Simple and Effective Carrier Sensing Adaptation for Multi Rate Ad-Hoc MESH Networks

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***Abstract*— Adaptive Physical Carrier Sensing(PCS) based on tuning the PCS threshold has been shown to be an effective mechanism for improving aggregate network throughput. However, earlier work [3] assumed a *single* link rate and a *common PCS threshold* for the entire network, as appropriate for a regular 2-D lattice grid of nodes with constant link (1-hop) distances. In an *ad-hoc* network topology, the 1-hop link distances vary significantly and a single PCS threshold is no longer suitable. Because IEEE 802.11 a/b/g networks provide *multiple data rates* over any link, *joint tuning of the link rate and PCS threshold* is thus desirable for achieving optimal aggregate throughput for ad-hoc networks. In this work, we first propose a simple yet effective principle for the above optimization. Next, we use the intuition offered by these formulations to suggest *run-time adaptive solutions* in OPNET simulations. We restrict ourselves to 1-dimensional random *linear* networks primarily to corroborate analysis with simulations and defer results with other topologies for future work.**

I. INTRODUCTION

Physical Carrier Sensing(PCS) allows a wireless node to assess the state of (shared) channel before transmitting to reduce the probability of collision, i.e., PCS is a key PHY/MAC attribute for management of mutual interference from simultaneous co-channel transmissions in a mesh network. Each node samples the energy level in the medium and initiates channel access only if the signal strength detected is below the physical carrier sensing (PCS) threshold. Although many of today's IEEE 802.11 [8] MAC implementation use a static PCS threshold, prior research [1], [2], [3] indicates the benefits of a tunable PCS threshold. An optimal PCS threshold achieves a trade-off between the amount of spatial reuse and the probability of packet collisions, thereby improving the overall network throughput. Zhu et al. [1] derive the optimal PCS threshold that maximizes the aggregate one-hop throughput for a regular topology given a minimum required SNR; an adaptive PCS threshold algorithm was suggested based on periodic estimation of channel conditions and evaluated on a real test-bed in [2]. A novel analytical model was introduced in [3] for determining the optimal carrier sensing range by minimizing the sum of the hidden terminal area and exposed terminal area. However, all the above have been limited to *single rate* networks; in this work, we focus on the impact of choice of PCS threshold in *multi-rate* networks.

We motivate the significance of this work by the initial simulation experiment reported in Fig. 1. The network topology in Fig. 2 is a 1-dimensional random network where each source-destination pair has a fixed separation of $d = 10\,m$ but the inter-source distance is randomly chosen as i.i.d from U(1,10) m. The network is configured such that all sources transmit to their respective destination with a constant rate (among $6, 12, 24$ or 48 Mbps) and the common PCS threshold shared by all nodes is tuned in each case for optimum aggregate 1-hop throughput. The results underscore two key observations:
- The optimum PCS threshold (and consequently the aggregate 1-hop throughput) is indeed a function of the (common) rate;
- The choice of link rates is fundamental to optimizing the aggregate 1-hop throughput.

In the above example, all source-destination distances were identical; in such topologies, a common PCS threshold is appropriate. However, our work is mainly intended for ad-hoc networks where the link (or 1-hop) distance d is a random variable. In such cases, the average siganl to interference ratio at any receive node varies considerably across the network, and accordingly the link capacity. Thus, the optimal PCS threshold should also logically vary across the network as part of any overall strategy for interference management. This would allow us to exploit the available degrees of freedom: *different link rates in conjunction with choice of PCS threshold* to optimize aggregate network throughput. However (as can be expected), the above joint optimization is demonstrably complex and our goal in this work is to develop simple yet effective heuristics for such optimization. In that spirit, we investigate the utility of using a single PCS threshold for all nodes in an ad-hoc network, while recognizing this is clearly sub-optimal. Nonetheless, we demonstrate that tuning the single PCS threshold in conjunction with appropriate rate set choices provides significant throughput gains for ad-hoc networks.

