# Quality of Experience in Dense CSMA Networks

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***Abstract*—Dense carrier sensing wireless networks are important scenarios to enable ubiquitous mobile Internet access. In this work, we study user experience from the end-to-end performance of dense $p$-persistent CSMA networks that suffers from operation interference among many non-coordinated APs. Results show that in dense networks, the effective coverage of APs shrinks and most STAs don't receive satisfactory services which renders the network useless. We find that a dense network with multiple non-cooperative APs does not always result in lower latency. The RTS/CTS handshake also does not guarantee better latency than the basic access method in dense networks. For end-to-end throughput and end-to-end drop rate, results show that a dense network with many non-coordinated STAs has poor performance compared to that with few due to high collision, contention, and outage. On the other hand, a dense network covered by multiple APs offers better end-to-end performance compared to one covered by few. The RTS/CTS handshake also brings similar performance enhancement. Appropriate optimization associated with application scenarios are useful.**

## I. Introduction

The variety of information and services on the Internet stimulate growth in the number of mobile devices and the usage of these devices. It is expected that the number of mobile-connected devices will exceed the world's population by 2014 and the monthly global mobile data traffic will surpass 15 exabytes by 2018 [1]. In order to meet the needs for connections at anytime and anywhere, wireless Local Area Networks (WLANs) based on the IEEE 802.11 standards have become popular and are expected to be deployed in environments characterized by a high density of STAs or BSSs such as hotspots in airport/train stations, malls, stadium, campus. Most of these environments are also characterized by the overlap, in the same area, of multiple Wi-Fi networks that need to cohabit efficiently and fairly. How to improve user experience in dense networks by a fair and efficient sharing of throughput among all users/applications and to increase area capacity becomes an important topic.

To fully comprehend the impacts of dense deployment of APs, we look into the performance of CSMA as it serves the fundamental mechanism of IEEE 802.11 MAC. We particularly focus on the quality of experience (QoE) in this new study, following many efforts in the past. [2] improves the resolution mechanism of CSMA/CA, specifically IEEE 802.11 MAC, by modifying the contention window and backoff counter update rules. In [3], [4], [5], random access

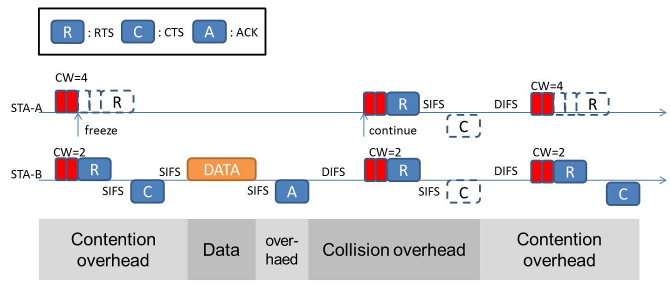



Fig. 1: IEEE 802.11 MAC overhead.

polling (RAP) and its variants are proposed as a multiple access protocol for multi-cell wireless networks. They are also effective mechanisms to resolve contention and collision overheads.

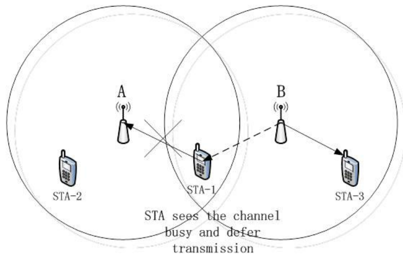
In [6], an adaptive CCA scheme based on the local SINR is proposed to improve spatial reuse and to increase the aggregate network throughput in 802.11 mesh networks. In [7], a heuristic algorithm that dynamically tunes the CCA threshold is proposed for QoS provisioning in a homogeneous network.

Most of the previous works aim at solving the resource allocation problem in dense networks. However, few works are dedicated to understand the problems themselves in dense CSMA networks which are the main focus of this paper. The organization of the paper is as follows: In section II, we review issues in dense $p$-persistent CSMA networks. Section III gives our simulation settings used to evaluate the performance. Section IV gives the simulation results and discussions. Section V concludes this paper.

