Harnessing Mobile Multiple Access Efficiency with Location Input

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***Abstract*—Benefiting from the abundant sensor hints of current mobile devices, their location information has become pervasively available and easy to access. As smartphones and tablets have become recently the main access devices of 802.11-based WLAN, location information provides large opportunity to improve the performance of underlying wireless communication. This paper presents CO-MAP (Co-Occurrence MAP) which leverages the position of devices to handle exposed and hidden terminal problems in mobile WLANs so as to improve the multiple access efficiency. With the location information, CO-MAP rapidly builds a co-occurrence map showing which two links can occur concurrently. Meanwhile, it selects the best settings of frame transmissions based on a novel analytical network model when hidden terminals are distinguished. CO-MAP improves the goodputs of both downlinks and uplinks in instant and distributed manner. Our implementation on a testbed of 6 laptops demonstrates that CO-MAP can accurately detect potential hidden and exposed interferers, and provide a large gain of goodput for both exposed terminal and hidden terminal scenarios. The simulation results of large scale networks on NS-2 also suggest that imperfect position hints can still bring substantial improvement on the multiple access efficiency.**

***Index Terms*—mobile WLAN, multiple access, exposed terminal, hidden terminal, location.**

I. Introduction

According to the statistics of Canalys [1], total global shipments of smartphones for whole 2011 overtook client PCs. These “smart” mobile devices have become the main approach to access 802.11-based wireless local area networks (WLAN) which have been widely deployed in public entities and private residences. Carrier Sense Multiple Access (CSMA) is the basic medium access method for such devices in WLANs. A major problem of CSMA is the performance degradation caused by exposed and hidden terminals due to the inaccurate estimations of channel condition at receivers by the measurements operated by senders. In two campus WLAN testbeds of [2], 40% links lose concurrent transmission opportunities due to Exposed Terminals (ETs) and 10% links suffer more than 70% throughput reduction because of Hidden Terminals (HTs).

A common way to enable concurrent transmissions of ETs and avoid HT collisions is to build an interference map of the whole network by site survey and then schedule transmissions accordingly. Unlike prior works based on heavy trial studies of conflicting relations among nodes, the key insight in this work is that, as location information of the current mobile devices has become easily available, we can detect ETs and HTs in WLAN by making proactive use of such information so as to improve the multiple access efficiency. In general 802.11 WLANs, the maximum transmit power of nodes is 100mW, which provides a communication range of more than 200m in free space environments and around 50m for indoor scenarios. On the other hand, based on the plentiful sensor hints on mobile devices, location information becomes easily accessible. In the experiments of [3], the average outdoor GPS error is 13.7m in urban area. Many existing indoor localization approaches [4–7] offer at least room-level estimation of positions. Compared to the large communication range of WLAN, we believe the accuracy of existing localization techniques provides us considerably meaningful position information to substantially improve the current multiple access design.

By leveraging the location information, this paper presents CO-MAP (Co-Occurrence MAP) which can rapidly infer the conflicting relations among nodes. Based on the intrinsic upload and download data and command frame transmissions, location information can be easily shared across all nearby participating nodes with little communication overhead. With the positions of its relative neighbors within 2-hop, a node computes its conflicting relations with them based on a radio propagation model and a Packet Reception Rate (PRR) model. A co-occurrence map is thus built, by consulting which a node makes decision on whether or not enabling its transmission concurrently. We propose an enhanced scheduling algorithm to enable most concurrent transmissions when multiple ETs are identified. On the other hand, in order to avoid potential collisions, we select the best settings of frame transmissions for each node based on a novel analytical network model when HTs are distinguished.

Rapid update of interference relations among nodes in CO-MAP is local and lightweight, which is more suitable for mobile WLAN with fast change of network topology due to random mobility and association of devices. Moreover, based on a distributed design, CO-MAP is able to efficiently schedule the transmissions of both uplinks and uplinks without the concern of central coordinator or extra connections among Access Points (APs). In summary, this paper provides three key contributions.

1) *We design CO-MAP, a unified framework that makes proactive use of device positions to handle HT and ET problems in mobile wireless networks.* It improves the network goodput by enabling concurrent transmissions of ETs and mitigating HT collisions.

2) *We implement CO-MAP on commodity hardware platforms.* Experimental results demonstrate that CO-MAP can detect accurately the hidden and exposed terminals, and provide 77.5% gain of goodput for ET scenarios and 34.8% for HT networks.
3) *We also implement CO-MAP on NS-2 platform to study its performance for large scale networks.* A combinations of simulations are performed and results show an average goodput increase of 38.5%. CO-MAP is also evaluated in terms of tolerance to position inaccuracy. The results suggest that imperfect position hints still bring substantial improvement in case of 10-meter position error range.

The rest of this paper is organized as follows. Section II reviews related works. Section III introduces the motivation of this work through two benchmarks. Section IV describes the main design of CO-MAP. Some other design details are discussed in Section V. Implementation and evaluation are presented in Section VI. We conclude this paper in Section VII.

II. Related Works

Protocol Design Using Sensor Hints. The first work to explore the benefits of integrating sensor hints into wireless network architecture is [8], in which heading and speed hints are used for vehicular network path selection and movement hint (whether a node is in motion or not) is utilized for bit rate adaptation, AP association and topology maintenance.

Hidden Terminals. By leveraging the wired Internet network of APs in home WLAN, RXIP [9] schedules the transmissions of downlinks with token passing. On the contrary, CO-MAP does not require any extra radio hardware or connection network among nodes, and hence is more flexible. As CO-MAP, the empirical optimal packet size is derived in error prone wireless channels in [10] to achieve optimal link throughput and time-bound fairness of 802.11 DCF protocol in scenarios with asymmetric topology.

