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Capture Aware Channel Access Protocol in Wireless Network

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Abstract: Spatial reuse in wireless networks is limited by the SINR threshold and it might be feasible to capture a packet in the presence of ongoing foreign transmission. This work considers a new capture aware channel access protocol by incorporating global channel state information in the decision making process for the channel access jointly with adaptive power framework. The protocol employs power heterogeneous ad-hoc networks; it assigns different transmission power level to individual nodes based on dynamic observation of the network traffic. It exploits spatial heterogeneity of flows at a given channel allocation and sets up either symmetric or asymmetric carrier sensing which in turn schedules the data packets transmission to maintain adequate service quality and fairness enjoyed by a user. It stands atop capture capable PHY to leverage the channel reuse which is of paramount importance in the design of high capacity ad-hoc networks. Through extensive simulations, the paper demonstrates the efficacy of the new protocol. It delivers high network utilization and also provides fair access to the media.

Keywords: DCF; Carrier sensing; MAC mechanism; Power control; Capture effect; Wireless network.

بروتوكول الدخول الى القنوات و الدراية بحدوث التقاط الارسال في الشبكة اللاسلكية

سماح مصطفى*

الملخص : ان إعادة الاستخدام المكاني في الشبكات اللاسلكية يكون محدودا بسبب حاجز إشارة نسبة التدخل (سينر). وقد يكون من الممكن التقاط حزمة ما في وجود ارسال أجنبي مستمر. ويأخذ هذا العمل في الاعتبار بروتوكولا جديدا للوصول إلى القنوات من خلال حالة دمج المعلومات بالقناة العامة في عملية صنع القرار من أجل الوصول إلى القناة وبالاستفادة من إطار القدرة على التكيف. ويستخدم البروتوكول قدرة غير متجانسة لشبكات مخصصة , حيث أنه يحدد مستوى قدرة الإرسال المختلفة بالنسبة إلى العُقد الفردية على أساس مراقبة ديناميكية لحركة مرور الشبكة. فهو يستغل عدم التجانس المكاني للتدفقات عند تخصيص قناة معينة ، ويحدد سواء كان الاستشعار متماثل أو غير متماثل للموجة الحاملة ويحدد بدوره إرسال رزم البيانات للحفاظ على وجود جودة خدمة كافية وعادلة يتمتع بها المستعمل. وهو يقف فوق عملية الالتقاط القادرة على الاستفادة من إعادة استخدام القناة التي تعتبر ذات أهمية قصوى في تصميم شبكات مخصصة عالية السعة. من خلال المحاكاة واسعة النطاق. تبرهن هذه الورقة على فاعلية البروتوكول الجديد. وهي توفر استخدام عال للشبكة وتوفر أيضا إمكانية الوصول العادل إلى وسائط الإعلام.

الكلمات المفتاحية : وظيفة التنسيق الموزع (دي سي اف)، الاستشعار الناقل، آلية التحكم بالوصول إلى وسائط الإعلام (ماك)، التحكم في الطاقة، تأثير الالتقاط. شبكة لاسلكية.

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1. Introduction

A key problem in ad-hoc wireless networking is the design of distributed media access control (MAC) mechanism to discover and negotiate the access to the reusable physical channels such that the transmission can occur without collision. A representative mechanism of MAC is the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) algorithm that forms the basis of the dominant wireless multiple access protocol Distributed Coordination Function (DCF) in 802.11 (Kurth and Redlich 2009). Physically a channel is sensed busy either when the detected energy level is above a certain threshold ζ_{ED}, when a signal with the same PHY characteristics is detected, or a combination of both (Larroca and Rodríguez 2014).

Carrier sensing is the main interference mitigation mechanisms used in the PHY/MAC layers of 802.11 WLANs, and its efficacy becomes a key factor in determining network capacity. A station defers its transmission for a random period upon detecting a carrier on the channel. However, the absence of a carrier does not mean a transmission will succeed, nor does the presence of a carrier mean that a transmission will interfere. Hereby carrier sense approach can unnecessarily reduce network throughput and strongly affect the delay characteristics at a station (Jamieson *et al*. 2005; Zhu *et al*. 2004; Ma *et al*. 2009). Many studies have been done to illustrate that physical carrier sense adversely limits the effective bandwidth utilization in the network because of fixed carrier sense threshold and inadequately chosen carrier sense range. Extensive research efforts advocate the tuning of carrier sense threshold for utilization improvement (Ma *et al*. 2009; Zhu *et al*. 2004; Zhu e *et al*. 2006; Haghani *et al*. 2010); however, many of today's 802.11 MAC implementations do not allow the threshold to be independently tunable or even accessible (Zhu *et al*. 2004). Moreover, (Pelechrinis 2009) claims that tuning carrier sense threshold opens the door for selfish users with lower back-off times to ignore other transmission and therefore obtain a higher unfair share of the spectrum.

There is a clear trade-off between the probability of interference and the utilization in setting carrier sense range. Larger sense range decreases both the probability of interference and the bandwidth utilization, whereas small carrier sense range will be more subject to interference. Exposed node prevents a successful transmission while hidden node wastes a transmission opportunity due to a collision. As has been pointed out in (Ma *et al*. 2009), the optimum value of carrier sense threshold is that at which the carrier sense range of the transmitter just covers the interference range of the receiver.

The setting of interference range is rather heuristic and remains an open problem. Many studies on wireless networks have largely considered an interference range as twice the transmission range, and others rely on equal interference and transmission ranges. Physically the interference range is defined to denote the range within which an interfering node will lower Signal-to-Interference ratio (SIR) below the threshold for successful decoding of a transmission (Maheshwari *et al*. 2008). It has been depicted in (Chen *et al.* 2007 and Lee *et al*. 2010), an interferer's impact becomes serious when its preamble is detectable such that the intended end-user device could engage with, even if it is not able to decode the frame correctly. Hereby the author recommends characterizing the interference range within which the preamble of a frame is detectable and the carrier sense range should be equal to this range.

Recall that spatial channel reuse relies on the carrier sense threshold and the transmit power each station uses. MAC like 802.11 DCF uses the same transmission power at all nodes regardless the link distance between transmitter-receiver pair as well as interference level at the receiver (Li et al. 2009). Moreover, it always transmits at full power which in turn potentially maximize the link utility from the medium. However, this selfish behavior leads to excessive mutual interference and degrades the network performance. In contrast, some proposed MAC mechanisms (Gomez *et al*. 2001; Lim and Yoshida 2005) transmit at minimum possible power to leverage the spatial reuse hence maximizing the interference probability.

