Link Availability Prediction Enhanced IEEE 802.11-Based Cooperative MAC with Mobile Relays

Peijian Ju, Wei Song, and Dizhi Zhou
Faculty of Computer Science
University of New Brunswick, Fredericton, Canada
Email: {i1689, wsong, q5frc}@unb.ca

***Abstract*—One of the most challenging issues in cooperative wireless networks at the medium access control (MAC) layer is to select a good helper (relay node) to start cooperation. The helpers' information is often stored in a CoopTable and updated via overhearing of the helpers' traffic. However, when the helpers are transmitting data infrequently or having random mobility, the cooperation may suffer from the out-of-date information in the CoopTable, since the source cannot gather enough timely information to make a good cooperation decision. In this paper, we propose to use link availability prediction to address such out-of-date information problem at the MAC layer. Making use of the possibly out-of-date information, our proposed solution does not introduce any additional signalling overhead but enables the source node to estimate the probability that the helper may appear in each cooperation zone. As such, the source node is able to make an intelligent decision even with the out-of-date information and benefit from a successful cooperation. The simulation results well demonstrate the source throughput improvement even when the helpers are less active in transmission and experiencing random walk mobility.**

***Index Terms*—Cooperative MAC protocols, throughput, mobility prediction, link availability, random walk mobility.**

I. Introduction and Related Work

Cooperation among mobile terminals is a promising approach to exploit spatial diversity without involving the multi-antenna overhead of multiple-input and multiple-output (MIMO). To enable cooperation at the medium access control (MAC) layer, e.g., in a contention-based wireless local area network (WLAN), a cooperative MAC protocol needs to address two fundamental questions [1,2]: ***When to cooperate?*** (Q1) and ***Whom to cooperate with?*** (Q2). The question Q1 is to find the conditions when cooperation can be enabled, or the regions where cooperation is beneficial. The question Q2 addresses how available helpers compete to become a candidate and how the optimal helper(s) are selected according to certain criteria and decision mechanism.

According to which entity addresses Q1 and/or Q2, the typical cooperative MAC protocols can be classified into different categories [2]. Particularly, many proposals address Q1 at the source, which is very similar to IEEE 802.11 MAC. The information of helper candidates is often collected and stored in a table at the source, e.g., the CoopTable in [3]. Although the table can be updated via overhearing the traffic of the helper candidates, the information may be out-of-date when inactive helpers have infrequent transmission and/or random mobility. In [3,4], throughput degradation is observed in various mobile scenarios when the obsolete information become severe. In [5], we address this problem by using perceptron training to differentiate static helpers from highly mobile helpers. However, a sufficient amount of overheard packets need to be collected as the training input, which is infeasible for a real-time implementation.

Link availability prediction is one of techniques to address user mobility. It is widely used at the network layer and application layer for functions such as reservation of network resources and location-based on-line advertising [6]. The existing work on link availability with the random walk model is rather limited. In [7], the non-continuous link availability probability with a time interval is analyzed. In [8], the continuous link availability performance is studied. In [9], instead of assuming that the magnitude of relative mobility vector between two nodes is Rayleigh distributed, a Markov chain model is developed to characterize the random movement of nodes and derive the continuous link availability.

Motivated by the idea of link availability prediction for the network layer routing, we address the out-of-date problem of CoopTable using link availability prediction and propose a real-time and cost-effective MAC solution, referred to as *LapCoopMAC*. LapCoopMAC follows the overhearing procedure of CoopMAC-II in [10] to update CoopTable. However, instead of abandoning the obsolete helper information, we propose to employ the link availability prediction technique to extract useful guidance from the out-of-date information. At first, the link availability prediction is extended to the scenario with cooperation zones. Then, the CoopTable is restructured with additional information from the prediction results, such as the most likely zone and estimated probability of cooperative link availability. An effective helper selection algorithm is designed by taking advantage of such information. Simulation results show that LapCoopMAC is able to enhance the source throughput by up to 18% when the CoopTable is out-of-date due to inactive helpers with infrequent transmission, and by up to 13% when helpers have a reasonably random mobility.