DBTMA [11] uses a busy tone sent by receivers to alert their potential HTs. A new MAC is proposed in [12] by combing the mechanism of power control and busy tones. Using power control can increase channel reuse and reduce co-channel interference with other neighbors. Several recent works exploit physical layer techniques to recover frames from collisions, such as ZigZag decoding [13] and successive interference cancellation (SIC) [14]. They have been shown to be efficient in USRP implementation, but do not support commodity 802.11 hardware.

Exposed Terminals. DCN [15] enables the concurrent transmissions on adjacent non-orthogonal channels by adjusting the CCA threshold. Moreover, an on-demand multi-channel MAC protocol is proposed in [16], which also leverages power control to improve spatial reuse and reduce interference in mobile ad hoc networks. However, the ET problem in co-channel is not addressed explicitly in these works.

CMAP [17] passively monitors the network traffic to build a conflict map with potentially interfering links. It suffers nevertheless from losses until conflict map entries populated. The rapid updated co-occurrence map of CO-MAP is more suitable to mobile wireless networks.

Hur et al. [18] enable concurrent transmissions by verifying the mutual impact of ETs with location information. However, it discovers ongoing transmissions by RTS/CTS exchange which is not enabled in many scenarios. Additionally, to synchronize ACKs, the payload is short which significantly limits its improvement. CO-MAP overcomes these limitations with the proposed enhanced scheduling algorithm. Moreover, CO-MAP handles the HT problem to offer a complete system design with hardware implementation.

Hidden and Exposed Terminals. Many algorithms try to find a reasonable trade-off between preventing HT collisions and increasing spatial reuses by tuning the CS threshold and/or power level [19], whereas CO-MAP separately discriminates between HT and ET to avoid this trade-off.

CENTAUR [2] schedules downlink transmissions in centralized enterprise WLAN with a controller based on an online conflict map generation technique. However, the time-consuming generation of conflict map (4 seconds for a topology with 10 APs and 10 clients) making it unsuitable for mobile wireless networks.

III. Motivation

We demonstrate the motivation of our work as well as studying the ET and HT phenomena through two experiments. Two APs are separated with 36m, each of which is associated with one laptop. The transmit power of each node is set to 0dBm. We change the positions of associated clients to study the effort location information on ET and HT verification, and modify the parameter settings (i.e., packet size) to explore its impact on protocol performance.

Exposed terminals. To validate the correlation between ETs and their positions, while two clients are transmitting TCP traffic to their associated APs respectively, we move one client to different positions to explore ET problems.

Fig. 1 shows that ETs exist in a large region and they are highly related to their positions. Initially, the client C2 is located 18m away from AP1, in the middle of two APs. C1 can detect the signal of C2 using Carrier Sense (CS), and thus it defers its transmissions while C2 is transmitting. Although the signal to noise ratios at APs are able to support the concurrent transmissions of both clients, they cannot transmit at the same time until C2 moves outside the CS range of C1.

In Fig. 1, when C2 is located 20∼34m away from AP1, it acts as a potential ET for the link from C1 to AP1. If we could infer this ET scenario through location information of each node, the goodput of the links from C1 to AP1 and from C2 to AP2 can both be improved significantly by enabling the concurrent transmissions with C2's link.

Hidden terminals. In the HT experiment, we deploy two clients with a distance of 37m to create a network under HT interferences, as illustrated in Fig. 2. Since C2 cannot sense the

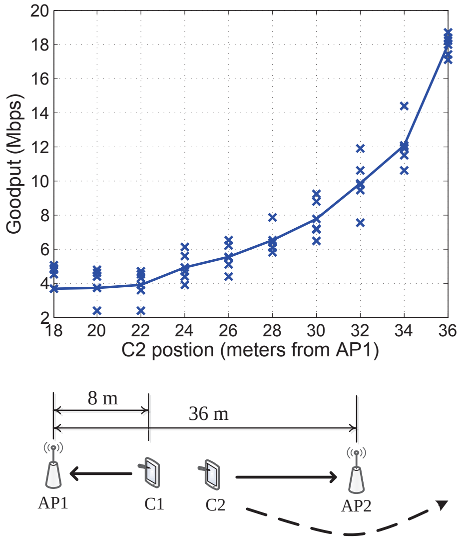


Fig. 1. Exposed terminal testbed: goodput of the link from C1 to AP1 and network configuration

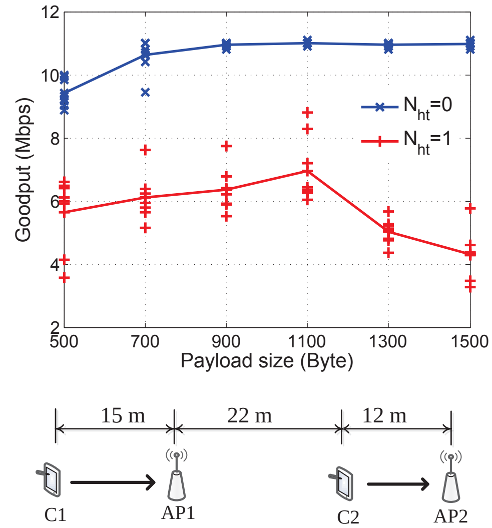


Fig. 2. Hidden terminal testbed: goodput of the link from C1 to AP1 and network configuration. N_{ht} represents the number of potential HTs

signal from C1, they transmit independently; however, when arriving at AP1, the signal of C2 corrupts the packets from C1.

We vary the size of transmitted packets during the experiment and find that the goodput of the link from C1 to AP1 is almost same for different packet sizes if there is no HT; however, with the existence of one HT, the goodput of this link varies when we change the packet size and the best goodput is achieved with a moderate packet size but not the largest one. That is because a larger packet size means a higher probability that the packet is corrupted by the transmission of potential HTs; however, a smaller packet size may reduce this probability but also increase the overhead of transmission in forms of multiple access backoff time and other header or ACK transmissions. Therefore, we believe a proper packet size should be set according to the number of potential HTs to achieve an optimal balance between collision probability and transmission efficiency.