There exists little prior guidance for *jointly optimizing* aggregate system throughput for a (single channel) multi-rate network with respect to the PCS threshold and link rates in the literature. Earlier link adaptation based approaches such as Auto Rate Fallback (ARF) [5], OAR [6] and Onoe [7] sought to improve the throughput of individual links according to dynamic channel conditions but did not consider use of PCS threshold as a parameter for improving aggregate network performance. Yang et al. [4] showed that for a higher PCS threshold and lower data rates, the MAC overhead can decrease and consequently the aggregate one-hop throughput improves; however this work was limited to single rate networks. In summary, the benefits of multiple channel rates with adaptive PCS threshold in a random network have not been explored.

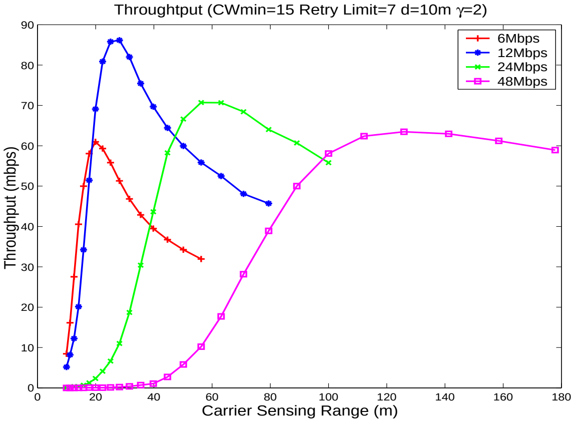

Fig. 1. Aggregate throughput of a linear network for path loss exponent $\gamma = 2$

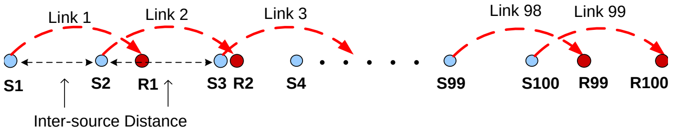

Fig. 2. Topology of a linear random network when all links have the same length

Accordingly, we first investigate the problem of *individual* channel rate assignments to links according to their distances in a multi rate network. Motivated by the desire to exploit the key result in [3], we propose a link-distance based rate assignment that *renders the interference range for all links equal*; this in turn allows a single carrier sense range to be used for the whole network. While this is certainly not optimal in general (e.g. a different carrier sense/interference range for each link is feasible), it affords a *simple* rate assignment mechanism that nonetheless yields significant improvement in aggregate network throughput compared to the baseline (single rate network) as will be supported by simulation evidence.

Needless to say, aggregate network throughput depends on a multitude of factors: network topology (link distances and node density), link rates, contention window size, and the traffic patterns, all of which contribute to the aggregate interference environment at any node transceiver. Investigating all the above is sufficiently complex to be beyond the scope of this work; here we only focus on a subset (that in our opinion is sufficiently significant) of the above factors, namely the choice of carrier sensing range and data rate. We also restrict ourselves to 1-dimensional (dense) linear networks as it allows underlying analysis in support of simulation results, and defer consideration of 2-D network topologies to future work.

Given a discrete set of available link rates (e.g. in 802.11a [9], these are 6, 9, 12, 18, 24, 36, 48 and 54 Mbps), the choice of link rates is fundamental to the tradeoff between spatial reuse and spectrum efficiency. Since the aggregate throughput is the product of the number of concurrent transmission links and the throughput per link, we would (ideally) like to maximize both. However, these two are at odds, as can be understood intuitively by the following simple argument: for a given link distance, choosing a higher link rate from the allowed set increases the interference range, i.e., it will cause more simultaneous transmissions to interfere with the reference link, and in turn reduce aggregate throughput. Clearly, the balance between promoting spectrum efficiency (higher individual link rates) and spatial reuse (number of simultaneous transmissions possible in a given network area) is governed via the resulting interference generated; in our work, we propose to achieve optimal interference management by tuning the CS range in conjunction with the chosen link rates.

The paper is organized as follows. Section II proposes the simple link to link rates assignment principle based only on individual link distance. In Section III, an adaptive algorithm for run-time optimization of PCS and multiple data rates is proposed and evaluated. Finally, we conclude the paper in Section IV.