The SINR threshold for successful reception depends on the timing and the relative order of signal and the interference at the receiver (Chen *et al*. 2007; Lee *et al*. 2010; and Mustafa 2015). The radio captures a new stronger frame above a predefined preamble capture threshold γ_P, if it arrives during the first frame's preamble reception. 802.11's PHY layer continuously monitors the received signal strength even the layer in data reception state. It enables a radio to correctly receive a second frame, even after it has already synchronized with the first one, if the ratio of powers is sufficiently high. This is called Message in Message MIM mode which is not exploited before in capture aware mechanisms. A typical ratio of powers required for body capture is γ_D=10dB (Chen *et al*. 2007 and Lee *et al*. 2010). Thus, the SINR at the intended receiver and transmission order are crucial factors for successful delivery.

This work presents an approach to leverage ad-hoc network's capacity relying on a distributed capture aware framework to coordinate the transmit power and time schedule the traffics to exploit the PHY capture effect with ultimate goals of improving utility and spectrum fairness. Time schedule the traffic is done by assigning transmit power level to set up either symmetric or asymmetric carrier sense scenario that can potentially schedule the data packets transmission. Asymmetric carrier sense situation is neither actually introduced nor applied in previous works. It is known that a hidden link would starve in presence of sensed link with high load traffic. The simulation study offers a new prospective regarding the asymmetric carrier sense scenario and demonstrates its benefit to time schedule the hidden traffic without an extra timing signal.

In this work, Capture Aware Multiple Access Protocol (CAMA) is proposed. It requires disseminating the locally measured link gain at individual stations throughout the network neighborhood for identifying links that can be concurrent and allowing them to coexist, thereby enhanceing the effectiveness of channel reservation. It doesn’t modify the carrier sense threshold. CAMA exploits spatial heterogeneity of flows at a given channel allocation by means of dynamic power control to manage the co-channel interference and allow for higher and fair utilization of resources.

The rest of the paper is organized as follows: section 2 goes through works related to this paper. Section 3 describes CAMA mechanism that adjusts the transmission power of the nodes to maximize the benefits of the capture effect. Section 4 presents the simulation results that describe the behavior of the default and CAMA mechanisms, and demonstrate the benefits of the proposed protocol. Finally, Section 5 concludes the paper with general observations and suggestions for future research.

2. Related Work

Extensive works have subjected different aspects of 802.11MAC protocol to enhance per-flow and aggregate throughput. This section presents an overview of some existing work that aims to improve network capacity by spatial diversity through tuning transmit power.

Ding *et al*. 2005 proposes transmit power control protocol to adjust the transmit power for each frame under the same decision rule as IEEE 802.11 which in turn achieves limited improvement. Mhatre *et al*. 2007 claim that different power levels at transmitters use the same carrier sense threshold in 802.11 networks introduces asymmetric links which in turn lead to throughput starvation. They demonstrate that cross layer approach by joint tuning of the clear channel assessment CCA threshold and transmit power ensures starvation free control system. Furthermore, the clients use the same transmit power and CCA threshold as their associated access point regardless of different channel state each sees. The current work demonstrates that asymmetric link do not necessarily introduce starving nodes.

The traditional access control cannot handle multiple packets without declaring a collision. A capture aware MAC mechanism was proposed in (Santhapuri *et al*. 2007), where primary node transmits Request-To-Send (RTS)/Clear-To-Send (CTS) and waits for one preamble time interval before transmitting data while secondary node(s) that overhears RTS will initiate its own transmission either during wait time for the primary user or during primary's DATA transmission depending on the estimated SINR at its receiver and at the primary user. However, this scheme doesn't address the synchronization issue due to the existence of propagation delay, and it incorporates that receiving the preamble of the interference frame helps to detect the frame of interest that arrives later while in contrast has been proved in (Lee *et al*. 2010).

In (Li *et al*. 2009), nodes transmit RTS/CTS at the same maximum power, and transmit DATA/ACK at the power based on the link distance, as well as the interference level at the receiver. Based on the overhead RTS or CTS, the protocol enables a concurrent transmission at a possible highest power level as long as it does not interfere with the ongoing ones. Although, the protocol considers the aggregate interference level, but it assumes equal contribution from the neighboring nodes, no matter how close they are as well as the transmit power they use.

There are some limitations on these mechanisms: hidden terminal problem still exists with RTS/CTS, and possible loss in ACK packets is ignored to benefit from fewer collisions and build inaccurate results.

Various PHY layer capture aware MAC mechanism are proposed for wireless area local area networks WLANs. To meet fair access and high overall throughputs, (Jeong *et al.* 2013) changes either the contention window or arbitration inter-frame space or transmission opportunity. The technique in (Patras *et al.* 2014) uses different power levels to result in packet capture in WLANs and improve the performance. However, an ideal channel condition is assumed where losses are only caused by collisions. The work in (Takahashi *et al.* 2015) configures the minimum contention window of the stations to reduce the collision in each network. These studies considered infrastructure mode where nodes are within carrier sense range of one another.

Further, these mechanisms don't exploit MIM mode and the assignment of concurrent links set satisfies a single SINR constraint. The study in (Mustafa 2015) demonstrates the inaccuracy of the well-known interference physical model.

3. Capture Aware Multiple Access CAMA Framework

The 802.11 DCF (Li *et al.* 2009) is strong transmit power MAC design wherein all nodes transmit with the same power no matter how close the sender and receiver are. The current work here claims that by moving beyond the maximum fixed transmit power, the fairness and channel utilization can be improved.

Further, successful unicast transmission depends on channel condition at both the receiver and sender due to downstream data traffic and upstream MAC layer acknowledgment ACK traffic. However, suggestion of simply extending the carrier sensing mechanism to the receiver does not address the MAC limitations of inefficient and unfair spectrum utilization. A capture aware multiple access mechanism is proposed based on broad channel observation to tune power level of each node to successfully retrieve the transmitted signal and make a decision to access the channel, while carrier sense range is fixed and set equal to interference range. In environment with users of homogenous technology competing for resources, the interference range in this work is characterized within which the preamble of a frame is detectable.

