Detecting Hidden and Exposed Terminal Problems in Densely Deployed Wireless Networks

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***Abstract*—In this paper, we discuss problems in densely deployed wireless networks. Particularly, we focus on wireless local area networks (WLANs) because they have enabled us to provide seamless and high capacity wireless access easily and inexpensively. However, recently, channel interference between different services has become a serious problem because access points (APs) of WLANs are located too densely. In the carrier sense multiple access with collision avoidance used in WLANs, the hidden terminal (HT) and the exposed terminal (ET) problems occur depending on the distance between stations and the carrier sensing range. In the higher dense deployment mentioned above, the HT and ET problems occur complicatedly. Therefore, we propose an AP cooperation system that detects the HT and ET problems between stations (STAs). In our system, APs are operated with time synchronization and obtain the information of connected STAs from received frames. The HT and ET problems are identified from the integration of the information obtained at different APs. The effectiveness is verified by simulations.**

***Index Terms*—Wireless local area networks, hidden terminal problem, exposed terminal problem, detection, densely deployed BSSs.**

I. INTRODUCTION

THE extensive use of IEEE 802.11 wireless local networks (WLANs) has been brought, thanks to their fast communication speed, license free operation and inexpensive deployment. In fact, they are widely used in homes, offices, and public spaces as part of our social infrastructure. However, because each service provider or each personal user has located his or her basic service set (BSS), which consists of an access point (AP) and one or more stations (STAs), distributedly and selfishly without taking into account other preexisting BSSs, interference between BSSs that are deployed too densely has become a serious problem. It is reported in [1] that a BSS is interfered with by eighty other BSSs in the worst case scenario observed in San Francisco. In such a dense WLAN environment, wireless bandwidth is used inefficiently due to frequent frame collisions and unnecessary suppression of transmission; the carrier sense multiple access with collision avoidance (CSMA/CA) protocol does not work properly. In such an environment, the well-known hidden terminal (HT) problem [2] can easily occur in different BSSs rather than in a single BSS. The HT problem causes frequent frame collisions between the HTs, which leads to wasted bandwidth. In addition to the HT problem, available bandwidth can be wasted because of the exposed terminal (ET) problem [3], in which the transmissions are suppressed unnecessarily by sensing signals that are actually ignorable.

Detecting the HT and ET problems, called MAC-level problems in this paper, is very important as a first-step solution to improve bandwidth use efficiency in densely deployed WLANs. Although previous papers have discussed the MAC-level problems [3]-[11], unfortunately, no work has discussed in detail the detection of the MAC-level problem in the dense deployment of WLANs.

This paper proposes a novel AP cooperation system that detects the MAC-level problems between STAs in the uplink of densely deployed WLANs. In our system, APs are operated with time synchronization and obtain information on STAs from received frames, and the information obtained at different APs is integrated on the database. The MAC-level problems between STAs are identified based on their connected APs, their carrier sensing relationship, and their frame-collision possibility, which are estimated from the information stored at the database. The contributions in this paper are that 1) we systematically organize the MAC-level problems into five categories ; 2) our system enables us to easily detect the MAC-level problems, which conventional methods cannot do, in the dense deployment of WLANs; 3) we successfully integrated various MAC-level problems into a mathematical formula so that the detection result is applicable for conventional or new control technology; 4) our system requires no modification from existing STAs and minimized modification from existing APs; and 5) the detection accuracy of our system will be evaluated quantitatively, which has never been done in the prior studies. In this paper, we discuss only the MAC-level problems of the uplink WLANs. Note that detection systems for the problems in the downlink will be addressed in a future study.

Before explaining the details of our system, it is necessary to understand how important it is to detect MAC-level problems. Suppose that, using our detection system, we have completely detected the HT problems in the BSSs shown in Fig 1. As shown in the figure, if we assign channel ♯1 or ♯2 to STA b, which is within the overlapping area of two BSSs, based on the detection result so that the number of HT relationships is

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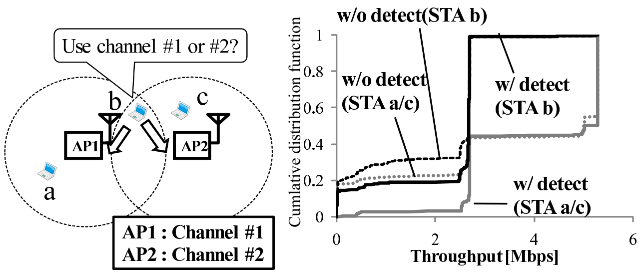

Fig. 1. Simulation of channel assignment based on detected HT problem; the QualNet4.5 [14] simulator was used; the topology is composed of two APs, to each of which an orthogonal channel is assigned, and STAs a and c, which are within the isolated areas of APs 1 and 2 respectively, and STA b, which is within the overlapped zone of the two APs; the positions of STAs were determined individually for each trial; every STA transmits saturated data to its connected AP with 1500 bytes of frame length; the transmission mode follows IEEE 802.11a with 6 Mbps; the indoor path-loss model [15] is used without shadowing or fading; 1000 trials were done; the transmit power, the antenna gain and the noise figure were set to 16 dBm, 0 dB, and 10 dB, respectively.