IV. CO-MAP Design

To enable the concurrent transmissions of ETs, there are two main subproblems we must solve. First, how a node can verify that an ongoing transmission does not interfere with its coming transmission and vice versa? Second, there may be more than one ETs that can detect the ongoing transmission. We need a mechanism to prevent the potential collisions between multiple ETs. In addition, to mitigate collisions of HTs, we first need to study the severity of HT collisions and then select the best setting of parameters.

In this section, we present the design of CO-MAP which provides an unified framework to handle the above problems.

A. Preliminary design of CO-MAP

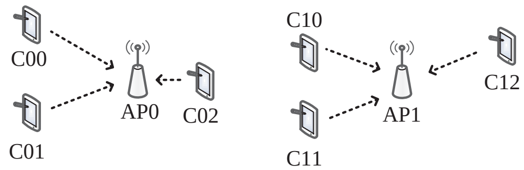
In CO-MAP, we let each node first report its position to its associated AP and such position information can be easily shared across all nearby participating nodes. The location exchange can be done with little communication overhead concerning the position upload from clients to APs and download from APs to all other nearby clients. Fig. 3 depicts an example scenario where C11 is able to obtain the positions of other nodes and organize such information into a neighbor table.

Based on the location information, a node estimates its conflicting relations with its neighbors using an accurate radio propagation model (Section IV-B). After that, each node generates a co-occurrence map recording all potential links with which it can transmit concurrently without causing packet loss at both sides. With CO-MAP, on detecting an ongoing transmission, a node verifies its concurrency opportunity by consulting its co-occurrence map. If succeeds, it competes for channel usage with other ETs using an enhanced scheduling algorithm (Section IV-C). For example, in Fig. 3, C11 can transmit independently to AP1 while C02 is sending packets to AP0; however, before its transmission, it also needs to assess channel so as to avoid possible collisions with C10.

With the neighbor table, a node can also find the number of potential HTs by studying the interference relations with its neighbors. By knowing this with CO-MAP, it selects the best setting of parameters according to an analytical model of networks containing HTs so as to reduce the potential HT collisions and thus increase goodput (Section IV-D).

B. Study of interference relations among nodes

For a successful transmission in wireless communication system, a minimum Signal to Interference plus Noise Ratio (SINR) should be guaranteed at the receiver. The minimum SINRs of 802.11b, for example, are normally 10dB for 11Mbps down to 4dB for 1Mbps. The noise in SINR refers to the noise floor which includes thermal noise, blackbody and cosmic noise. It is normally a constant for environments with



Neighbor table of C11					
Neighbor	C00	C01	C02	C10	C12
X	0	0	20	60	90
Y	0	-10	0	8	8

Fig. 3. Example of 802.11-based WLAN and neighbor table of nodes

limited area. A typical noise floor is -95dBm in 2.4GHz 802.11 WiFi networks. Therefore, instead of SINR, we use Signal-to-Interference Ratio (SIR) to study the conflicting relations between two links. A node can decode successfully the packets with a SIR larger than a given threshold, T_{SIR}.

To calculate the strength of interference signal, we use the log normal shadowing propagation model, which has been widely applied in many experiments, e.g., wireless interference modeling [20] and deployment of sensor motes [21]. It can accurately capture the radio propagation behaviors for various environments. According to this model, the received signal strength P_d at a given distance d is given by [22]:

$$P_d[dBm] = P_{d_0}[dBm] - 10\alpha log\left(\frac{d}{d_0}\right) - X_\sigma \tag{1}$$

where P_{d_0} represents the received power at a reference distance d_0, α refers to the path loss exponent, and X_σ denotes a zero-mean Gaussian random variable with standard deviation σ drawn from the log normal shadowing distribution. The reference power P_{d_0} can be obtained through field measurements close to the transmitter or calculated using the free space Friis equation. X_σ models the path loass variation caused by artifacts in the environment. As a result, the received signal strengths at different locations with equal distance from the transmitter are not the same. While this log normal propagation model captures the signal variations over large scale, the received signal may vary over small distance and time scale due to multipaht fading. As in [23], we assume that the overall impact of multipath fading is limited to a few dB. It generally holds true for wideband modulations like 802.11's.

Suppose an interferer is located r meters aways from the receiver of an ongoing transmission and the transmit powers of two senders are same. The packet reception probability of the receiver can be calculated as:

$$\begin{aligned} PRR &= Pr\left\{SIR > T_{SIR}\right\} \\ &= Pr\left\{X_\sigma^{'} - X_\sigma > T_{SIR} + 10\alpha log\left(\frac{d}{r}\right)\right\} \end{aligned} \tag{2}$$

where X_σ and $X_\sigma^{'}$ are independent values drawn from the log normal shadowing distributions of useful and interfering signals respectively. The composed variable $\left(X_\sigma^{'} - X_\sigma\right)$ is still a zero-mean Gaussian random variable with standard deviation $\sqrt{2}\sigma$. The PRR in (2) can be thus calculated as:

$$PRR = 1 - \Phi\left(\frac{T_{SIR} + 10\alpha log\left(\frac{d}{r}\right)}{\sqrt{2}\sigma}\right) \tag{3}$$

where $\Phi(x) = \left(1/\sqrt{2\pi}\right)\int_{-\infty}^{x} e^{-t^2/2}dt$ is the Cumulative Distribution Function (CDF) of standard normal distribution. If the addresses of two senders and two receivers are known, based on (3), a node can verify the mutual interferences of any two links. It is essential for ET and HT detection. In this work, we mainly focus on scenarios with one interferer. The aggregated impact of multiple HTs and ETs will be handled in future works. However, we will handle the multiple access problem of ETs to avoid the potential collisions among them.

C. Exposed Terminals

To enable the concurrent transmissions of ETs, in CO-MAP, a node first discovers the ongoing transmission to know the addresses of its sender and its receiver, and then verifies the feasibility of concurrent transmission with relative neighbors. Before transmission, it executes an enhanced scheduling algorithm to avoid the potential collisions with other ETs.

