Our main contributions are summarized as follows.

1) We propose an AoI optimization framework that integrates the AoI queueing analysis with the 802.11 MAC performance analysis. We contribute an innovative method to address the impact of the MAC channel attention on the message service time of the tagged node and compute the minimal AoI iteratively.
2) Our method incorporates a local probing of the conditional collision probability due to MAC contention, which equips our analysis with the capability to handle generic heterogeneous networking environments. To the best of our knowledge, such a low-complexity yet generic AoI-minimizing method was not available in the existing literature.

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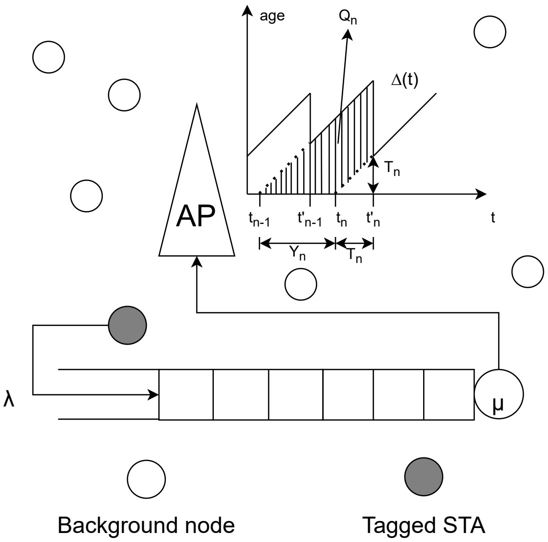

Fig. 1: A tagged STA sends updates through a MAC queue in a WiFi network

3) To handle the heterogeneous analysis, we introduce a bounded analysis with saturated approximation to background traffic. Such approximation itself is of valuable reference to the community.
4) We conduct simulations with various network settings. The simulation results show that the minimal AoI can be very closely approached following the proposed method for an arbitrary network environment, justifying the effectiveness and accuracy of our analysis.

The remainder of this paper is organized as follows. We describe the system model in Section II. The Methods proposed are illustrated in Section III. Numerical results are presented in Section IV. Finally, we conclude the paper in Section V.

II. SYSTEM MODEL

In this section, we describe our proposed framework and illustrate the details of each step.

A. Monitoring over WiFi

The scenario we are interested in is that, under an IEEE 802.11 network setting, a particular wireless station called a tagged station (tagged STA) is associated with an access point (AP). The other wireless stations connected to this AP are considered background stations. By the contention-based property of the WiFi network, these stations are contending to access the wireless channel according to the IEEE 802.11 standard. In this scenario, we intend to investigate a rational strategy for the tagged STA to achieve optimal average AoI depending on the knowledge gained from the perspective of the tagged STA, preferably in a cost-efficient way. In the remainder of this paper, we use the term STA and node exchangeably for the convenience of presentation.

Fig. 1 depicts a WiFi network with several wireless stations associated with an AP. The AP acts as a gateway to provide network services to all the wireless stations connected and plays a server's role regarding each station's MAC queue. The updates are sent by the tagged STA at arrival rate λ through a MAC queue and get serviced by the physical layer with a service rate μ. Intending to achieve the tagged STA's optimal AoI, our strategy is to measure the collision probability P_c observed by the tagged STA and to calculate the service rate μ based solely on P_c. Then use an iterative method to find an optimal arrival rate λ, which results in a minimized AoI.

AoI defines the time period elapsed since the latest update. When a source generates update i with timestamp $u_i(t)$, the update i is transmitted through the system and finally reaches the monitor. At time t, the monitor sees its latest received update time-stamped by $u_i(t)$ with age $t - u_i(t)$. AoI in this paper refers to the average AoI, which is evaluated via graphical methods to the sawtooth age waveform $\Delta(t)$

$$\langle \Delta \rangle_\tau = \frac{1}{\tau}\int_0^\tau \Delta(t)dt \tag{1}$$

in the limit of large τ. For the nth update, $Y_n = t_n - t_{n-1}$ and $T_n = t_n^{'} - t_n$ denote the interarrival and system time. As shown in Fig. 1, the sum of each shaded area

$$Q_n = \frac{1}{2}(T_n + Y_n)^2 - \frac{1}{2}T_n^2 \tag{2}$$

can be equivalent to the integral defined in (1). The average AoI can be obtained by

$$\Delta = \lim_{\tau\to\infty} \langle \Delta \rangle_\tau = \frac{E[Q_n]}{E[Y_n]}. \tag{3}$$