3.1 Two Sender-receiver Pairs

Consider two sender-receiver pairs: (S_1;R_1) and (S_2;R_2) transmitting over communication links L_1 and L_2 respectively, and sharing a single wireless channel as shown in Fig. 1. $SINR|_{D-D}^{R_i}$ experienced by R_i due to concurrent data DATA-DATA transmissions from S_i and S_j is given by

$$SINR|_{D-D}^{R_i} = \frac{G_{i,i}^{SR}\, P_{Si}}{G_{j,i}^{SR}\, P_{Sj} + \eta} \tag{1}$$

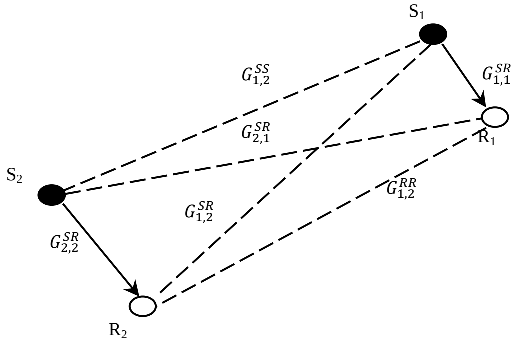


Figure 1. Two flows sharing a wireless channel. Depending on propagation paths between the four stations, link(s) may or may not be established between the nodes.

P_{si} denotes transmit power level at S_i and η is the noise floor. $G_{i,j}^{SR}$ denotes S_i-R_j link gain where a propagation model suited for the surrounding environment is used to describe the fluctuation in the received signal strength such that the mean received power falls off as $(1/d)^{\alpha}$. α is a path loss exponent. A receiver can engage with a delivered packet if the received signal power is greater than the receiver sensitivity threshold ζ_S, *i.e.*

$$G_{i,i}^{SR}\, P_{Si} \geq \zeta_S \tag{2}$$

Whether parallel data transmissions of data packets are successful or failure depends on the observed SINR basically at receivers that should be higher or equal to γ_D. It enables the radio to correctly receive an intended frame irrespective of the timing relation between overlapped transmissions. γ_D is usually set to 10 that map to ten times the signal power over interference power, as stated earlier in first section. This condition holds if R_i is closer to S_i than to both S_j and R_j by a sufficient factor, and vice versa. It may happen that this condition holds even though CSMA/CA would prevent the second pair from transmitting.

To illustrate this possibility, consider the following example. The four nodes are on a line in the order, from left-to-right R_1; S_1; S_2; R_2. Their locations on the x-axis are 0; 1; d+1; d+2, respectively. Assume all the nodes transmit with a unit power and $(G_{i,i}^{SR}/G_{j,i}^{SR}) \geq 10\text{dB}$. A capture-aware protocol that would let the sender transmit even if it sense the other transmission could potentially have a throughput almost twice as large as the standard DCF protocol. CAMA looks for a minimum possible power level that guarantees correct packet delivery and hide the sender from other. Further, it is able to throwing out carrier sense line by disabling randomized backoff and allows two senders to transmit packets continuously and simultaneously.

Now, consider the four nodes on the x-axis in the order from left to right S_1; R_1; R_2; S_2, at locations 0; 1; d+1; d+2, respectively. Depending on the channel state the nodes see, DATA-ACK and DATA-DATA packets collision are possible. For example, $SINR|_{D-A}^{R_i}$ due to simultaneous transmission of data and ACK packets from S_i and R_j, respectively is given by

$$SINR|_{D-A}^{R_i} = \frac{G_{i,i}^{SR}\, P_{Si}}{G_{j,i}^{RR}\, P_{Rj} + \eta} \tag{3}$$

P_{Ri} denotes the transmit power of R_i. Assume the nodes transmit with a unit power over a single channel of state such that $G_{i,i}^{SR}/G_{j,i}^{RR}$ is less than a sufficient factor ζ_D. ζ_D=5dB is the SINR threshold to guarantee a successful packet delivery if the receiver is not engaged with another packet (IEEE Std. 2007, Chen e*t al.* 2007, Lee et al. 2010). It may happen that the senders are hidden and don't preclude data transmission if any. Failed transmission not only wastes energy but also has the potential to corrupt other transmissions. The proposed approach evaluates the state and makes an efficient decision to access the channel. It assigns a transmit power to set up mutual carrier sensing and dependently schedule the transmission opportunity.

Homogenous links in terms of channel gain are assumed in previous examples, nevertheless they are not usually. CAMA exploits spatial heterogeneity of flows and assigns different power level at each station. Recall that link S_2-R_2 has higher quality than link S_1-R_1. While the default solution for sender(s) out of the capture range of the intended receipt is to preclude the concurrent transmissions, a more efficient solution is addressed by achieving asymmetric carrier sensing through heterogeneous power to schedule the transmission time. High power node S_2 does not sense the transmissions of low power node S_1. CAMA looks for possible minimum and different power levels at each sender to set $[\mathbf{P_{S2}G_{2,2}^{SR}}/(\mathbf{P_{S1}}\,\mathbf{G_{1,2}^{SR}} + \boldsymbol{\eta})] \geq \mathbf{10dB}$ and $[\mathbf{P_{S1}G_{1,1}^{SR}}/(\mathbf{P_{S2}G_{2,1}^{SR}} + \boldsymbol{\eta})] \geq \mathbf{5dB}$, and lets the senders achieve high throughput. Transmit power plays a vital role in our mechanism to enable either the MIM or capture effect at the nodes and set possible concurrent transmissions on a single wireless channel.

S_1 (being hidden from S_2) transmits only if the channel is idle and commences a data transmission prior to S_2 which doesn't block any transmission request from an upper layer on sensing a clear channel. It can potentially initiate transmission that overlap with lower power transmission. Thereby, R_1 captures the first coming packet if there is an overlapping transmission on the channel and R_2 will begin receiving S_1's packets first, and later re-lock onto S_2's new packet which is much stronger than S_1's. The senders can successfully and fairly utilize the channel if the following conditions hold:

- $SINR|_{D-D}^{R_1}$ and $SINR|_{D-A}^{R_1}$ exceed a threshold guarantees a successful packet detection threshold ζ_D.
- $SINR|_{D-D}^{R_2}$ and $SINR|_{D-A}^{R_2}$ exceed γ_D and ζ_D, respectively.