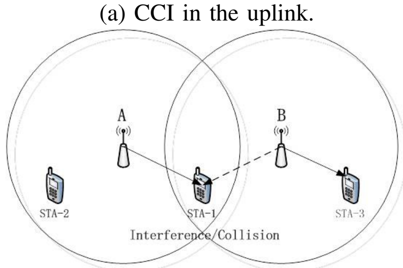
## II. IEEE 802.11 Issues in Dense Networks

There are three main dense scenarios: dense STA (i.e. high number of associated STAs per AP), dense AP (i.e. high density deployment of APs), or combined. In the following, we will look at issues of 802.11 MAC protocol in each of these dense scenarios. Fig. 1 shows a typical transmission period of an 802.11 device. There are three main overheads associated with the protocol: the contention overhead, the management overhead and the feedback overhead.

For a single dense BSS, collisions and contentions are the major causes of performance degradation. The 802.11 protocol defines the binary exponential backoff (BEB) mechanism




(a) CCI in the uplink.




(b) CCI in the downlink.

Fig. 2: CCI in high density deployment of APs.

to resolve collisions when they happen. However, the BEB mechanism resets the contention window (CW) size whenever a packet is successfully transmitted which creates unnecessary future collisions when the number of contending STAs is large. There have been many works on solving this problem [8], [9], [10]. Besides the contention overhead, the management frames (e.g. probe request/responses, association/re-association frame) also consume a large fraction of the available bandwidth when there is a large number of STAs coming and leaving the network. Last, the feedback overhead that is used to notify the transmitters about the successful reception of packets also increases with the number of STA/AP. Among the three types of overhead, we will focus on the contention overhead as it is a major performance limiting factor in a dense STA/AP environment.

When more than one dense BSS are closely deployed, co-channel interference (CCI) causes additional performance degradation. An example is given in Fig. 2. In Fig. 2a, the uplink transmission of STA 1 is prohibited by the downlink transmission of a co-channel AP 2 of BSS 2. This is similar to the well-known exposed terminal problem. In Fig. 2b, the downlink reception of STA 1 is interfered by the downlink transmission of a co-channel AP 2 of BSS 2. Similar phenomenon can be observed with more overlapped BSS. These two CCI problems exist in every wireless network, however, they are most prominent in dense network scenarios. Since the APs/STAs are in close proximity of each other in dense environment, there will be less signal attenuation due to path loss and fading, and the CCI will affect the performance more seriously. Moreover, since only limited non-overlapping channels are available, and there are usually no coordination among or centralized control over the APs, CCI is inevitable in dense environment.

Due to the above limitations, increasing the throughput per user in dense CSMA networks becomes a challenging work. One way to improve performance in such dense environment is to increase spatial reuse and hence the number of simultaneous transmissions. In a CSMA network, the spatial reuse is primarily determined by the physical carrier sensing (PCS) mechanism: a user attempting to transmit must sample the energy in the channel first; if the sampled energy is below a threshold, known as the physical carrier sensing (PCS) threshold, the user gains the right to transmit. Due to the wireless propagation properties, PCS is usually accompanied with two problems: the hidden terminal problem and the exposed terminal problem. The hidden terminal problem increases the packet loss rate while the exposed terminal problem reduces spatial reuse in the network. PCS threshold is the key parameter that determines the tradeoff between the two problems: higher PCS threshold reduces exposed terminal but increases the probability for hidden terminals; on the other hand, lower PCS threshold reduces hidden terminal collisions at the cost of increasing exposed terminals. Finding the optimal PCS threshold has been the focus of many recent works [11], [12].

In the past, most data transmissions are on the downlink. With the emergence of new applications, e.g. user generated content upload, interactive multimedia and gaming and wearable devices, there are more traffic in the uplink and the uplink performance becomes the limiting factor for user experience [13]. As a result, we will focus on evaluating the uplink performance in dense networks. Moreover, since the IEEE 802.11 MAC protocol are based on CSMA/CA which is a refinement of $p$-persistent CSMA, and to make our results more general and applicable to other CSMA-based protocols, we will specifically consider uplink performance in dense networks with $p$-persistent CSMA protocol.

