Distance-and-Rate Dependent RTS/CTS Reservation in Wireless LAN for Enhancing Spatial Reuse

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Abstract—With the emergence of functional wireless terminals, increased network capacity is needed for wireless LANs. Considering the limited available frequency channels for wireless LAN, improving spatial channel reuse performance of MAC protocol is a key requirement for this purpose. In this paper, we present a novel RTS/CTS reservation scheme for CSMA/CA which improves spatial reuse by taking account for inter-node distance in the network. The main feature of the proposed scheme is that it adaptively change range of NAV(Network Allocation Vector) depending on the distance between a source node and a destination node. The range of NAV is also changed on the current required SINR(Signal and Interference Noise Ratio) which is determined by the current transmission rate, thus this scheme can be used for multirate data transmission. Performance evaluation using a synchronous frame based media access model shows the proposed scheme improves bandwidth efficiency by about 30\% at maximum compared with existing CSMA/CA with RTS/CTS.

Keywords Wireless LAN, CSMA/CA, spatial reuse, RTS/CTS, NAV, distance, multirate

I. INTRODUCTION

With the explosive growth and prevalence of functional wireless terminals such as smart phones and netbooks, demand for high speed wireless LANs as cost effective wireless access has been substantially increasing. From operators of 3G and 4G cellular systems, wireless LAN access is expected to play a key role to bypass a part of data traffic generated by functional terminals to the Internet and alleviate congestion. In terms of development of local community services driven by the prevalence of smartphones, regional platform network using wireless mesh networks has also attract attentions. It will enable more just-in-time and personalized community services to people in city areas, such as providing time-limited and area-limited shop advertisement information to users that may replace digital signage, a variety of personalized monitoring service such as children monitoring, and so on[1,2].

Though all of these trends are demanding increased capacity of wireless LANs, available channels of ISM bands are limited and globally common, and thus improving channel use efficiency has been highly needed for MAC protocols. One of key technique for this purpose is improving spatial channel reuse. It has impact on channel use efficiency to increase density of source-destination pairs communicating simultaneously in the same channel while maintaining required signal quality. Spatial reuse will be optimized when multiple source-destination pairs communicate simultaneously in the same channel with the appropriate physical distance between each pair depending on the received signal quality. In the most widely used MAC protocols of CSMA/CA and CSMA/CA with RTS/CTS protocols that are adopted in IEEE802.11 DCF[3], multiple access is performed by carrier sensing and RTS/CTS reservation. However, these mechanisms are designed not taking account of receiving signal quality at receiver nodes mainly due to design simplicity, and work in the conservative manner to avoid packet collision in the worse cases. Consequently they do not obtain sufficient channel use efficiency by spatial reuse.

In this paper, we focus CSMA/CA with RTS/CTS protocols and present distant-and-rate dependent RTS/CTS reservation scheme that can be applied both for fixed-rate and multirate wireless LANs. The main feature of the proposed scheme is that it adaptively change range of channel reservation called NAV(Network Allocation Vector) depending both on the distance between a source node and a destination node and on the current required SINR(Signal and Interference Noise Ratio) which is determined by the transmission rate. The proposed scheme can significantly improve spatial reuse efficiency while avoiding packet collisions, by let distance between active node pairs be variable depending on the distance between a source and a destination, and also on the transmission rate.

II. BACKGROUND AND MOTIVATION

In CSMA/CA schemes, packet collisions are inevitably incurred, often at the receiver nodes. Typical network models that have been used for MAC protocol studies assume that collision always occurs when a node receives packets from multiple nodes simultaneously within its radio range. Further, it is well known that a node receives interference from surrounding nodes which are distant by more than radio range and it may also cause packet collision. When we assume that signal power of received packets \(Pr\) is determined only by distance between a sender and a receiver denoted by \(r\), \(Pr\) is expressed as \(Pr = P_t \cdot r^{-\alpha}\), where \(P_t\) is transmission power and \(\alpha\) pathloss exponent. Let \(R\) and \(\text{SINR}_{\text{min}}\) denote radio range of each node and signal interference and noise ratio required for packet reception, respectively. Then, interference range \(R^*\), which is maximum distance with which two nodes give...
interference to each other and cause packet collision, is expressed as $R' = R \cdot \frac{1}{\sqrt{\text{SINR}_{\text{min}}}}$. In general, carrier sensing threshold of CSMA/CA is adjusted taking account for $R'$ to avoid collisions.

Although configurations considering interference range are basic in CSMA/CA, when each node has the same transmission power and a source node is close enough to a destination node, they are successful in sending data packets if surrounding nodes are within their interference range.