The rest of this paper is organized as follows. In Section II, we introduce the cooperation topology and CoopMAC-II protocol, and show the impact of out-of-date CoopTable on

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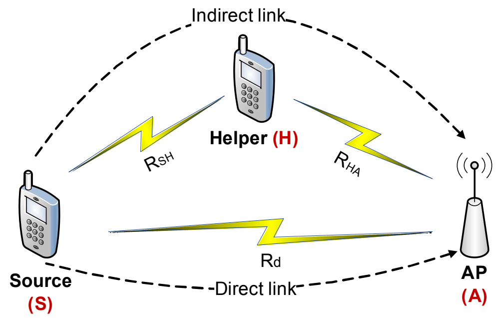

Fig. 1. The cooperation scenario.

throughput. Then, LapCoopMAC is presented in Section III. We provide the simulation results and discussions in Section IV, followed by conclusions and future work in Section V.

II. Impact of Out-of-Date CoopTable

Consider the cooperation scenario in Fig. 1 for 802.11 WLAN. Suppose that multiple transmission rates are supported. Letting R_r denote the effective data rate over the indirect link, we have $R_r = (R_{SH}^{-1} + R_{HA}^{-1})^{-1}$, where R_{SH} is the transmission rate between the source S and the helper H, and R_{HA} is the transmission rate between the helper H and the access point A. Given a fixed transmit power, the transmission rate decreases with a longer transmitter-receiver distance. Hence, it is reasonable to select the indirect link if the feasible transmission rate of the direct link (denoted by R_d) is less than the effective data rate of the indirect link, i.e., $R_d < R_r$. For example, when $R_{SH} = R_{HA} = 11$ Mbit/s and $R_d = 1$ Mbit/s, the indirect link is preferred since $R_r = (11^{-1} + 11^{-1})^{-1} = 5.5 > R_d = 1$.

Assume that a transmission rate is achievable within a signal coverage of radius R_i. Then, several cooperation zones [3] are formed as shown in Fig. 2 depending on R_{SH} and R_{HA}. For example, if H is in Z_4 with its relative distance to S and A, R_{SH} is 11 Mbit/s, R_{HA} is 2 Mbit/s and R_r with a helper in Z_4 is 1.69 Mbit/s. For helpers in other cooperative zones, R_{SH}, R_{HA} and the effective rates of the indirect link can be found in Table I.

TABLE I
Transmission Rates (Mbit/s) within Cooperation Zones.

Zone	Z_1	Z_2	Z_3	Z_4	Z_5	Z_6	Z_7	Z_8
R_{SH}	11	11	5.5	11	2	5.5	5.5	2
R_{SH}	11	5.5	11	2	11	5.5	2	5.5
R_r	5.5	3.67	3.67	1.69	1.69	2.75	1.47	1.47

A. Traditional CoopTable Updating and Data Transmission

CoopMAC-II proposed in [10] does not introduce any extra control frames and thus maintains backward compatibility with the legacy IEEE 802.11 protocol. It specifies the following procedures to accomplish a cooperative transmission:

- ***Overhearing and CoopTable Updating.*** When S is not using the channel, it keeps overhearing the transmission between H and A.

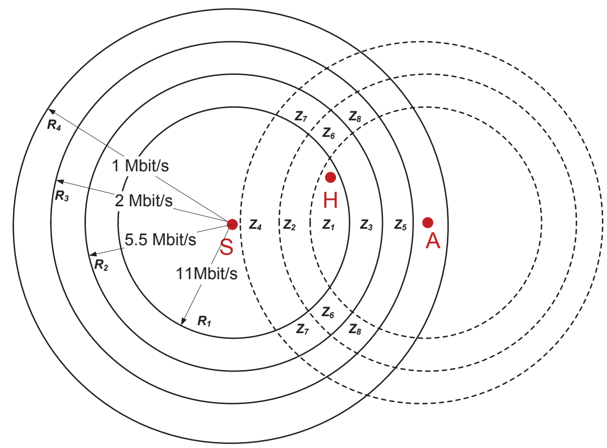

Fig. 2. The cooperation zones of S and A.