1) Concurrency Validation: RTS/CTS exchange is optionally adopted by 802.11 standards. It is not enabled in many cases due to its overhead and inefficiency of detecting all HTs. Moreover, it aggravates the ET problem. Without using RTS/CTS, nodes transmit frame packets directly using CSMA. To enable the discovery of ongoing transmissions, a separate header is encapsulated at the beginning of MAC Protocol Data Units (PDU). The header includes the destination and source addresses of its frame packet. On receipt of this header, a node recognizes the sender and receiver before the incoming frame transmission. This property ensures that nodes start or defer their exposed transmissions in a timely manner.

On detecting an ongoing transmission, a node searches in its neighbor table to find the positions of relative nodes and calculates two distances used in (3). As illustrated in Fig. 4, one is the distance between the current transmitter and receiver (d_1). The other is between itself and the current receiver (r_1). Based on these distances, the node estimates its interference to the ongoing transmission. If the PRR is larger than a given threshold, T_{PRR}, it infers that its incoming transmission will not interfere with the ongoing transmission.

Meanwhile, to enable a concurrent transmission, the node also needs to verify the impact of the ongoing transmission to its coming transmission. We can also utilize (3), where d_2 represents now the distance between this node and its receiver, and r_2 is the distance between its receiver and the ongoing transmitter. If the result is smaller than T_{PRR}, this node cannot transmit concurrently because its receiver is too close to the ongoing transmitter. It may choose another receiver further away from the current transmitter and verify again; otherwise, it abandons this exposed transmission opportunity and waits for the end of current transmission to compete for channel access with other nodes using CSMA.

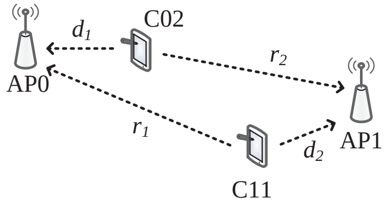


Fig. 4. Concurrency validation. Node C11 first estimates its interference to the ongoing transmission using equation (3) with distance d_1 and r_1 , and then verifies the impact of ongoing transmission on its coming transmission with distances d_2 and r_2.

Neighbor table of C11					
Neighbor	C00	C01	C02	C10	C12
X	0	0	20	60	90
Y	0	-10	0	8	8

PRR table of C11					
Neighbor	C00	C01	C02	C10	C12
PRR of Neighbor	2.3%	2.3%	97%	0%	0%
PRR of C11	97%	97%	97%	0%	0%

Co-occurrence map of C11	
Source	C02
Destination	AP0

Fig. 5. Location information process of node C11 in the example network of Fig. 3: from neighbor table to co-occurrence map with an intermediate transition of packet reception ratio table.

In such a way, the position information is converted to the interference relations which are indicated by PRRs of the node under consideration and one of its neighbors if they transmit simultaneously. The results are recorded in a PRR table as illustrated in Fig.5.

2) Co-Occurrence Map: To improve the efficiency, every node builds a co-occurrence map based on the PRR table, as illustrated in Fig. 5. Each entry in this map records one link with which it can transmit concurrently. If the node is a mobile device, it only has one receiver, i.e., its associated AP; therefore, its co-occurrence map only stores possible concurrent links. However, for an AP, an entry of co-occurrence map contains one link and all the potential receivers to which it can transmit concurrently. For example, in Fig. 3, while C02 is sending packets to AP0, C10 can communicate with AP1 and $AP1$ can transmit to $C12$, but not $C10$ and $C11$.

On detection of an ongoing transmission, the node first searches in its co-occurrence map. If no entry with current link is found, it will verify the concurrency opportunity with this link by computation based on (3). If the validation is passed, this node will start its transmission process immediately. It then inserts this link and its possible concurrent receivers into the co-occurrence map. By doing this, nodes incur quick and light-overhead table searching to verify concurrency instead of executing the same calculation repeatedly when a given transmission occurs. Initially, the co-occurrence map is empty. It is built gradually as the network operates. Therefore, CO-MAP does not require any off-line site survey or suffer from any network performance degradation during initialization.

3) Multiple Exposed Terminals: There may be more than one nodes succeeding in concurrency validation. An enhanced scheduling algorithm is proposed to avoid collisions among multiple ETs.

For the typical CSMA process in Distributed Coordination Function (DCF) of 802.11 standard, when a node detects an ongoing transmission, it pauses its backoff timer until it finds the medium free for more than Dcf Interframe Space (DIFS) duration. After the transmission of one node, it starts a new backoff timer for its next frame transmission and other nodes resume their frozen backoff process, as illustrated in Fig. 6.

With the enhanced scheduling algorithm of CO-MAP, on receipt of an ongoing transmission, ETs record their current RSSI (named as $RSSI_1$) and resume their backoff process. During the backoff period, they keep monitoring the channel and measuring their RSSIs (denoted as $RSSI_2$). If the $RSSI_2$ of an ET holds that $RSSI_2 = RSSI_1 + T_{cs}^{'}$, this node infers that the transmission of another ET occurs and it will abandon its concurrent transmission opportunity; otherwise, it will start transmitting when its backoff counter reaches zero. T_{cs} represents the Clear Channel Assessment (CCA) threshold and $T_{cs}^{'}$ is the part of T_{cs} not containing the noise floor.

One frame includes the transmissions of header, data frame and ACK, one DIFS and one short interframe space (SIFS). In Fig. 6, while C02 is transmitting, C10 and C11 detect this ongoing transmission by receiving its header. They thus resume their backoff counter. After a short moment, the counter of C11 first expires and it starts transmitting. C10 senses this second transmission and freezes its backoff counter until the transmissions of C02 and C11 end.

