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Spectrum Sharing In Multi-Hop Wireless Networks Using Explicit Pacing Mechanism

S.Pradeep,

R. NavaneethaKrishnan,

&

K. KalianaPragash

Assistant Professors,
Bharathiyar College of Engg., & Tech., Karaikal, U.T. of Puducherry
India

Abstract:

Basically, IEEE 802.11 MAC protocol was not designed for multi-hop networks. Although it can support some ad hoc network architecture, it is not intended to support the wireless mobile ad hoc network, in which multi-hop connectivity is one of the most prominent features. Spectrum sharing is a crucial issue to the overall throughput performance of multi-hop wireless networks. It is observed that for multi-hop wireless networks, it is hard to resolve the scheduling conflict, and most *distributed algorithms consider the neighbors' traffic independent of each other and* ignore the multi-hop nature of flows, leading to the spectrum wastage and inefficiency. By incorporating the multi-hop nature of flows, here proposing a new *distributed scheme based on IEEE 802.11 standard, namely "Multi-*hop MAC with *explicit pacing mechanism" with better pipeline efficiency. Simulation resu*lts show that the proposed scheme outperforms the original 802.11 MAC.

Keywords--- Multi-hop, MAC, IEEE 802.11, spectrum allocation, RTS/CTS

Introduction :

Wireless local area networks (WLANs) based on the IEEE 802.11 standard are becoming increasingly popular and widely deployed. IEEE 802.11 MAC protocol is the standard for wireless LANs; it is widely used in test beds and simulations in the research for wireless multi-hop ad hoc networks [4]. However, this protocol was not designed for multi-hop networks. Although it can support some ad hoc network architecture, it is not intended to support the wireless mobile ad hoc network, in which multi-hop connectivity is one of the most prominent features. The surprisingly poor performance of multi-hop wireless networks has attracted more and more attentions in the literature [3]. During recent years, new transmission techniques are sprouting quickly. However, the traffic rate in multi-hop wireless networks is not increasing accordingly. Usually, when the scale of the networks becomes large, due to the increasing interference and the increasing number of intermediate hops of flows, the end-to-end throughput performance starts to deteriorate.

IEEE 802.11 was originally designed for the single-hop Wireless LANs. Its performance in multi-hop scenarios is much below our expectation due to inefficient resource usage [2]. The standardization of the IEEE 802.11 Medium Access Control (MAC) protocol has triggered significant research on the evaluation of its performance.

Random access MAC provides a roughly fair mechanism for wireless nodes to access the medium. The effort of differentiating the uplink and downlink resource allocation has been first applied to WLANs because of the observation that as the central point, APs should occupy more resource than other nodes [4]. To achieve better performance in multi-hop networks, several previous schemes attempt to break the fairness by prioritization. These schemes heuristically search for better spectrum sharing mechanism among wireless nodes, by differentiating the forwarding priority according to the priority tags of packets or flows. However, when the traffic pattern is more complicated, these schemes cannot guarantee significant performance improvement.

On the other side, with centralized approaches, scheduling based MAC can allocate the resource in a more efficient way. This approach can find the optimal solution with knowledge of the topology and traffic when the network is not large. These two approaches give us the insight of how good performance the networks can achieve. However, they always require a perfect scheduling, a MAC with no collision and no hidden/exposed terminals, which is almost impossible in multi-hop wireless networks

[4],[5]. Previous distributed scheduling schemes also ignore the multi-hop nature of flows in multi-hop networks, which causes a lot of wastage in spectrum allocation. Moreover, within a neighborhood range, different neighbors can sense different condition of channels, resulting in potential conflicts of distributed scheduling, which is difficult to solve in distributed scheduling schemes.

Proposed scheme:

Multi-hop MAC

For practical ad hoc networks the traffic is not totally ad hoc. Usually traffic aggregates at some points or areas with certain patterns. So, we assume that the multi-hop wireless networks which we concern have certain traffic patterns and the flows inside have relatively stable traffic load [4]. For these ad hoc networks, we design an efficient MAC which can utilize the limited spectrum resource in a more efficient way.