  - By overhearing the request-to-send (RTS) frames from H to A, R_{SH} is estimated.
  - By overhearing the clear-to-send (CTS) frames from A to H, R_{HA} is estimated.
  - When S reserves the channel using RTS, the direct transmission rate (R_d) between S and A is obtained by extracting the information from the CTS of A.

  Then, R_{SA} and R_{SH} are used to update the source's CoopTable as shown in Table II, where *Time* is when the last packet is heard from a helper and *Failures* is the count of sequential transmission failures.

TABLE II
CoopTable structure.

MAC Address	Time (s)	R_{SH} (Mbit/s)	R_{HA} (Mbit/s)	Failures
H_1 address	0.1	5	1.69	5
H_2 address	0.2	5	5.5	0
...	...	...	...	...

- ***Data Transmission.*** Whenever the source has a packet to transmit, it checks whether there exists a better indirect link than the direct one. If there is, an RTS whose *Address4* field is filled with the helper's MAC address is sent. Otherwise, normal RTS is used. On receiving CTS, S sends its packet to H. If an ACK is received from A, it means that H relayed the packet. Otherwise, it means that cooperation failed and the packet is retransmitted by direct transmission with *Failures* of that helper added by one. When *Failures* exceeds a certain threshold, this row in the CoopTable will be deleted. At H side, if it is able to receive the packet at the rate R_{SH}, H relays the packet to A to achieve a higher rate over the indirect link. Otherwise H discards the packet.

B. Impact of Out-of-Date Information in CoopTable

As mentioned in Section I, there are two major causes that may result in an out-of-date CoopTable. The first one is inactive helpers, which are transmitting infrequently. Consider an on-off traffic pattern at the helper, which means that the helper alternates between an on-state of sending packets and an off-state of idling. Denoting the average on-period and off-period by t_{on} and t_{off}, respectively, we use t_{off} to indicate the activeness of the helper. Given a fixed t_{on}, the higher t_{off} is, the less active the helper is, and the less traffic the helper transmits. The out-of-date problem of the CoopTable is thus more severe with less overheard packets at the source.

Secondly, the helper mobility may cause the out-of-date problem. In this paper, we consider the random walk model [7] to characterize the helper mobility, which is specified by a profile $\{t_{avg}, v_{max}\}$. Whenever a helper starts to move, it follows a speed uniformly distributed in $[0, v_{max}]$ and an angle uniformly distributed in $[0, 2\pi]$, and travels for an *epoch* of t seconds, where t follows an exponential distribution of an average t_{avg}. Specifically, the higher t_{avg} or v_{max} are, the longer the distance travelled in an epoch, and the higher the probability the helper moves into another cooperation zone. The higher mobility randomness can exacerbate the out-of-date problem.

To examine the impact of the above two causes on the source throughput, Fig. 3 shows the simulation results of CoopMAC-II in the scenario of Fig. 2 when the helper activeness or mobility profile are varying. The initial position of the helper is assumed in Z_6. As seen in Fig. 3(a), given a mobility profile $\{t_{avg} = 2s, v_{max} = 5m/s\}$, the source throughput is dropped by around 19.5% when t_{off} is increased from $2s$ to $20s$, i.e., the helper becomes less active. For $t_{off} = 20s$, Fig. 3(b) shows that when v_{max} is increased to 12 m/s the cooperation gain almost diminishes and the source throughput approaches that with only direct transmission.