## III. Simulation Settings

We evaluate the performance of $p$-persistent CSMA networks with and without the RTS/CTS handshaking. The values of the parameters used for the simulations are summarized in Table I. In our simulation, STAs are uniformly scattered in a $200 \times 200$ square area. The APs are deployed in a planned manner similar to a lattice structure. An example of our network topology is shown in Fig. 3. The APs are deployed in the way such that all STAs are covered by at least one AP. All STAs are assumed to associate with the AP that has the strongest mean received signal strength. The scenarios where the STAs and APs are deployed in a non-uniform and non-symmetric way are left for future study.

We assume all data packets arrived at the source at constant interval and are destined for a destination two-hop away. We assume a slotted channel and all transmission are synchronized to start at the beginning of each slot. All STAs start from the *idle* state and transit into the carrier sensing state once data arrive at the STAs. The carrier sensing is done using an energy detector in our simulation. A STA must make sure the channel is idle before it can transmit its packet. The channel is considered idle by a STA if the energy at the STA is lower

TABLE I: Simulation parameter settings

| | |
|---|---|
| RTS Length | 2 slots |
| CTS Length | 2 slots |
| Data Length | 10 slots |
| ACK length | 2 slots |
| CTS Timeout | 2 slots |
| ACK Timeout | 2 slots |
| $p_0$ | 1/32 |
| Retry Limit | 6 |
| Mean arrival rate per user | 0.01 Data/slot |
| CCAT threshold $\eta$ | -82 dBm |
| SIR threshold $\rho$ | 6 dB |

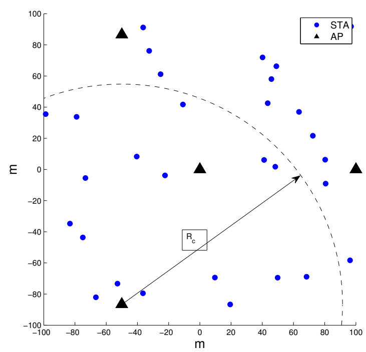



Fig. 3: Simulation network topology: 4 AP case.

than a threshold $\eta$ whose value is given in Table I. In the basic mode, a STA will transmit a Data packet in an idle slot with probability $p_0 2^{-m}$ where $m$ is the number of times that the Data packet has been retransmitted. In the RTS/CTS mode, a transmitter will first transmit a RTS with probability $p_0 2^{-m}$ when it senses an idle slot and wait for the CTS replied by its receiver. Only when the CTS packet is successfully received at the transmitter will it start transmitting its Data packet. If the CTS is not received after a CTS Timeout, or the CTS is received in error due to outage, the transmitter increment $m$ by one and tries again in the next idle slot.

A Data packet is retransmitted only if the transmitter does not receive the corresponding ACK within ACK Timeout or the ACK is received in error. A packet is received in outage (error) if at any time slot during the transmission period, the SINR at the receiver is lower than a threshold $\rho$. A Data packet is dropped if it is not successfully received after Retry Limit times of re-transmissions.

The channel model we used in our simulation is given equation 1 and 2. This model is typically used to model LOS conditions in a large open space indoor or an outdoor environment.

$$PL(d) = \begin{cases} 20log(d), & d \leq 10 \\ 20 + 35log(d/10), & d > 10 \end{cases} \quad (1)$$

$$X_\sigma = \begin{cases} N(0,3^2), & d \leq 10 \\ N(0,5^2), & d > 10 \end{cases} \quad (2)$$

The performance metrics used in our work is given as follows:

1) *End-to-end Throughput* The end-to-end throughput is defined as the ratio between the number of successful received packet at the destination and the total number of transmissions at the source in a given interval.
2) *Latency* The latency of a packet is an end-to-end version of delay and is defined as the time between its arrival at the source and its successful reception at the destination. Latency consists of the following components: the propagation delay, the node processing delay, the transmission delay, the queueing delay. Latency counts these delay components over all transmitter and receiver pair on the path that a packet take through from the source to the destination. It is obvious that latency strongly depends on the routing algorithm and the hop number. Since we consider two hop case, the effect of routing will be negligible and will be neglected in our simulation. In our simulation, a source is always a STA, a relay is always an AP, and a destination is always a STA.
3) *End-to-end Drop rate* The drop rate is defined as the ratio of the number of dropped packet over the total number of transmitted packets in a given interval. A packet is dropped if it is not successfully received for more than Retry Limit times.

## IV. Performance Evaluation

### A. End-to-end Throughput

Fig. 4 shows the mean end-to-end throughput for each position in each of the 4 APs' coverage. The value at each point is an average over all possible destinations for packets from a source at this point. We can see that the AP at the center, surrounded by the other APs, suffers lower throughput compared to the other APs due to higher collision, interference, and outage probability. STAs that are associated with the center AP suffer lower throughput than the others.

Fig. 5 gives the mean end-to-end throughput for a different number of APs and STAs. It is obvious from the result that for fix number of APs, the throughput degrades with increasing number of STAs which is due to more collision, contention, and interference. On the other hand, for a fix number of STAs, increasing the number of APs effectively improves the mean throughput performance. This is not only because the contentions are shared among the APs but also because denser deployment of APs improves the SIR performance. STAs are closer to their associated APs in a dense AP environment and hence the received signal strength at the AP is stronger. Also, in our simulation, APs act only as relays and do not have their own packets to transmit hence increasing the number of APs does not increase the interference for the other APs. This assumption is of course not true in other network settings where APs may have their own packets to transmit. In those cases, the improvement in received signal with denser APs may be compromised by the additional interference from more transmitting APs. It is also clear from Fig. 5 that the RTS/CTS handshake significantly improves the end-to-end throughput performance. This is because the handshaking forces the STAs

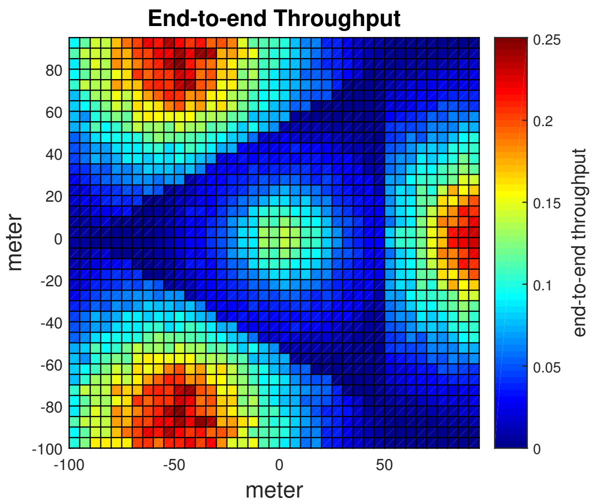



Fig. 4: End-to-end throughput distribution in each AP coverage: 4 APs, 80 STAs case.

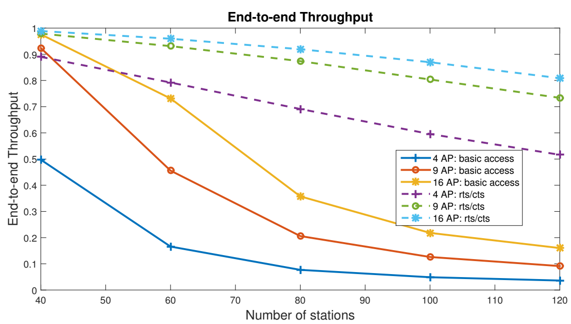



Fig. 5: Mean end-to-end throughput under different number of APs/STAs.

to be more conservative in accessing the channel and hence all STAs suffer less collision and outage. Although being more conservative, less collision and interference significantly increases the success probability and the throughput performance.