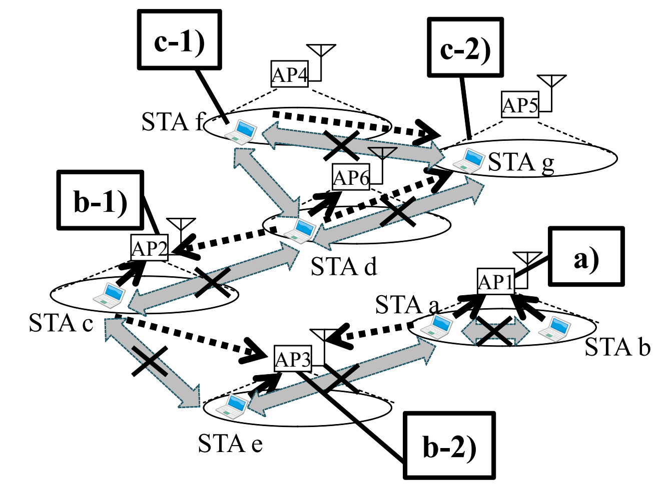

Fig. 2. MAC-level problems in densely deployed WLANs.

minimized, the probability that the throughputs of every STA will increase is higher than 50%. In addition to frequency channel assignment, detection results from our system are applicable for AP assignment algorithms, the HT/ET solutions such as the request-to-send/clear-to-send protocol, and routing protocols in wireless mesh networks [4]-[6].

The rest of the paper is organized as follows. We first summarize previous works in Section II. In Section III, we list the MAC-level problems and present the simulation study of the throughput performance in the presence of MAC-level problems. In Section IV, we propose an AP cooperation system that detects the MAC-level problems between STAs in the dense deployment of WLANs. The simulation parameters are described in Section V, and Section VI shows the performance of the proposed system. We mentioned the remaining issues in Section VII. Finally, Section VIII concludes this paper.

II. Related Work

Since the majority of existing works about the MAC-level problems have focused on mitigating the effects of problems, the detection of the problems remains ill-argued. Especially, it has been thought that the ET occurrences are harder to detect than the HT because the only way to detect is by disabling carrier sensing at the STAs and testing for loss-free simultaneous communication. In [8], the authors have proposed Mutual Observation with Joint Optimization (MOJO) to detect the HT problem between STAs in a single BSS. Choi proposed a scheme that an AP collects the carrier sensing information among the STAs associated with it and detects HT problems[9]. However, these schemes do not take into account the ET problem. Moreover, the detection accuracy has not been validated quantitatively. Alternatively, several works have tried to mitigate the effect of MAC-level problems by the indirect detection of observing the interference and collisions. The authors in [11] design an AP selection strategy by using the potential HT problems. However, all the above schemes require large modifications from the existing STAs.

The AP cooperation system has attracted much attention in the dense deployment of WLANs[7], [12], [13]. The authors in [12] proposed a multi-AP architecture with which AP Controller (AC) is employed to enable each STA to associate and cooperate with multiple APs. In the architecture, the effect of MAC-level problems was mitigated by the information sharing between APs and the centralized scheduling of APs. The authors in [7] have proposed the hybrid architecture that centrally handles the MAC-level problems in the downlink. Although previous works verified the effectiveness of AP cooperation, all these works require a significant change to CSMA/CA.

III. MAC-Level Problems in Densely Deployed WLANs

The IEEE 802.11 WLAN adopts the distributed coordination function based on CSMA/CA as a basic medium access protocol, where each STA distributedly determines the timing of transmission of its frames. In CSMA/CA, to avoid frame collisions, each STA senses if the medium is being used by another STA before it starts transmission. However, improper carrier sensing results in frequent frame collisions between STAs and excessive suppression of transmitting frames, which leads to the waste of bandwidth. As shown in Fig. 2, all of the MAC-level problems caused by the improper carrier sensing in the uplink are classified into the following five categories:

a) *HT problem in a single BSS*:
If STAs a and b in a single BSS cannot hear each other, either of them might start transmission even while the other is transmitting the frame; frame collisions between STAs a and b would frequently occur at AP 1.

b-1) *HT problem between different BSSs*:
If STAs in different BSSs cannot hear each other, frame collisions will occur at either or both of the APs in the BSSs. Collisions that occur only at either AP are considered to be an asymmetric HT problem. In Fig. 2, frames from STA c are destroyed by transmission of STA d at AP 2, while STA d is not affected by transmission of STA c.

b-2) *HT problem by superimposed power*:
The simultaneous transmission of STAs a and c

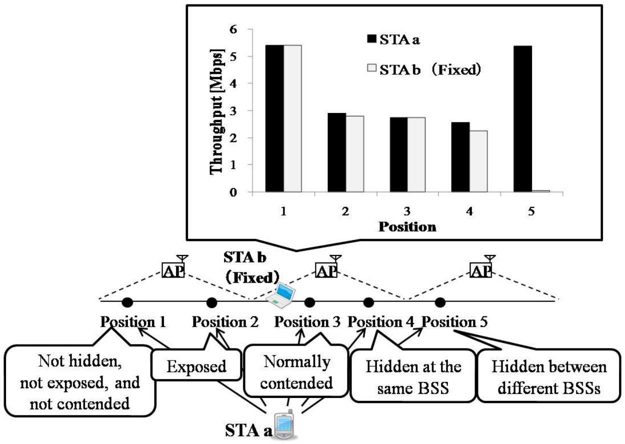

Fig. 3. Simulated network topology is composed by 3 co-channel APs and 2 STAs. The position of STA a is changed from positions 1 to 5, while STA b is fixed within the range of AP 2. Each STA is transmitting saturation data with the frame length of 1500 bytes to its connected AP. The wireless system consists of IEEE 802.11a with fixed physical rate of 6 Mbps. The pathloss model[15] is used for the indoor environment. Shadowing and fading are not considered; the transmit power, the antenna gain and the noise figure were set to 16 dBm, 0 dB, and 10 dB, respectively.

destroys frames transmitted by STA e. In other words, STA e suffers from the HT problem because of the superimposed power of STAs a and c.

c-1) *ET problem*:
Even though STA d and STA f do not need to hear each other because of no possibilities in the occurrence of collisions between them, they can hear each other. This unnecessary carrier sensing of STA d's transmission does not allow STA f to transmit frames, and vice versa.

c-2) *ET problem by superimposed power*:
When both of STA d and STA f are transmitting, STA g can not initiate a transmission by the carrier sensing of the sum of transmit power of STA d and STA f despite no occurrence of collisions. This is also only caused by the superimposed power like b-2).