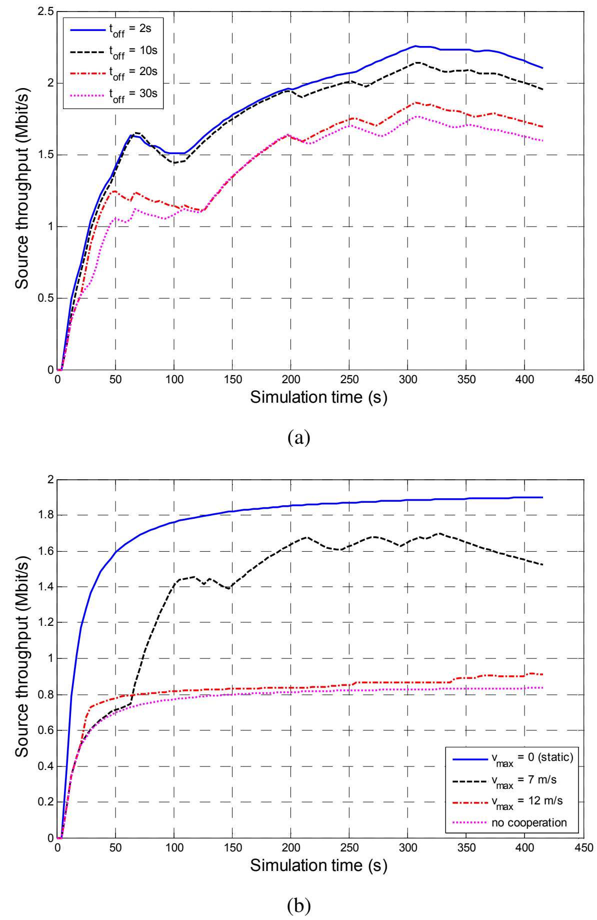

Fig. 3. (a) Source throughput with varying t_{off} (assume a mobility profile $\{t_{avg} = 2s, v_{max} = 5m/s\}$). (b) Source throughput with varying maximum speed v_{max} (given $t_{off} = 20s$).

III. Cooperative MAC with Link Availability Prediction

To alleviate the negative impact of out-of-date CoopTable, we propose a solution referred to as *LapCoopMAC* in this section. Analyzing the out-of-date information in the CoopTable, we first extend the link availability prediction technique [7,9] to the cooperation zones in Fig. 2. Accordingly, we evaluate the probability that the helper appears in each cooperation zone. The CoopTable is then reformatted to include the predication results and enable an effective helper selection algorithm.

A. Link Availability Prediction

Link availability prediction has been widely studied for mobility prediction in mobile ad hoc network. It is a probabilistic model to predict the future status of a wireless link [11]. Let $d_{mn}(t)$ denote the distance between nodes m and n at time t. It is often assumed that the link between m and n breaks when $d_{mn}(t)$ exceeds a bound R, i.e., $d_{mn}(t) > R$ [7]–[9]. Given $d_{mn}(t_0) = d_0$, where d_0 is the initial distance at time t_0, the link availability after a time period Δt, denoted by $A(d_0, R, \Delta t)$, is defined as

$$A(d_0, R, \Delta t) \triangleq P\{d_{mn}(t_0 + \Delta t) < R | d_{mn}(t_0) = d_0\}. \quad (1)$$

The node distance d_{mn} can be accurately estimated from signal strength [9,12]. Regarding the link availability A, there are continuous and non-continuous availability. Continuous availability requires that $d_{mn} < R$ for any moment in Δt [8]. Non-continuous availability only requires $d_{mn} < R$ at time $t = t_0 + \Delta t$ [7]. In this paper, we use the non-continuous availability metric, since we only care about the helper location when a packet needs to be transmitted. During the small packet transmission time, the helper is assumed static.

B. Link Availability in Cooperation Zones

To calculate the link availability in cooperation zones, let us first consider the link availability between two nodes m and n. Assume that m is static and the mobility profile of n is $\{t_{avg}, v_{max}\}$. According to [7], the distance $d_{mn}(t_0 + \Delta t)$ follows a Rayleigh distribution of a cumulative distribution function (CDF):

$$F_R(r) \triangleq P\{d_{mn}(t_0 + \Delta t) \leq r\} \approx 1 - \exp\left(\frac{-r^2}{a_n}\right) \quad (2)$$

where $0 \leq r \leq \infty$ and

$$a_n = \frac{2 t_{avg} \Delta t}{\sigma_n^2 + \mu_n^2}, \quad \sigma_n^2 = \frac{v_{max}^2}{12}, \quad \mu_n = \frac{v_{max}}{2}. \quad (3)$$

Applying a similar method as in [9], we derive the link

TABLE III
EXTENDED COOPTABLE STRUCTURE.

