Cross-layer routing and transmission rate control strategies in wireless multi-hop CSMA/CA networks

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Cross-layer routing and transmission rate control strategies in wireless multi-hop CSMA/CA networks

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Abstract

We investigate multi-hop wireless ad hoc networks in which nodes use software controlled radios and 802.11-based CSMA/CA MAC. Each node independently selects its cross-layer parameter vector for each packet that it forwards. The latter consists of the setting of the transmission data rate and the identification of the neighboring node to which the packet is forwarded (and thus the selection of the route). We present an analytical model to calculate, for each candidate parameter vector, the corresponding attainable throughput and transport throughput capacity rates. To enable the network to transport traffic in a throughput-effective manner, we present cross-layer schemes under which each node configures its parameter vector by using the corresponding link transport capacity measure that it computes as a key metric. Depending upon whether certain neighborhood activity status data is collected, we present two such datagram-based cross-layer parameter vector selection schemes. We compare the throughput performance behavior attained through the use of these schemes, as well as with that exhibited by schemes that do not use the link transport capacity function as a metric. Our results confirm the precision of our analysis and demonstrate the distinct effectiveness demonstrated by schemes that employ the link transport capacity measure.

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I. Introduction

Multi-hop wireless ad hoc networks have been widely studied over the past several years. While multi-rate operations have been commonly considered as a cross-layer MAC control problem, the impact of such operations on the throughput efficiency of the network is largely unexplored. In this paper, we investigate key cross-layer issues involving combined adaptations across the physical, link, and network layers. While transmissions at a higher data rate lead to shorter packet transmission times and thus may potentially induce a higher throughput, they require a higher acceptable SINR (Signal to Interference and Noise Ratio) at the intended receiving nodes. This may lead to the use of shorter link layer communication forwarding ranges. From network layer point of view, a flow may then have to be transported along a route that contains a larger number of hops. This thus produces higher network internal traffic loads, which may in turn increase the interference power measured at the receiving nodes. Hence, by increasing the data rate, one does not necessarily secure an overall upgrade in the end-to-end throughput performance behavior. It is not readily determined as to how one should make the best joint selection of the transmission data rate in combination with the setting of the packet’s forwarding range, under prescribed or observed network loading conditions.

In this paper, we investigate our proposed methodology for the selection by each node of the cross-layer “parameter vector”. The latter is defined to involve the next hop’s associated forwarding range and the data rate to be used by a node for the transmission and routing of a packet that it wishes to forward towards its destination. This methodology is based on a computation of a relative link level transport throughput capacity measure. The transport throughput capacity attained across a link relative to a specified flow is calculated as the product of the computed link throughput capacity rate and the effective progress range gained when sending flow packets across the link. In this paper, we select the cross-layer parameter vector so that the corresponding transport throughput capacity metric is optimized. We show in this paper that by selecting the nodal cross layer parameter vector in such a manner, a distinctly upgraded cross-layer operation is realized.

To design the underlying cross layer mechanisms, we proceed in the following manner. We consider first the operations involving a single network station. We assume this tagged station to monitor (on a sliding window basis) certain key elements that represent the activity of its neighboring links and nodes. Using such statistical data, we derive mathematical expressions for the performance
behavior experienced by packets and flows traversing this node and its attached links. When designing distributed mechanisms for the selection of the parameter vector, to attain network-wide upgraded performance behavior, one must consider the impact of the operations executed at each node on those undertaken by other nodes. We first examine the Independent Scheme, in which each node acts independently, based on its monitored status indicators, without coordinating with other nodes. We discover however that this approach may, under certain conditions, reach a suboptimal solution. Recognizing that CSMA/CA mechanisms tend to induce fair sharing of the multiple access medium, we develop a scheme under which each node computes the parameter vector, under the assumption that a fair occupancy of the channel takes place. It is identified as the Homogeneous Scheme. Our results demonstrate that the Homogeneous Scheme yields highly enhanced network performance. Since it is distributed, involving calculations that can be carried out in realtime, we conclude it to provide the efficient setting of the parameter vector investigated in this paper.

The contributions provided in this study are multi-fold: a. We develop a nodal centric cross-layer analytic model for calculating key throughput performance measures. b. We present a stochastic two-level (combined collision and SINR based) interference model. Using this model, we derive easy to compute mathematical expressions that are then used to derive the optimal cross-layer settings. c. We use the link transport capacity measure as a key metric for the setting of the cross-layer parameter vector. d. We present and evaluate two mechanisms for the selection of the parameter vector. Both are based on the maximization of an estimated transport throughput capacity measure. e. Through simulation evaluations, we confirm the precision of our analytical methods, as well as show that even under non-homogeneous loading scenarios, our analytical models can be employed to provide for the efficient setting of the cross-layer parameter vectors. The organization of this paper is as follows. Section II summarizes related works. In section III, we present the nodal-centric model and derive formulas that characterize the system performance measures. In section IV, we present and examine the performance of the two schemes for the setting of the parameter vector. We further investigate in V the performance behavior of the network under a multitude of networking scenarios when the latter scheme is employed. Simulation evaluations are presented in VI and conclusions are drawn in VII.

II. Related works

Typical routing protocols used for wireless ad hoc networks employ minimum hop length routes.
Such mechanisms have been shown to often produce poor throughput performance behavior ([2]). To upgrade the performance exhibited, alternative routing metrics have been studied ([11]). Recently, routing metrics have been proposed for use in multi-rate ad hoc wireless networks (see [3]-[5], [7]-[10], [23], [35]). In [33]-[34], routing mechanisms that act to balance the distribution of traffic loads across the network have been devised. The algorithms presented in [31]-[32] employ multiple path routing. We have also noted published papers that utilize optimization techniques for the selection of the cross-layer parameters ([6], [8]). Due to the complexities involved in modeling the behavior of such networks, we introduce in this paper a simplified analytical model that enables each node to compute in a low complexity manner the optimal parameter vector.

The network transport throughput capacity achievable by an ad hoc wireless network is noted in [1] to grow at an order of $O(n^{1/2})$ bit-meters per second. When nodes are permitted to select the neighbor to which they forward the packets, an optimal link forwarding distance level has been noted to exist (see [13]). In [5], it is shown that routing over fewer but longer hops may yield better energy efficiency than that attained under nearest-neighbor routing. The work in [7] has investigated the selection of an optimum physical carrier sensing range that maximizes the throughput performance in an 802.11-based ad hoc network operation. The impact of variable transmission range levels realized under the use of variable data rates have been studied, assuming a static interference process. In contrast, in our study, we examine the performance of the network when the interference processes may stochastically and dynamically fluctuate. Accordingly, we develop cross-layer algorithms that employ system state monitors for current selection of the best parameter vector. In [8], the authors have formulated a joint routing and link scheduling (and rate allocation) optimization problem to find a path for a flow that offers the highest path capacity value. In connection with the analysis of CSMA/CA based networks, we also note the contributions in [15], [21]-[22], [24]-[25], [36]-[37]. To the best of our knowledge, there are no published works that provide comprehensive mathematical based approaches for adaptive rate control and routing for ad hoc networks that employ 802.11 based MAC protocols.