Fig. 6, 7 show the end-to-end throughput coverage under various number of STAs and APs respectively. Each curve is a summarize of 4. The $y$-axis coverage value gives the percentage of the area at which the mean throughput is larger than or equal to the $x$-axis value. It is clear from the results that as the number of STAs gets larger, the coverage curve is shifted to the left and more points experience low mean throughput. The RTS/CTS handshake helps improve the throughput performance as the coverage curve is shifted to the right.

## B. Latency

Fig. 8 shows the mean latency for each position in each of the 4 APs' coverage. The value at each point is an average over all possible destinations for packets from a source at this point. We see that the AP at the center, surrounded by the other APs, suffers high latency compared to the other APs.

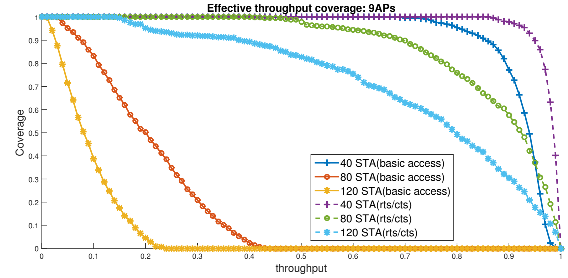



Fig. 6: End-to-end throughput coverage under different number of STAs.

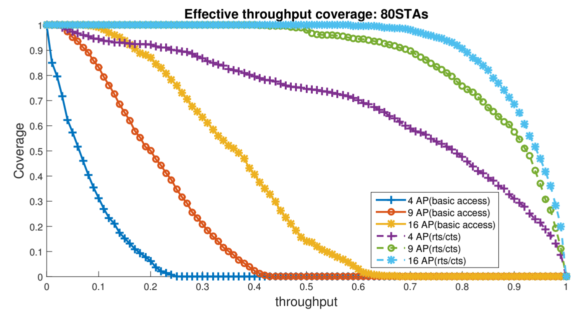



Fig. 7: End-to-end throughput coverage under different number of APs.

This is consistent with the throughput result in Fig. 8 where high latency corresponds to low end-to-end throughput. Note that low throughput may be caused by either high drop rate or high latency. As a result, areas with low throughput do not always imply high latency. The areas in dark blue, with latency close to zero, also has low throughput, as can be seen in Fig. 8 and 4. However, this area suffers high drop rate as will be shown in the next subsection.

Fig. 9 gives the mean end-to-end latency for different number of APs and STAs. For the basic access, a network with more APs has lower mean latency when the number of STAs is low. As the number of STAs grows, the mean latency is greatest for the network with more APs. This is because more APs allow more concurrent transmission and the signal strength on a busy channel is higher. Hence STAs are more likely to sense a busy channel and avoid colliding on it. Being more conservative, the drop rate, shown in next subsection, will be lower at the cost of higher latency. For the RTS/CTS case, we see that a network with 16 APs has lower latency than that with 9 APs. This is because the received SINR value is in general lower in the 9 AP case than that in the 16 AP case due to smaller distance between the STA and the AP hence a higher chance to experience outage. Moreover, the RTS/CTS handshake is effective in reducing the latency when the number of STAs is not large due to the reduction of outage. However, as the number of STAs grows, adding RTS/CTS handshakes causes higher latency due to longer postponement to the RTS/CTS messages.

Fig. 10, 11 show the latency coverage under various number

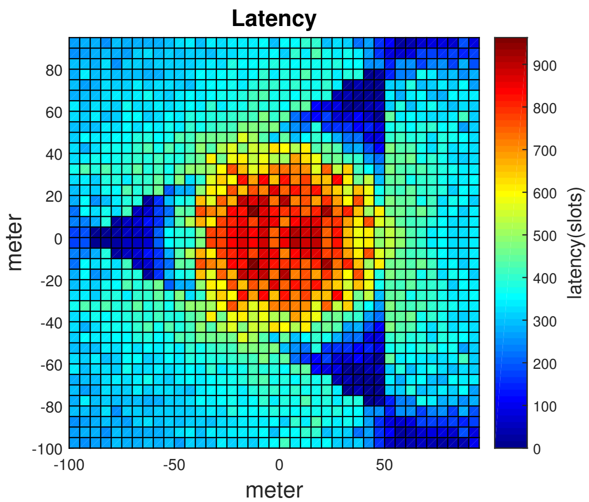



Fig. 8: Latency distribution in each AP coverage: 4 AP, 80 STAs case.