MAC Address	Time (s)	SH Distance (m)	HA Distance (m)	Most Likely Zone	Availability	R_{SH} (Mbit/s)	R_{HA} (Mbit/s)
H_1 address	0.1	48	80	2	0.3	11	5.5
H_2 address	0.2	59	90	4	0.7	11	2
...	...	...	...	...	...	...	...

availability $A(d_0, R, \Delta t)$ as follows:

$$A(d_0, R, \Delta t) = \begin{cases} A_1(d_0, R, \Delta t), & \text{if } d_0 < R \\ A_2(d_0, R, \Delta t), & \text{otherwise} \end{cases} \tag{4}$$

where $A_1(d_0, R, \Delta t)$ and $A_2(d_0, R, \Delta t)$ are given by (5) and (6), respectively, on the top of next page.

Let d_0^{SH} and d_0^{HA} denote the initial distance between the source and the helper and that between the helper and the access point, respectively. For presentation clarity, we abbreviate $A(d_0^{SH}, R, \Delta t)$ as $A_{SH}(R)$ and $A(d_0^{HA}, R, \Delta t)$ as $A_{HA}(R)$. Then, the availability of the helper in the cooperation zone Z_i ($i = 1, 2, ..., 8$) is given by

$$A_{z_i}(d_0^{SH}, d_0^{HA}, \Delta t) = \tag{7}$$
$$\begin{cases} A_{SH}(R_1)A_{HA}(R_1), & \text{in } Z_1 \\ A_{SH}(R_1)\big[A_{HA}(R_2) - A_{HA}(R_1)\big], & \text{in } Z_2 \\ \big[A_{SH}(R_2) - A_{SH}(R_1)\big]A_{HA}(R_1), & \text{in } Z_3 \\ A_{SH}(R_1)\big[A_{HA}(R_3) - A_{HA}(R_2)\big], & \text{in } Z_4 \\ \big[A_{SH}(R_3) - A_{SH}(R_2)\big]A_{HA}(R_1), & \text{in } Z_5 \\ \big[A_{SH}(R_2) - A_{SH}(R_1)\big]\big[A_{HA}(R_2) - A_{HA}(R_1)\big], & \text{in } Z_6 \\ \big[A_{SH}(R_2) - A_{SH}(R_1)\big]\big[A_{HA}(R_3) - A_{HA}(R_2)\big], & \text{in } Z_7 \\ \big[A_{SH}(R_3) - A_{SH}(R_2)\big]\big[A_{HA}(R_2) - A_{HA}(R_1)\big]. & \text{in } Z_8. \end{cases}$$

C. LapCoopMAC Extension

Making use of the link availability prediction results in Section III-B, we restructure CoopTable to Table III. The cooperation procedure is also modified as follows:

- **Overhearing and CoopTable Updating**. When S overhears a pair of RTS and CTS frames of the helper H, the fields *SH Distance* (d_{SH}) and *HA Distance* (d_{HA}) are updated in addition to the fields *MAC Address* and *Time*. The distance d_{SH} is estimated according to the strength of received signal from H, while d_{HA} is extracted from the piggyback information in the CTS of A.
- **Helper Selection and Data Transmission**. The helper is then selected based on the CoopTable according to the algorithm in Table IV:
  - When the source S has a packet to transmit at time t, it obtains Δt for each helper by subtracting the field *Time* from t;
  - Then, S applies the fields *SH Distance* (d_{SH}), *HA Distance* (d_{HA}) and Δt of each helper to Eq. (7);

TABLE IV
HELPER SELECTION ALGORITHM WITH LINK AVAILABILITY.

```
H ← ∅
A[1...8] ← 0
if a packet is ready to transmit at t then
    if CoopTable is empty then
        Transmit using direct link
    else
        for each row i in CoopTable (Table III) do
            t_0 ← Time
            Δt ← t − t_0
            d_0^{SH} ← SH Distance
            d_0^{HA} ← HA Distance
            for each cooperation zone i = 1 → 8 do
                A[i] ← A_{z_i}(d_0^{SH}, d_0^{HA}, Δt)
            end for
            Availability ← max(A[1...8])
            Most Likely Zone ← arg max(A[1...8])
            Update R_{SH}, R_{HA} based on Most Likely Zone
        end for
        H ← MAC Address with the highest Availability
    end if
    Return H
end if
```