### III. System model and nodal performance behavior characterizations

Consider an ad hoc wireless multi-hop network carrying multiple end-to-end data packet flows. In this section, we focus on one tagged station and mathematically model its performance behavior as
flows traverse this station through its attached links, under given, or monitored, network activity conditions. The analytical results are then used in subsequent sections to facilitate at each node the selection of the parameter vector that serves to yield upgraded network performance behavior.

a. Performance measures and metrics

For a given flow whose packets are distributed across a selected path, the flow transport throughput rate is computed as the product of the flow’s throughput rate and the effective spatial progress made by the flow as it is directed from the source to its destination across its route. The network’s transport throughput is defined as the sum, over all network flows, of each flow transport throughput rate. We use the network transport throughput as a measure of the effective transport service offered by the network to its clients. This is an effective performance metric, noting that it involves statistical averaging that is performed over both temporal and spatial resources.

To express the potential utility gained by flow packets when transmitted across a selected link using a selected data rate, it is advantageous to use the associated link transport throughput capacity as a performance measure. To calculate this metric, we consider a given link with respect to a specific flow that has its packets directed across this link. We assume, for the sake of the computation, that this flow is currently the only one using the link resources. This metric is calculated as the product of the computed throughput capacity of the link and the projection of the forwarding range across the line vector connecting the source towards the destination. Under this definition, the same link may provide different link transport capacity levels when calculated with respect to different flows.

In this paper, we propose mechanisms that base their selections of the parameter vector on the link transport capacity measure. This approach is motivated as follows. The network attainable throughput capacity (TH) is expressed in terms of the network’s average spatial reuse factor (SRF), identifying the mean number of simultaneous transmissions that can take place over the area of operations, and the average path length L (hops) traversed by each flow as follows: \( TH \sim r_c \cdot SRF / L \), where \( r_c \) denotes the average data rate selected by nodes. Consider a homogeneous network layout and loading scenario. To analyze the network’s ability to produce high throughput, assume the network is loaded to saturation. Assume each node to select the parameter vector \((r_c, d)\) for the forwarding of each packet, operating at data rate \( r_c \) over a link whose projected range (along the straight line connecting the source-destination with an average value \( d_{SD} \)) is equal to \( d \). Hence, \( L \sim d_{SD}/d \). Noting that the
realized SRF level is not impacted by the selection of the parameter vector and having 

\[ \text{TH} = (\text{SRF} / d_{sd}) \cdot r_c \cdot d, \]

each node to maximize the throughput rate should thus select a parameter vector that yields the highest \( r_c \cdot d \) product level (expressing the link transport capacity rate).

In accordance with the traffic class to which flows and packets belong, certain packets / traffic flows may impose end-to-end delay-throughput performance requirements. Under a QoS (quality of service) oriented cross-layer operation, it is desirable to select at each node a parameter vector from a set whose members meet such desired QoS levels. In this paper, to implement and evaluate a simple mechanism, we do not assume such procedures to be invoked. We consider here each node to rather implement datagram based mechanisms. Clearly, the algorithms presented here can be further enhanced by the inclusion of such flow oriented end-to-end performance considerations. Our analytical models can then be readily used to compute the achievable end-to-end delay-throughput performance behavior. Such an operation will be presented in a separate study.

\textbf{b. System model}

The nodal transmission power \( P \) is fixed at every station. Half-duplex radios are assumed to be used. Nodes are spatially Poisson distributed. In general, for a prescribed modulation coding scheme (MCS) that operates at a data rate \( r_c \), we can describe, 1) the relation between \( r_c \) and the required minimum SINR threshold \( \gamma(r_c) \) at the intended receiver, and 2), the relation between \( r_c \) and the packet transmission time duration \( T(r_c) \), \( r_c \in R_c \). \( R_c \) denotes the set of data rates offered by the available MCS structures. We consider a power law path loss model. Thus, the corresponding \((i, j)\) link’s channel gain function is set as: \( G_{ij} = d_{ij}^{-\alpha} \), where \( d_{ij} \) is the physical distance between nodes \( i \) and \( j \) and \( \alpha \) is the attenuation factor, \( \alpha > 2 \). Other channel gain functions can also be incorporated into our model.

Assume packets to contain a payload whose average length is equal to \( b \) bits. We consider a system that employs 802.11 DCF (Distribution Coordination Function) CSMA/CA type MAC. We assume that the use of RTS/CTS dialog is not invoked, as this is the customary default state and the suggested configuration by recent studies (see [37]). A station \( i \) that desires to transmit its packet, proceeds first to sense the channel. During the carrier sensing process, transmissions initiated by nodes located within its carrier sensing area (identified as a disk area centered at node \( i \) whose radius is equal to the

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\(^2\text{We do not impose here power control adjustments, so that the nodal transmit power is fixed. The carrier sensing sensitivity is kept fixed as well.} \)
carrier sensing distance) are assumed to cause node $i$ to defer its transmission. We use $CW_j$ to denote the contention window size in the $j$-th backoff stage. The minimum and maximum window sizes are represented by $CW_{\text{min}} = CW_0$ and $CW_{\text{max}} = 2^m CW_{\text{min}}$ respectively, where $m$ is an integer. After $CW_{\text{max}}$ is reached, the window size is fixed. The retransmission limit is set equal to $L$, $L \geq m$. Note that the carrier sense range (CS) is assumed to be fixed and not a function of the data rate. Alternatively, one may jointly adapt the value assumed for the carrier sensing range for each data rate (see [26]).

**c. Characterizing the CSMA/CA MAC operations from the point of view of a tagged station**

Consider a station $i$ that desires to select the parameter vector to be used for the forwarding of each of its queued packets. Station $i$ observes the channel state of the wireless medium in its carrier sensing area. Denote the number of stations (including itself) that currently contend for channel access, and that reside in the considered carrier sensing area, by $K$. For our analytical derivation, the following two-level (combined collision-SINR based) interference model is used to determine successful packet reception events. A packet transmission made by station $i$ to station $j$ is successful iff: 1) none of the other $K-1$ stations initiates a packet transmission at the same slot as that selected by station $i$; and 2) the SINR level at receiver $j$ is higher than a threshold $\gamma(r_c)$, where $r_c$ is the data rate employed to transmit this packet. In this manner, we employ a collision model to account for interferences originated (by nodes residing) inside the carrier sensing area, and a SINR model to account for interferences originated outside the latter area. Under our model, we neglect the possibility of the intended transmission capturing the receiver when other simultaneously executed transmissions originated inside the sender’s carrier sensing range take place. In this regard, this approximation provides a conservative estimate of the attained throughput performance. Practically, the latter approximation has been shown to yield highly accurate throughput performance behavior.