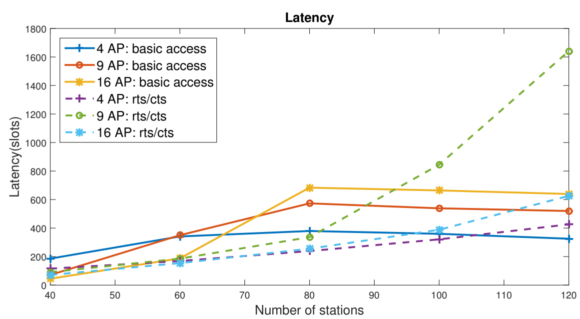



Fig. 9: Mean latency under different number of APs/STAs.

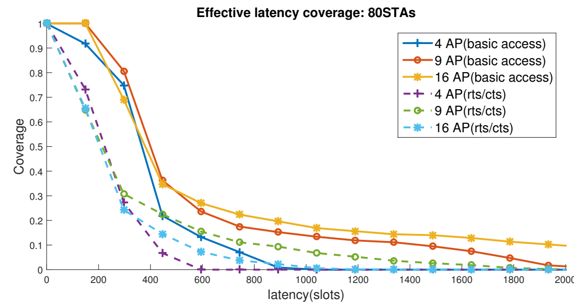



Fig. 11: Latency coverage under different number of APs.

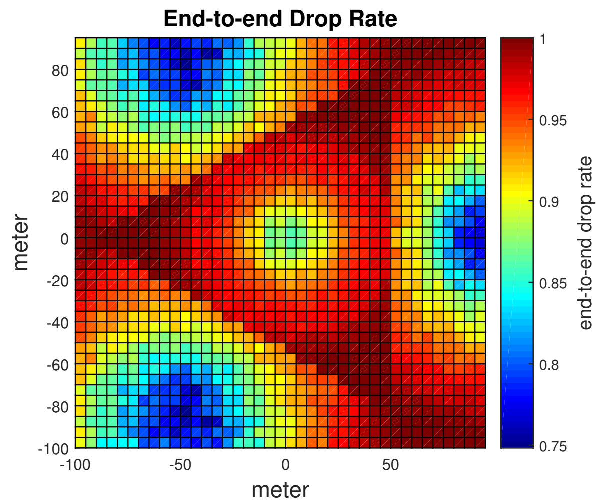



Fig. 12: End-to-end drop rate distribution in each AP coverage: 4 AP, 80 STAs case.

of STAs and APs respectively. Each curve is a summarize of Fig. 8. The $y$-axis coverage value gives the percentage of the area at which the mean latency is larger than or equal to the $x$-axis value.

### *C. End-to-end Drop Rate*

Fig. 12 shows the mean end-to-end drop rate for each position in each of the 4 APs' coverage. The value at each point is an average over all possible destinations for packets from a source at this point. We see that the STAs associated to the center AP suffer higher drop rate than those associated to the peripheral APs. These STAs experience higher collision,

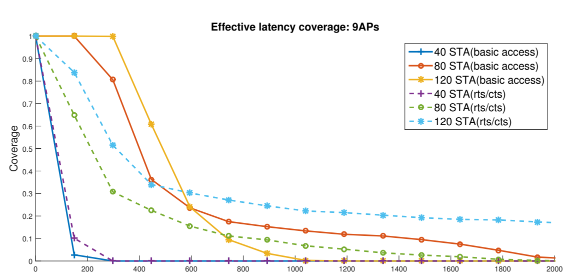



Fig. 10: Latency coverage under different number of STAs.

contention, and lower SINR because they or their receivers are under the coverage of more APs than the others.