B. IEEE 802.11 DCF MAC

IEEE 802.11 distributed coordination function uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. An optional mechanism called request-to-send/clear-to-send (RTS/CTS) is used to solve the hidden-terminal problem. Whenever the channel is sensed idle for longer than DCF Interframe Space (DIFS), the station switches to a backoff stage. The time during the backoff stage is slotted and is uniformly chosen from $[0, CW-1]$, where CW is the contention window size. The backoff counter will reduce by one if an idle slot is sensed or freeze if the channel is busy. The frozen backoff counter would continue when the channel is sensed idle for longer than a DIFS. When the backoff counter reaches zero, the node would first send an RTS at the beginning of the next slot and receive a CTS after a Short Interframe Space (SIFS). Then after receiving the CTS for SIFS, the node can start to transmit at the beginning of the next slot. After finishing the transmission for SIFS, the sender will receive an ACK indicating the receipt of the DATA. If the sender does not receive the CTS within the CTS timeout, the RTS is considered as collided. A retransmission will be scheduled with a new doubled contention window size up to CW_{max}. The sender will drop the data frame once the retransmission limit is reached.

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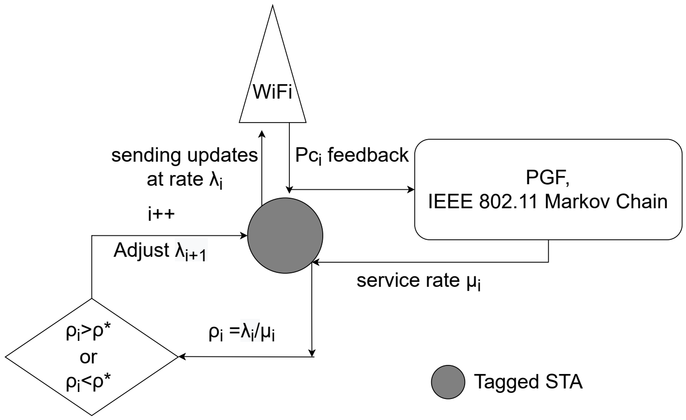

Fig. 2: A flowchart of the proposed AoI optimization algorithm.

C. AoI over the MAC Queue

Generally, the update packets generated by the upper layer are inserted into the MAC queue and wait to be served by the IEEE 802.11 radio. The packet service time is defined as the duration of time taken from a packet starting to contend for the channel to the dequeuing event triggered either by a successful transmission or a failed and discarded transmission if it reaches the maximum retransmission limit. The MAC queue of each device can be modeled as a single-source single-server queue. In queueing theory, a queue with arrival rate λ and service rate μ has offered load ρ. For a single node, altering the λ and directly measuring the AoI is impractical as it is laborious and time-consuming for the AoI to converge to its minimum. As discussed in [1], a first-come-first-serve (FCFS) queue has an optimal point $\rho^* \approx 0.53$ for minimal average AoI if the queue is an M/M/1 queue. The ρ^* value shifts a bit for M/D/1 and D/M/1 queue. Thus, we have a target AoI-minimizing ρ^*. Also, a node knows its update rate, say, the arrival rate λ here. The queue's service rate μ is the last ingredient to get the offered load ρ. However, monitoring the queue to get the service rate takes up many node resources. Also, the randomness of the medium access brings uncertain fluctuation for service time measurement. [13] provides a way to calculate μ through the conditional collision probability of the node. But adjusting the update rate would also lead to service rate change. This complex interplay between the background node traffic, the single test node λ, and the calculated μ leads to the challenging task of reaching ρ^* in a short time.

III. MINIMIZING THE AGE OF INFORMATION

In this section, we first present our iterative optimization framework to search for the optimal sampling rate that can minimize the AoI. We then demonstrate how to calculate the average frame service time at the link layer through the PGF technique. In particular, we propose a bound approximation to handle generic heterogeneous background traffic.