  - The highest link availability and the corresponding zone are used to update the fields *Availability* and *Most Likely Zone*, respectively;
  - According to the field *Most Likely Zone*, S updates the fields R_{SH} and R_{HA} following Table I;
  - Last, S selects the helper of the highest *Availability* and sends the packet at a rate R_{SH}.

IV. SIMULATION RESULTS

Following the topology in Fig. 2, we conduct simulations using OPNET [13] to evaluate the performance of LapCoopMAC in different scenarios. The simulation parameters are given in Table V, while the random mobility is defined in Section II-B. In this section, the source throughput with LapCoopMAC is compared with that of CoopMAC-II to illustrate how LapCoopMAC effectively addresses the out-of-date problem.

A. Throughput Improvement with Inactive Helper

Suppose that the feasible transmission rate is 1 Mbit/s for the direct 802.11 link between the source S and the destination access point A. Thus, the source throughput can be improved via a helper in any of the 8 cooperation zones in Fig. 2. Assume that S and A are stationary. Consider a helper of a random mobility profile $\{t_{avg} = 2s, v_{max} = 5m/s\}$, which

$$A_1(d_0,R,\Delta t)=\frac{1}{2\pi}\int_0^{2\pi}F_R\Big(-d_0\cos(\varphi)+\sqrt{R^2-d_0^2\sin^2(\varphi)}\Big)d\varphi \tag{5}$$

$$A_2(d_0,R,\Delta t)=\frac{1}{2\pi}\int_{\pi-\arcsin(d/d_0)}^{\pi+\arcsin(d/d_0)}\Big[F_R\Big(-d_0\cos(\varphi)+\sqrt{R^2-d_0^2\sin^2(\varphi)}\Big)-F_R\Big(-d_0\cos(\varphi)-\sqrt{R^2-d_0^2\sin^2(\varphi)}\Big)\Big]d\varphi. \tag{6}$$

TABLE V
MAIN SIMULATION PARAMETERS.

Parameters	Values
Packet payload	1024 bytes
Source packet arrival rate	500 packet/s
R_1 for rate 1 Mbit/s	48.2 m
R_2 for rate 2 Mbit/s	67.1 m
R_3 for rate 5.5 Mbit/s	74.7 m
R_4 for rate 11 Mbit/s	100 m

initially stays in Z_6 and sends packets in an on-off pattern. Fig. 4 shows the source throughput of original CoopMAC-II and LapCoopMAC when t_{off} varies from $2s$ to $20s$. As seen in Fig. 4(a), although there is throughput fluctuation caused by the random mobility, the throughput of CoopMAC-II when the helper is very active ($t_{off}=2s$) is significantly higher than that when the helper is less active ($t_{off}=20s$). This is because S cannot gather sufficient timely information to update CoopTable when the helper is less active, which results in more unsuccessful cooperative transmissions and throughput degradation. On the other hand, when $t_{off}=20s$, LapCoopMAC improves the throughput from 1.6 Mbit/s to 1.9 Mbit/s at the end of the simulation. Although LapCoopMAC cannot approach the performance when $t_{off}=2s$ with frequent updates, LapCoopMAC is able to make good use of the out-of-date inaccurate information and enhance the performance by predicting the helper's movement and its future cooperation zone. Similar observation is found in Fig. 4(b) where the mobility profile is $\{t_{avg}=2s, v_{max}=8m/s\}$.