In the following, we carry out analysis to quantitatively describe station $i$'s behavior. We introduce a model that characterizes the underlying system activity in terms of the following parameters: 1) The probability $p_0$ that any of the other ($K-1$) stations starts to transmit at a given slot that belongs to the backoff period of station $i$. 2) The average channel occupancy time $E[T_o]$, which represents the time duration during which the medium is sensed busy and thus made unavailable to station $i$, once any of the $K-1$ other stations start to transmit its packet. Its value includes the time occupied for data (and ACK if successful) transmission and the lengths of the involved inter-frame spacing (DIFS and SIFS).
periods. 3) A probability distribution function of the cumulative interference power level $I^D$, originated by nodes residing outside node i's carrier sense region, measured at receiver j.

In practice, node i can obtain these parameters by monitoring its observed network activity states and by receiving data from other nodes concerning activities in the neighborhood. Good estimates for the first two are readily derived from direct state observations by station i. Alternatively, the third parameter can be approximated by combining direct activity measures with assumptions of uniformity in the statistical behavior of nearby nodes. Such an approach is used in III-d.

Given that node i has selected a specific slot for the transmission of its packet, we set $1 - p$ to denote the probability that this packet is received successfully by its intended link layer receiver j and that its ACK is received successfully by node i. We set $P_{\text{capture}}^D$ to denote the conditional probability of the successful reception of this packet under the impact of the cumulative interference at receiver j (originated outside node i’s carrier sensing zone). Given a successful data transmission, we set $P_{\text{capture}}^A$ to denote the conditional probability of a successful ACK reception under the impact of the cumulative interference detected at node i (originated outside the latter carrier sensing zone). We use $I^D$ and $I^A$ to denote the power levels interfering with the reception of the data and ACK packets, respectively, as detected at their corresponding intended receivers. Hence, we obtain the following:

$$ p = 1 - P_{\text{capture}}^D \cdot P_{\text{capture}}^A \cdot (1 - p_0), \quad (3-1) $$

$$ P_{\text{capture}}^D = P\{I^D \leq Pd^{-\alpha} / \gamma(r_e) - N\}, \quad (3-2) $$

$$ P_{\text{capture}}^A = \{I^A \leq Pd^{-\alpha} / \gamma(r_e) - N\}, \quad (3-3) $$

where forwarding range $d$ represents the distance across the link connecting station i to station j, and $N$ represents the thermal noise power level. In Eqs. (3-2) – (3-3), $P_{\text{capture}}^D$ and $P_{\text{capture}}^A$ denote the probabilities that the SINR levels at the receivers of nodes i and j, respectively, involving the respective receptions of the data and ACK packets, are larger than or equal to the threshold $\gamma$.

The head-of-line delay ($T_{\text{HOL}}$), also identified as the medium access delay (see [20]), expresses the time period elapsed between the instant at which the packet enters the head of the line position in station i’s transmission queue and the instant of time at which the station is ready to transmit the next packet across this link. In computing $T_{\text{HOL}}$, included are the time durations during which 1) station i backs off, 2) the channel is busy and the backoff process is frozen and 3) station i acquires the medium for transmitting its packet. Its expected value $E[T_{\text{HOL}}]$ is given by
\[ E[T_{HOL}] = (T_c \cdot (1 - p_0) + E[T_o] \cdot p_0) \left( \sum_{i=0}^{l} p_i \cdot \frac{CW - 1}{2} \right) + E[T_b] \cdot \left( \sum_{i=0}^{l} p_i \right), \]  

(3-4)

where

\[ E[T_b] = pT_c + (1 - p)T_s, \]

(3-5)

and \( T_c, T_b, T_s \) and \( T_c \) are respectively the slot time duration, node i’s channel occupancy time for a packet transmission, the mean time duration of a successful transmission and the mean time duration consumed by an unsuccessful transmission. \( T_s \) and \( T_c \) are further expressed in terms of SIFS (short inter-frame spacing), DIFS (distributed inter-frame spacing) and ACK durations. Thus,

\[ T_s = E[T(r_c)] + SIFS + ACK + DIFS. \]

(3-6)

\[ T_c = E[T(r_c)] + DIFS + P_{capture}^D \cdot (SIFS + ACK). \]

(3-7)

The packet queueing and transmission processing is described by an M/G/1 queueing system model, for which the effective packet service time is set equal to the message head-of-line delay \( T_{HOL} \). The throughput capacity attained across the communications link (i, j), denoted as \( C_S \), is calculated by dividing the payload data length by the mean head-of-line delay incurred by a packet transmitted across this link, accounting only for successful transmissions. Its expression is thus given by Eq. (3-7). Noting the dependence of \( E[T_{HOL}] \) and \( p \) on the following parameters through Eqs. (3-1)-(3-4), we further express \( C_S \) in terms of the number of stations residing within node i’s CS region (K), the forwarding range \( d \) of (i, j) link, and the employed data rate \( r_c \), denoted as \( C_S = C_S(K,d,r_c) \).

\[ C_S = C_S(K,d,r_c) = \frac{b}{E[T_{HOL}]} \cdot (1 - p^{t+1}). \]

(3-8)

The transport capacity attained across the identified link, such as the (i, j) link, assuming prescribed parameters \((K,d,r_c)\), with respect to a given flow, is defined as the product of the throughput capacity across the link multiplied by the averaged value of the link’s range when projected in the direction of the line vector connecting the flow’s source with the final destination, yielding:

\[ C_{Sr} = C_{Sr}(K,d,r_c) = C_S(k,d,r_c) \cdot d \cdot \cos(\theta), \]

(3-9)

where \( d \cdot \cos(\theta) \) expresses the described projection.

\textit{d. Characterizing the cumulative interference process and the probabilities of capture}

Recall the parameters that need to be monitored to enable the calculations introduced earlier in this Section. Often, it is costly to implement a mechanism that serves to monitor the cumulative interference power at a node. Hence, we also present here an approach under which the interference
power at a node is computationally estimated rather than being measured. The evaluation results (as demonstrated later) show that our method provides accurate predictions of the performance behavior. Specifically, the cumulative power level ($I^D$) induced by random interference signals sensed at tagged node i's link receiver j is expressed as the sum of two components, identified by the random variables $I_{in}^D$ and $I_{out}^D$. $I_{in}^D$ denotes the interference level originated by nodes located outside station i's CS area but inside a disk area centered at node j, with a radius equal to the carrier sensing distance CS plus the forwarding range d between nodes i and j. The latter area is denoted by $A_{in}$ (see Fig. 1). In turn, the second component, $I_{out}^D$, represents the interference power level originated by nodes located outside both the CS area of station i and the $A_{in}$ region. The probability of capture is thus given as:

$$P_{capture}^D = P[I^D \leq d^{-\alpha}/\gamma(r_j) - N/P] = P[I_{in}^D + I_{out}^D \leq d^{-\alpha}/\gamma(r_j) - N/P].$$