We focus on a), b-1), and c-1) in the following sections, while b-2) and c-2) are briefly discussed in Section VII.

The bandwidth wasted by the MAC-level problems presented in a), b-1), and c-1) is verified by QualNet4.5[14] simulation, using the topology shown in Fig. 3. The problem between STA a and STA b depends on the position of STA a as follows: STA a at position 1 can transmit frames independently of the transmission of STA b connected to the different AP. STA a at position 2 can hear STA b despite no occurrence of collisions, which results in the ET problem discussed in c-1). STA a at position 3 contends with STA b for channel access according to normal CSMA/CA. STA a at position 4 suffers from the HT problem with STA b, as mentioned in a). Finally, STA a at position 5 suffers from the asymmetric HT problem described in b-1) with STA b, where STA b is the HT for STA a, while STA a is not for STA b.

In Fig. 3, we observe how throughputs of STAs change depending on their positional relationship. We varied the position of STA a, while the position of STA b is fixed. First, STA a at position 4 obtains lower throughput than at position 3 because of problem a) with STA b. Next, we observe the throughput of STA b is nearly zero because of the asymmetric HT defined as problem b-1) when STA a is positioned at position 5. Finally, when STA a is at position 2, problem c-1) halves the throughput of STA a compared with that at position 1. Thus, these examples prove that the MAC-level problems significantly waste bandwidth and they suggest that we accurately detect those problems.

Suppose that our system has perfectly detected the HT and ET problems in Fig. 3. Even when STA a has the ET problem with STA b at position 2, they ignore each other and can send frames simultaneously. The throughput would be increased to the one observed at position 1. When STA a is at position 4 or 5, the HT problem should be solved. The ideal solution is to connect STA b to an AP using another channel. We would see the same throughput as the one observed at position 1. The second option is to introduce such a protocol as request-to-send/clear-to-send (RTS/CTS) to suppress the HT problem. The throughput would be lower than the one observed at position 3 because of the overhead of the protocol.

IV. Proposed System

In this section, we propose an AP cooperation system that detects the MAC-level problems particularly a), b-1) and c-1) defined in the previous section. Note that, in the following discussion, the description of thermal noise is omitted even though it was taken into account. For example, channel errors occur because of thermal noise in the simulation. Moreover, we do not consider the usage of RTS/CTS because it is reported that RTS/CTS often degrades performance in densely deployed WLANs [16] though our approach is applicable to networks using RTS/CTS.

A. Key elements of identifier

We first present the identifier that allows us to identify the MAC-level problems, and also review the elements in the identifier. When we identify the relation of STA j (HT, ET, or not) to STA i, we use subscript ij. The problem can be identified from: 1) connected AP κ_{ij}: if $\kappa_{ij} = 1$, STA j is connected to the same AP as STA i; 2) carrier sensing relationship λ_{ij}: if $\lambda_{ij} = 1$, STA i can hear STA j; 3) frame-collision possibility μ_{ij}: if $\mu_{ij} = 1$, frames from STA i can be destroyed by those from STA j. Each of these identifiers is independently determined from the results of observation during a predetermined observation period. Then, let S_{ij} be the identifier that indicates the relation of STA j to STA i:

$$S_{ij} = \begin{cases} F_a & \kappa_{ij} = 1,\ \lambda_{ij} = 0,\ \mu_{ij} = 0 \cup 1 \\ F_b & \kappa_{ij} = 0,\ \lambda_{ij} = 0,\ \mu_{ij} = 1 \\ F_c & \kappa_{ij} = 0,\ \lambda_{ij} = 1,\ \mu_{ij} = 0 \\ F_{normal} & \text{otherwise,} \end{cases} \tag{1}$$

where $S_{ij} = F_a$ indicates STA j is connected to the same AP as STA i but STA i cannot hear STA j, which corresponds to problem a) listed in the previous section; $S_{ij} = F_b$ indicates STA j is connected to a different AP from STA i but frames from STA j can destroy frames from STA i, which

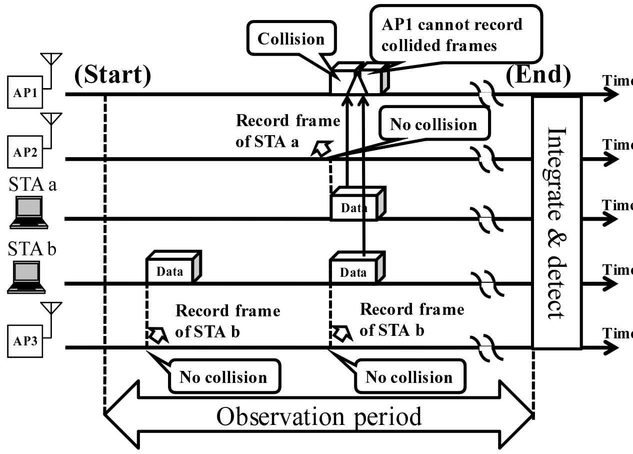

Fig. 4. Basic procedure of our system. In this example, since STAs are in the HT problem at AP 1, AP 1 cannot record their frames. Instead, APs 2 and 3 record frames from STAs a and b, respectively. APs in our system are able to decode the PLCP preamble, PLCP header and MAC header in the data frame sent to other APs.

corresponds to problem b-1); $S_{ij} = F_c$ indicates frames from STA j do not destroy frames from STA i but STA i hears STA j, which corresponds to problem c-1); $S_{ij} = F_{normal}$ means that STA j works properly for STA i based on CSMA/CA.