To better evaluate how much useful information LapCoopMAC can extract from the out-of-date CoopTable caused by the inactive moving helper, we measure the following normalized throughput gain

$$G \triangleq \frac{Thruput(\text{LapCoopMAC})-Thruput(\text{CoopMAC-II})}{Thruput(\text{CoopMAC-II})}.$$

Fig. 5 shows how the throughput gain varies with t_{off} given a mobility profile $\{t_{avg}=2s, v_{max}=5m/s\}$. When t_{off} goes up from $5s$ to around $26s$, i.e., the highly active helper becomes moderately active, the throughput gain of LapCoopMAC constantly increases up to a peak of 18%. This indicates that LapCoopMAC is very effective in synthesizing the moderately out-of-date information in the CoopTable. When t_{off} is further increased beyond $26s$, the helper is only active in transmitting a couple of times during the simulation. CoopTable suffers severely from the out-of-date problem. With a random mobility, the helper's state becomes almost unpredictable to the source. Even in this case, LapCoopMAC

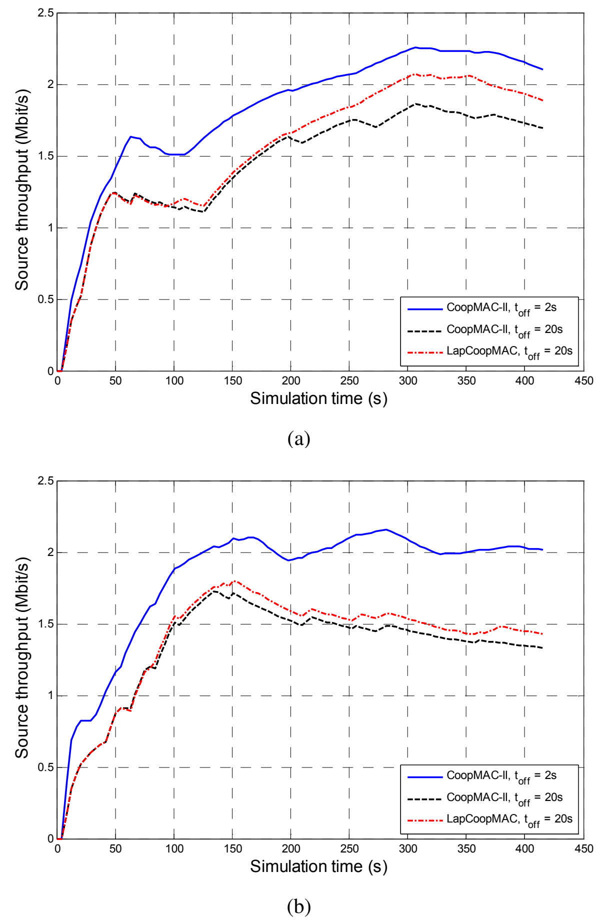

Fig. 4. Throughput improvement with inactive helper. (a) $\{t_{avg}=2s, v_{max}=5m/s\}$. (b) $\{t_{avg}=2s, v_{max}=8m/s\}$.

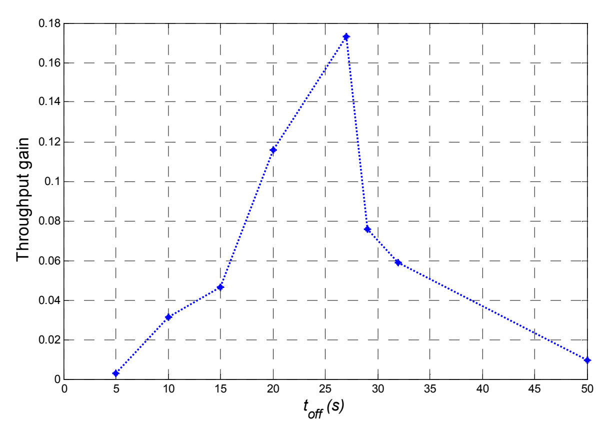

Fig. 5. Throughput gain with different t_{off}.