(3-9)

This method is motivated by the work in [16]. The results there identify the dominating contribution made by the most significant interferers and the imprecision of a pure Gaussian approximation of the cumulative interference, when spatially Poisson networks are considered. For calculating the $I_{in}^D$ component, we use the following approximation. Noting that the probability that two nodes residing in $A_{in}$ simultaneously initiate a transmission at the same slot is quite low, we assume that at most one interfering node can be active in $A_{in}$. Observing the area to be represented by the disk of radius (CS+d), punctured by the disk that represents node i’s CS area, we have:

$$A_{in} = \pi(CS + d)^2 - \pi CS^2.$$  

(3-10)

Induced by the Poisson statistics characterizing nodal spatial locations, we note that under a prescribed realized number of nodes across the area, nodal locations are governed by uniformly distributed i.i.d. random variables. Let X denote the distance between node j and a uniformly distributed location in $A_{in}$. If we denote the angle of the sector kjv by $\varphi$, the probability density function (p.d.f.) of X is noted to be given as:

$$f_X(x) = C_1 x \varphi = C_1 x \cos^{-1}(-\frac{d^2 + x^2 - CS^2}{2dx}), \quad CS - d \leq x \leq CS + d,$$

(3-11)

where $C_1$ is a normalizing constant. The random variable representing the interference power caused by an active node located in the $A_{in}$ region is then expressed as:

$$I_{in}^D = \begin{cases} PX^{-\alpha}, & \text{with probability } (1-e^{-A_{in} \tau'}), \\ 0, & \text{else.} \end{cases}$$

(3-12)
instant of time. \( \nu \) denotes the active nodal spatial density. One can obtain \( \tau' \) by setting it to be equal to the average fraction of time available to each active station in the latter region for transmitting. However, because the considered region is outside station \( i \)'s CS area, it can be operatively expensive to monitor or learn the activities therein. Alternatively, several approximations can be made. One is to simply assume the activities observed by the nodes there are statistically similar to those by station \( i \). This approximation can be justified by noting closely located nodes are likely to observe similar channel activities. In this manner, by assuming the nodes locating in node \( i \)'s proximity to see the same parameters, namely, the parameters \( p \) and \( E[T_b] \), \( \tau' \) is thus calculated as follows:

\[
\tau' = \Pr\{\text{non-empty nodal queue}\} \frac{E[T_b] + p \cdot E[T_b] + \ldots + p^i \cdot E[T_b]}{E[T_{HOL}]} = \begin{cases} \lambda \cdot (1 + p + \ldots + p^i) \cdot E[T_b], & \rho < 1, \\ \mu \cdot (1 + p + \ldots + p^i) \cdot E[T_b], & \rho \geq 1. \end{cases} \quad (3-13)
\]

An even simpler approximation can be derived in the following. Noting that the average number of active stations in a CS area can be approximated as \( \Pr\{\text{non-empty nodal queue}\} \cdot E[K] \), we may set \( \tau' \) to be equal to \( \min\{1, (E[K] \cdot \Pr\{\text{non-empty nodal queue}\})^{-1}\} \), ignoring unutilized idle slots.

As depicted in Fig. 1, we use \( I_{\text{out}}^D \) to denote a random variable that models the aggregate interference caused by nodes located at a range from node \( j \) that is farther than \((\text{CS+d})\). The \( I_{\text{out}}^D \) component involves active nodes that are distributed across outside a disk area, so that the results presented in [16] can be applied for the calculation, yielding the following Gaussian distribution:

\[
I_{\text{out}}^D \sim N\left(P \frac{\nu 2\pi r (\text{CS+d})^{2-\alpha}}{\alpha - 2}, P^2 \frac{\nu 2\pi r (\text{CS+d})^{2-2\alpha}}{2\alpha - 2}\right) = N(\mu_D, \sigma_D^2). \quad (3-14)
\]

Combining Eqs. (3-9) – (3-14), we obtain the capture probability to be expressed as follows:

\[
P_{\text{capture}}^D = \Pr\{I_{\text{in}}^D = 0\} \cdot \Pr\{I_{\text{out}}^D \leq d^{-\alpha} / \gamma - N / P\} + \Pr\{I_{\text{in}}^D > 0\} \cdot \Pr\{I_{\text{in}}^D + I_{\text{out}}^D \leq d^{-\alpha} / \gamma - N / P\}.
\]

Similarly, for the calculation of \( P_{\text{capture}}^A \), recall that \( I_A \) represents the aggregate interference power level monitored at station \( i \), as caused by nodes located outside the CS area of station \( i \). We use a Gaussian approximation technique for the calculation of the distribution of this cumulative interference power level, noting that interfering nodes include active nodes that are symmetrically located in a disk centered at node \( i \) (with radius CS). The probability of capture is therefore given as:

\[
I_A \sim N(P \frac{\nu 2\pi r \text{CS}^{2-\alpha}}{\alpha - 2}, P^2 \frac{\nu 2\pi r \text{CS}^{2-2\alpha}}{2\alpha - 2}) = N(\mu_A, \sigma_A^2). \quad (3-15)
\]

\[
P_{\text{capture}}^A = P\{I_A \leq d^{-\alpha} / \gamma (r_0^i) - N / P\}. \quad (3-16)
\]

IV. Designing mechanisms for cross-layer joint routing and rate control
Using the model developed in III, we aim to design a distributed mechanism for selecting the parameter vector at each node, for each packet that it forwards. We assume the network system to be highly loaded and thus saturated with packet traffic, so that we aim to devise a cross-layer operation that yields upgraded network throughput capacity. Note that in a non-saturated network, one may want to select the parameter vector to yield an acceptable packet delay performance. In the rest, we however focus on the former objective in designing our parameter vector selection algorithm.

For implementation simplicity, we consider the following relatively simple distributed mechanisms. We note that the algorithms used here require each node to forward its packets to a neighboring node that provides positive progress towards the destination, and thus ensure the realization of loop-free routes. For each packet that a node receives and forwards, it considers all of its neighboring nodes (when operating at the lowest data rate). The corresponding parameter vector that is used to forward the packet is then determined in accordance with one of the following candidate schemes.

**Scheme 1 - Independent Transport-Based Scheme:** The forwarding node continuously monitors and calculates channel activity statistics (updates of $p_0$ and $E[T_o]$). Using these statistics, the node computes for each of its neighbors and selects the parameter vector that yields the highest link transport capacity level. The computations follow directly by using the formulas presented in III.

**Scheme 2 - Homogeneous Transport-Based Scheme:** For each neighbor, the forwarding station computes the parameter vector that yields the highest link transport throughput capacity level. For this computation, rather then using monitored channel statistics, it proceeds by assuming all other nodes to be statistically operating under the same conditions that characterize its own behavior, even when this may not be the case. Such an assumption is motivated by access fairness behavior imposed by the CSMA/CA MAC when the nodal region operates in a highly loaded (or saturated) mode.