CO-MAP improves the network goodput by enabling extra exposed transmissions. From Fig. 6, we can see that CO-MAP provides an almost twofold raise in goodput. Meanwhile, the concurrent transmissions do not cause extra collisions, since ETs still use CS to monitor channel during backoff process. The transmission of the final succeeded ET will not interfere with other ongoing transmissions, except the HT problem which exists in the basic 802.11 DCF and will be addressed in Section IV-D. Additionally, CO-MAP increases the network efficiency by parallel transmissions without changing the sequence of transmissions fixed by basic 802.11 DCF or adding more extra transmission loads to some particular nodes. It does not thus impact the fairness of basic 802.11 DCF or cause the energy unfairness problem in duty cycle wireless networks as presented in [24].

4) ACK Loss Problem: Because the ongoing transmission may not finish synchronously with the exposed transmission, their ACKs have a high probability to be corrupted with the remaining data packet transmission. To solve this ACK loss

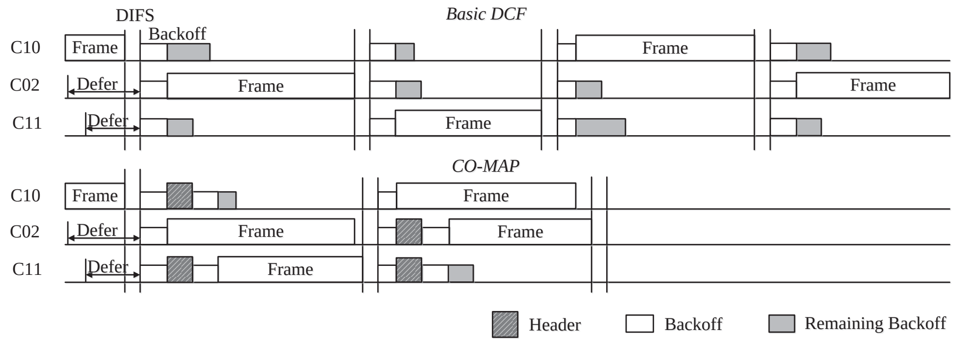


Fig. 6. Communication procedure for basic 802.11 DCF and for the enhanced scheduling algorithm of CO-MAP in the context of multiple exposed terminals

problem, we adopt the selective repeat Automatic Repeat-Request (ARQ) method [25]. This windowed ACK mechanism avoids unnecessary retransmissions of frame packets in cases that frame packets have been correctly received by receivers but ACKs were lost due to the interferences from ETs.

With selective repeat, a transmitter sends a set of frames with consecutive sequence numbers specified by a window size up to W_{send}. After sending a frame, it waits for an ACK from the receiver for a duration $t_{ACKwait}$. If no ACK arrives in this time, it transmits next frame in the sending window instead of retransmitting the non-acknowledged packet. On receipt of a frame, the receiver sends back an ACK acknowledging the sequence numbers of former missing frames. Once the sender has sent all frames in its window, it resends the lost frames indicated in the ACKs it received.

D. Hidden Terminals

A collision caused by HTs occurs in three cases. First, a given node starts transmitting when one of its HTs is emitting radio signal. Second, this node under consideration starts transmitting exactly simultaneously with one of its HTs. Third, during the transmission of this node, one of its HTs starts transmitting. Based on this observation, we find that the HT collision probability is determined by the number of potential HTs and the channel occupancy time of the node under consideration and its HTs.

CO-MAP mitigates the collisions caused by HTs with dynamic adaptation of packet size according to the number of potential HTs, denoted as N_{ht}. When N_{ht} is large, it uses a short packet size to minimize the channel occupancy of each node and thus reduces the collision probability; otherwise, it adopts a long one to pursue higher transmission efficiency (i.e., goodput).

1) Number of Potential Hidden Terminals: For a given link from S to R, its HTs are located inside its interference range and outside the CS range of S. To find the number of potential HTs, by using (3), S first finds all interference nodes which may cause its PRR below a certain value if any of them transmits concurrently. Among these nodes, it further chooses the ones that cannot catch its signal by CS.

Due to the effects of random shadowing, every neighbor of S has a probability that its received signal from S is less than a certain CS value, T_{cs} in dBm. Based on (1), we obtain this probability as:

$$Pr\left\{P_r < T_{cs}\right\} = \Phi\left(\frac{T_{cs} - P_{d_0} + 10\alpha log\left(\frac{r}{d_0}\right)}{\sigma}\right) \tag{4}$$

where r is the distance between the sender and its relative neighbor. The relation between $Pr\left\{P_r < T_{cs}\right\}$ and r is monotonically increasing. A larger r corresponds to a higher probability that S's signal cannot be sensed by this neighbor. In our study, we treat a node as HT if its $Pr\left\{P_r < T_{cs}\right\} > 90\%$.

2) System Model: Bianchi [26] provided an analytical model to study the performance of the IEEE 802.11 DCF MAC protocol under the hypothesis of ideal channel (i.e., no HT and capture). It mainly focus on the networks in which every node has immediately a packet available at the end of a transmission.

To find the best parameter settings for the optimal network goodput, we extend this model to the networks considering HTs. The goodput S of a link from node i in the networks with HTs can be calculated as:

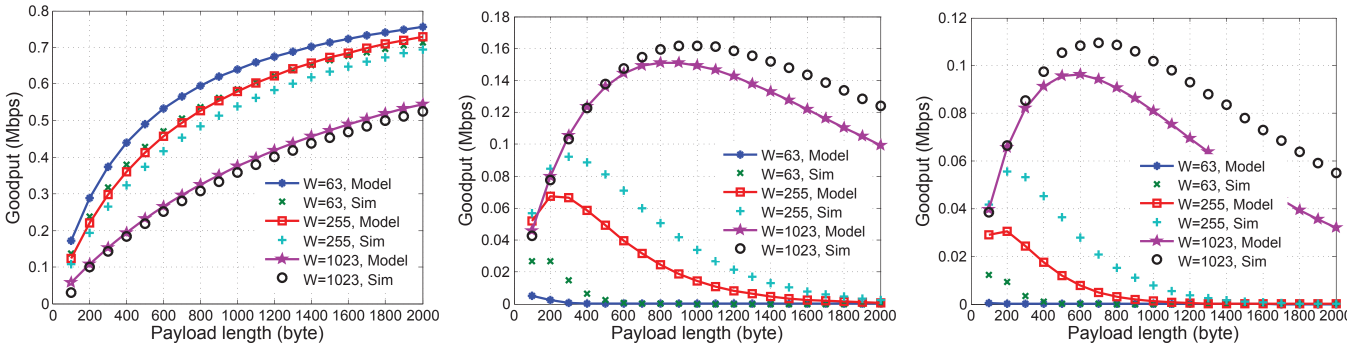
$$\begin{aligned} S_i &= \frac{E[Payload\ transmitted\ in\ a\ slot\ of\ node\ i]}{E[Slot\ length]} \\ &= \frac{P_s^i L^i}{(1-P_{tr})T + P_{tr}P_sT_s + P_{tr}(1-P_s)T_c} \end{aligned} \tag{5}$$

where P_s^i represents the probability that the transmission of node i succeeds in a randomly selected time slot considering the interference of HTs, L^i denotes its payload length. Since HTs do not change the slot length viewed from the point of contending nodes, we can use the method in [26] to calculate $E[Slot\ length]$, the average length of slot.

For a link from node i with c contending nodes and h hidden nodes, where $h = \hat{N}_{ht}$ and c can be obtained using the same derivation process of $\hat{N}_{ht}$, P_{tr} refers to the probability that there are at least one transmission in the considered slot.

$$P_{tr} = 1 - (1-\tau)^{c+1} \tag{6}$$

where τ is the probability that a node transmits a frame in a randomly chosen slot time and $\tau = \frac{2}{W+1}$ for networks with



(a) No HT (b) 3 HTs (c) 5 HTs

Fig. 7. Theoretically calculated goodput and simulation validation of a link with five contending node and several HTs

constant backoff window size W. P_s is the probability that a transmission in the networks without HTs is successful.

$$P_s = (c+1)\tau(1-\tau)^c / P_{tr} \tag{7}$$

In equation (5), T is the empty slot length, T_s is the successful packet transmission time, and T_c represents the expected time for a failed packet transmission.

$$\begin{aligned} T_s &= T_{HDR} + T_{E[l]} + SIFS + T_{ACK} + DIFS \\ T_c^i &= T_{HDR} + T_{E[l^*]} + DIFS \end{aligned} \tag{8}$$

HDR refers to the PHY and MAC header, $E[l]$ and $E[l^*]$ are the average packet length of all nodes and the longest packet size involved in a collision. For small scale networks, we assume all nodes are homogeneously distributed; therefore, $E[l]$ and $E[l^*]$ are same throughout the network.

By considering HTs, a node can transmit successfully only in the conditions that none of its HTs is using the channel when it starts transmitting and none of its HTs begins sending packets during its transmission; therefore, P_s^i can be given as:

$$P_s^i = \tau(1-\tau)^c[(1-\tau)^h]^k \tag{9}$$

where $k = (T_s + T_i)/E[Slot\ length]$ is the average number of slots during the transmissions of node i and one of its HTs.

3) Packet Size Adaptation: Based on the above equations, we can find the best parameter setting to achieve the optimal goodput for the networks with HTs. For a link with five contending nodes and different numbers of HT, we plot its goodputs for various sizes of packet and contention window in Fig. 7, which suggests that there exists a best setting of CW and packet size to achieve the highest goodput for different numbers of HTs and contending nodes. We also validate the accuracy of this theoretical system model through NS-2 simulations. The results are presented in Fig. 7 as well. The explanation of simulation configuration and results will be given in Section VI.

To reduce the computation overhead on mobile devices, we calculate the best packet configurations for different number of HTs and contending nodes beforehand. The results are recorded in a 2-dimension array. An element of *i*th row and *j*th column represents the best CW and packet size values for a node with *i* HTs and *j* contending nodes.

V. Discussions

Overhead of exchanging location information. To identify HTs and ETs, a node only needs to know the positions of neighbors within 2-hop instead of all nodes in the network. For instance, in Fig. 3, C10 and C11 are HTs to C00 and C01. To verify HTs, C00 and C01 should know the positions of C10 and C11 which are located one transmission range (R_t) added by one interference range (R_{in}) away. These ranges of each node are calculated by its AP using the radio propagation model and the probabilistic approach of Section IV-D1. In addition, C02 is an ET to C10 and C11. The maximum distance between them is $2R_t$.

Mobility management. Users access Internet commonly while sitting in a place or with little movement in most scenarios, such as conference room, hospitals and universities. Every node updates its position only if its movement is larger than a certain distance. We set it to the half of the highest position inaccuracy we can tolerate. By doing this, it only causes extra communication overhead when long distance movement happens.

Implementation of header. The header added to normal 802.11 packets to discover ongoing transmissions can be implemented in two ways. One is to insert an extra Frame Check Sequence (FCS) after the sequence number field in MAC PDU so that the PHY layer can pass the source and destination addresses to upper layers before the receipt of frame payload using partial packet recovery techniques [27]. This method adds only four bytes overhead on the current 802.11 frame format. However, commodity hardware platforms may not support it. An alternative approach sends a separate small header packet with its own FCS field before frame packet transmission. It realizes the discovery of ongoing transmission without modifying the current PHY implementations. We adopt the second method in our testbed implementation which does not require any hardware modifications.