B. Detection system

Our system integrates information observed at APs using the same channel on the database and then estimates κ_{ij}, λ_{ij}, and μ_{ij} defined above from the database. The basic procedure of our system is simply described as in Fig. 4 and follows: i) APs enter the predetermined observation period; ii) during the observation period, each AP obtains the information, i.e., MAC address, time stamp, and received power from data frames that it received from STAs; iii) after the observation period, our system integrates the information observed at APs and identifies the MAC-level problems from the integrated information.

In step ii), each AP records time stamps T^i_{start} and T^i_{end}. T^i_{start} is the time it starts to receive the Physical Layer Convergence Protocol (PLCP) preamble of the data frame of STA i; T^i_{end} represents the end of the transmitting data frame. It is calculated from T^i_{start} + (data frame size / physical rate). The information on the physical rate and the data frame length is included in the PLCP header. APs can identify the transmitter of a data frame only when they successfully decode the MAC header. For instance, if the HT problem between STAs a and b exists in AP 1 as shown in Fig. 4, AP 1 cannot receive data frames from STAs a and b because of collisions. However, if a neighboring AP 2 can receive the data frame from STA a, and a neighboring AP 3 does so for STA b, T^a_{start}, T^b_{start}, T^a_{end}, and T^b_{end} can be successfully recorded. Thus, such cooperation among neighboring APs makes it possible to obtain the information of STAs that exhibit the HT problem. In addition, each AP measures received signal strength (RSS) from each STA; R^x_i denotes the RSS from STA i measured at AP x. APs update the RSS information from an STA every time they receive a data frame from the STA. Since the instantaneous RSS from STA i, $R^{x\prime}_i$ includes thermal noise and interference as well as the signal strength from STA i, R^x_i should be obtained from $R^{x\prime}_i$ with a filtering function: $R^x_i = G(R^{x\prime}_i)$. Thus, since our system only observes normal transmissions, STAs are operated on normal CSMA/CA and are not required to measure any additional parameters or send any additional messages. However, an AP in our system has to receive signals from STAs connecting to other APs. It will be briefly discussed how to realize it in practice in Section VII.

In step iii), our system integrates T^i_{start}, T^i_{end}, R^x_i, and the MAC address of the AP connected by STA i, BSS_i, obtained at every AP on the database. In this paper, we assume that the information obtained at every AP is collected after the observation period and managed at a central server, although this can also be done in a distributed manner. The central server integrates time stamps obtained at every AP and generates a received frame list for each STA with considering two or more frames with the same time stamp observed at different APs to be one frame. s_i denotes the counter of time stamps of STA i. Here, if the total number of received frames from STA i is smaller than threshold θ, the problems regarding the STA are considered to be undetectable because there is not enough information to detect them. The following subsections describe in detail how three elements κ_{ij}, λ_{ij}, and μ_{ij} are produced from the integrated information.

1) Connected AP: Assuming that during the observation period, each STA does not change the connected AP, the connected AP κ_{ij} is given by

$$\kappa_{ij} = \begin{cases} 1 & BSS_i = BSS_j \\ 0 & \text{otherwise.} \end{cases} \tag{2}$$

2) Carrier sensing relationship: Carrier sensing relationship λ_{ij} is produced by comparing $T^{s_i}_{start}$ and $T^{s_i}_{end}$ with $T^{s_j}_{start}$ and $T^{s_j}_{end}$. If the received timing of frames from STA i has overlapped with that of STA j, we can determine that they cannot hear each other. On the other hand, if their received timings have never overlapped, we can determine that they can hear each other. Therefore, λ_{ij} is given by

$$\lambda_{ij} = \begin{cases} 1 & \sum_{s_i}\sum_{s_j}\sigma_{ij} \le \alpha \\ 0 & \text{otherwise,} \end{cases} \tag{3}$$

where α denotes the threshold to determine whether STA i can hear STA j or not. In most cases, α should be set to 0. To determine an STA can hear another STA, one multiplicity of received timing is enough to reject the supposition. To determine an STA can NOT hear another STA, one multiplicity of received timing is enough to accept the supposition. The multiplicity of received timings σ_{ij} is given by

$$\sigma_{ij} = \begin{cases} 1 & T^{s_i}_{\text{start}} > T^{s_j}_{\text{start}} + \delta t,\ \ T^{s_i}_{\text{start}} < T^{s_j}_{\text{end}} \\ 0 & \text{otherwise,} \end{cases} \tag{4}$$

where δt can exclude the concurrent transmission between STA i and STA j due to the concurrent backoff expiration on the normal CSMA/CA. Hence, we should mention that APs are required to maintain time synchronization with each other using a conventional synchronization technique for wired networks [17] or beacon signals broadcasted by APs.

This estimation algorithm for carrier sensing was inspired by MOJO [8], which was designed to detect only the HT

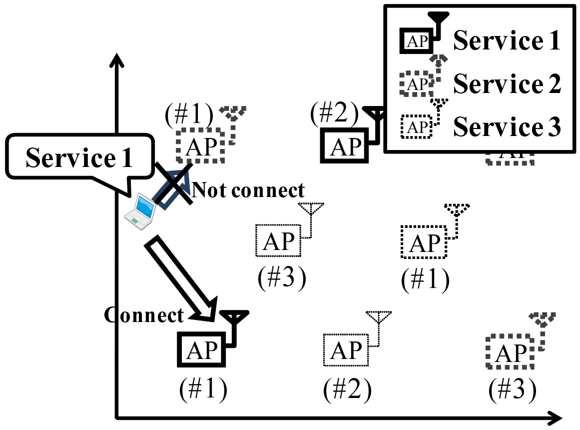

Fig. 5. Simulation model: APs were hexagonally located in a 100 m × 100 m square area; the positions of the APs were randomly located within 3 m from the center of each hexagon; three channels ♯1, ♯2, and ♯3 were assigned to the APs in a three-cell reuse manner; 300 STAs were randomly located in the area; for example, when the AP interval is set to 10 m, about 90 to 100 APs are deployed in the simulation field and around 3 STAs are connected to each AP; every STA transmitted saturated data to its connected AP with 1500 bytes of frame length; the transmission mode followed IEEE 802.11a with the auto rate fallback [18]; the indoor path-loss model [15] was used with log-normal shadowing which remains constant during a simulation period; the transmit power, the antenna gain, the noise figure and the minimum received-signal sensitivity set to 16 dBm, 0 dB, 10 dB and -92 dBm, respectively; 100 trials were conducted; the positions of APs and STAs were determined individually for each trial.

problem at a single BSS. Another difference of our system from MOJO is that it does not require any modification of STAs.