II. PRINCIPLES OF RATE ALLOCATION ON INDIVIDUAL LINKS

In this section, we investigate the problem of individual link rate assignments according to their distances in a multi rate network. Our rate adaption principle is a link-distance based rate assignment that *renders the interference range identical for all links*. This implies that rate assignment must be coordinated at the network level.

A. Rate Allocation on Individual Links

We assume that the $r_i, i = 1, \ldots K$ are the available link rates. For our analysis and simulations, we only permit r_i to take values from $6, 12, 24$ and 48 Mbps, i.e. $K = 4$. Among the available rate set $\{r_1, \ldots, r_K\}$, which is ordered $r_1 < r_2 < \ldots < r_K$ without loss of generality, we choose a subset $\{r_{i_1}, \ldots, r_{i_M}\}(M <= K)$ in various examples, which is ordered $r_{i_1} < r_{i_2} < \ldots < r_{i_M}$. Note that IEEE 802.11a actually allows more rates, notably $6, 9, 12, 18, 24, 36, 48$ and 54 Mbps; however each pair $(6, 9), (12, 18), (24, 36)$ and $(48, 54)$ Mbps use the same modulation scheme and have very similar rate-range performance as can be verified by the OPNET [10] simulation results in Fig. 3 (the transmission power is 1 mW and $\gamma = 2$). The choice of the reduced 4-set results in some minor loss in performance but also greatly reduces the search complexity of finding the jointly optimal CS range-rate set for any network.

Let β_i represent the SINR (Signal to Interference and Noise Ratio) threshold required for adequate packet reception (i.e. acceptable packet loss rate) for rate r_i. Then the interference range $R_I(i)$ as an implicit function of the link rate r_i is given by [3]

$$R_I(i) = (\beta_i)^{\frac{1}{\gamma}} \frac{R_{tr}(i)}{((R_{tr}(i)/d)^{\gamma} - 1)^{\frac{1}{\gamma}}} \qquad (1)$$

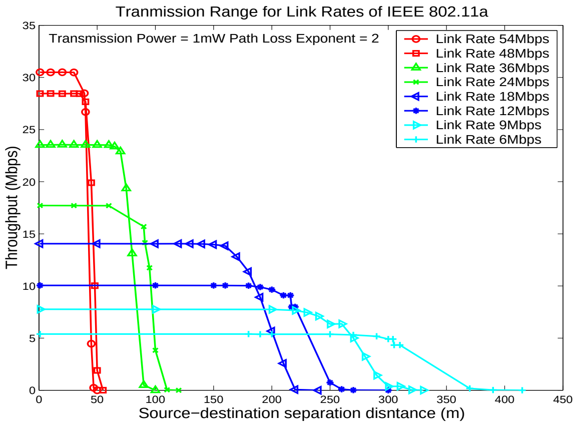

Fig. 3. Range-rate curves of IEEE 802.11a with OPNET simulation

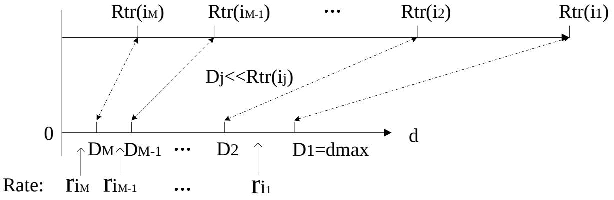

Fig. 4. Principles of rate allocation on individual links

where d is any link distance, γ is the path loss exponent and $R_{tr}(i)$ is the transmission range corresponding to rate r_i. Here, the channel between any two nodes is assumed to be identical and non-fading. The mean received signal power is related to the transmission power by a propagation power law characteristic.

Eq. (1) provides a *theoretical* expression for $R_I(i)$ based on the amount of link margin available when $d < R_{tr}(i)$; i.e., only a secondary transmitter within a radius $R_I(i)$ of the intended *receiver* will disrupt the reference transmission (i.e. lead to loss of reference packet). For d and r_i fixed, it can be shown by taking partial derivative of Eq. (1) with $R_{tr}(i)$ that $R_I(i)$ is monotonic decreasing, implying that increasing $R_{tr}(i)$ results in the link becoming less vulnerable to interference. Further, when $R_{tr}(i) >> d, i = 1, \dots K$, the $R_I(i)$ can be well-approximated by

$$R_I(i) \approx (\beta_i)^{\frac{1}{\gamma}} d \qquad (2)$$

The above condition is critical for high density ad-hoc networks, since increased network capacity is directly related to the extent of spatial reuse (concurrent co-channel transmissions). We will thus assume that this condition holds by suitably choosing the transmission power.