**Scheme 3 - Max Progress Scheme:** The forwarding station selects the node that provides the highest (positive) progress range towards the destination node. In communicating with the selected node, it employs a data rate that is equal to the highest feasible such rate that enables the forwarding of the packet. This scheme thus aims to forward packets along shorter (lower hop length) routes.

**Scheme 4 - Max Transmit Rate Scheme:** The forwarding node strives to select the highest data rate that enables it to forward a packet to a neighboring node yielding positive progress. If multiple neighbors can be reached at this rate, the one that yields the highest progress range is selected.
Scheme 5 – Nearest neighbor scheme: For each neighbor, the forwarding node selects the closest node that yields positive progress towards the destination node. It then uses the highest transmission data rate that enables it to forward the packet to the selected node.

The computation of the parameter vector carried out by each node in accordance with Scheme 2 is presented in the following Section. The corresponding computations carried out by Schemes 3-5 are straightforward. The latter schemes provide benchmark comparisons to Schemes 1-2. They do not base the selection of the parameter vector on the computation of a transport throughput capacity measure, as employed by Schemes 1-2. In the remainder of this section, we discuss (and illustrate via a simple example) the potential advantages to be gained by using Scheme 2 when compared to Scheme 1. In VI, we provide via simulations a comparison of the performance attained through the use of the above five schemes. We demonstrate the advantages gained by the use of Scheme 2.

Even though many distinct mechanisms may be used to select the parameter vector at each node, we expect the use of Scheme 1 to be quite effective, when each node acts independently by basing its selections on its monitored status indicators, without coordinating with other nodes. However, we note through the following illustrative scenario that the use of Scheme 1 may at times lead to the selection of a sub-optimal parameter vector.

We consider a simple example where two active stations that reside in each other’s CS region. Assume that currently they are the only active stations in the neighborhood. Assume that the nodes can select 802.11a data rate values that are equal to either 18 Mbps (low rate) or 36 Mbps (high rate). Consider an operation based on the use of Scheme 1. Assume that the monitored state points out to each node the rate employed by the other node. Then the node will proceed, for each of the 2 possible rates used by the other node, to calculate the highest achievable link transport throughput capacity level realized when it operates at the high or low data rate levels. In Fig. 2, we depict the results of these computations as represented by four curves. We use solid and dashed lines, respectively, to present the performance attained when the rate selected by the other node is equal to the low and high rate value. We use +-marked and x-marked curves to present the performance attained when the node itself selects to use the high and low rates, respectively. For illustration simplicity, assume the nodal density to be sufficiently high so that the selected forwarding range can be implemented.

When Scheme 1 is employed, each node proceeds to select the parameter vector that yields the
highest transport capacity level. For this example, each node will consequently select to operate at the 
low rate (noting it to yield higher transport capacity independently of the rate used by the other node). 
The resulting realized transport throughput rate is then given at each node by operating point V. 
Clearly, this is not the overall optimal operating point of the system even if a fairness constraint is 
imposed. Operating point V’ (under which both nodes have selected to use the high data rate) yields a 
strictly higher transport throughput performance vector.

Performance upgrade can be attained when more complex schemes are considered. For example, 
effective coordinated operations can be imposed through the introduction of proper incentives and 
rewards. A game theoretic approach may however also induce undesirable features: 1 Network 
dynamics sometimes change rapidly; equilibrium might or might not be reached in a time effective 
manner. 2. The scheme’s operational complexity may increase. It is therefore desirable to use a 
parameter vector selection strategy that is simple to implement and is rapidly converging.

Consequently, we consider in this paper mechanisms that do not impose such coordination in the 
selection of the parameter vector at each node. The Homogeneous Scheme presents such a simplified 
distributed structure. In the following, we explain that nevertheless we expect this scheme to yield 
excellent throughput performance behavior since it is set to operate under the assumption of network 
conditions that will be realized due to the employment of the CSMA/CA MAC. To this end, assume a 
high nodal density level, so that any desirable forwarding range can be realized. We consider a 
symmetric nodal outfitting configuration so that all stations employ the same set of MCS. Note that 
the hidden terminal problem is often eliminated under many multi-hop CSMA/CA operations, even 
without engaging RTS/CTS (see [27]), and consequently the underlying CSMA/CA mechanism 
imposes access fairness (among active network nodes) when operated in saturation mode, as 
illustrated in [28]. We assume each node to use a stationary parameter vector policy that calculates 
the selection as a function of its realized channel activity and/or throughput rates, or related 
observables. Assuming the network to be loaded to saturation (to assess the attainable throughput 
capacity level), the actions undertaken by each node, as automatically induced by the MAC scheme, 
are statistically similar to those undertaken by any other node. Hence, each node will determine its 
parameter vector in a manner that is statistically similar to that performed by each other node. Thus, 
each forwarding node will proceed to select the same parameter vector as that chosen by any other
node. To optimize the network-wide throughput performance, it is therefore best for each node, in selecting its parameter vector, to recognize the symmetric behavior imposed by the CSMA/CA MAC scheme. Furthermore, by assuming a sufficiently high nodal density level, the same parameter vector will be selected by a node for the forwarding of packets that belong to different flows.

Under practical topological layouts, a node may not be able to find a neighboring node that is located at a range that is equal to the calculated optimal distance value. Selections made by certain nodes may differ from those made by others. Consequently, a parameter vector computation at a node that is based on the assumption that the computations at other nodes lead to the same result may lead to suboptimal performance. Nevertheless, this strategy provides a simple yet effective alternative to that used by Scheme 1. Under Scheme 2, every node can be programmed to select the parameter vector automatically without needing to monitor channel activities. This is particularly desirable when channel state monitoring is considered to be non cost-efficient. To justify the use of Scheme 2 for a heterogeneous network, notice that the selected strategy can reflect the willingness of each node to offer a ‘fairness’ based level of cooperation. In section VI, we present simulation based performance results that well confirm the performance effectiveness of Scheme 2, assuming nodes to employ no status monitoring means and to not engage in cooperative behavior.

When mechanisms that include end-to-end performance objectives are considered, a hybrid of Schemes 1 and 2 along with a nodal congestion control (CC) operation (see [30]) can be employed to further enhance the system performance. Below we define such an on-demand routing mechanism, identified as Scheme 1.2/CC. Under the latter scheme, the parameter vector at each node along the route and the route itself, for each new flow, is determined during the route discovery process. For each received route request packet (RREQ), each node calculates a candidate parameter vector by using either Scheme 1 or 2, as determined by current loading conditions (whereby Scheme 1 is used under relatively light loading). Each then forwards selected RREQs that induce high cumulative performance, except that highly congested nodes discard RREQs. When the RREQs reach the destination, the best one is selected. We do not proceed to further specify and study such a scheme here, since, as stated above, we invoke a datagram operation and do not attempt to include mechanisms that enforce end-to-end flow based performance objectives.