One example is illustrated in Fig.1. Here, we assume $\alpha = 3.5$, and $\text{SINR}_{\text{min}} = 10\text{dB}$. Then $R'$ is calculated as $R' = 2R$. When $S_1, S_2$ and $S_3$ sends a packet to $D_1, D_2, D_3$ respectively, packet collision may occur at $D_1$ and $D_2$. Looking at $\text{SIR}$ (Signal Interference Ratio) at each node by assuming that noise power is negligible, $\text{SIR}$ at $D_1$ is $(R/4)^{-\alpha}/R^{-\alpha} \approx 20\text{dB}$ and larger enough than $\text{SINR}_{\text{min}}$. On the other hand, $\text{SIR}$ at $D_2$ is $(R/2)^{-\alpha}/R^{-\alpha} \approx 10\text{dB}$, which is close to $\text{SINR}_{\text{min}}$. Thus, collision will not occur at $D_1$, whereas $D_1$ will suffer from collision if noise power and other interference power is not negligible.

Since existing CSMA/CA based scheme is designed so that each node always stops communication if any active surrounding node is within its interference range, $S_1, S_2$ and $S_3$ cannot send packet simultaneously in this example. However, considering the nature of packet collisions described above, if each source-destination node pair can share information of the ‘inter-pair distance’ (distance between a source and a destination node) with other pairs, $S_1$ and $S_2$ will be able to send packets simultaneously and system throughput will be improved.

CSMA/CA has the option of RTS/CTS handshake in order to alleviate packet collisions that occurs due to the hidden terminal problems. However, this option neither takes account for possibility of throughput improvement as shown in Fig.1.

### III. PROPOSAL OF DISTANCE-AND-RATE DEPENDENT RTS/CTS RESERVATION SCHEME IN CSMA/CA

This paper proposes a novel RTS/CTS reservation scheme applied for CSMA/CA named as DDNAV(Distance-and-rate Dependent Network Allocation Vector) in order to improve spatial reuse by taking account for inter-node distance. In this scheme, a source-destination node pair announces its inter-pair distance to surrounding nodes using RTS/CTS and adaptively control the range of NAV(Network Allocation Vector) depending on the announced distance.

In DDNAV, transmission power of RTS/CTS is set to larger value than data packets so that RTS/CTS are received by nodes within the sender’s interference range. Subsequently, each node can have information of surrounding active nodes within its interference range. It can judge whether or not it is able to begin communication with its corresponding node without causing collision at surrounding nodes as well as without suffering collision by interference from them. Though the similar function is done by existing carrier sensing, DDNAV can achieve the judgment more accurately by using distance information, improving spatial reuse in high node density environment.

#### A. Protocol operation of DDNAV

Protocol operation of DDNAV is described by the following sequence.

1) Each node periodically broadcasts hello packet to its neighbor nodes. It estimates distance to each of neighbor nodes using signal power of hello packets received from them.

2) A node having data to send (called as a source node) estimates the distance to the destination of the data packet (called as a destination node) denoted by $D$, and calculates a node-specific interference range $D_{\text{int}}$ defined by the following equation.

$$D_{\text{int}} = \beta \cdot D \cdot \frac{R}{\sqrt{\text{SINR}_{\text{min}}}} (\text{Rate})$$  \hspace{1cm} (1)

where,

- $\text{SINR}_{\text{min}}$(Rate): Required SINR for data packet reception at the current transmission rate
- $\alpha$: Pathloss component
- $\beta$: Range extension parameter accounting for cumulative interference ($\beta > 1$)

Range extension parameter $\beta$ is newly introduced in this scheme, and its purpose is described in the last of this section.

3) If none of nodes surrounding the source node is sending data packets, the source node writes the value of $D_{\text{int}}$ in the newly defined field in RTS frame and broadcast it to announce $D_{\text{int}}$ to them. In the same way, the destination node checks whether or not any surrounding nodes is sending data packets, upon receiving RTS, and if not it broadcasts writes the value

![Figure 1. Possibility of packet collisions and its dependency on the inter-pair distance](image-url)
of $D_{int}$ in CTS and announces $D_{int}$ to them. Data packet and ack packet transmission after RTS/CTS reservation are performed in the same as that of existing CSMA/CA with RTS/CTS. On the other hand, in the case that any surrounding nodes of the source or the destination node is communicating with its corresponding node at this time, the protocol works as described in 5).