Further constraint should be followed since it is also possible that a data packet is received correctly, but the ACK packet is lost

$$SINR|_{A-D}^{S_i} = \frac{G_{i,i}^{SR}\, P_{Ri}}{G_{j,i}^{SS}\, P_{Sj} + \eta} \geq \zeta_D \tag{4}$$

Briefly, the channel is utilized efficiently only if S_1 commence transmission before S_2.

Flow of higher transmit power can afford to start later. It is important to highlight that we are not using a special timing signal to schedule the data transmission; we only depend on carrier sense scenario to time order the traffic.

It is well understood that asymmetric links in power heterogeneous network unfairly degrades the utility experienced by low power links (Mhatre *et al*. 2007, Shah *et al*. 2007). However, our simulation study confirms that diversity in transmit power does not necessarily starve low power users if some constraints are followed.

3.2 N Sender-receiver Pairs

The intended stations are responsible for estimating and disseminating the channel quality around to make a joint prediction about whether more than a flow can transmit simultaneously through minimum possible transmit power at each station to mitigate the interference and optimize the per-flow and overall network throughput on a collision free channel. If the prediction result is positive, the stations should not block their own transmissions, if any. Otherwise, an approach that considers tuning of transmit power as a PHY parameter, should be applied to set a suitable sense interaction and subsequently schedule the access to a shared medium.

Simulation results in section 4 illustrate that such an access scheme performs better than the CSMA/CA even at high traffic loads, and applying it has the benefit of improving per-flow and aggregate utility in wireless networks.

To estimate the complexity of such a protocol, assume there are N sender/receiver pairs willing to access the media. The nodes in pair i should estimate the channel gain over link(s) that may establish; $G_{i,j}^{SR}, G_{i,j}^{SS}$ and $G_{i,j}^{RR}$ $\forall$ neighbor pair j, either periodically or whenever it has data to transmit and/or node(s) observes degradation in the performance. They then post these values to a distributed control system to coordinate the channel access and transmit power of the nodes according to the specified policy. The stations may exchange simple control signaling to initiate the process and run the optimization algorithm. Despite that the optimal algorithm provides optimal utility of the channel, it is rather computationally expensive for a large network.

To guarantee successful concurrent transmissions that would not change the result of the capture effect, SINR constraints should consider joint and maximum interference strength at a station.

$$SINR_1|_{D-D}^{R_i} = \frac{G_{i,i}^{SR}\, P_{Si}}{\sum_{j=1,j\neq i}^{N} G_{j,i}^{SR}\, P_{Sj} + \eta} \geq \zeta_D \quad (5)$$

$$SINR_2|_{D-D}^{R_i} = \frac{G_{i,i}^{SR}\, P_{Si}}{max_{j\neq i}\,(G_{j,i}^{SR}\, P_{Sj}) + \eta} \geq \gamma_D \quad (6)$$

If the simultaneous transmissions could ban the capture on a subset of M links, higher transmit power should be assigned at the senders of these links that being oblivious of lower power flows within their sensing range. SINR constraints should satisfy the earlier inequalities at the receivers of the M links. SINR experienced at the receivers of the remaining N-M links should exceed ζ_D as given by

$$SINR|_{D-A}^{R_i} = \frac{G_{i,i}^{SR}\, P_{Si}}{\sum_{j=1,j\neq i}^{N} G_{j,i}^{RR}\, P_{Rj} + \eta} \geq \zeta_D \quad (7)$$

Further, SINR experienced at the senders should exceed ζ_D for successful delivery of ACK packets, as given by

$$SINR|_{A-D}^{S_i} = \frac{G_{i,i}^{SR}\, P_{Ri}}{\sum_{j=1,j\neq i}^{N} G_{j,i}^{SS}\, P_{Sj} + \eta} \geq \zeta_D \quad (8)$$

CAMA determines the appropriate minimum transmit power that ensures that the sender can sustain a data rate to reach the intended receipt and the interference level perceived at other nodes can be mitigated thereby higher number of concurrent transmissions can be achieved.

4. Simulation Results

In this section, we present simulation-based studies using NS-2.34 which incorporates the modeling details of the IEEE 802.11 MAC and PHY modules (Chen *et al*. 2007). The PHY module includes cumulative SINR computation, preamble and PLCP header processing and capture, and frame body capture. The MAC accurately models transmission and reception coordination, back off management and channel state monitoring in a structured and modular manner to presents the CSMA/CA mechanism.

All nodes implement the 802.11g technology. The senders and receivers are placed in an indoor environment, and the radio propagation reflects shadowing model with path loss exponent of 4 over the distance (Srinivasan and

Haenggi 2009). Parameters as antenna gain and system loss are assumed to be fixed. The default values of configuration parameters are used.

Compared to preamble detection threshold ζ_P where preamble detection starts to work, energy detection threshold ζ_{ED} in terms of SNR is higher (Lee *et al*. 2010).

Table I lists the main parameters in our simulation study. The minimum PHY bit rate δ=6Mbps is considered in the simulation. Hence the minimum SINR which guarantees a reliable packet communication $\zeta_D=\zeta_P=5$dB, as a hardware defined threshold (IEEE Std. 2007; Chen *et al*. 2007; and Lee *et al*. 2010). The simulation is restricted to one-hop unicast UDP traffic. Each link carries constant bit rate (CBR) traffic. Each simulation runs for 60 seconds with disabled RTS/CTS virtual carrier sensing. The nodes are configured to be always backlogged with packets to send and each MAC data frame to be 1028 bytes long.

During the simulation we consider utility in terms of MAC layer goodput at the receiver and Channel Usage Efficiency CUE in terms of the ratio of MAC layer goodput at the receiver to PHY layer throughput at the transmitter over a given channel as two distinct metrics. We first have activated one link to find the maximum achievable throughput, goodput and CUE of unicast traffic that are approximately 5.19 Mbps, 5.05 Mbps and 0.973 respectively due to MAC/PHY layers overhead. Low CUE indicates that a node has gained access with failed transmission which consumes energy and may cause interference to neighbors over the same channel.

Fairly Shared Spectrum Efficiency (FSSE) index is considered to measure the portion of System Spectral Efficiency SSE that is shared equally among all active users. In case of scheduling starvation, FSSE would be zero during certain time intervals. In case of equally shared resources, FS SE would be equal to SSE. If FSSE is maximized, the max-min fairness can be achieved (Eriksson 2001).