We now propose the following principle for link rate assignment: *the interference range for all link rates are equal*, irrespective of link distance. Our earlier work for a single rate network [3] showed that for a network with a common carrier sensing range, the aggregate throughput is optimized when $R_{cs} \approx R_I$. Thus the aggregate one-hop throughput for a *multi-rate* network is also expected to improve significantly compared to a single-rate baseline using the above principle, i.e. when all links share a common carrier sensing range. However, since the available link rates in IEEE 802.11 are discrete and limited, rendering the interference range for all links equal cannot be fulfilled exactly.

As shown in Fig. 4, we will assign link rates to the individual links as follows: any generic link distance d is divided into M subranges $(0 = D_{M+1}, D_M], (D_{M-1}, D_{M-2}], ...(D_2, D_1]$, which maps to one of the M available link rates $r_{i_j}, j = 1, \dots M$. I.e, if $d \in [D_{j+1}, D_j]$, the corresponding rate r_{i_j} is selected. Note that D_1 is the longest possible link distance in a network. In order to achieve Eq. (2), if suffices to let $D_j << R_{tr}(i_j)$ by suitably choosing the transmission power. Further, if $d < R_{tr}(i_2)$ and $D_2 < d < D_1$, we assign r_{i_1} to that link instead of r_{i_1} implying that the lower rate is preferred.

Thus, using Eq. (2) for the break-points

$$R_I = D_j \cdot \beta_{i_j}^{1/\gamma} \qquad for \qquad j = 1, \dots M \qquad (3)$$

which yields

$$D_1 : D_2 : \dots : D_M = \beta_{i_1}^{-1/\gamma} : \beta_{i_2}^{-1/\gamma} : \dots : \beta_{i_M}^{-1/\gamma} \qquad (4)$$

Consider an illustrative example for $M = 4, \gamma = 2$ and $r_{i_1}, r_{i_2}, r_{i_3}, r_{i_4}$ equal to $6, 12, 24$ and 48 Mbps (which happen to be r_1, r_2, r_3, r_4) respectively, with maximum link distance $D_1 = 10\,m$. The link distances are divided into four subranges $(0, D_4], (D_4, D_3], (D_3, D_2]$ and $(D_2, D_1]$ corresponding to the four rates (48, 24, 12 and 6 Mbps) respectively. Given β_i= 4.5312, 7.5415, 15.0418, 21.5521 dB [1], from Eq. (3) we can find $D_1 : D_2 : D_3 : D_4 = 1 : 0.7071 : 0.2982 : 0.1409$, from which $D_1 = 10\,m$, $D_2 = 7.071\,m$, $D_3 = 2.982\,m$,$D_4 = 1.409\,m$. With the transmission power set to a sufficiently high value (1 mW) such that $D_j << R_{tr}(i_j)$, the corresponding range-rate curves[2] were found by OPNET simulation and shown in Fig. 3. The specific values for $R_{tr}(1)$, $R_{tr}(2)$,$R_{tr}(3)$ and $R_{tr}(4)$ found were 304 m, 216 m, 90 m and 43 m respectively and will be used in our simulation experiments in Section II-A.

B. Benefits of Rate Diversity

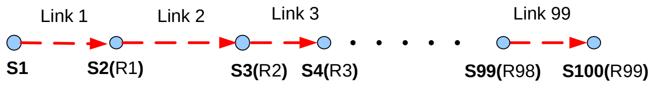

Fig. 5. Topology of a linear random network when links have variable lengths

1) Simulation Set-up: We evaluated the rate allocation principle in OPNET using the modified Physical Sensing Module [11] developed in [3] for a random linear network where the link distance is randomly chosen from a uniform distribution U(1,10)m, as shown in Fig. 5. Each transmitter sends saturated traffic to its right-hand neighbor. The reception sensitivity was set such that the reception range was 10 m; thus a receive node can only receive packets up to a maximum distance of 10 m. Different PCS threshold will be used in the simulation

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[1] The SNR thresholds are for 1500 Byte packets at 10% packet error rate, acquired from OPNET modulation curves.