V. Characterizing the performance behavior under the homogeneous scheme
As discussed in IV, we use the Homogeneous Scheme to choose the parameter vector that maximizes the attained link transport capacity. For each arriving packet, node i proceeds with the joint selection of the next hop node j and the transmission data rate $r_c$ to be employed.

\textit{a. Characterizing multi-hop CSMA/CA operations under the Homogeneous Scheme}

To calculate the system’s throughput performance, we need to first calculate the underlying variables that include the probability $p_0$ and the average channel occupancy time $E[T_0]$. We then apply the results derived in III-b to carry out performance analysis for the system. For a station that is contending for access with $K-1$ other stations that are located in its carrier sense area, recalling our assumption that the system’s offered traffic load is sufficiently high so that it is driven to saturation state, the corresponding contention rate $p_0$ is expressed in terms of $\tau$ as follows:

$$p_0 = 1 - (1 - \tau)^{K-1}. \quad (5-1)$$

Since, for calculating the parameter vector, each station assumes other stations to act in a homogeneous fashion (i.e., to statistically exhibit behavior similar to its own), $E[T_0]$ is then set to be equal to the mean channel occupancy time realized at station i, to be given by $E[T_0] = E[T_b]$.

We employ the two-dimensional Markov chain model developed in [14] to characterize the backoff process. The detailed derivations are omitted here, and the result is given below:

$$\tau = \left[ \sum_{l=0}^{L} \sum_{n=0}^{\frac{CW_l - n}{p'}} p' \right]^{-1} \left[ \frac{1 - p^{L+1}}{1 - p} \right] = \left[ \sum_{l=0}^{L} \frac{CW_l - 1}{2} p' \right]^{-1} \frac{1 - p^{L+1}}{1 - p}. \quad (5-2)$$

Using the latter results, we solve the system of equations given by Eqs. (3-1)-(3-3) and (5-1)-(5-2) through numerical computations. Noting from Eq. (5-2) (see [29]) that $\tau$ is non-increasing function of $p$, and, from Eqs. (3-1) – (3-3) and (5-1), that $p$ is non-decreasing function of $\tau$, we conclude that a unique fixed point is guaranteed to exist (see [29] for more details).

To obtain $K$ (in Eq. (5-1)), we assume active nodal locations over the area of operations to be two-dimensional Poisson spatial distribution with parameter $\nu$. According to the spatial Poisson nodal distribution assumption, $K$ is a random variable characterized by the following distribution function:

$$\Pr\{K = k\} = \frac{\nu \pi CS^2 k^{k-1} e^{-\nu \pi CS^2}}{(k-1)!}, \quad k = 1, 2, \ldots. \quad (5-3)$$

Recall that Eq. (3-7) expresses the link throughput capacity $C_s(K,d,r_c)$ and is a function of the number of nodes $K$, forwarding distance $d$, and data rate $r_c$. We use $\overline{C_s}$ to express the link throughput capacity rate attained along such a link (link distance is d) by averaging over the values
assumed by K. Hence, we write:

$$\overline{C}_S = \overline{C}_S(d, r_c) = \sum_{k=1}^\infty \Pr(K = k) \cdot C_S(k, d, r_c) .$$

(5-4)

In a similar manner, the link transport capacity rate $$\overline{C}_{Sr} = \overline{C}_{Sr}(d, r_c)$$, averaging over the values assumed by K, with respect to a given flow direction, is written as

$$\overline{C}_{Sr} = \overline{C}_{Sr}(d, r_c) = \sum_{k=1}^\infty \Pr(K = k) \cdot C_S(k, d, r_c) \cdot d \cos(\theta).$$

(5-5)

Note that the directional penalty factor (expressed by the cosine term) depends on the relative nodal spatial layout. Its realized value is effectively independent of the configured parameter vector. For illustrational purposes, we thus do not include this cosine factor in the following figures.

b. Performance Results

We consider the underlying multi-MCS implementation provided by IEEE 802.11a systems. The data rate and the corresponding required SINR levels for successful reception, per MCS, are given in Table 1 for a targeted BER value of $$10^{-5}$$ ([17]). For the IEEE 802.11a protocol, the PLCP preamble plus SIG duration and the data rate dependent overhead length induced by the headers are denoted as $$T_0$$ and $$b_0$$, respectively. The average packet length $$b$$ is assumed to be 1000 bytes. The remaining parameter setup levels are summarized in Table 2. The packet transmission time $$T$$ is calculated by

$$T(r_c) = T_0 + (b+b_0)/r_c .$$

(5-6)

The transmission power is fixed at 0.01 mW and the background noise power level is assumed to be equal to $$10^{-9}$$ mW. The effective communications ranges for the set of modulation coding schemes under consideration are given as: 39.8, 36.0, 33.4, 30.2, 21.1, 19.1, 14.1 and 13.7 meters.

1. Parameter vector selection and performance behavior under the Homogeneous Scheme

In Fig. 3, the achievable link throughput capacity intensity (expressed in units of bits per second per unit area) is plotted vs. the selected forwarding range, for various data rate levels when the CS distance is equal to 50 m. Notice that the protocol overhead reduces the efficiency attained by high data rate operations. In addition, the performance curves representing the high data rate levels induce more abrupt degradations as the forwarding range level increases.

In Fig. 4, the link transport capacity level is plotted against the forwarding range, under selected data rate levels, when the CS distance is set equal to 50 m. Corresponding to each data rate value, there exists a unique optimal forwarding range level. The latter is the longest forwarding range that enables the signal to be received at a sufficiently high SINR level. We note that the link transport
capacity performance becomes a more sensitive function of the forwarding range at higher data rate levels. As one acts to dynamically adapt the parameter vector to actual locations of nodes (so that a node must select a neighbor from those nodes that currently reside in its vicinity), only a subset of parameter vectors are under consideration. When constrained by the location of neighboring nodes that are located at short, intermediate and long forwarding ranges, we observe from Fig. 4 that the best data rate level to choose is equal to 54 Mbps, 36 Mbps and 18 Mbps, respectively. When considering the availability of neighboring nodes at any selected range, we note from Fig. 4, that the optimal link transport capacity level is achieved by employing a data rate that is equal to 36 Mbps.

2. The impact of carrier sensing sensitivity and nodal spatial density

We investigate the impact of the setting of the CS sensitivity level on the performance. Related discussions can be found in [18], [19] and [7]. Figs. 5 and 6 show, respectively, the link throughput capacity and link transport capacity performance functions plotted versus the selected forwarding ranges, for various CS ranges, when \( r_c = 18 \text{ Mbps} \). Note that the assigned CS sensitivity level must be configured to provide a node with a sufficient number of stations to be located inside its CS region. Otherwise, the CSMA mechanism becomes ineffective, leading to a MAC operation that is effectively identical to that exhibited by a pure random access (ALOHA type) protocol. In the latter case, we refer to [12] for the characterization of the performance behavior for multi-rate random access multi-hop networks. We set here the CS distance levels to yield an average number of CS-neighborhood nodes (K) that is equal to at least 2, so that a station is able to find at least one other station that is located in its CS region.