3) Frame-collision possibility: Frame-collision possibility μ_{ij} is produced by comparing the signal-to-interference ratio (SIR) with a threshold;

$$\mu_{ij} = \begin{cases} 1 & R_i^x/R_j^x \leq \gamma \\ 0 & \text{otherwise,} \end{cases} \tag{5}$$

where R_i^x and R_j^x are the RSSs measured at AP x; When the ratio of R_i^x to R_j^x is smaller than γ, frames from STA i are destroyed by frames of STA j. γ is predetermined considering required bit error rate.

C. Possibility of detection error

Like other detection systems, detection results from our system can include errors, which are due to two factors: 1) the total number of received frames from an STA is not sufficient to determine Eqs. (3) and (5). 2) measured RSSs are not accurate enough to determine Eq. (5). In case 1), the multiplicity of received timings could not be counted even though they were never able to hear each other, which corresponds to the false negatives and positives in the detection of HT and ET problems; HT is identified as non-HT; non-ET is identified as ET. Note that, in this case, the false positives in HT problems and the false negatives in ET problems do not happen because our system determines the relationship as non-HT or ET even if the total number of received frames is unsatisfactory. On the other hand, in case 2), both false negatives and positives can occur in the HT and ET detections due to the inaccurate RSS measurement.

V. Simulation Description

Simulations were carried out to validate the effectiveness of our system using the topology shown in Fig. 5. We fixed the field size and the number of STAs in the simulation, while we varied the AP interval which is the distance between APs. Here, we consider the scenario that three WLAN services are mixed in the area; each AP is managed by one of the service providers, while each STA is connected to the AP with the highest RSS among only the APs provided by the service it subscribes to. This scenario allows us to reproduce various MAC-level problems illustrated in Fig. 3. We observed APs and STAs in the three services using a particular channel (♯1). APs belonging to different services can cooperate to detect the MAC-level problems if they use the same frequency band. In this simulation, the number of observed STAs was 100. γ in Eq. (5) is set so that a bit error rate lower than 10^{-5} is ensured when the lowest physical rate is used. In that condition, when $R_i^x/R_j^x \leq \gamma$, the bit error rate is lower than 10^{-5} in any physical rate. R_i^x in Eq. (5) is ideally measured in the simulation. α in Eq. (3) is set to 0. δ t in Eq. (4) and the observation period in Fig. 4 are set to 50 μs and 30 s. In this paper, detection accuracy P is defined as

$$\begin{aligned} P &= 1-(P_p+P_n) \\ &= 1-\frac{\sum_{[i,j]\in\vec{v}} f_{ij}^p + \sum_{[i,j]\in\vec{v}} f_{ij}^n}{\sum_i \sum_j t_{ij}}, \end{aligned} \tag{6}$$

where P_p and P_n are the probabilities that the false positive and the false negative occur, respectively. $\vec{v}$ corresponds to the set of STAs i and j with $t_{ij}=1$, which denotes if STA j can be a potential HT for STA i; to detect the HT problem defined as problem a), since it only occurs within a single BSS, t_{ij} is set to 1 if $\kappa_{ij}=1$; to detect the HT problem defined as problem b), since it occurs only between different BSSs, t_{ij} is set to 1 if $\kappa_{ij}=0$. The false positives f_{ij}^p and the false negatives f_{ij}^n are given as

$$\begin{cases} f_{ij}^p=1, f_{ij}^n=0 & S_{ij} \neq S'_{ij} \cap S'_{ij} = F_{normal} \\ f_{ij}^p=0, f_{ij}^n=1 & S_{ij} \neq S'_{ij} \cap S'_{ij} \neq F_{normal} \\ f_{ij}^p=0, f_{ij}^n=0 & \text{otherwise,} \end{cases} \tag{7}$$

where S_{ij} is the detection result from Eq. (1), while S'_{ij} is the actual relationship of STA j to STA i.

As a benchmark, we introduced a location based method which is able to calculate the signal reachability from the positions of STAs, the transmit power, and the path-loss model. When these factors are ideally known, the location based method can detect the MAC-level problems between STAs completely if there is no shadowing effect. Why we introduced the location based method as a baseline method is because, as illustrated in Fig. 3, the MAC-level problems between STAs have strong dependence on their positions.

VI. Simulation Evaluation

A. Detection accuracy and no. of detected STAs vs. AP interval

Figures 6 and 7 respectively show the detection accuracy P of a) and b-1) when the average interval between APs was varied. First, it should be highlighted, in both figures, our

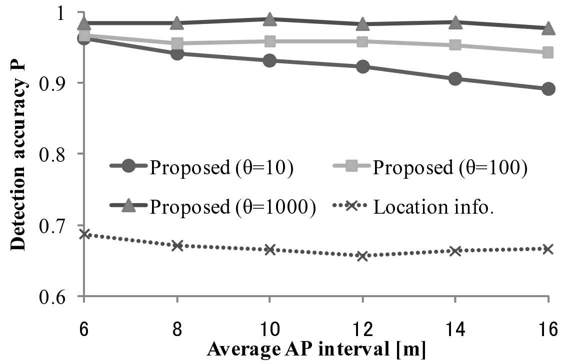

Fig. 6. Detection accuracy P of a) with varied AP intervals: the standard deviation of shadowing was set at 12 dB.