A. The Iterative Optimization Framework

Fig. 2 is the flowchart illustrating the proposed iterative optimization framework. After joining the AP, the tagged STA starts sending updates at rate λ_0 at the initial stage. While sending updates, the tagged STA calculates the collision probability P_c of sent packets by counting the total number of RTS sent and the number of failed RTS. After that, with the knowledge of the collision probability, the tagged STA can acquire the mean of the MAC layer service rate μ_0 through the analysis of the 802.11 protocol combining the probability generating functions (PGF) and Markov Chain modeling. Next, by comparing the acquired ρ_0 to our target offered load ρ^*, the tagged STA can refresh its updating rate to λ_1 for the next round until approaching the optimal point for AoI-minimized load ρ^* closely after several iterations.

As mentioned above, we aim to adjust the arrival rate λ to get a ρ close enough to the AoI-minimizing ρ^*. Given N background nodes with arrival rates $\vec{\eta} = [\eta_1, \eta_2, \cdots \eta_N]$, the service rate is a function of the traffic from the tagged STA and all the background nodes; $\mu = f_{MAC}(\lambda, \vec{\eta})$. Thus, our goal is to get the optimal λ by solving the equation

$$\frac{\lambda}{\mu} = \frac{\lambda}{f_{MAC}(\lambda, \vec{\eta})} = \rho^*. \tag{4}$$

A very challenging part is that if the tagged STA changes its packet arrival rate, the packet collision probability observed by the tagged STA would also change. Therefore, regularly tuning the arrival rate is inefficient and impractical. Motivated by this, we develope an iterative method to solve it quickly. We denote the tagged STA's arrival rate in the i^{th} iteration as λ_i. In the initial iteration, the tagged STA first starts sending updates to the WiFi network at rate λ_0 and calculate the $P_{c_0} = (number\, of\, failed\, RTS)/(total\, number\, of\, RTS)$. Secondly, the corresponding μ_0 can be calculated using the method proposed in [13] and our proposed approximation method for heterogeneous and generic networks. Next, the tagged STA compares its offered load ρ_0 to the known AoI-minimizing ρ^*. If $\lambda_i/\mu_i > \rho^*$, then for the next iteration

$$\lambda_{i+1} = \beta \times \lambda_i, \tag{5}$$

where β is an attenuation factor ranging $(0, 1)$. If $\lambda_i/\mu_i < \rho^*$, then for the next iteration

$$\lambda_{i+1} = \theta \times \lambda_i, \tag{6}$$

where θ is an amplification factor ranging $(1, \infty)$. In a certain iteration round, if $|\lambda_i/\mu_i - \rho^*| \leq \rho^*/100$, the algorithm converges and then stops.

In our iterative optimization, β and θ for step-wise adjustment are heuristic parameters. Our numerical experiments find that $\beta = 0.8$ and $\theta = 1.2$ are good settings that lead to robust convergence.

B. Service Rate Calculation

The MAC layer service time for a first-come-first-serve (FCFS) queue is the duration from the moment that a packet moves to the head of the queue and begins to contend for the medium access, to the moment that an acknowledgment of the packet is received or the packet gets discarded due to reaching the maximum retransmission limit. Getting the service rate via

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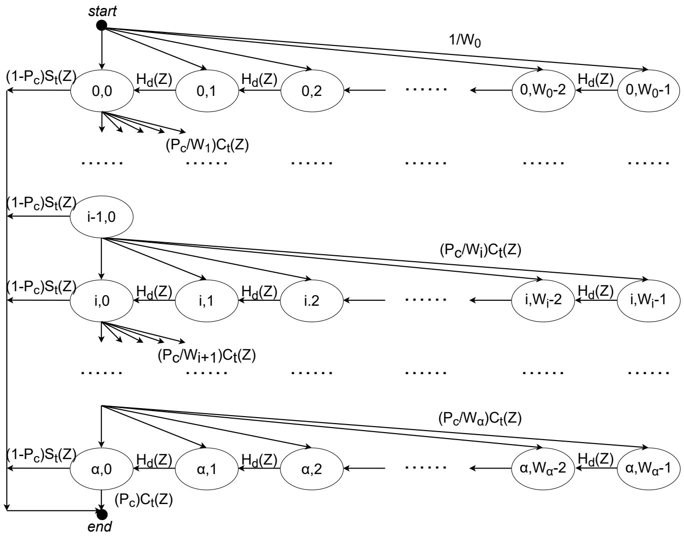

Fig. 3: Generalized state transition diagram for transmission process. [13]

measuring requires an accurate timer and continuous MAC queue monitoring, which consumes considerable resources and time of the mobile device. [13] proposed a method for calculating service time based solely on the collision probability observed, leveraging the PGF analysis.