4.1 Performance Evaluation of Default DCF

Determining how well carrier sense works in wireless networks is the focus of the simulation studies in this section. We show few examples where the default bandwidth utilization by the 802.11MAC is far from optimal setting. Carrier sense may sometimes make incorrect access decisions thereby leading to inefficient channel usage, as explained before when exposed and/or hidden terminals are present. Utility in terms of goodput and CUE are our basic metrics for comparison of link performance across various carrier sensing settings and for measuring the efficiency of default channel access scheme.

Consider a scenario of a simple four nodes topology in a 100x100m2 indoor environment to compose two wireless links, with symmetric incomplete view of channel state in Fig. 2a. The senders are within sense range of each other and within the capture range of their intended receiver. Hence, if S1 commences a data transmission, S2 should not block its own transmissions, if any, and vice-versa despite the presence of the ongoing data delivery. They could simultaneously transmit without causing excessive interference at the receivers to disrupt

Table 1. Configuration parameters in the simulation study.

parameters	Configuration value
γ_P	4dB
γ_D	10dB
ζ_{ED}	10dB
$\zeta_P = \zeta_D$	5dB
δ	6Mbps
η	-96dBm

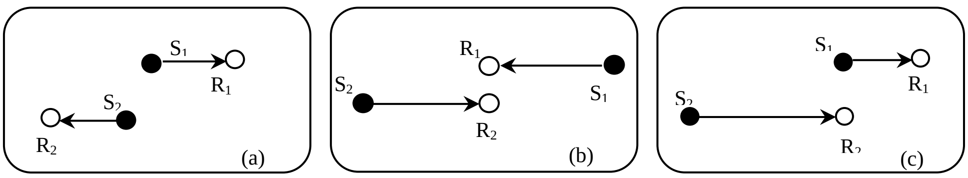


Figure 2. Three scenarios of two flows sharing a wireless channel. In scenario (a) the intended links could always present, given that senders are in capture range of their respective receiver. Scenario (b) portrays hidden terminal case where the intended links could not present simultaneously. Scenario (c) shows a topology of two heterogeneous wireless links in terms of channel gain, given that the senders are hidden terminals and S_1-R_1 link only is always present.

successful communication. However, the default MAC mechanism based on local channel assessment may mispredict the channel state and consequently waste the transmission opportunity.

Figure 3 illustrates the normalized utility on two communication links L_1 and L_2 when the senders depend on local channel observation only or extend the observation to the intended receiver. Having a single exposed node potentially drops the overall throughput to 50% of the optimal setting.

Further complications arise in cases where hidden nodes are likely, scenario (b). Suppose S_1 is oblivious of ongoing flow from S_2 and vice-versa. The receivers are in close proximity such that S_1 (S_2) data transmission and/or R_1 (R_2) ACK transmission could corrupt R_2 (R_1) reception. The incomplete view of channel state possessed by the sender causes hidden terminal where the absence of a carrier at the sender does not mean a transmission will not collide. Both links experience packet loss due to the concurrent transmissions from the hidden terminals. The senders double their contention window size for each failure of data transmission; hereby an obvious drop in the channel utilization is illustrated in Fig. 3. Misprediction of channel state can drop the utility significantly than if an access decision is extended to the intended receiver.

It is obvious that exposed and hidden terminals in the previous scenarios affect the two flows equally. The third scenario in Fig. 2 considers a topology of hidden terminals with heterogeneous link quality. S_1 and S_2 are out of each other's sensing range, and S_2 cannot corrupt R_1 reception. However, S_1 may initiate a transmission while S_2 is transmitting, and disrupt the reception at R_2. If S_1 occupies the channel for a long time, S_2 will starve.

The simulation in Fig. 3 shows extreme unfairness due to asymmetric interference and diverse transmission opportunity the senders have, which cannot be addressed in this scenario with extending the channel observation to the intended receiver. The unfairness in access opportunity which is undesirable as it can adversely affect delay sensitive applications cannot be addressed without coordination with the surrounding nodes.

Next, we have evaluated the performance of hidden terminals in the topology of Fig. 2c with different traffic load on the wireless links and default MAC mechanism. S_1 is located within the capture range of its intended receiver while S_2 is not always depending on the traffic rate on the interfering link L_1.

Regarding the simulation results in Fig. 4 in terms of normalized utility on L_2, R_2's default MAC layer has recorded nothing at traffic load of 3Mbps. It could work better at low traffic load wherein the target utility of 1Mbps is attained. However, CUE metric considered here is not satisfying even with low traffic load. Failed transmissions not only alleviate CUE and waste energy but also have the potential to corrupt other transmissions.

Generally, the overall performance claim that the default mechanism doesn't work efficiently even with low traffic load, and simply extending the observation to the intended receiver don't address the limitation. An intuition to maximize the utility and channel usage efficiency is to set up capture aware MAC scheme jointly with adaptive transmit power as has been described in section 3.

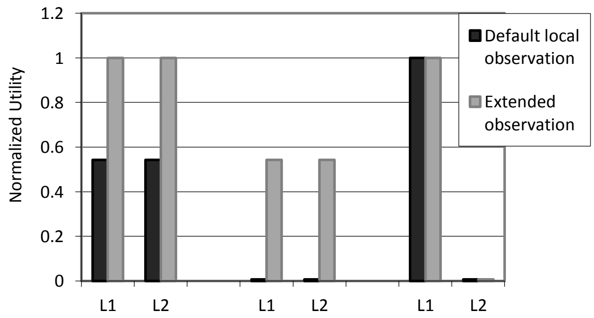


Figure 3. Normalized utility for the scenarios in Fig. 2, in terms of MAC's layer good put with default channel assessment at the senders and extended assessment to the intended receiver.

4.2 *Performance Evaluation of CAMA*

In this section we assess the performance of our proposed framework to mitigate the interference and leverage the spatial reuse via a broad picture of the channel state. In this paper, we assume that information exchange works perfectly as well as the coordination. We conducted three different sets of simulations using different number of sender-receiver pairs use CBR applications on the same channel.

4.3.1 First Scenario

First, we have conducted a number of simulations using two links for illustrative purpose. The position of nodes is sampled from a two-dimensional distribution in 100x100 m^2 indoor environment, as shown in Fig. 5. The receivers are deployed in overlapping area of the senders and each tolerates a certain level of interference depending on channel gain and the transmit power. The unicast traffic considered is generated and flowed at a rate sufficient to saturate the medium. The link gain is assumed as being fixed for the duration at which power updates are performed in CAMA framework.