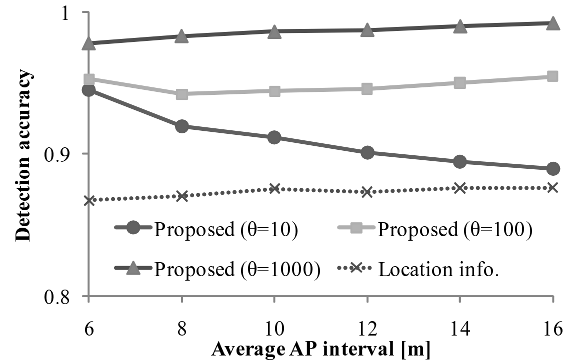

Fig. 8. Detection accuracy P of c-1) with varied AP intervals: the standard deviation of shadowing was set at 12 dB.

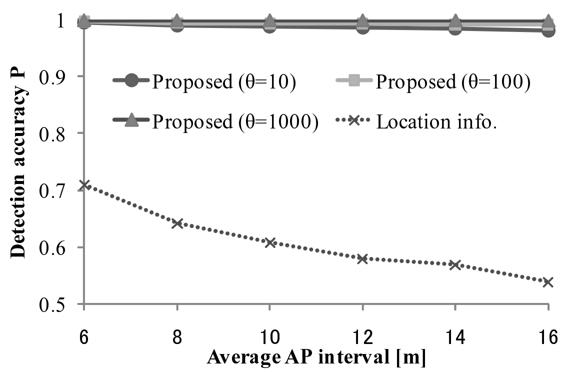

Fig. 7. Detection accuracy P of b-1) with varied AP intervals: the standard deviation of shadowing was set at 12 dB.

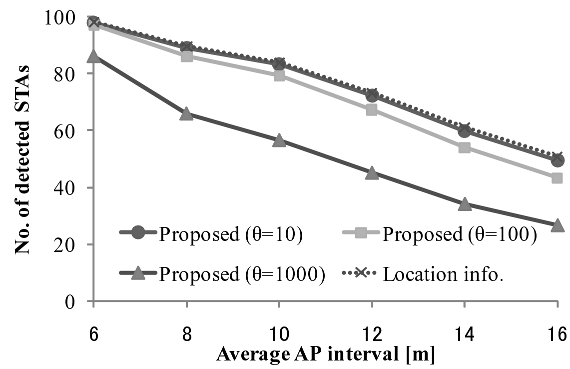

Fig. 9. Number of detected STAs after observation period with varying AP intervals.

system keeps high accuracy independently of the AP interval and θ introduced in Sect. IV-B. However, in Fig. 6, as the AP interval increases, P decreases, while it remains almost 1.0 in Fig. 7. This difference comes from the difference of mechanisms between problems a) and b-1); as neighboring APs decrease, an STA experiences problem a) more because more STAs connects to the same AP even if it is far from them. Moreover, as illustrated in Fig. 4, the neighboring APs help detecting problem a) that occurs at an AP, which works less effectively as the AP interval increases. For problem b-1), the longer AP interval just suppresses interference between STAs connecting to different APs.

Figure 8 plots P of c-1) with varying the AP interval. We see in the figure that our system works with high accuracy for problem c-1). However, the AP interval increases, P increases or decreases dependently on how we set θ. Basically, as the AP interval increases, the number of data frames received by neighboring APs monotonically decreases, resulting in the decrease of P in our system. Particularly, the criterion of Eq. (3) is "no overlapped transmission between two STAs is that they have the ET problem (problem c-1)". The false negative increases as the number of received data frames decreases. However, by increasing θ, we can suppress the false negative because we detect only the problems associated with STAs with the larger number of received data frames than θ. Figure 9 plots the number of detected STAs, from which APs receive a larger number of frames than the required number θ. We see in Fig. 9, as θ increases, the number of detected STAs decreases. Note that, in Fig. 9, the plot of the location based method indicates the upper bound of detectable STAs. This is not always equal to 100% because as the average AP interval increases, there are more STAs in the simulation area that cannot connect to any APs.

B. Detection accuracy and error probability vs. shadowing

Figure 10 shows P as a function of the standard deviation of shadowing. We can see from this figure that while the location based method works less effectively as the standard deviation increases, our system slightly increases in accuracy. As the standard deviation of shadowing increases, the channel relationships between STAs and APs become more diversified, which increases the probability that a frame that collides at an AP can be recorded at other APs. In the location based method, as the standard deviation of shadowing increases, P decreases. Particularly, P for problems a) and b-1) decrease faster than it for problem c-1). This difference comes from the difference of mechanisms between the HT and ET problems. Basically, the HT and ET problems should be more and less sensitive to shadowing because each problem occurs when received signal strength between two STAs is weak and strong, respectively. However, our method works better than the location based around 12 dB that is the typical standard deviation value of indoor shadowing reported in [15]. The results show that the location based method cannot work under shadowing environment.

Figure 11 plots the false positive probability P_p and the

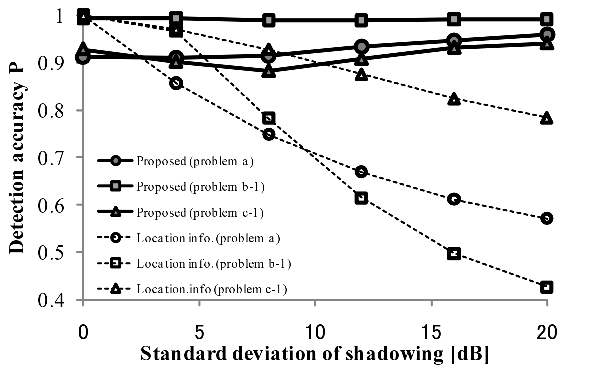

Fig. 10. Detection accuracy P with varying standard deviation of shadowing: the average AP interval is fixed at 10 m; θ is set at 10; problem a) is the HT problem in a single BSS; problem b-1) is the HT problem between different BSSs; problem c-1) is the ET problem.