4) A node which receives RTS (or CTS) reads $D_{int}$ written in the frame and compares it with distance from the sender of the frame to itself. It judges whether to set NAV according to the following policy.
   - If $D_{int}$ is equal to or larger than the distance from the sender of the frame to itself, it always sets NAV until the time according to the duration specified in RTS (or CTS). This is performed to avoid that this node gives interference to cause collisions at the sender of RTS or CTS.
   - If $D_{int}$ is smaller than the distance from the sender of the frame to itself, it judges whether to set NAV when it sends a data packet to or receive it from its corresponding node in the next time according to the policy described in 5).

5) If the source node received RTS or CTS frames in the past and its duration time continues to the present time, it compares $D_{int}$ of the source node with $D_{int}$ written in all of them. If $D_{int}$ of the source node is larger than at least one of $D_{int}$ specified in received RTS or CTS frames, it sets NAV. Otherwise, it does not set NAV. The destination node judge NAV setting in the same way. The source node starts to send data packets if both of two nodes do not need to set NAV. This operation is performed to avoid that the source or the destination suffered collision by the interference.

B. Example of operation

An example of DDNAV operation is illustrated in Fig.2. There are three communication pairs of S1-D1, S2-D2, S3-D3, where S1, S2 and S3 have data to send. Definition of R and the value of $\alpha$, $\text{SINR}_{\text{min}}$ the same as Fig.1.

Transmission power of RTS/CTS is set so that its range is equal to 2R. Here, $D_{int}$ for S1-D1 pair is calculated as R. Similarly, $D_{int}$ for S2-D2 pair and for S3-D3 pair is R and 2R, respectively. In advance of data packet transmission, these six nodes notify its own $D_{int}$ using RTS or CTS. Looking at S1-D1 pair and S2-D2 pair, distance between any two nodes among these four nodes is more than R. Thus S1-D1 pair and S2-D2 pair sends data packets simultaneously. By contrast, distance between S2 and D3 is less than 2R, which is $D_{int}$ of S3-D3 pair. Accordingly, when either of S2-D2 pair and S3-D3 pair is sending data packets, the other set NAV.

In this way, the proposed scheme aims to improve channel reuse efficiency while avoiding packet collisions.

IV. PERFORMANCE EVALUATION MODEL

A. Network model and wireless communication parameters

We use a network model where nodes are randomly placed within 500m square area. The number of nodes is varied from 60 to 130. In this model, half of total nodes represent wireless access points and the rest represent user terminals. Source-destination pairs are set between wireless access points and user terminals.

This model represents the situation where wireless access points are located in the urban area, each of which is independently operated as the access network to the Internet by different users. Thus, wireless access points do not communicate with each other such as in the wireless mesh networks, but they are operated by sharing the same channel frequency.

Parameters of the channel model are set as shown in Table I. Fig.3 shows the one of node placement patterns in the area, where solid lines represent wireless links between nodes corresponding to parameters shown in Table I. We set multiple source-destination pairs in this network performing single hop packet transmissions, and evaluate aggregate bandwidth efficiency of all pairs. Each result is obtained by averaging results for five different node placement patterns.

Transmission rate of multirate wireless LAN is assumed to be ideally determined based on $\text{SINR}$, where symbol modulation mode is varied among BPSK, QPSK, 8PSK, 16QAM and 64QAM. We first calculate bandwidth efficiency $f(\gamma, p)$[bit/sec/Hz] of a wireless link, which is defined by the following equation using received $\text{SINR}$ $\gamma$ and required bit error rate $p$[4].

$$f(\gamma, p) = \log_2(1 + \beta \gamma)$$

$$\frac{1}{\beta} \leq \gamma < 63/\beta$$

$$\beta = \begin{cases} -1.5/\ln(0.5p) & \text{(BPSK)} \\ -1.5/\ln(5p) & \text{(QPSK, 8PSK, 16QAM, 64QAM)} \end{cases}$$

In this paper, $p$ is set to $10^{-3}$. Based on the value of bandwidth efficiency, symbol modulation mode is selected for a packet traversing the link. For example, BPSK mode, whose
bandwidth efficiency is 1, is selected when bandwidth efficiency is no less than 1 and less than 2. Similarly, QPSK mode is selected when bandwidth efficiency is no less than 2 as well as less than 3. Table II shows minimum required value of $\gamma$ for each symbol modulation mode. We assume the data packet does not reach the destination node when bandwidth efficiency is less than 1. On the other hand, symbol modulation mode of RTS and CTS packets is always set to BPSK, which corresponds with bandwidth efficiency of 1.

Subsequently, we average bandwidth efficiency of modulation mode selected for each data packet sent by all of source-destination pairs. This is used as a metric to indicate system throughput.