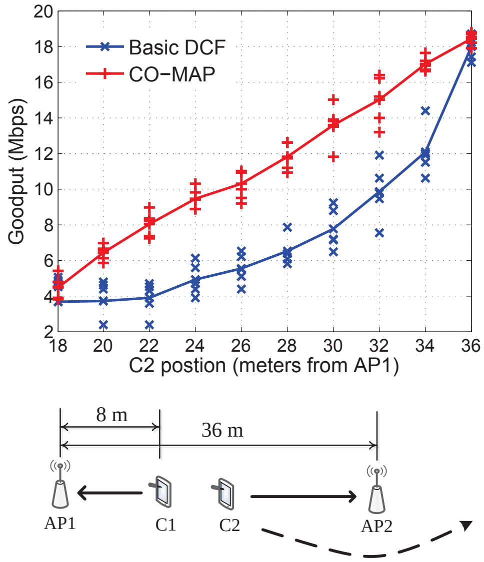


Fig. 8. Goodput improvement of CO-MAP for the link from C1 to AP1 in exposed terminal scenarios.

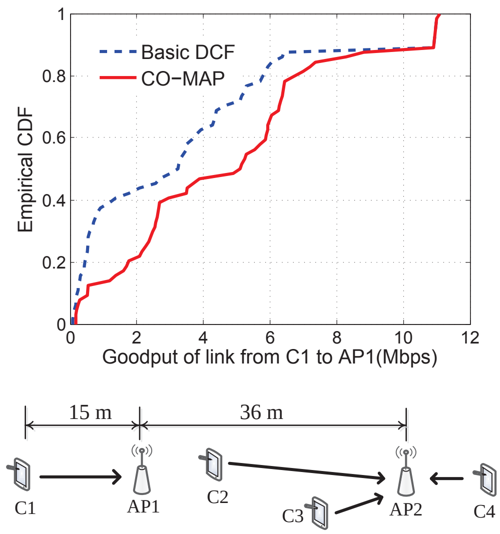


Fig. 9. Goodput improvement of CO-MAP for the link from C1 to AP1 in hidden terminal scenarios

VI. Implementation and Evaluation

We implement CO-MAP on both commodity hardware platforms and NS-2 simulator. In this section, we evaluate the performance of CO-MAP with many experiments on real testbeds and NS-2 simulations. First, we show the goodput improvement provided by CO-MAP for ET and HT scenarios respectively in small scale testbed experiments. Second, we conduct many experiments for large scale networks with various topologies on NS-2.

A. Hardware testbeds

Implementation. The testbed is composed of 6 laptops equipped with Intel Wireless WiFi Link 4965AGN network adapter running Linux kernel 3.2.0 with MAC80211 and iwlegacy wireless drivers. We implement CO-MAP through extending iwlegacy with 3 components: (1) generation of co-occurrence map and interference relations among nodes; (2) header and concurrent ET transmission; (3) dynamic packet size adaptation according to the number of potential HTs. We use *Iperf*, a widely-distributed network measurement tool. It keeps sending TCP traffic from one or multiple terminals to another one. The goodput of each link is recorded. For all tests, we disable virtual carrier sense (RTS/CTS) since it is not enabled in many cases due to its limitations, such as overhead, inefficiency, and aggravation of ET problem. The default data rate adaptation algorithm in MAC80211, Minstrel [28], is enabled to verify the effectiveness of CO-MAP under real bitrate conditions.

The transmit power of each node is set to 0dBm. By measurements in our office, a large room of $800m^2$ with hard partition panels, the path loss exponent α is set to 2.9 and the Gaussian random variable σ is 4dB for the log normal shadowing propagation model used in CO-MAP. T_{sir} is set to 4 for the lowest data rate. The receiving sensitivity is high for the low data rate; therefore the interfering node could be near to the ongoing receiver. Since we enable the data rate adaptation, when a node infers it is an ET to an ongoing transmission with this low T_{sir}, it can transmit simultaneously with an higher data rate if it is located further away from the ongoing transmission.

Goodput improvement for exposed terminal scenarios. To verify the goodput improvement provided by CO-MAP over basic DCF, we redo the experiments of section III with CO-MAP enabled. The network configuration and parameter setting are unchanged.

Results presented in Fig. 8 show that CO-MAP can accurately discover the concurrent transmission opportunities and provide 77.5% average increase of goodput. We find that C2 plays as an ET for the link from C1 to AP1 when it is located 20$\sim$34m away from AP1. In this region, by enabling the concurrent transmissions of C1 and C2, their goodputs are both improved significantly.

As C2 is removed further away from AP1, the goodputs of basic DCF and CO-MAP are both increased. This is the result of data rate adaptation by Minstrel. When the interferer is located far, its impact to the ongoing transmission is weak and the required signal to interference ratio of the ongoing receiver is low to successfully decode the useful information. Therefore, a higher data rate could be used to the link from C1 to AP1; otherwise, a lower data rate should be adapted. Fig. 8 demonstrates that CO-MAP is complementary to the data rate adaptation and can further improve the performance of WLAN under data adaptation. CO-MAP infers a node to be an ET using the lowest data rate corresponding to the shortest distance from the ongoing receiver. If the node is located beyond this distance, a higher data rate could be adapted.

Goodput improvement for hidden terminal scenarios. To

TABLE I

PARAMETER SETTING FOR THE NS-2 SIMULATIONS

Parameter	Value	Parameter	Value
Data rate	6Mbps	TX power	20dBm
T_{PRR}	95%	T_{cs}	-80dBm
Path loss exponent α	3.3	$T_{cs}^{'}$	-80.14dBm
Standard deviation σ	5dB	T_{sir}	10

validate the accuracy of packet size adaptation, instead of one HT in the experiment of Section III, we place 3 clients around AP2 with various positions to explore different configurations of HT and contending nodes, as illustrated in Fig. 9. C2 works as a contending node for the link from C1 to AP1; C3 is a HT; and C4 is an independent node whose transmission has no impact on C1's. Therefore, we can totally configure 10 different network topologies by changing the positions of these three clients.