Fig. 3 re-plots the generic state transition diagram of frame transmission process according to the IEEE 802.11 distributed coordination function. In the generalized state transition diagram, the label of each branch is generated in such a manner: the state transition time is expressed as an exponent of Z variable, and this value is then multiplied by the state transition probability. The probability generating function of the total transition time can be obtained from the generalized state transition diagram using the well-known Mason formula [14].

Let W denote the minimum contention window, α the retransmission limit (equal to 7 in 802.11 DCF), and m the maximum backoff stage (equal to 5 in 802.11 DCF). Let T_{suc} and T_{col} denote the successful transmission time and collision time, respectively, which can be readily determined according to the 802.11 MAC standard. Further, define $S_t(Z) = Z^{T_{suc}}$ and $C_t(Z) = Z^{T_{col}}$. The PDF of the frame service time, denoted as $B(Z)$ can be computed as follows [13]:

$$HW_i(Z) = \begin{cases} \sum_{j=0}^{2^jW-1} \frac{(H_d(Z))^j}{2^iW}, & (0 \le i \le m) \\ HW_m(Z), & (m < i \le \alpha) \end{cases} \tag{7}$$

$$H_i(Z) = \prod_{j=0}^{i} HW_j(Z), \qquad (0 \le i \le \alpha) \tag{8}$$

$$\begin{aligned} B(Z) =& (1-P_c)S_t(Z) \sum_{i=0}^{\alpha} (P_c C_t(Z))^i H_i(Z) \\ &+ (P_c C_t(Z))^{\alpha+1} H_\alpha(Z) \end{aligned} \tag{9}$$

Thus, we can get the mean of the service time $E[T_S]$:

$$E[T_S] = \frac{dB(Z)}{dZ}|_{Z=1} = \mu^{-1}. \tag{10}$$

In the above computation, $H_d(Z)$ represents the PGF of the random time consumed by the tagged STA to have its backoff counter decrement by one. The existing analysis of $H_d(Z)$ [13] unfortunately only handles the homogeneous situation where all the nodes in the WiFi have exactly the same traffic models. Next, we discuss how to obtain $H_d(Z)$ in a generic heterogeneous environment.

C. Approximations in Heterogeneous Contexts

Adapting to the analysis of $H_d(Z)$ in [13] to a generic heterogeneous context where each node may have different traffic arrival rates, we can have

$$H_d(Z) = \frac{(1-P_c)Z^\sigma}{[1 - P_{suc}^B S_t(Z) - (P_c - P_{suc}^B) C_t(Z)]}, \tag{11}$$

where σ denotes the empty slot time.

Consider there are n nodes in total in the WiFi network. The conditional probability P_c of the tagged STA is also the probability that there is at least one packet transmission among other $n-1$ stations. Thus, the backoff timer of the tagged STA has the probability of $1-P_c$ to decrement by 1 after an empty slot time σ. We use P_{suc}^B to denote the probability that there is one successful transmission among other $n-1$ background stations in the considered slot time given that the tagged STA does not transmit. Thus, the backoff timer of the tagged STA has the probability of P_{suc}^B to stay at the original state after T_{suc}, and the probability of $P_c - P_{suc}$ to stay at the original state after T_{col}.

The particular challenge in a generic heterogeneous context is that it is very hard to compute the probability P_{suc}^B. This is because the successful transmission can be from different background nodes. As different nodes have different traffic arrival rates and may have different utilization factors in their MAC queues, different background nodes will see different successful transmission probabilities. To compute P_{suc}^B, the queuing and backoff process of all the nodes need to be solved jointly, which is too hard to handle. We thus resort to two approximation techniques.

a) Homogeneous approximation with light collisions: When the conditional collision probability probed by the tagged STA is small, we can infer that the total background traffic rate is low. In this situation, as the absolute traffic arrival rate at each background node is low (upper bounded by the total background traffic load), when we use a homogeneous approximation, the approximate error is well limited in a small range. With such an approximation, we consider all nodes have the same conditional collision probability and same queue utilization factor. The computation details of $H_d(Z)$ is given in [13].

b) Saturated approximation with heavy collisions: When the conditional collision probability probed by the tagged STA is high, we can infer that the total background traffic rate is high. In such a situation, it is reasonable to infer that each

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TABLE I: IEEE 802.11b CONFIGURATIONS