Fig. 6a shows the normalized utility experienced by users to illustrate the performance improvement compared to the default DCF at different power levels. The default MAC mechanism depends on local channel assessment to decide whether to commence a transmission or to defer it. With default DCF and transmit power level of 19dBm (Case1), the senders are hidden and transmit independently. L_2 hits the maximum utility with sender in capture range of the intended receiver, whereas L_1 is seriously affected by co-channel interference. Fig. 6b shows inefficient channel usage by S_1, in contrast to S_2 that being oblivious of the collisions experienced by R_1.

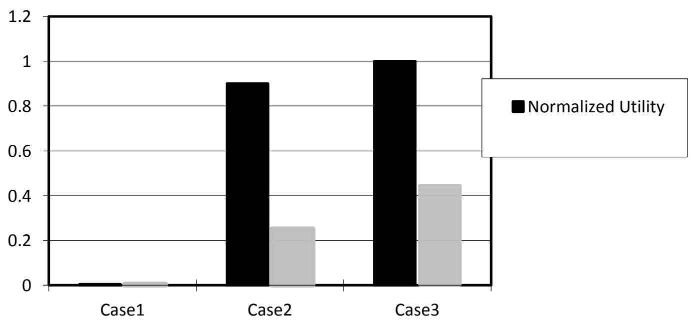


Figure 4. Performance evaluation in terms of normalized utility and channel usage efficiency on L2 for the scenario (c) in Fig. 2 at different traffic loads. In case1, traffic loads Ʈ1= Ʈ2 = 3Mbps. Case2 considers Ʈ1=2Mbps and Ʈ2=1Mbps, while in case3, Ʈ1 = Ʈ2 = 1Mbps.

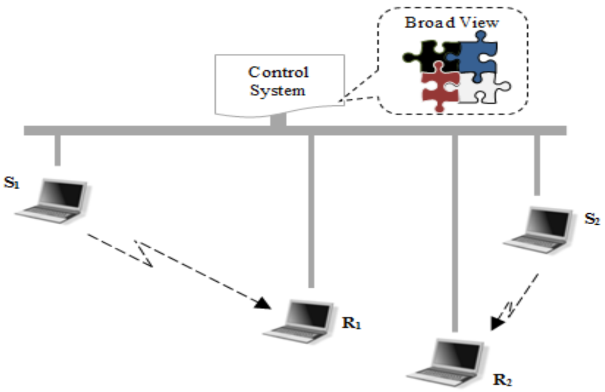


Figure 5. Network model and topology as used in the simulation. The nodes disseminate the estimated link gain to get broader view and perform joint optimization.

Higher transmit power can be used to set symmetric carrier sensing between the senders, for example 27dBm (Case2). The goal is to silence a sender when the other initiates a transmission. Slight different performance: 0.48 and 0.59 of the maximum utility is hit, respectively over the transmission links. Collisions occur at R_1 when two senders choose the same slot in the contention window to transmit their frames since L_1 observes less degree of channel quality; however, this case doesn't happen as often compared to the case when the senders are hidden from each other.

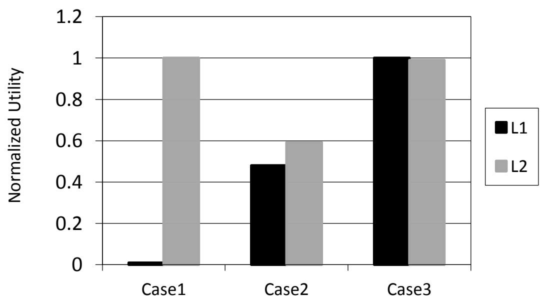
While the default solution for sender out of the capture range of the intended receiver, is to preclude the concurrent transmissions, CAMA framework shows the existence of optimal transmit power for each node in this scenario to set up asymmetric carrier sense and satisfy SINR constraints, where an obvious improvement in per-flow and aggregate utility is resulted (Case 3). By switching for example to transmit power 27dBm at S_1 and 19dBm at S_2, R_1 and R_2; S_2 is able to carrier sense data transmissions from S_1 but not vice-versa.

The sender S_2 can access the channel during time interval between successive transmitted frames of high power sender within its sensing range. S_1 doesn't block any transmission request from an upper layer that could overlap with existing flow. Moreover, if S_1's frame arrives when S_2 is in transmission state, S_2 will not be able to hear this frame even if its transmission would end very soon after, since the received energy from S_1 is below energy detection threshold and S_2 would have missed the preamble and PLCP header. We confirmed the above argument by tracing the transmission order and inter-transmission time NS-2.34 trace file.

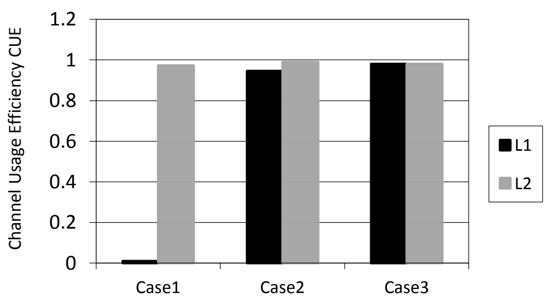
Albeit the transmission time of the terminals could overlap and eventually the frames based on the traffic size, the concurrent transmissions with the new setting of transmit power don't introduce enough interference to deprive the reception. Low power data flow survives the collision with the early interference frame from S_2 with $SINR|_{D-D}^{R_1}$ ≥10dB and hits the maximum utility. Higher power flow attains that utility with $SINR|_{D-D}^{R_2}$ ≥5dB that guarantees data packet delivery: the first captured frame from S_2 tends to survive the collision with a later interference packet from S_1. Other SINR constraints: $SINR|_{D-A}^{R_i}$ ≥5dB and $SINR|_{A-D}^{S_i}$ ≥5dB are also met to preclude data and ACK packets collision.

The senders successfully and fairly utilize the channel wherein normalized utility and CUE results in Fig. 6 are almost one. The results demonstrate no starving with asymmetric links in power heterogeneous network, and confirm the efficacy of CAMA framework to provide collision free channel. Our simulation results with unicast traffic in contrast to the results have been observed in (Rao and Stoica 2005) with broadcast traffic over asymmetric sensing links. Extended Inter Frame Space (EIFS) is supposed to be the main reason for the unfairness in the transmission opportunity.