From Fig. 9, we can see that CO-MAP offers 38.5% mean gain of goodput. When all the clients of AP2 are located far away from AP1, they transmit independently and the goodput of the link from C1 to AP1 achieves the highest value, 11Mbps. As the number of HTs increases, we reduce the payload size of transmitted packets gradually to maximize the goodput. For instance, when the HT number is 3, we set the payload size to 900 bytes according to the results of the theretical system model in SectionIV-D2.

B. NS-2 simulations

With large scale simulations on NS-2, we evaluate the accuracy of the theoretical system model developed in Section IV-D2 and the overall performance of CO-MAP as well as its tolerance to the inaccuracy of position information.

Accuracy of the theoretical system model. We verify whether equation (5) can capture the network behaviors with different settings of parameters. The default 802.11 WLAN module distributed in NS-2.35 is used to do this test.

Results presented in Fig. 7 prove that the theoretical system model can accurately capture the network behavior and find the best setting of parameters for networks with different configurations. The highest goodput of a link without HT is achieved with the largest payload length and a small CW size. In this case, because every contending node can detect the transmission of this link by using CS, the largest payload length raise the transmission efficiency without causing extra collisions, and a moderate CW size finds a reasonable balance between collision avoidance and transmission efficiency. When the number of HTs increases, CW size should be set to the maximum value to slow down the transmission of all nodes and to reduce their impact on each other; however, a large payload length can still be used to pursue high transmission efficiency. When the number of HTs is large, a small payload length should be used to shorten the channel occupancy time of nodes and thus reduce the collision probability with HTs.

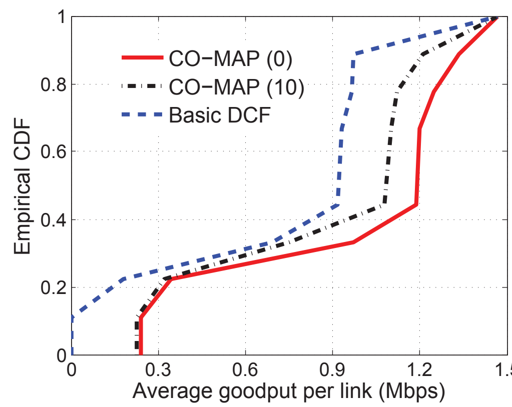


Fig. 10. Empirical CDF of goodput in large scale network test. CO-MAP (0) presents that the perfect position information is used, while CO-MAP (10) refers to that a random error within 10m is added to the position of each node.

Goodput improvement for large scale networks. In the testbed implementation, because we cannot access the hardware-supported backoff process, on detecting an ongoing transmission, we enable the concurrent transmissions of one ET by disabling its carrier sense with a high CCA threshold. To comprehensively evaluate the performance of CO-MAP, we implement all its functionalities including the proposed enhanced scheduling algorithm in NS-2.

We deploy three APs separated about 60m to mimic the real-life deployment in our office floor. Eight APs with three separate non-overlapping frequency bands are deployed in this floor, only the ones using the same frequency band are considered. Nine clients are randomly deployed around these APs to form 30 distinct topological configurations. By statistics, in this network, 47.6% links have at least one ET and 19.4% links have HTs. Clients and their relative APs are transmitting Constant Bit Rate (CBR) TCP traffic in two-way. The CBR generation rate is set highly, 3Mbps, to emulate the multimedia or VOIP applications which are commonly used on smartphones. The parameter settings are summarized in Table I. The path loss exponent α and Gaussian random variable σ of the log normal shadowing propagation model are higher than the testbed experiment, because the network area is larger and the radio enviroment is more complex. All other parameters are set to the default values of HR/DSSS PHY specifications for the 2.4GHz band defined in the standard [29]. All the simulations are run 100 times and the average results are recorded.

The empirical CDF of average goodput per link presented in Fig. 10 shows that CO-MAP provides 1.385X mean aggregated goodput gain over basic DCF protocol with accurate position information of nodes. These experiments suggest that CO-MAP can efficiently improve the spatial reuse and channel usage with positive scalability of its distributed design.

To verify the tolerance of our approach to the position inaccuracy, we add random error within a certain range to the coordinates of each node in the above experiments. In

Fig. 10, we can see that CO-MAP is still able to provide 18.7% improvement of network goodput with 10m position error range instead of 38.5% with perfect position information.

Position inaccuracy can cause four misclassifications: wrong ET (non-ET nodes inferred as ETs), missing ET (ETs to non-ETs), wrong HT (non-HTs to HTs), and missing HT (HTs to non-HTs). The non-ET nodes refer to the ones that can sense and impact the signal of ongoing transmissions. The missing ET detection just causes the miss of concurrent transmission opportunity but do not reduce goodput. The wrong and missing HT detection slightly change the number of HT which does not impact much our improvement gain of goodput. Only the wrong ET detection makes goodput degrade; however, because of its small percentage, its impact is limited.

VII. Conclusion

This paper leverages the room level location information provided by current smartphones and tablets to improve the multiple access efficiency of underlying mobile wireless networks. By converting the position information to a co-occurrence map, it schedules the channel access of multiple exposed terminals in a distributed manner. It also improves the goodput by avoiding collisions according to the number of hidden terminals. With the rapid update of co-occurrence map, CO-MAP enables WLAN to provide users higher performance when they associate with the network without site survey. We believe CO-MAP is the first integrated framework handling both hidden and exposed terminal problems with location information for downlink and uplink optimizations. Moreover, it is a successful practice of using sensor hints of mobile devices in communication protocol design.

Despite mobile WLAN, the models and techniques developed in this paper can also be applied to the stationary wireless mesh networks where the locations of mesh stations are prior knowledge. We are planning to implement CO-MAP in our mesh sensor network for wind measurement and water quality monitoring [30]. CO-MAP can maximize the exposed concurrent transmissions and mitigate collisions caused by hidden terminals of this long distant mesh network.

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