[2] The transmission range is defined as the maximum source-destination separation for 10% packet error rate (PER) relative to the maximum throughput.

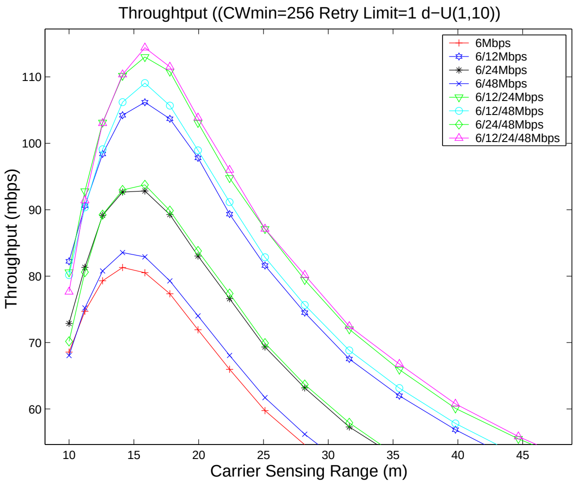

Fig. 6. Throughput in a linear network as a function of the carrier sensing range

to determine the optimal one-hop throughput for each rate set. For intuition, we will show the carrier sense ranges instead of PCS threshold in the results, which are equivalent to each other.

Defn. 1: *Carrier Sensing Range*

The carrier sensing range R_{cs} is defined by

$$\gamma_{cs} = \frac{P_{ref}}{R_{cs}^{\gamma}} \quad (5)$$

where P_{ref} is the power received at a reference point in the far field region at distance $\bar{d}$ from the transmitting antenna, which can be given by $\frac{P_{tx}\lambda_w^2}{16\pi^2}$, where P_{tx} is the transmission power and λ_w is the wavelength. Thus R_{cs} is the distance at which the received signal power equals a pre-set sensing threshold value γ_{cs}. The implication is that only one among all contending nodes within an area defined by R_{cs} may transmit, and the others defer transmission via the CSMA mechanism in IEEE 802.11 DCF. Thus if a reference node S_0 is transmitting, concurrent transmissions can only originate from stations which lie outside a circle of radius R_{cs} centered at S_0.

The lowest link rate r_{i_1} in the network was set at 6 Mbps, used by the longest link. We searched exhaustively through all possible rate combinations $\{r_{i_1}, \ldots, r_{i_M}\}$ and determined the best rate set subject to Eq. (3).

The frequency band used was 5.18 GHz, the packet size 1500 bytes, the transmission power 1 mW, path loss exponent of 2 and the RTS/CTS mechanism was disabled. Each node has a traffic source rate of 2000 packets/s to send to it's right hand neighbor. We set retry limit to 1 in order to disable the binary exponential backoff (BEB) mechanism, because packet retransmissions with BEB is known to lead to unfairness among different transmitters with different error rates. Further, we increase the minimum contention window value CWmin from the default value 15 in IEEE 802.11a to 256 to minimize collisions resulting from simultaneous transmission. This configuration allows us to focus on the effects of adaptive PCS with multiple rates in mitigating co-channel interference, which is the primary focus of this work.

We generated several topologies with the same distribution for simulation; only the results from one topology are shown since the results from all others were found to be nearly identical.

2) Simulation Results: Fig. 6 shows the aggregate one-hop throughput in the linear network as a function of the carrier sensing range which is defined later in Section III-B. By Eq. (1), the interference range corresponding to a separation of 10 m for 6 Mbps is 16.9 m. From the figure, we can see that the 8 curves approach their respective throughput peak almost simultaneously at a carrier sensing range of 16 m, close to the predicted. Also, we find that with our rate allocation principle, the maximum aggregate one-hop throughput with *all multiple rate sets* exceeds that of a baseline network where *only* 6 Mbps is used. Specifically, using 6/12/24/48 Mbps can increase the maximum aggregate one-hop throughput by 44% corresponding to a single rate (6 Mbps) network. In addition, 6/12/24/48 Mbps outperforms all other multi rate combinations that include 6 Mbps, which implies that when the lowest link rate is fixed (6 Mbps in this case), using *all* available higher rates yields improved throughput.