As for media access timing, synchronized media access scheme is used for simplicity. Assuming each node establishes synchronization between surrounding nodes, access frame is defined which consists of control period and data transmission period. During control period, nodes having data to send and their destination nodes send RTS and CTS packets after performing random backoff, and determine transmission rate. Surrounding nodes receiving RTS or CTS packets set NAV if necessary. During data transmission period, source nodes which were successful to exchange RTS and CTS packets and also do not set NAV send data packets without backoff. Receiving data packets, destination nodes send immediately ack packets.

Note that carrier sensing is not performed for data packets transmission since they are sent synchronously. Also, we assume collisions of RTS and CTS packets do not occur for simplicity.

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<table>
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<tr>
<th>Symbol modulation mode</th>
<th>Required SINR $\gamma$ [dB]</th>
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<tbody>
<tr>
<td>BPSK</td>
<td>5.3</td>
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<tr>
<td>QPSK</td>
<td>10.1</td>
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<tr>
<td>8PSK</td>
<td>13.8</td>
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<tr>
<td>16QAM</td>
<td>17.1</td>
</tr>
<tr>
<td>64QAM</td>
<td>23.3</td>
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alleviated to the same extent for $\beta=1.5$ and 2, and thus $\beta$ should be tuned to 1.5 in this model.

Secondly, Fig. 5 compares average bandwidth efficiency of each scheme. DDNAV scheme improves bandwidth efficiency by approximately 30% at maximum compared with existing RTS/CTS. Simple RTS/CTS range extension scheme exhibits worst performance among three schemes. While this scheme achieves least packet collisions owing to that NAV area is always larger than other two schemes, it makes unnecessarily many surrounding nodes refrain from data transmission, leading to inefficient spatial channel reuse.

Finally, bandwidth efficiency performance with varying the number of network node is shown in Fig. 6. We found that the optimal value of $\beta$ in DDNAV is not affected by the number of nodes in the network. Further, as shown in Fig. 6, performance benefit of DDNAV over existing two schemes is greater for larger number of nodes in the network, which is higher node density network. With higher node density, communication of each source-destination pair tends to be more localized, where distance between each source-destination pair is larger compared with the distance between the source node and the destination node. Spatial reuse can be more easily enhanced in this condition by the use of DDNAV.

VI. RELATED WORKS

There are a number of studies on controlling spatial channel reuse in CSMA/CA. We summarize them into two categories: One is varying carrier sensing threshold and transmission power. Zhu et al. [5] determines the optimal carrier sensing threshold to maximize spatial channel reuse for a fixed transmission rate, and presents adaptive threshold adjustment algorithm using the estimated average SINR. Kim et al.[6] studies the effects of transmit power control and varying carrier sensing threshold on network capacity, and reveals that spatial reuse depends only on the ratio of the transmit power to the carrier sense threshold. Zhai et al. [7] present the strategy to set the optimum carrier sensing threshold for multihop flows. Varying carrier sensing threshold has the advantage in that it can be performed without modification of IEEE 802.11 specification. However, it is well known that only carrier sensing or transmit power control cannot avoid packet collisions at the destination node due to the hidden terminals problem.

The other category is controlling radio range of RTS and CTS. Xu[8] presents a scheme to dynamically adjust range of NAV by controlling received power threshold of RTS packet at the destination node above which it sends CTS packet. Ye[9] presents a scheme in which RTS and CTS frame format is extended to explicitly specify range of NAV, and NAV range is varied depending on the distance between the source and the destination node. These schemes are evaluated for a fixed transmission rate. Configuration and the performance in multirate wireless LAN environment are not investigated in the literature.

VII. CONCLUSION

We have proposed an RTS/CTS reservation scheme improving spatial reuse of CSMA/CA that can be applied for multirate wireless LAN. The proposed DDNAV dynamically changes NAV range specified by RTS/CTS depending on the
distance between a source node and a destination node as well as on the required SINR. With performance evaluation using the synchronous frame based medium access model, it was shown that the proposed DDNAV improves average bandwidth efficiency per node by about 30% at maximum compared with existing RTS/CTS, by tuning range extension parameter appropriately. Although it is also shown that throughput is slightly degraded in node pairs for which source-destination distance is relatively large and use the lowest transmission rate at most of time, its effect on average throughput is negligible.

For future works, it is required to add carrier sensing function to DDNAV so that it can be applied to general asynchronous media access environments. Adaptive carrier sense threshold control considering on measured SINR and required SINR studied in the past literature can be accommodated into DDNAV. We are currently working on them and confirming advantages of DDNAV over existing CSMA/CA with RTS/CTS as for average throughput. Detailed and quantitative performance of DDNAV under asynchronous media access environment will be reported in our future paper.

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**REFERENCES**