The basic procedure can be described as follows. Each node is required to broadcast its traffic demand to its neighbors, which is the same as previous works. Meanwhile, each node is required to notify its neighbors about the traffic dependency between them, which differentiates our work from others. Afterwards, each node allocates the spectrum individually according to the information collected and apply the calculated traffic rate to its transmission.

Traffic dependency information from different neighbors affects the estimation of accurate traffic load in different ways. Three different roles of neighbors are defined in this paper. When one neighbor has traffic for the current node to forward, we name this role as upstream neighbor. Similarly, when the current node has traffic for its neighbors to forward, these neighbors are called downstream neighbors [6]. Other neighbors are called uncorrelated neighbors. It should be noted that only when traffic demand of neighbors are correlated with the current node, are these neighbors to be seen as upstream neighbors or downstream neighbors. Therefore, one node sees the neighbors who have traffic ending at itself as uncorrelated neighbors because the traffic ending at itself will not affect its traffic demand [18].

The traffic demand from each node consists of two parts: the traffic that requires to be forwarded from its upstream neighbors and the traffic originated from its upper layer locally. It can be expressed by the following formula (1)

$$TD_i = TDO_i + \sum_{j \in \mathrm{N}_i} TDfwding_{j,i} \quad \text{……………………………………………….(1)}$$

where TD$_i$ is the traffic demand, TDOi is the traffic originated from local upper layer, TDfwdingj,i is the traffic that requires to be forwarded from its upstream neighbor j and Ni is the set of neighbors for node i. The latter part is dependent with its neighbors' traffic demand and the former part is independent [8]. Therefore, an accurate traffic demand of one node should be based on the knowledge of all upstream neighbors' traffic dependency information. In this scheme, upstream nodes should notify their downstream neighbors about their forwarding request. Consequently, the downstream nodes update their traffic demand accordingly [10]. The knowledge of accurate local traffic demand is not enough for ideal spectrum allocation. It is also important to acquire the correct traffic demand of the neighbors, TDi. When downstream nodes broadcast their new traffic demands, since the downstream neighbors' traffic includes forwarding requirement from the upstream nodes, the upstream nodes should be able to extract the dependent traffic from the messages, thus the pure change of the original traffic of the downstream nodes can be known. This knowledge is important in obtaining the accurate traffic demand of neighbors.

The traffic demand from each node consists of two parts: the traffic that requires to be forwarded from its upstream neighbors and the traffic originated from its upper layer locally. In this scheme, each node maintains three tables which record its own traffic information, its neighbors' traffic information and the traffic dependency information [16]. Each node periodically gets knowledge of its original traffic load and forwarding traffic load from its upper layers and updates these tables. It also updates these tables when it receives/overhears messages from its neighbors [21].

Each node should maintain a parameter set as described in Table I which includes its own traffic information: Each node should also maintain a table which records its neighbors corresponding information as the potential input of distributed spectrum allocation [14]. The detail information is listed in Table II.