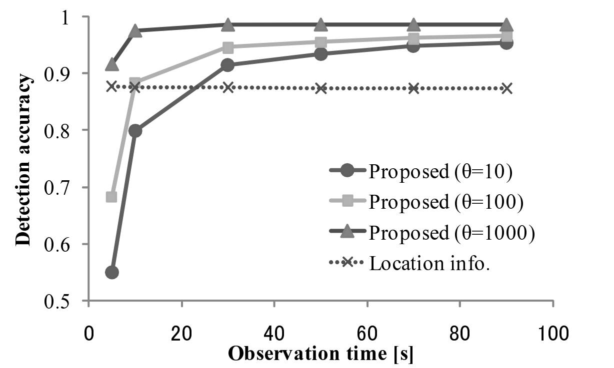

Fig. 12. Detection accuracy P of c-1) with varying the observation period: the average AP interval was fixed to 10 m; standard deviation of shadowing was set at 12dB; θ is set to 10.

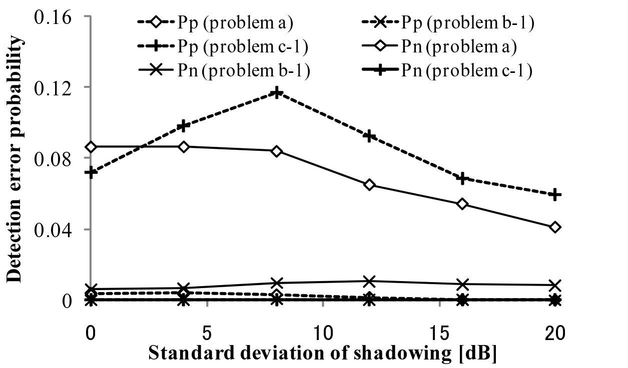

Fig. 11. Detection error probability of our system with varying standard deviation of shadowing: the average AP interval is fixed to 10m; θ is set to 10; problem a) is the HT problem in a single BSS; problem b-1) is the HT problem between different BSSs; problem c-1) is the ET problem.

false negative probability P_n. We can find from this figure that P_p in problem a) and b-1) and P_n in problem c-1) are closed to zero, respectively. This is because false positives and negatives in the HT and ET detections respectively occur only when RSS measurements are inaccurate as mentioned in Sec. IV-C. As we observed in Fig. 10, the detection accuracy for problem b-1) is the highest among the detections for the three problems. Figure 11 shows the reason for this: as for the comparison between problems a) and b-1), the probability that data frames from STAs suffering from problem b-1) will be destroyed by collisions is lower than that for STAs enduring problem a), which leads to a lower P_n in problem b-1) than a). The higher P in problem b-1) than in c-1) in Fig. 10 is explained by the fact that the false-positive probability for problem c-1) is much higher than the false-negative probability for problem b-1) as shown in Fig. 11.

C. Detection accuracy vs. observation period

Figure 12 represents P detection accuracy for problem c-1) as a function of the duration of observation period. We can see from this figure that as the observation period increases, the detection accuracy monotonically improves, which is consistent with our intuition; too short observation period makes it hard to accurately estimate the elements in Eqs. (3) and (5). However, since the detection accuracy is finally saturated, too long observation period is meaningless. Furthermore, as we described in the above observation regarding Figs. 6 to 9, the larger θ means our system detects only the relationship between STAs with a larger number of received frames. That is why, in Fig. 12, larger θ required shorter observation period to ensure certain detection accuracy. This suggests that, if the total number of STAs in the system increases, we should set θ larger to limit the detected STAs or the observation period longer to increase the number of received data frames.

VII. Remaining Issues

We have explained how to detect the HT and ET problems in densly deployed WLANs. However, there remain the following three issues.

1) HT and ET problems by superimposed power, which are categorized as b-2) and c-2) in Section III. We here explain how we apply the identifier defined above to problem b-2) and c-2), both of which are caused by superimposed power of multiple STAs. We redefine subscript j and introduce a virtual STA concept. When the number of STAs in a system is N, we can express all the combination of STAs using $j = j_1 + j_2 \times 2 + j_3 \times 2^2 + \cdots + j_N \times 2^{N-1}$, where j_n is 1 if STA n is included in the combination and otherwise 0. For example, the combination of STA 1 and 2 is represented as a virtual STA $j = 1 + 1 \times 2 + 0 + \cdots + 0 = 3$. Then, the three elements in Eq. (1) κ_{ij}, λ_{ij}, and μ_{ij} are redefined as:

- $\kappa_{ij} = 1$, if STA i is connected to the same AP with at least one of N STAs included in virtual STA j.
- $\lambda_{ij} = 1$, if STA i hears the superimposed power of the STAs included in virtual STA j.
- $\mu_{ij} = 1$, if frames of STA i collide with the superimposed power of the STAs included in virtual STA j.

Virtual STAs may be produced and managed in a centralized way. The detailed discussion will be included in future study.

2) How to implement our system in practice. Our system requires the following modifications from existing APs when the system is managed by a central server.