As illustrated in Fig. 5, provided that a node can find a neighboring forwarding node that is sufficiently close, the use of lower CS distance leads to the a higher link throughput capacity, at the expense of higher sensitivity of the achieved throughput rate to the selected forwarding range. This is explained by noting that one is able to achieve higher spatial reuse gains with shorter CS range levels, provided the selected forwarding range is not too high. Realistically, attainable performance level is dependent on the forwarding range selections that can be realized. In Fig. 6, we observe that for each CS distance level, there exists a forwarding range that maximizes the link transport capacity.

It is also essential to evaluate the sensitivity level of the attained throughput performance rate to the nodal layout configuration. In Fig. 7, we show link transport capacity depicted against the
selected forwarding range. Three sets of curves are shown, each set involving a prescribed data rate (18 Mbps, 36 Mbps and 54 Mbps). In each set, we depict various performance curves, whereby each corresponds to a given nodal spatial density level that ranges from 0.0005/m$^2$ to 0.01/m$^2$. By setting the CS distance to 50 m, the latter nodal density levels translate to an average number of CS-neighborhood nodes (K) that ranges from 4 to 79. We observe that the link transport capacity increases marginally with nodal density when the density level is very low, but monotonically decreases with nodal density at higher density levels. Notice that in the latter case, the performance degradation ratio, for each set of prescribed data rates, is approximately invariant to the forwarding range level. Thus, the effects of forwarding range and nodal density are noted to be approximately decoupled. This is explained by noting that the carrier sensing based operation regulates channel access activities so that the interference level is properly controlled, regardless of the nodal spatial density. Thus, the key impact of nodal density is not on the packet capture probability, but is rather on the occurrence of collision activities within the CS region. Furthermore, we find that even though the link transport capacity varies with nodal density, the relative optimality of the operating point remains approximately unchanged.

Recall again that the results presented in this section, depicting the expected behavior of the link transport capacity function are used as metrics employed in the selection of the parameter vector, when employing the Homogeneous Scheme.

VI. Simulation performance results and comparisons of parameter vector selection algorithms

We consider the same network system configuration and parameters as those used in V. We have used a discrete event based C++ simulator to conduct various evaluations, under a multitude of cross layer joint routing and rate control strategies. This section contains two parts. The first part is used to verify the precision of our analytical model. The second part of our evaluation is aimed to investigate the usefulness of our analysis results in realistic scenarios where multiple traffic flows traverse the network. Assuming each node to learn the location of its neighbors and the direction towards destination nodes, each node proceeds to independently compute its parameter vector. We examine and compare the performance results by considering the 5 schemes introduced in IV.

a. Confirmation of the derived performance formulas for the Homogenous Scheme

We generate link layer homogeneous traffic processes that load the system at a sufficiently high
rate, causing it to be saturated. To validate our model, we first assume the forwarding range to be set to a prescribed value. We randomly place 640 transmitter nodes in an area of 800 m x 800 m (so that $u = 0.001/m^2$), and then place link layer receivers away from their link layer transmitters at the prescribed range in a random angle. In Fig. 8, we exhibit link throughput capacity vs. forwarding range performance curves, for selected data rate levels, when the CS distance is set equal to 50 m. We observe the performance values obtained by simulation to be very close to those predicted by the use of the analytical model. In Fig. 9, the link transport capacity performance functions are plotted against the selected forwarding range, for various selected CS distance levels, when the data rate is set equal to 18 Mbps. We note that our analytical expressions again provide accurate prediction of the throughput performance behavior of the system, except for the case in which the CS distance is set to be very low (i.e. 10 m (not shown here) or 20 m). In such cases, we observe that the resulting average number of forwarding stations that are located inside the CS region around a station is low (being equal to about 0.3 or 1.2). In this case, the CSMA/CA MAC is effectively identical to that exhibited by a random access scheme. Note that for the case in which CS is configured to be equal to 20 m, our analytical model tends to overestimate the peak performance value but still accurately predicts the position of the peak. In turn, we confirm the simulation results to be close to those predicted by the ALOHA based analytical model presented by us in [12].

b. Distributed combined rate control and routing algorithms

In the second set of simulations, we let the 5 schemes introduced in IV to be used independently by network nodes to compute the parameter vector to forward traversing packets across multihop routes to their destinations. We randomly place 120 nodes in a 150 m x 150 m area of operation and randomly set the network to be loaded by 4 source-destination flows. We note that at the lowest data rate a path that covers a distance of 150 m will use about 4 hops; at the highest data rate, such a path will employ 12 hops. We configure the loading level to be sufficiently high to lead to a saturated operation. For the effective communication range calculations carried out by the protocols employed by Schemes 3 - 5, we have considered a model that assumes the total noise plus interference power at the receiver to be equal to 1) the noise power (N), 2) noise plus a 3 dB margin or 3) noise plus a 6 dB margin. Twenty distinct spatial topology realizations were generated and used to evaluate the performance of the 5 schemes. The resulting aggregate (over all end-to-end flows) throughput performances are
shown in Table 3. It is observed that Scheme 2 outperforms every other mechanism for 12 out of the 20 experiments, while Scheme 1 does so for 6 experiments. For 90% of the experiment cases, Schemes 1–2 together provide the best performance levels. Schemes 3 and 4 display top performance each for a single case. Scheme 5 displays poor performance behavior for all simulated cases. As we further increase the assumed supplemental interference power (beyond the 6 dB level), we have noticed (not shown here) the throughput performance level to further degrade. The results thus clearly point out the performance superiority exhibited by Scheme 2 in the selection of the parameter vector. We also notice that the performance levels attained under Scheme 2 reach the 80th percentile level of the highest displayed level of all schemes for 95% of the time. Using these results, we conclude that the effectiveness of Scheme 2 has also been well demonstrated under heterogeneous traffic patterns and a multitude of heterogeneous spatial and temporal network conditions. We note that we have considered here simplified datagram based next hop route selection implementations. Clearly, in certain cases, it can be more effective, if feasible, to discover and configure end-to-end routes in a manner that takes into consideration current topological, loading and capacity availability conditions. Yet, such an operation is more complex and will be further investigated in future studies.

VII. Conclusions

We consider in the context of multi-hop ad hoc wireless networks the settings of the cross layer operational parameters for software defined radio modules. To jointly measure the ability of the network to transport traffic flows in a throughput effective manner, we employ the link transport capacity measure as a key performance metric. Each node uses the radio module to jointly select, for each packet, the corresponding parameter vector that involves the preferred data rate and forwarding link across the selected route. We develop an analytical model that examines the detailed operation when a CSMA/CA MAC scheme is employed. We demonstrate the effectiveness of the cross layer operations that are based on our introduced schemes and of the analytical formalism developed to select the parameter vector. We present and evaluate the cross-layer effectiveness of two distributed datagram-based cross layer schemes. We show the use of the link transport capacity metric as a basis for the setting of the cross layer parameter vector to yield significantly enhanced performance. Our models provide important guidelines for the design and implementation of such joint rate adaptation and routing algorithms.
Figure 1. Illustration of a transmission from node i to node j.