3) Discussion: Until now, we have shown via simulation that when the lowest rate r_{i_1} in a network is fixed, using multiple rates based on our rate allocation principle can lead to significantly improved throughput vis-a-vis single rate networks. In addition, we have shown that when the lowest link rate is fixed, using *all* available higher rates yields improved throughput. This greatly reduces the problem of choosing the optimum rate-set (from among all combinations of $6, 12, 24$ and 48 Mbps) to that of choosing the *lowest* rate, i.e, reduces search from 2^4 to only 4 rate combinations (“6/12/24/48 Mbps”,“12/24/48 Mbps”,“24/48 Mbps” and “48 Mbps”). For convenience, we call the lowest rate in a rate-set the **the minimum rate** for the network.

We have found (via analytical formulation and simulations that could not be included here due to space limitations) that the optimal throughput is sensitive to the choice of the minimum rates; and the optimal minimum rate for a given network varies significantly based on the link distance distribution and the path loss exponent. For the same link distance distribution, with increasing path loss exponent, optimal throughput is achieved for higher minimum rate. As a result, knowledge of the link distance distribution is needed for the minimum rate selection. In general, the link distance distribution depends on a multitude of factors including the node density, the transmission powers and traffic patterns and routing protocols. For example, minimum hop routes will favor more longer (lower rate) links. Assuming that the statistical characteristics of link distance distribution is stable and can be estimated from network measurements, it becomes a key input to adaptive algorithms of the type described in Section III for run-time network optimization.

III. ADAPTIVE PCS WITH MULTIPLE LINK RATES

Based on the principles enunciated, we next develop and evaluate a *run-time* algorithm - Adaptive PCS with Multiple Rates (APMR) for joint optimization of PCS threshold and link rates. This algorithm is the first of it's type and generalizes considerably that in [2] for single rate network. Besides adaptively searching the optimal PCS threshold, APMR also allocates rates to individual links dynamically for optimized aggregate network performance (throughput) subject to maximum PER constraint on each link.

A. Algorithm for Adaptive PCS with Multiple Link Rates

Our PCS adaptation policy seeks to maximize aggregate throughput while maintaining the PER in a target range to balance the hidden and exposed terminals. The algorithm has two phases: first, we determine the optimal minimum rate *off-line*. As we have pointed out earlier, the optimal minimum rate is impacted by the link distance distribution and the path loss exponent. Of these, the path loss exponent can be assumed fixed and known. Since our work is aimed at ad hoc mesh networks with little or no node mobility, we assume that the statistics of link distance distribution vary much slower than the characteristic time constants of the PCS threshold adaptation. Thus the minimum rate r_{i_1}, an input for our algorithm adapts to changes in the link distance distribution. Next, we dynamically update the rate allocation to individual links. Since our rate allocation principle only requires knowledge of the *longest currently active* link distance in the network (which may change with time), our adaptive algorithm estimates this and uses it to update the link subranges for rate allocation periodically.

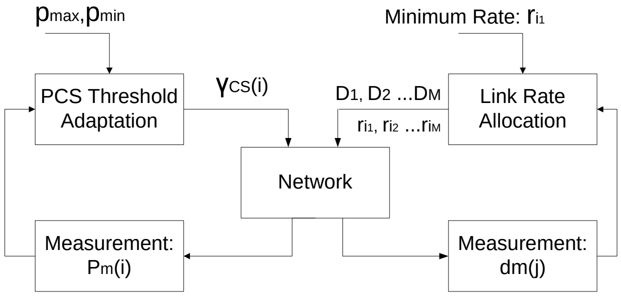

Fig. 7. Block diagram of run-time algorithm for joint optimization of PCS and multiple link rates

A schematic block diagram of the optimization algorithm APMR is shown in Fig. 7 and we define the following:

- i: iteration index corresponding to PCS threshold updating period
- j: iteration index corresponding to Subrange updating period
- T: PCS threshold updating period
- kT: Subrange updating period, where $k \in N, k > 1$
- r_{i_1}: The minimum rate
- $d_m(j)$: The **longest link distance** in the network within jth subrange updating period
- $D_1, D_2, ..., D_M$: subrange boundaries
- $r_{i_1}, r_{i_2}, ..., r_{i_M}$: the rates of each subrange
- $P_m(i)$: The PER of the link with **highest PER** within ith PCS threshold updating period
- p_{min}, p_{max}: Targeted minimum, maximum PER
- $\gamma_{cs}(i)$: PCS threshold used after ith PCS threshold update
- δ: PCS adaptation step
- $\gamma_{min}, \gamma_{max}$: minimum, maximum PCS threshold

In the algorithm, the PCS threshold and the link subranges for rate allocation are updated after a period T and kT respectively. A central server collects PER and link distances of all links for processing and broadcasts the new system parameters to all stations: $\gamma_{cs}(i)$, $D_1, D_2, ..., D_M$ and $r_{i_1}, r_{i_2}, ..., r_{i_M}$.

All stations measure the per-link PER (the ratio between the number of received ACK and the number of transmitted data packets within T) and their link distance periodically. The PER of the link with highest PER $P_m(i)$ will be used in the same linear adaptation algorithm as that in [2] to determine the PCS threshold for the next period based on Eq. (6):

$$\gamma_{cs}(i) = \begin{cases} max(\gamma_{cs}(i-1) - \delta, \gamma_{min}) & \text{if } P_m(i) > p_{max} \\ min(\gamma_{cs}(i-1) + \delta, \gamma_{max}) & P_m(i) < p_{min} \\ \gamma_{cs}(i-1) & \text{otherwise} \end{cases} \tag{6}$$

The rate allocation scheme updates use a larger period kT based on the measured longest link distance $d_m(j)$ using Eq. (4). This is appropriate because for any given set of subranges, several rounds of updates are needed to find the optimal PCS threshold.

B. Evaluation of the Algorithm of APMR

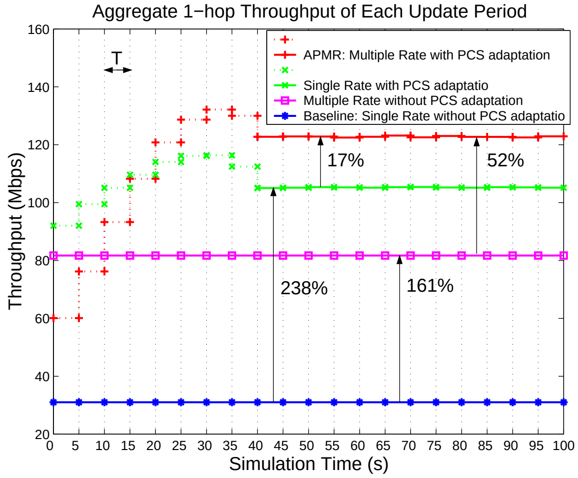

Fig. 8. Average throughput of each update period

1) Simulation Set-up: We implemented APMR in OPNET to evaluate its performance. In the simulation, we are particularly interested in 1) whether APMR converges to the optimal operational point (optimal carrier sensing range for the correct subrange division) and 2) what performance gain results compared to cases where no PCS adaption and/or no rate adaptation is used. For the latter, we will compare the aggregate throughput of APMR with three other cases: (a) Single Rate with PCS adaptation, (b) Multiple Rate without PCS adaptation and (c) Single Rate without PCS adaptation.

Case (a) is the same as the PCS adaptation algorithm proposed in [2]. For Case (b), PCS adaptation is disabled but rate adaptation is enabled. In the simulation of this case, we let