- Although a normal AP discards data frames sent to other APs, the AP in our system has to record the information of the physical rate, the data frame length, received signal strength, and MAC address from them. A solution for this is to incorporate a sniffing function with every AP. It can

be a separated device but set nearby the AP [19][20] or can be integrated to the AP receiver. In our system, the PLCP preamble, the PLCP header, and the MAC header of every received data frame have to be decoded with the received signal strength being measured.
- The recorded information including time stamps, MAC addresses, and RSSs is forwarded by APs to the central server via wired network.
- APs have to maintain time synchronization with each other using a conventional method [17]. However, synchronization loss may occur at an AP in practical. If we can detect the loss, the system can handle it by ignoring the information from the AP and by compensating for the lost information by the one obtained from other APs. If the synchronization loss is not detectable, it could be hard to handle it.

The further discussion and the real implementation will be included in future work.

VIII. Conclusion

In this paper, we focused on the uplink and categorized the MAC-level problems that occur in densely deployed WLANs: a) HT problem in a single BSS, b-1) HT problem between different BSSs, b-2) HT problem due to superimposed power, c-1) ET problem, and c-2) ET problem due to superimposed power. Next, we proposed a detection system particularly for problems a), b-1), and c-1). In our system, APs using the same channel cooperatively share their observed information. Our system integrates the observed information and then detects the MAC-level problems based on their connected APs, their carrier sense relationship, and their frame-collision possibility, which are estimated from the integrated information. Our simulation results showed that our system can detect the MAC-level problems accurately, regardless of AP density or shadowing effect. In the future, in addition to the remaining issues in Section VII, we have to investigate the detection of MAC-level problems in the downlink.

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References

[1] A. Akella, G. Judd, S. Seshan, and P. Steenkiste, “Self-management in chaotic wireless deployments,” *Wireless Networks*, vol. 13, no. 16, 2007.
[2] S. Khurana, A. Kahol, and AP. Jayasumana, “Effect of hidden terminals on the performance of IEEE 802.11 MAC protocol,” in *Proc. 1998 IEEE LCN*, pp. 12–20.
[3] L. B. Jiang and S. C. Liew, “Improving throughput and fairness by reducing exposed and hidden nodes in 802.11 networks,” *IEEE Trans. Mobile Comput.*, vol. 7, no. 1, pp. 34–49, Jan. 2008.
[4] M. Abusubaih, B. Rathke, and A. Wolisz, “Collaborative setting of RTS/CTS in multi-rate multi-cell IEEE 802.11 wireless LANs,” in *Proc. 2008 IEEE LANMAN*, pp. 31–36.
[5] K. K. Leung and B. J. Kim, “Frequency assignment for IEEE 802.11 wireless networks,” in *Proc. 2003 IEEE VTC 2003 – Fall*, vol. 3, pp. 1422–1426.
[6] L. Xiaozhu and Z. Rongbo, “Efficient channel assignment and routing algorithm in WLAN mesh networks,” in *Proc. 2008 CCC*, pp. 211–215.
[7] V. Shrivastava, N. Ahmed, S. Rayanchu, S. Banerjee, S. Keshav, K. Papagiannaki, and A. Mishra, “CENTAUR: realizing the full potential of centralized WLANs through a hybrid data path,” in *Proc. 2009 MobiCom*.
[8] A. Sheth, C. Doerr, D. Grunwald, R. Han, and D. Sicker, “MOJO: a distributed physical layer anomaly detection system for 802.11 WLANs,” in *Proc. 2006 MobiSys*.
[9] Y. Choi, “Clustering algorithm for hidden node problem in infrastructure mode IEEE 802.11 wireless LANs,” *ICACT*, vol. 2, pp. 1335–1338, Feb. 2008.
[10] Y. Kim, J. Yu, S. Choi, and K. Jang, “A novel hidden station detection mechanism in IEEE 802.11 WLAN,” *IEEE Commun. Lett.*, vol. 10, pp. 608–610, 2006.
[11] L. Du, Y. Bai, and L. Chen, “Access point selection strategy for large-scale wireless local area networks,” in *Proc. 2007 IEEE WCNC*, pp. 2161–2166.
[12] Y. Zhu, “Leveraging multi-AP diversity for transmission resilience in wireless networks: architecture and performance analysis,” *IEEE Trans. Wireless Commun.*, vol. 8, no. 10, Oct. 2009.
[13] O. Brickley, S. Rea, and D. Pesch, “Load balancing for QoS optimisation in wireless LANs utilizing advanced cell breathing techniques,” in *Proc. 2005 IEEE VTC – Spring*, vol. 3.
[14] “QualNet,” http://www.qualnet.com/
[15] ITU-R Rec. P.1238, Propagation data and prediction models for the planning of indoor radio communication systems and radio local area networks in the frequency range 900 MHz to 100 GHz, ITU, Geneva, 1997.
[16] M. Abusubaih, B. Rathke, and A. Wolisz, “A framework for interference mitigation in multi-BSS 802.11 wireless LANs,” in *Proc. 2009 IEEE WoWMoM*, pp. 1–11.
[17] J. C. Eidson, M. C. Fischer, and J. White, “IEEE 1588 standard for a precision clock synchronization protocol for networked measurement and control systems,” in *Proc. 2002 ISA/IEEE Sensors for Industry Conference*, pp. 98–105.
[18] A. Kamerman and L. Monteban, “WaveLAN-II: a high-performance wireless LAN for the unlicensed band,” *Bell Labs Technical J.*, vol. 2, no. 3, pp. 118–133, Aug. 1997.
[19] I. Ramani, R. Kompella, S. Ramabhadran, and A. Snoeren, “Convenant: an architecture for cooperative scheduling in 802.11 wireless networks,” *IEEE Trans. Wireless Commun.*, vol. 9, no. 1, Jan. 2010.
[20] L. Feng, L. Mingzhe, L. Rui, W. Huahui, M. Claypool, and R. Kinicki, “Tools and techniques for measurement of IEEE 802.11 wireless networks,” in *Proc. 2006 WiOpt*.

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