Figure 7 shows FSSE and SSE results wherein CAMA mechanism obviously has much better spectral efficiency and fairness since it gets off hidden and exposed node scenarios, which are the well known sources for the limitation of the default mechanism. The results shows that coordinated and collaborative framework enables efficient use of the wireless resource and achieves potential improvement over DCF.



(a)



(b)

Figure 6. Performance evaluation in terms of a) Normalized utility, and b) CUE of possible scenarios with default DCF and CAMA.

4.3.2 Second Scenario

We substantiated the proposed CAMA mechanism on larger networks of sender-receiver pairs distributed in three-dimensional distribution in $100x100x100m^3$ indoor environment with disparity in link quality. The probability with which a given frame could be captured by intended receipt is a function of the number of ongoing transmission. The energy received from the intended packet should be higher than total accumulated energy received from the remainder parallel transmission over the capture interval, as defined in the equations (5)-(8). The optimal solution consists of defining a set of willing end-users to transmit, and apply CAMA mechanism to enable possible concurrent transmissions over the channel.

To portray the impact of the aggregate interference, consider a set of four sender-receiver pairs (Fig. 8). The distance between the senders S_1, S_2, S_3 and S_4 is roughly 40m except the distance between S_3 and S_4 is 70m. The position of the receivers is sampled such that R_3 is within the interference range of S_1 and S_2, i.e. either R_3 is able to decode the foreign frame correctly or not, it could engage with overheard S_1 or S_2's preamble. R_4 is also within the interference range of S_1. Each flow is sending separate CBR flows to the corresponding receiver on the same channel.

In a scenario where the nodes have no knowledge of ongoing hidden transmission (Case1), S_1 and S_2 monopolize the channel and achieve the maximum utility at the expense of the starving nodes S_3 and S_4, as simulation results in terms of utility and FSSE demonstrate in Figs. 9 and 10, respectively. Average CUE in terms of the ratio of the aggregate MAC layer good put at the receivers to the aggregate PHY layer throughput at the corresponding transmitters, is also presented in Fig. 10. We have recorded 10.4Mbps an aggregate utility. In the next case (Case2), mutual sensing leverages FSSE and drops SSE with an aggregate utility reaches roughly 7.2Mbps.

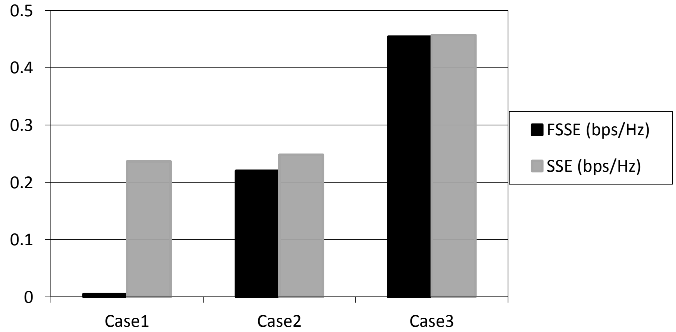


Figure 7. Performance evaluation in terms of fairness and overall spectral efficiency of the scenarios in Fig. 6.

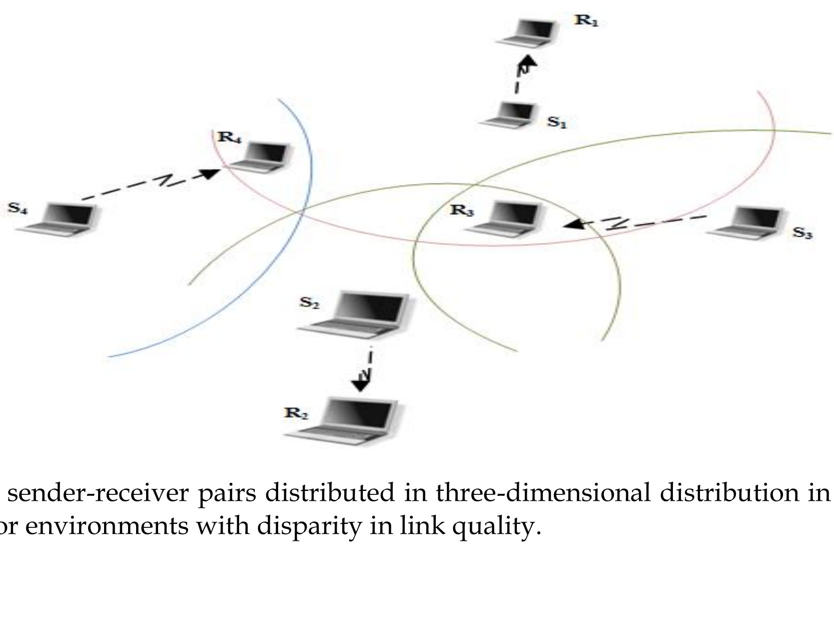


Figure 8. Four sender-receiver pairs distributed in three-dimensional distribution in 100x100x100m3 indoor environments with disparity in link quality.

Later, we have applied CAMA mechanism in Case 3 to find the appropriate transmit power for each node depending on the interfering environment it sees, such that parallel uplink and downlink transmissions cannot introduce enough interference to corrupt the reception at neighbor send-receive pairs.

Higher transmit power of 23dBm and 21dBm are set at S_3 and S_4, respectively due to the link quality each sees. Lower power level 13dBm is set at the remaining nodes such that:

- S_1 and S_2 are sensing S_3 and S_4's traffic but not vice versa.
- S_1 and S_2 transmit independently as well as S_3 and S_4 since they don't experience peer interference.

Power heterogeneous network is required here to schedule the possible largest number of successful concurrent transmissions in a single time slot on a single wireless channel. Various power levels are set at the nodes to drive a sender in or out of sensing range of others herby schedule the time to transmit, and to satisfy the SINR constraints in equation (5-8). An obvious improvement is portrayed in the simulation based results.

Energy detection threshold here is set at the default value. Individual transmission of S_3 and S_4 results in SNR higher than ζ_{ED} and ζ_P, respectively at S_1 and S_2 that enables either S_3's preamble or energy detection, and S_4's energy detection if S_1 or S_2 are listening. It is obvious that their concurrent transmission is also detectable. As for individual links, we observe that power adaptation according to CAMA maximizes S_3 and S_4's utility only, and their saturated traffic especially of S_3 reduces obviously other's opportunity to access the channel. Nevertheless, obvious improvement in FSSE and SSE is attained.