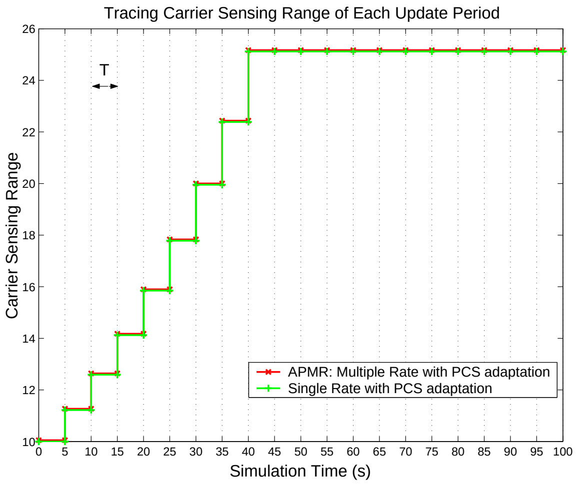

Fig. 9. Tracing the carrier sensing range of each update period

each link explore all possible link rates and use the highest link rate which can assure its PER is lower than 20%. So Case (b) is very close to the underlying design idea of link adaptation based approaches such as Auto Rate Fallback (ARF) [5] and should give performance similar to these approaches. Case (c) does not use either PCS adaption and rate adaptation and serves as the baseline to evaluate the performance of other cases.

The simulation was conducted for the same linear network used in Section II-A shown in Fig. 5. In the network, the link distance is randomly chosen from a uniform distribution U(1,10) m. Each transmitter sends saturated traffic to its right-hand neighbor. We let the path loss exponent $\gamma = 2$ and with this path loss exponent, we find that for the various link distance distributions, the optimal minimum rate is always 12Mbps from simulations. So in this case we let $r_{i_1} = 12Mbps$ in all simulations irrespective of link distance distribution. We will defer the detailed discussion of the r_{i_1} selection for future work. $12Mbps$ is also used as the single link rate in Case (a) and (c) for comparison. We set $T = 5s$ and $k = 5$, thus for a simulation run of 100 second, there will be 20 PCS updating periods altogether. The reception sensitivity was set to $-66.8dbm$ such that the reception range was 10 m; thus a receive node can only receive packets up to a maximum distance of 10 m. In addition, we set $(p_{max}, p_{min}) = (0.2, 0.1)$, $\delta = 1dB$ and $(\gamma_{min}, \gamma_{max}) = (-90dbm, -66.8dbm)$ for PCS adaptation. The initial PCS threshold is set to γ_{max}.

Further, for case (b) and (c), where there is no PCS adaptation, the PCS threshold γ_{cs} is set to -90 dBm (a typical value of PCS threshold in today's hardware) and used as the baseline to evaluate the algorithm of Case (a) in [2]. For transmission power of 1 mW, from Eq. (5), the corresponding carrier sensing range is 146m. All other simulation parameters here are identical to those in Section II-A.

2) Simulation Results and Discussion: Fig. 8 shows average throughput of each update period for APMR and all other three cases. The dotted curves represent durations where the system did not meet operational constraints, i.e., the PER of some link is higher than 20%. Thus although the throughput of the dotted part may be higher, we do not include them in the evaluation of network throughput. Fig. 9 traces the changes of the carrier sensing range in APMR and case (a).

We first note in Fig. 8 that the algorithm for Case (a) always converges to the optimal operational point. As shown in Fig. 9, the carrier sensing range is gradually increasing from 10m at 0s to 25.1m at 40s to decrease the PER of the worst link. During [40s,100s], the carrier sensing range and aggregate throughput is stable.

Second, APMR outperforms the other three cases greatly. During [40s, 100s], compared with the baseline (no rate adaptation and no PCS adaptation), case (a) (with PCS adaptation only) and case (b) (with rate adaptation only) improves the throughput by 238% and 161% respectively. However, using case (a) and (b) as reference, APMR further improves the throughput by 17% and 52%, which confirms the importance of *joint optimization* of link rates and PCS for random networks. In case (a) where all links work at the same link rate, a common carrier sensing range 25.1m is too conservative for short links. But APMR can fully take advance of such capacity by joint rate allocation and PCS threshold. If the proportion of the short links are higher, the throughput increase is greater.

IV. CONCLUSION

In this paper, we have proposed and verified a novel and simple yet effective principle for the joint optimization of PCS and multiple rates in ad-hoc networks. An adaptive algorithm for run-time optimization of PCS and multiple data rates is also proposed and evaluated. The results strongly underscore the improvements to the aggregate throughput via suitable rate allocation and adaptive tuning PCS threshold.

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