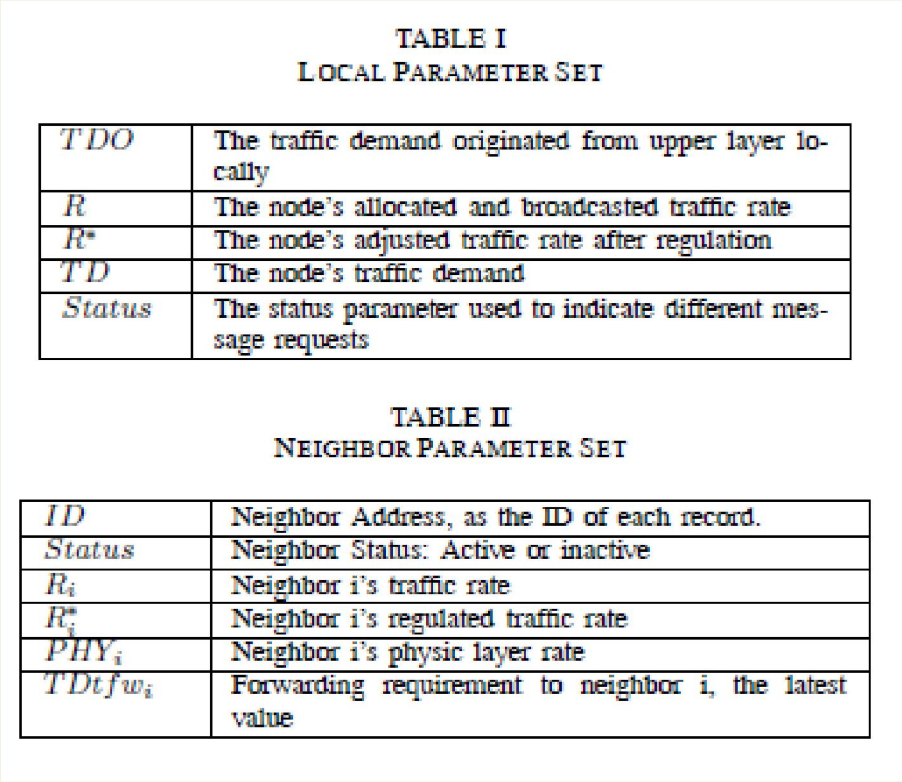

TABLE I
LOCAL PARAMETER SET

TDO	The traffic demand originated from upper layer locally
R	The node's allocated and broadcasted traffic rate
R^*	The node's adjusted traffic rate after regulation
TD	The node's traffic demand
$Status$	The status parameter used to indicate different message requests

TABLE II
NEIGHBOR PARAMETER SET

ID	Neighbor Address, as the ID of each record.
$Status$	Neighbor Status: Active or inactive
R_i	Neighbor i's traffic rate
R_i^*	Neighbor i's regulated traffic rate
PHY_i	Neighbor i's physic layer rate
$TDtfw_i$	Forwarding requirement to neighbor i, the latest value

The traffic dependency information is stored in an (n + 1) × (n+1) matrix D, with the local traffic demand included. Di,j means the forwarding requirement from node i to node j. When i equals to j, Di,j stores the original traffic excluding its forwarding demand from its neighbors in this neighbor set. Note that this original traffic demand may not purely be original. In node i's storage, if neighbor j has some forwarding request from its neighbor k, which is not a neighbor of node i, neighbor j's original traffic demand in the matrix includes this part of forwarding request. Obviously, we have the relationship as follows:

$$TD'_i = \sum_{j \in N} D_{i,j} \quad \text{……………………………………………………} \quad (2)$$

TD'i in Formula means the broadcasted version of TDi. Throughout this paper, superscript ,, stands for the broadcasted version and superscript * stands for the regulated version. Apparently, matrix D‟s storage has some overlapped information with the former two tables. The difference is that matrix D only stores the broadcasted version and the other two tables gather the latest information. The broadcast messages should contain the following information: the traffic demand of the node (TD), the traffic load/rate (R) and the adjusted traffic rate(R*) of the node, a list of traffic that the host needs the neighbor to forward (TDtfwi), an indicator that a traffic regulation is necessary or this regulation is to be deactivated. There is one more parameter, unit demand allocation ε, is implied in the broadcast messages.

$$\varepsilon = \frac{R}{TD} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \quad (3)$$

Procedure

The tables are updated according to local cross-layer notification or neighbors notification as mentioned above [24]. The accurate traffic load of each node in the neighborhood is calculated according to these tables. Spectrum allocation is executed with the knowledge of traffic load and channel limit. Meanwhile, a check for regulation indicator or deactivation indicator is necessary to avoid the allocation conflicts due to asymmetric neighbourhood [13].