Fig. 13 gives the mean end-to-end drop rate for different number of APs and STAs. It is obvious from the result that the drop rate increases with increasing number of STAs which is due to more collision, contention, and interference. On the other hand, drop rate decreases with increasing number of APs because the STA is closer to the associated AP and the SINR is improved. Note again that, in our simulation, APs act only as relays and do not have their own packets to transmit hence increasing the number of APs does not increase the interference to the other APs too much. It is also clear that the RTS/CTS handshake significantly improves the end-to-end drop rate due to less collision and interference.

Fig. 14 and 15 show the end-to-end drop rate coverage under various number of STAs and APs respectively. The $y$-axis coverage value gives the percentage of the area at which the mean drop rate is larger than or equal to the $x$-axis value. These figures confirm our previous statements that dense APs and RTS/CTS handshake improves the end-to-end drop rate performance while dense STAs deteriorates it.

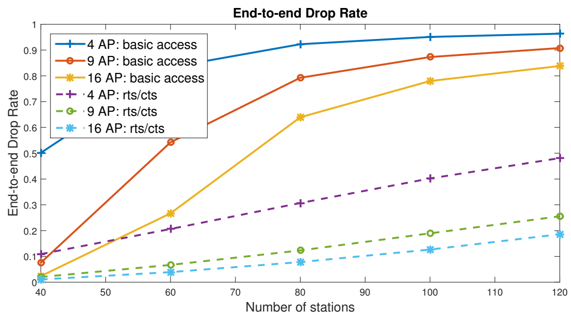



Fig. 13: Mean end-to-end drop rate under different number of APs/STAs.

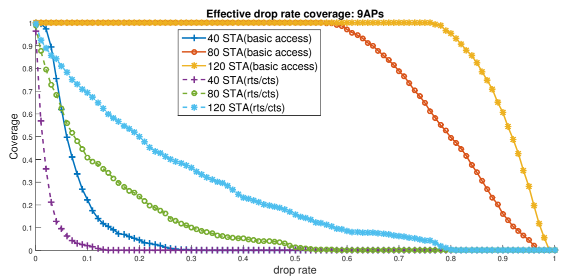



Fig. 14: End-to-end drop rate coverage under different number of STAs.

## V. Conclusion

Dense carrier sensing wireless networks are important scenarios to enable ubiquitous mobile Internet access. In this work, we study user experience from the end-to-end performance of dense $p$-persistent CSMA networks that suffers from operation interference among many non-coordinated APs. Results show that in dense networks, the effective coverage of APs shrinks and most STAs don't receive satisfactory services which renders the network useless. We find that a dense network with multiple non-cooperative APs does not always results in lower latency. The RTS/CTS handshake also does not guarantee better latency than the basic access method in dense networks. For end-to-end throughput and end-to-end drop rate, results show that a dense network with many non-coordinated STAs has poor performance compared to that with few due to high collision, contention, and outage. On the other hand, a dense network covered by multiple APs offers better end-to-end performance compared to one covered by few. The RTS/CTS handshake also brings similar performance enhancement. Appropriate optimization associated with application scenarios are useful.

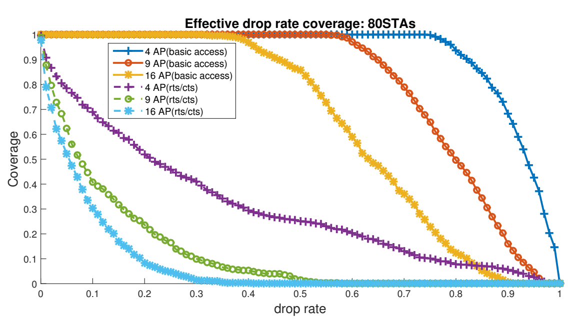



Fig. 15: End-to-end drop rate coverage under different number of APs.

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