Figure 2. A two-node illustrative example of the link transport capacity versus employed forwarding range performance, under selective values of the node’s employed data rate level $r_i$ and the employed data rate level ($r_j$) by the other node located inside the node’s CS region. $p_i$ is set equal to 0.0571 in plotting the figure, derived under a 2-node contending CSMA/CA MAC saturation operation.

Figure 3 Link throughput capacity illustration versus forwarding range performance results for selected values of $r_i$ when CS = 50 m.
Figure 4 Link transport capacity versus forwarding range performance results for selected values of $r_c$ when $CS = 50$ m.

Figure 5. Link throughput capacity versus forwarding range performance results for selected values of carrier sensing distances, when $r_c = 18$ Mbps.

Figure 6. Link transport capacity versus forwarding range performance results for selected values of carrier sensing distances, when $r_c = 18$ Mbps.
Figure 7. Link transport capacity versus forwarding range performance results for selected values of nodal spatial density, when carrier sensing distance is equal to 50 m.

Figure 8. Throughput capacity versus forwarding range performance results obtained by simulations for selected values of $r_c$ when the carrier sensing distance = 50 m. Simulation results are depicted in points and analysis results are depicted in dashed lines.

Figure 9. Transport throughput capacity versus forwarding range performance results obtained by simulations for selected values of carrier sensing distances, when $r_c = 18$ Mbps. Simulation results are depicted in points and analysis results are depicted in dashed lines.
Table 1. Data rate vs. SINR threshold table for target BER = $10^{-4}$.

<table>
<thead>
<tr>
<th>Rate (Mbps)</th>
<th>6</th>
<th>9</th>
<th>12</th>
<th>18</th>
<th>24</th>
<th>36</th>
<th>48</th>
<th>54</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$ (dB)</td>
<td>6.02</td>
<td>7.78</td>
<td>9.03</td>
<td>10.79</td>
<td>17.04</td>
<td>18.35</td>
<td>24.05</td>
<td>24.56</td>
</tr>
</tbody>
</table>

Table 2. System parameters.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission power</td>
<td>0.01 mW</td>
</tr>
<tr>
<td>N</td>
<td>1e-9 mW</td>
</tr>
<tr>
<td>$C_{\text{wmin}}$</td>
<td>32</td>
</tr>
<tr>
<td>m</td>
<td>5</td>
</tr>
<tr>
<td>L</td>
<td>6</td>
</tr>
<tr>
<td>SIFS</td>
<td>16 us</td>
</tr>
<tr>
<td>DIFS</td>
<td>34 us</td>
</tr>
<tr>
<td>Te</td>
<td>9 us</td>
</tr>
<tr>
<td>ACK</td>
<td>24 us</td>
</tr>
<tr>
<td>PHY overhead ($T_0$)</td>
<td>20 us</td>
</tr>
<tr>
<td>MAC+PHY+IP header (b0)</td>
<td>406 bits</td>
</tr>
</tbody>
</table>

Table 3. Aggregate end-to-end throughput performance (in Mbps) under selected forwarding algorithms (Colored entries represent best performance levels among the simulations tested with the same seed)

<table>
<thead>
<tr>
<th>seed no.</th>
<th>independent</th>
<th>homogeneous</th>
<th>0dB</th>
<th>2dB</th>
<th>4dB</th>
<th>6dB</th>
<th>0dB</th>
<th>2dB</th>
<th>4dB</th>
<th>6dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.7972</td>
<td>2.1288</td>
<td>0.4424</td>
<td>1.8296</td>
<td>1.8184</td>
<td>0.044</td>
<td>0.784</td>
<td>0.5152</td>
<td>0.008</td>
<td>0.0864</td>
</tr>
<tr>
<td>2</td>
<td>5.5064</td>
<td>8.148</td>
<td>3.1952</td>
<td>5.3672</td>
<td>5.2504</td>
<td>2.4096</td>
<td>5.7776</td>
<td>4.2688</td>
<td>1.3144</td>
<td>2.8304</td>
</tr>
<tr>
<td>3</td>
<td>0.8528</td>
<td>1.1606</td>
<td>0.3256</td>
<td>0.9048</td>
<td>0.4244</td>
<td>0.0176</td>
<td>1.0744</td>
<td>0.02</td>
<td>0.0008</td>
<td>0.9024</td>
</tr>
<tr>
<td>5</td>
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<td>3.3368</td>
<td>4.176</td>
<td>2.568</td>
<td>4.2335</td>
<td>2.6768</td>
<td>3.8744</td>
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</tr>
<tr>
<td>6</td>
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<td>5.748</td>
<td>3.352</td>
<td>5.3536</td>
<td>3.772</td>
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<td>1.96</td>
<td>0.596</td>
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<tr>
<td>7</td>
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<td>2.2272</td>
<td>2.7984</td>
<td>0.0296</td>
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<td>0.948</td>
<td>2.836</td>
<td>2.5104</td>
</tr>
<tr>
<td>9</td>
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<td>3.0368</td>
<td>0.8456</td>
<td>1.9488</td>
<td>1.024</td>
<td>0.2016</td>
<td>0.9704</td>
<td>0.0488</td>
<td>0.0088</td>
<td>0.6176</td>
</tr>
<tr>
<td>10</td>
<td>5.4</td>
<td>6.5045</td>
<td>0.444</td>
<td>3.3032</td>
<td>4.3136</td>
<td>0.5032</td>
<td>3.668</td>
<td>1.4152</td>
<td>0.004</td>
<td>1.4592</td>
</tr>
<tr>
<td>11</td>
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<td>3.1312</td>
<td>3.6888</td>
<td>1.592</td>
<td>1.9696</td>
<td>0.7368</td>
<td>3.7016</td>
<td>1.7152</td>
<td>0.444</td>
<td>2.5848</td>
</tr>
<tr>
<td>12</td>
<td>0.8696</td>
<td>3.3004</td>
<td>0.336</td>
<td>0.6408</td>
<td>1.7568</td>
<td>0.0224</td>
<td>0.4256</td>
<td>0.28</td>
<td>0.1952</td>
<td>0.0864</td>
</tr>
<tr>
<td>13</td>
<td>2.796</td>
<td>5.1496</td>
<td>5.2408</td>
<td>4.6616</td>
<td>3.2048</td>
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<tr>
<td>15</td>
<td>7.252</td>
<td>6.5034</td>
<td>0.932</td>
<td>5.9008</td>
<td>6.6896</td>
<td>0.3896</td>
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<tr>
<td>17</td>
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<td>1.1616</td>
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REFERENCES