For upstream neighbors, traffic demand is as broadcasted since no other nodes in the *neighborhood can affect this value. However, local node‟s traffic demand is affected by* its upstream neighbors. The local traffic demand calculation can be found in equation. For downstream neighbors, the traffic demand depends on local traffic change. It can be calculated as follows:

$$TD_i^{down} = \sum_{j \in \mathbb{N}} D_{j,i} - TDtfw'_i + TDtfw_i \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where *TDtfw'i* can be found in matrix D according to the current node index (If it is calculated by Node k, *TDtfw'i* =Dk,i). Since each node can play different roles simultaneously, the overall traffic demand can be calculated in this way: If local node index is not i, TDOi uses the value of Di,i. We can see that TDtfwi changes when upstream neighbours traffic changes, which embodies the traffic dependency. Through this way, the accurate traffic demand can be calculated by each node locally and the ideal spectrum allocation can be fulfilled [23].

When one node senses the total spectrum allocation by individual neighbours exceeding the channel limit, a regulation indicator is sent out. The regulation mechanism in this scheme uses the parameter of ε. This parameter stands for the uniform allocatable traffic air-time per unit traffic demand in air-time form. Each individual node allocates the traffic rate based on the air-time fairness. When it senses that the conflicts happen and the total channel limit has been exceeded, if each of its neighbours can follow its ε by applying ε**TDi* to their traffic rate, the over-injection can be regulated. When the node senses the total traffic demand decreasing and the regulation is no longer necessary, a regulation deactivation indicator is required to recover the neighbors‟ traffic rate. Before every data transmission, if parameters in the record have been updated, a distributed spectrum allocation algorithm is carried out. When the node starts to transmit, it piggybacks its broadcast information in RTS or DATA packets. After broadcasting, the newly calculated values update the old record. If TD, R and TDtfwi are not changed since last broadcasting, no information is attached to the data.

Hidden node problem

Existing IEEE 802.11 MAC protocol only govern single-hop data delivery based on the interference information collected within the scope of a single hop, and lack support for concerted transmissions among relay nodes in a larger area. Adaptive RTS/CTS (request to send/clear to send) schemes are used in IEEE 802.11 for reducing the delay and collision avoidance [23]. This scheme in its raw form is found to be not efficient for multi-hop networks due to hidden node problem. So, by reducing the effect of hidden node problem, we can increase the pipeline efficiency of the multi-hop networks. The pipeline efficiency is characterized by the simultaneous use of the same spectrum along the path of data flow, relies on the coordination of transmissions at each relay node and becomes a dominant factor affecting the throughput and latency as the hop count grows. So by increasing the pipeline efficiency, we can increase the throughput also.

The hidden node problem or hidden terminal problem occurs when a node is visible from a wireless access point (AP), but not from other nodes communicating with said AP. A hidden terminal is one that is within the range of the intended receiver but out of range of transmitter. Consider the Hidden node problems in fig.1 shown below. Station B is transmitting to station C. Station D cannot hear the transmission from B. During this transmission when D senses the channel, it falsely thinks that the channel is idle. If station D starts a transmission, it interferes with the data reception at C. In this case station D is a hidden terminal to station B. Hence, hidden terminals can cause collisions on data transmission.