Later in Case4, higher ζ_{ED} is configured such that S_1 and S_2 do not sense a delivered energy of ongoing transmission when the corresponding preamble is missed. Preamble detection only is required to schedule the instantaneous transmissions of senders with homogenous technology. S_1 and S_2 knock the channel frequently to achieve the maximum utility and subsequently lead to the maximum fairness, though the power levels are not changed. Fairly and efficiently channel utilization demonstrates the efficacy of CAMA framework.

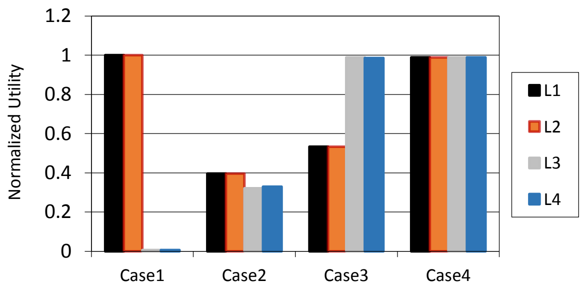


Figure 9. Performance evaluation of different scenarios of four heterogeneous wireless links in terms of channel gain, and distributed in 3D indoor environment.

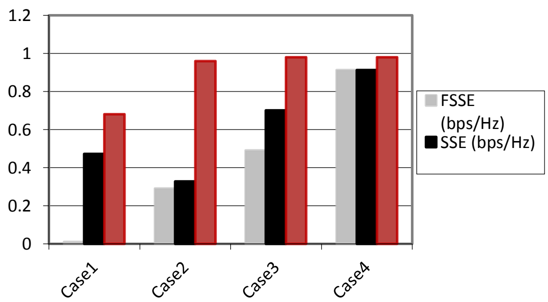


Figure 10. Performance evaluation in terms of fairness, overall spectral efficiency and average channel usage efficiency.

4.3.3 Third Scenario

We next randomly distribute 20 and 50 nodes in a 100x100 m² indoor environment, respectively. Each sender has its own receiver chosen randomly from the set of immediate neighbors. A random traffic model at each sender is used with a sufficiently high load such that a sender to be always backlogged with packets to send. A high ζ_{ED} is configured at each node such that they do not sense a delivered energy of ongoing transmission when the corresponding preamble is missed. In this case study, CAMA uses a genetic algorithm GA approach for optimal power distribution in a network. The GA is applied to find the optimal power level for each user under different operating conditions based on the constraints defined earlier. The problem is formulated as a multi-objective optimization problem which aims at maximizing the utilization and fairness. GA can work even when the objective function is not exactly known since it relies only on an objective function's evaluation. It is well-known for their remarkable generality and versatility, and has been applied in a wide variety of settings in wireless networks. The author skipped the details of GA since it is not in the scope of the work rather than for applying an optimization algorithm in CAMA framework. For details on GA, the author recommends (Sivanandam and Deepa 2007).

Figure 11 illustrates the aggregate one-hope utility achieved using 20 and 50 nodes in a random topology using the default DCF and CAMA as a channel access mechanism. The aggregate utility is found as the aggregate throughput of concurrent one hop communication in the network. The results are averaged over three independent simulation runs. Our approach offers clear improvement against DCF.

Figure 12 illustrates the average value of the FSSE and CUE using the default DCF and CAMA in random topology of 50 nodes. Performance evaluation in terms of fairness and the channel usage demonstrates the significant improvement using CAMA based on a broad observation of the channel state.

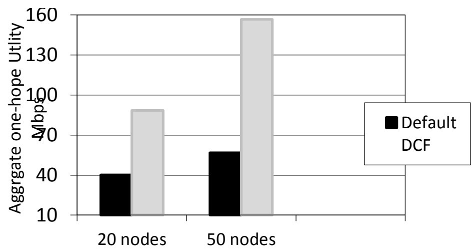


Figure 11. The average of the aggregate one-hope utility in random topology of 20 and 50 nodes. The results are achieved using default DCF and CAMA mechanism.

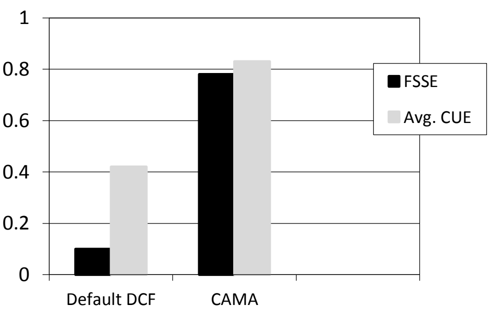


Figure 12. Performance evaluation of 50 nodes in a random topology in terms of fairness FSSE and average channel usage efficiency CUE, using the default DCF and CAMA mechanism.

Through the investigated use cases, asymmetric carrier sense is introduced and applied in CAMA. The simulation results portray the benefit of asymmetric sense scenario to time schedule the overlapped traffic without an extra timing signal. CAMA employs power heterogeneous ad-hoc network to optimize criteria involving throughput and fairness. This requires obtaining effective spatial reuse while satisfying the interference constraints.

5. Conclusion and Future Work

Based on local channel assessment, the default DCF mispredicts transmission failures and wastes potential transmission opportunities when they exist. It ignores the possibility of parallel transmissions that make use of the capture effect. It can be ineffective even at low traffic load.

This paper proposes a new capture-aware mechanism for ad-hoc networks while their benefit is amplified by properly adjusting the transmission power of the nodes based on broad observation of the channel. Through simulations, such a mechanism is shown to deliver high network utilization and provide fair access to the media than the standard DCF that these networks use. Using the simulator trace files, we have found that tuning transmit power is helpful in setting specific sense scenario and subsequently schedule the access to a shared medium without modifying carrier sense threshold, as has been exploited in CAMA framework in an interference-free fashion.

The nodes cooperate in power updating process via exchanging simple control signaling in power heterogeneous network. Further, based on the simulation results, we have found that throwing energy detection carrier sense line offers higher network utility.

In environment with heterogeneous technologies, foreign preambles are undetectable and energy detection may results in lower per-flow utility. However, the target SINR by CAMA at the corresponding heterogeneous nodes is expected to be lower since a receiver would not engage to a first coming foreign preamble, which in turn enables more concurrent transmissions and records higher aggregate utility and overall spectral efficiency. Our future work will demonstrate it. We also propose to explore how a similar mechanism can be used to adjust more PHY parameters like the PHY rate or/and contention window size as MAC parameter.

Conflict of Interest

The author declares no conflicts of interest.

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