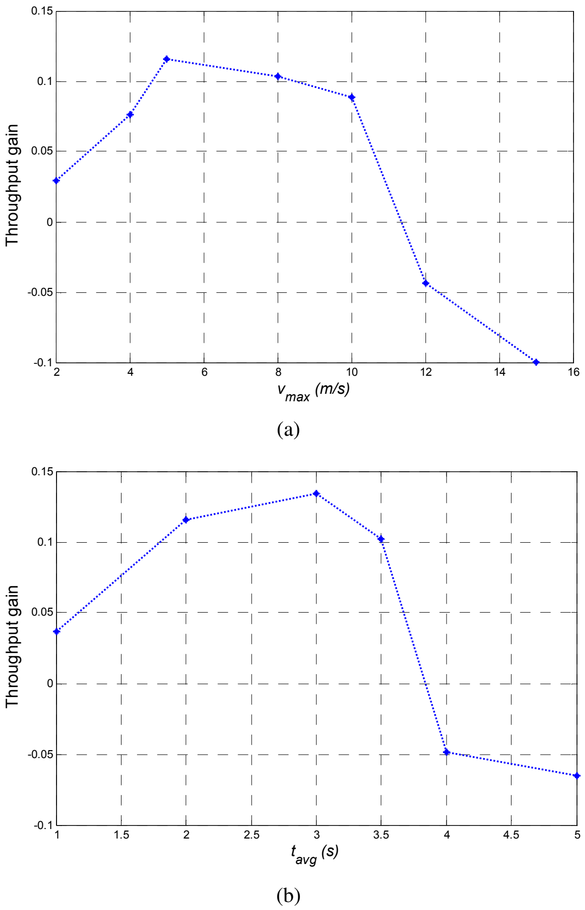

Fig. 6. (a) Throughput gain with different v_{max}, $\{t_{off} = 20s, t_{avg} = 2s\}$. (b) Throughput gain with different t_{avg} $\{t_{off} = 20s, v_{max} = 5m/s\}$.

can still improve the throughput in a degree.

B. *Performance Effect with Helper Mobility*

Another reason of out-of-date CoopTable is the helper's random mobility profiled by $\{t_{avg}, v_{max}\}$. The higher t_{avg} or v_{max} are, the longer the distance that a helper would travel within an epoch and the higher the probability it may move to another cooperative zone. Fig. 6 illustrates how well LapCoopMAC addresses the mobility randomness. Consider a very inactive helper of a mobility profile $\{t_{off} = 20s, t_{avg} = 2s\}$. As seen in Fig. 6(a), the throughput gain increases as the speed v_{max} goes up to 5 m/s (18 km/hr). That is, when the speed and mobility randomness of the helper are low, LapCoopMAC can effectively correct the out-of-date information in the CoopTable and make good prediction. When v_{max} further increases to 10 m/s (36 km/hr), LapCoopMAC still works well, but the throughput gain gradually drops. This is because the probabilities that the helper appears in different cooperation zones become more balanced when v_{max} goes up, which reduces the accuracy of the link availability prediction. When v_{max} goes above 11 m/s (40 km/hr), the prediction error become too high to be helpful for improving the cooperation success rate. Similar trend can be observed in Fig. 6(b) with different t_{avg}. A larger t_{avg} also has a negative effect, since the helper travelling a longer distance within an epoch will move into another cooperation zone at a higher probability.

V. Conclusions and Future Work

Cooperation at the MAC layer provides a promising approach to make use of the multi-rate capability of 802.11 WLANs. With good backward compatibility, CoopMAC-II can improve the throughput by involving relaying helpers. Nonetheless, it may suffer from the out-of-date CoopTable when the helper is actively transmitting and/or subject to random mobility. In this paper, we consider using link availability prediction to address the CoopTable out-of-date problem. By synthesizing even out-of-date information in the CoopTable, the proposed solution LapCoopMAC predicts the probability that a helper moves to each cooperation zone. The chance of successful cooperation can be improved by adapting transmission based on the most likely zone that the helper may move into. Simulation results demonstrate that LapCoopMAC can achieve a good throughput gain when the helper has a moderate level of activeness and mobility randomness. As discussed in [2], the cooperative MAC solutions with the source-based CoopTable have an inherent weakness in addressing mobility, i.e., the source relies on overhearing packets from the helpers to update its knowledge of the helpers in the CoopTable. In the future, we would investigate the possibility of addressing mobility in a more distributed manner, e.g., by aggregating the intelligence of the helpers to maintain timely and complete information.

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