Bit rate for DATA frame	11 Mbps
Bit rate for RTS/CTS/ACK frame	1 Mbps
Bit rate for PLCP & Preamble	1 Mbps
Slot time	20 μs
DIFS	50 μs
SIFS	10 μs
PHY header	192 bits
MAC header	224 bits
IP header	160 bits
DATA frame	8000 bits + PHY header + MAC header
RTS	160 bits + PHY header
CTS, ACK	112 bits + PHY header
Initial contention window size	31
Maximum backoff stages	5
Maximum retransmission limit	7

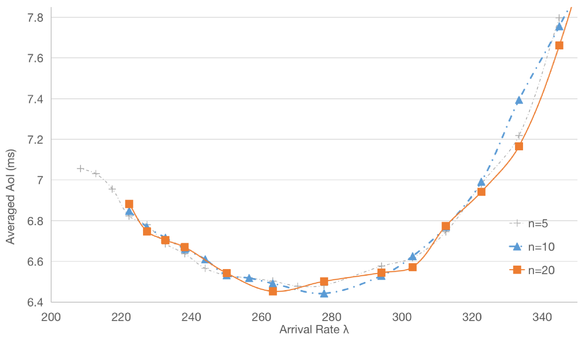

Fig. 4: AoI in homogeneous light traffic network

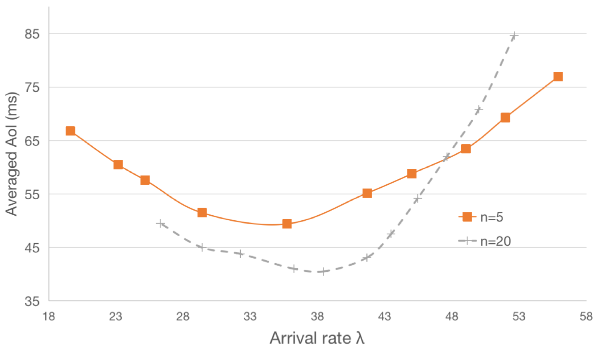

Fig. 5: AoI in homogeneous heavy traffic network

background node can be well approximated by a saturated queue (i.e., the empty probability of the MAC queue is low). Then the probability P_{suc}^{B} can be readily computed by referring to the saturated 802.11 DCF analysis [15], [16], and then used in $H_d(Z)$.

With $H_d(Z)$ well handled, it can then be used in equation (9) to obtain the PGF of the service time. The PGF analysis will then facilitate our iterated optimization given in section III-A. Finally, we present numerical results to validate our approximation techniques.

D. *The Choice of MAC Queuing Model*

The AoI-minimizing offered load ρ^* is determined by the characteristics of the queue. An analysis given in [1] shows that for an FCFS queueing system, the optimal ρ^* for M/M/1 queue and M/D/1 queue is approximately 0.53 and 0.625, respectively. Based on our simulation together with the analysis shown in [13], [17], the service time follows an exponential distribution with P_c larger than a certain threshold $\gamma = 0.001$, and can be deemed as a deterministic distribution if $P_c < \gamma$. The corresponding MAC queue models can be treated as M/M/1 and M/D/1, respectively.

Intuitively, P_c reflects the extent of the busyness of the network. We observe that $\gamma = 0.001$ also works excellently to classify the light and heavy traffic when deciding which approximation technique in the heterogeneous contexts. The light collision approximation will be used if $P_c < 0.001$; otherwise, the heavy collision approximation will be used.

IV. NUMERICAL RESULTS

In the following, we show the simulation results from some case studies to illustrate the performance of our proposed strategy. All the simulations are conducted using the discrete-event network simulator NS-3. The simulations implement the 802.11b DCF MAC protocol with the configurations listed in Table I.

A. *AoI in Homogeneous Network*

We first observe the performance of our method applied to WiFi networks containing background nodes with homogeneous traffic. In this setting, we first test three cases by deploying the number of background nodes $n = 5, 10, 20$. For each background node, the arrival process is a Poisson process with arrival rates $\lambda = 1, 0.5, 0.25$, respectively. All the tested feedback $P_c < \gamma$ are fairly close in value. We get the averaged AoI versus λ in Fig. 4. The results of the three cases are quite close, although the number of background nodes differs, as long as the tested P_c are close. The AoI reaches minimum when $\lambda = 277$ and $\rho = 0.641$, which is very close to the theoretical $\rho^* = 0.625$ for the M/D/1 FCFS queue.