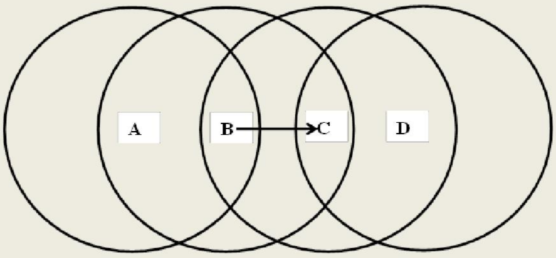

Figure 1 Hidden node problems

This leads to difficulties in media access control. Hidden nodes in a wireless network refer to nodes that are out of range of other nodes or a collection of nodes. RTS/CTS (Request to Send / Clear to Send) is the optional mechanism used by the 802.11 wireless networking protocol to reduce frame collisions introduced by the hidden terminal problem. A node wishing to send data initiates the process by sending a Request to Send frame (RTS) [21]. The destination node replies with a Clear to Send frame (CTS). Any other node receiving the RTS or CTS frame should refrain from sending data for a given time (solving the hidden node problem). The amount of time the node should wait before trying to get access to the medium is included in both the RTS and the CTS frame. This protocol was designed under the assumption that all nodes have the same transmission range. The main drawback of this mechanism is that a backlogged node always attempts to transmit whenever it considers the channel in its vicinity to be idle, through physical and virtual carrier sensing [12]. Ironically, this may result in lower pipeline efficiency because of the unattended RTS problem. However, MAC layer pacing can solve the unattended RTS problem and improve the pipeline efficiency.

MAC layer pacing

The proposed coordination scheme is deployed at the link layer and consists of two steps: (1) information collection and (2) a pacing mechanism [4]. The information collection step uses a new control signal to obtain explicit information on intentional RTS drops and the associated congestion. This information is then used by the pacing mechanism to control and coordinate the rate at which a node makes transmission attempts.

We use a Token Bucket Filter (TBF) to pace transmission attempts and provide support for MAC coordination. In the proposed architecture, a TBF is inserted between the interface queue and the MAC function. The TBF controls the rate at which the MAC layer receives packets and initiates transmission attempts. The rate at which the TBF generates tokens is adaptive and changes based on the network conditions. This adaptive pacing is accomplished by issuing tokens at a dynamic pace set forth by a pace tuner [28]. The tuner coordinates the transmission rate between neighboring nodes through explicit MAC feedback. The MAC feedback is provided in the form of information on the incidence of unattended RTS packets and the rate of token generation is inversely proportional to it.

An unattended RTS represents an early indication of throttled spatial reuse. We thus use it as a feedback for triggering pace adjustments at a sender so that it may probe for the optimal transmission rate in its neighborhood. We modify the 802.11 DCF to incorporate this MAC feedback [11].

Modifications on the MAC Receiver Side: The receiver is responsible for tracking any unattended RTS frames and conveying this information to MAC sender.

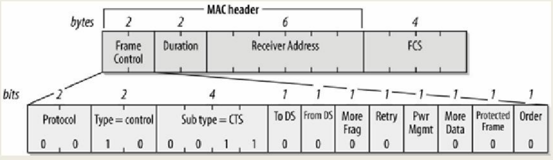

Figure 2. CTS frame structure

Fig.2 shows the CTS frame structure. Inside the 2- byte Frame Control field of the CTS frame, there are two unused subfields named More Fragments field and Retry field, respectively, with each taking up one bit and always set to zero. We use these two single-bit fields to deliver the pacing feedback to the sender while keeping our scheme compatible with the original 802.11 [23],[28]. We introduce two new bits to replace the unused old fields: EPF bit for backward compatibility, and SLW bit for pace tuning.

EPF (Explicit Pacing Feedback): This bit is set to 1 if explicit pacing feedback is enabled on the receiver node. For backward compatibility, it is set to 0 on non-pacing nodes.

SLW (Slow Pacing): This bit is set to 1 by the receiver if it successfully receives but intentionally declines at least one RTS request due to deferral since its last CTS transmission; otherwise it is set to 0. This bit informs the sender whether its transmission rate is too fast causing unattended RTS and thus if it should slow down. The SLW bit is always set to 0 on non-pacing nodes.

Modifications on the MAC Sender Side: When a sender receives the CTS frame containing the pacing feedback, it uses a token bucket filter to update its transmission rate. Since our scheme uses the same mechanism for contention-based access as in

802.11 DCF, all routine backoff or deferral operations are not shown in this algorithm. For each outgoing RTS, the sender starts a timer to wait for the corresponding CTS, and retransmits the RTS after a backoff in case of timeout. The total retransmission attempts should not exceed a limit, set to 7 in 802.11. Once the expected CTS is received, the sender proceeds to retrieve its EPF bit to check if pacing feedback is carried in this CTS frame [19]. If feedback is available, the pace is decreased if the SLW bit is set to 1 and increased otherwise. The pace update method can be either linear or multiplicative.