We also test two cases by deploying the number of background nodes $n = 5, 20$. For each background node, the arrival process is a Poisson process with arrival rates $\lambda = 100, 20$, respectively. In the two cases, the tested feedback $P_c > \gamma$ are with value 0.2 and 0.15. We get the averaged AoI versus λ in Fig. 5. The tagged nodes have low service rates due to the heavy traffic, and the optimal AoI is achieved at a lower arrival rate than in the light traffic scenario. The AoI reaches minimum when $\lambda = 35, 39$ and $\rho = 0.54, 0.49$, which is very close to the theoretical $\rho^* = 0.53$ for the M/M/1 FCFS queue. This is also evidence that our strategy can decide its best λ regardless of the details of the background network.

B. *AoI in Heterogeneous Network*

We deploy $n = 5, 20$ background nodes in the heterogeneous network with different arrival rates. We set arbitrary arrival rates for each node and keep the tested P_c at a similar level as the homogeneous setting where $n = 5$, $\lambda = 1$ and $n = 10$, $\lambda = 2$

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TABLE II: Performance of Theoretical vs Simulation

		n	(λ^*, AoI^*)	$(\hat{\lambda}^*, A\hat{o}I^{*})$
light traffic	homo.	5	$(270.754, 6.820\,ms)$	$(270.270, 6.479\,ms)$
		10	$(270.287, 6.831\,ms)$	$(277.778, 6.443\,ms)$
		20	$(270.512, 6.826\,ms)$	$(263.158, 6.453\,ms)$
	hetero.	5	$(270.283, 6.831\,ms)$	$(270.270, 6.250\,ms)$
		10	$(268.962, 6.865\,ms)$	$(270.270, 6.609\,ms)$
heavy traffic	homo.	5	$(34.324, 53.956\,ms)$	$(35.743, 49.425\,ms)$
		20	$(42.234, 43.727\,ms)$	$(38.462, 40.525\,ms)$

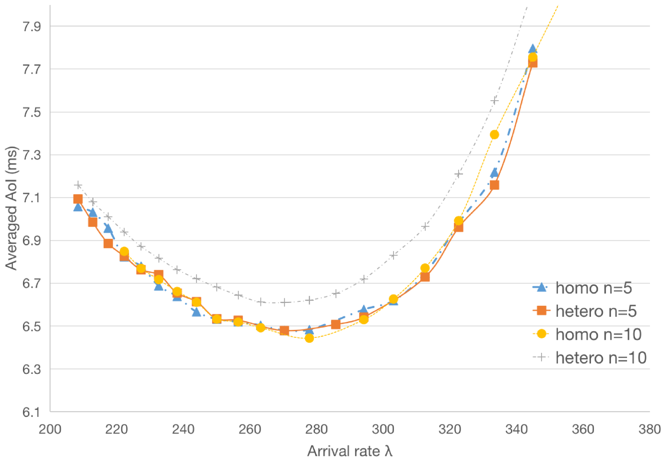

Fig. 6: AoI in homogeneous and heterogeneous network

for all background nodes. In Fig. 6, the AoI of all scenarios reaches its minimum when the λ is around 275. This verifies that our method can help determine the optimal update rate for minimal AoI only based on the P_c. The obtained AoI level in the ten heterogeneous background nodes environment is slightly higher than that of the homogeneous setting but shares the same optimal update rate. The tiny difference is almost negligible and comes from the variance of the background traffic in ten nodes heterogeneous setting.

The table II lists the theoretical optimal points and the optimum obtained through simulations, where (λ^*, AoI^*) and $(\hat{\lambda}^*, A\hat{o}I^{*})$ denote the theoretical optimum and the optimum via simulations. When the traffic is light, the AoI obtained by our methods matches very well with the theoretical results, regardless of the number of nodes or whether the background nodes are homogeneous. The simulation results in the heavy traffic setting using the approximated P^B_{suc} method match the theoretical results, verifying the effectiveness and accuracy of our proposed solutions.

V. CONCLUSION

This paper provides a solution to an AoI minimization problem for remote monitoring over a WiFi network with generic heterogeneous network settings. Specifically, we develop efficient computation methods to handle the MAC contentions between the tagged STA and background traffic and obtain the optimal sampling rate (that minimizes the AoI) with an innovative iterative method. The simulation results demonstrate that our analytical methods are very accurate and robust in a wide variety of networking contexts.

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