Performance analysis:

NS-2 tool is used for the performance analysis of the proposed MAC. Continuous bit rate (CBR) traffic sources are used. The source-destination pairs are spread randomly over the network. Only 512-byte data packets are used. The number of source-destination pairs and the packet sending rate in each pair is varied to change the offered load in the network.

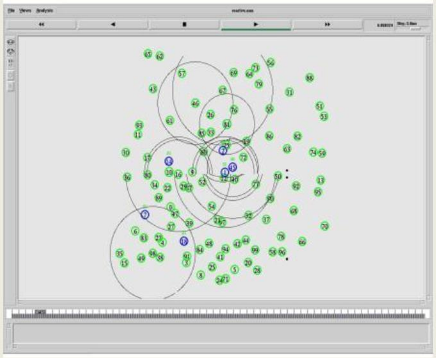

Figure 3. Node arrangement

Figure 4 and Figure 5 shows the comparison graphs of Multi-hop MAC with explicit mechanism and Multi-hop MAC without explicit mechanism. It is clear from the graphs that the number of unattended RTS attempts is in Multi-hop MAC with explicit mechanism is less when compared to Multi-hop MAC without explicit mechanism. At the same time the packet delivery ratio of the proposed scheme is better than the MAC algorithm without explicit mechanism. Thus the proposed scheme holds high throughput with less number of unattended RTS attempts.

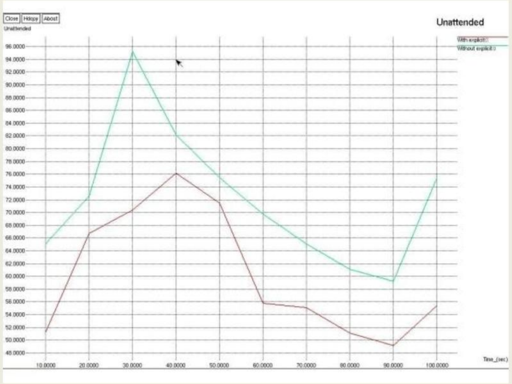

Figure 4 Comparison of number of unattended RTS between Multi-hop MAC with explicit mechanism and Multi-hop MAC without explicit mechanism.

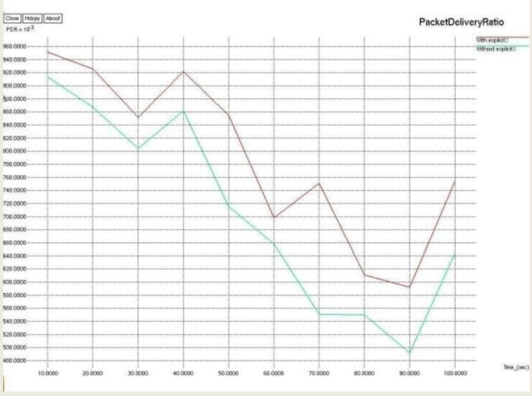

Figure 5 Comparison of Packet Delivery Ratio between Multi-hop MAC with explicit mechanism and Multi-hop MAC without explicit mechanism

Conclusion:

Throughput performance is always a key issue in multi-hop ad hoc networks. Distributed spectrum allocation/scheduling algorithms are commonly applied in the multi-hop networks to improve the efficiency of the spectrum usage and thus improve the poor throughput performance. However, without considering the multi-hop nature of flows, the spectrum allocation can have significant wastage especially for long hops flows. In this paper, we propose Multi-hop MAC scheme with explicit pacing mechanism. This scheme incorporates multi-hop consideration in spectrum allocation and increases the pipeline efficiency so that the spectrum allocated for one hop transmission will not be wasted due to lack of spectrum at the next hop. The proposed adaptive pacing mechanisms using a token bucket filter can balance the transmissions on adjacent nodes for better spatial reuse. Simulation results demonstrated the performance improvements of our scheme over the original 802.11 MAC.

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