A Distributed Packet Concatenation Scheme for Sensor and Ad Hoc Networks

Hongqiang Zhai and Yuguang Fang
Department of Electrical & Computer Engineering
University of Florida, Gainesville, Florida 32611-6130
Tel: (352) 846-3043, Fax: (352) 392-0044
E-mail: zhai@ecel.ufl.edu and fang@ece.ufl.edu

Abstract— **Along with the growing popularity of sensor and ad hoc networks, various kinds of services are expected to be supported. In wireless ad hoc networks, there are increasing demands for web traffic, voice over IP and streaming video from and to the Internet via the access points. In sensor networks, event-driven or periodically monitoring services are common. However, various lengths of packets are used in different services. Short packets have relatively large overhead at the MAC (medium access control) and physical layers and hence can significantly decrease the network throughput. In this paper, we analyze the performance of a distributed adaptive packet concatenation (APC) scheme which is proposed to improve the network throughput. The APC scheme works at the interface queue of the data link layer. It adaptively concatenates several short packets which are destined to the same next hop into a long packet for MAC layer's transmission according to the congestion status as well as the observed channel status. The theoretical analysis is conducted in both single hop networks and multihop networks, and the result shows that the APC scheme can increase the throughput by up to 4 to 16 times.**

I. INTRODUCTION

Recent years have seen greatly increasing interests in sensor and ad hoc networks. These networks can be quickly deployed with low cost and provide desired mobility. They are finding a variety of applications such as disaster rescue, battlefield communications, inimical environment monitoring, collaborative computing and broadband mobile Internet. And various kinds of traffic often coexists in one network, such as voice, video, email, FTP, routing and web traffic. They have different characteristics and requirements, such as bandwidth, delay and packet length, which provide great challenges for network protocols to work efficiently.

Short data packets occupy a relative large channel resource due to the fixed physical and MAC layers' overhead. They also lead to congestions and severe MAC contentions more easily than long data packets given a certain amount of data traffic. For the IEEE 802.11 protocols, the physical layer overhead includes a preamble, which is used to synchronize the transmitter and the receiver, and some control fields to notify the receiver of the channel coding and modulation schemes. The MAC layer overhead includes several MAC layer control frames consisting of RTS (ready to send), CTS (clear to send) and ACK (acknowledge), MAC address of the DATA frames and interframe spacings, such as SIFS and DIFS. The shorter the payload of the DATA frame, the smaller the throughput and the more the wasted channel resource.

Several schemes ([1]–[4]) have been proposed to efficiently utilize the time-varying channel in wireless LANs where nodes can directly communicate with each other. When the channel quality is good, several packets are transmitted back to back with a large channel rate at a time. Otherwise, a single packet is transmitted with a small channel rate. These schemes are efficient in reducing the relative protocol overhead when a large channel rate is used.

In sensor and ad hoc networks, data packets often need to be forwarded several times before they reach the destinations. Each forwarding node needs to contend for the channel with other nodes before it can transmit a packet. The MAC layer contention becomes more severe when congestion happens and a lot of backlogged packets keep nodes contending for the channel. Thus concatenating several packets into a large super packet can efficiently reduce the MAC layer contention and collision. However, a long packet may need a long transmission time during which the channel quality may change and hence encounter a high probability of bit errors. Therefore it is necessary to consider the channel

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status when combining the packets to guarantee that the total transmission time does not exceed the channel coherence time as well as to consider the queue status to check the availability of packets. This is the proposed adaptive packet concatenation (APC) scheme in this paper. And the performance of APC is analyzed theoretically in both single hop and multihop ad hoc networks.

The rest of this paper is organized as follows. Section II introduces the basics of the IEEE 802.11 MAC protocol. The proposed scheme and its performance analysis are given in Section III. Finally, Section IV concludes this paper.

II. PRELIMINARIES

In this section, we discuss the basic procedures of the IEEE 802.11 MAC protocol. Since it is widely used, we will analyze the proposed adaptive packet concatenation scheme based on this protocol in next section.

A. Operations of the IEEE 802.11

The basic access method in the IEEE 802.11 MAC protocol is DCF (Distributed Coordination Function), which is based on carrier sense multiple access with collision avoidance (CSMA/CA). Before starting a transmission, each node performs a backoff procedure, with the backoff timer uniformly chosen from [0, CW-1] in terms of time slots, where CW is the current contention window. When the backoff timer reaches zero, the node transmits a DATA packet. If the receiver successfully receives the packet, it acknowledges the packet by sending an acknowledgment (ACK). If no acknowledgment is received within a specified period, the packet is considered lost; so the transmitter will double the size of CW and choose a new backoff timer, and start the above process again. When the transmission of a packet fails for a maximum number of times, the packet is dropped. To avoid collisions of long packets, the short RTS/CTS (request to send/clear to send) frames can be employed. The timing structure of message sequences are shown in Fig. 1.

Note that the IEEE 802.11 MAC also incorporates an optional access method called PCF (Point Coordination Function), which is only usable in infrastructure network configurations of wireless LANs and does not support multihop communications. In this paper, we thus focus on the IEEE 802.11 DCF.

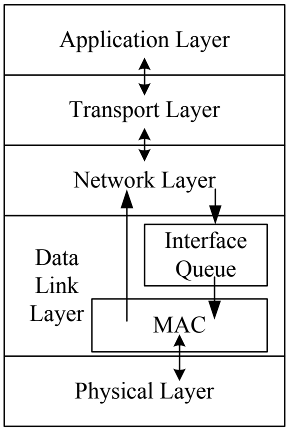

Fig. 2. Protocol stack

III. ADAPTIVE PACKET CONCATENATION (APC) SCHEME AND PERFORMANCE ANALYSIS

In this section, we first introduce the basic mechanisms of APC scheme. Then we analyze how much this scheme can improve the throughput in both single hop and multihop networks.

A. Basic Scheme

APC works at the data link layer consisting of a shared interface queue and a MAC sublayer as shown in Fig. 2. It concatenates several packets in the interface queue which have the same next hop into a super packet. A super packet instead of the original packets is sent to the MAC layer each time when the MAC layer is idle and the queue is not empty.

The super packet structure is shown in Fig. 3. It contains one or more data packets. The subfields for each data packet consist of three parts: length, the data packet itself and an optional CRC field. The length subfield is used at the receiver to split the super packet into the original data packets. The CRC subfield is used to check the integrity of the data packet to combat the possible channel bit errors. It should be used if the receiver enables selective acknowledgements which can indicate which data packets are corrupted by channel errors and need retransmissions. If not all data packets have no errors, the transmitter only needs to retransmit those corrupted data packets and reconstruct the super packet according to the available data packets in the queue at each time of retransmission.

The length l_{sp} of a super packet is always less than or equal to a *concatenation threshold* L_{th}. This threshold is determined by the channel coherence time T_{cc} during which the channel quality remains stable [3].

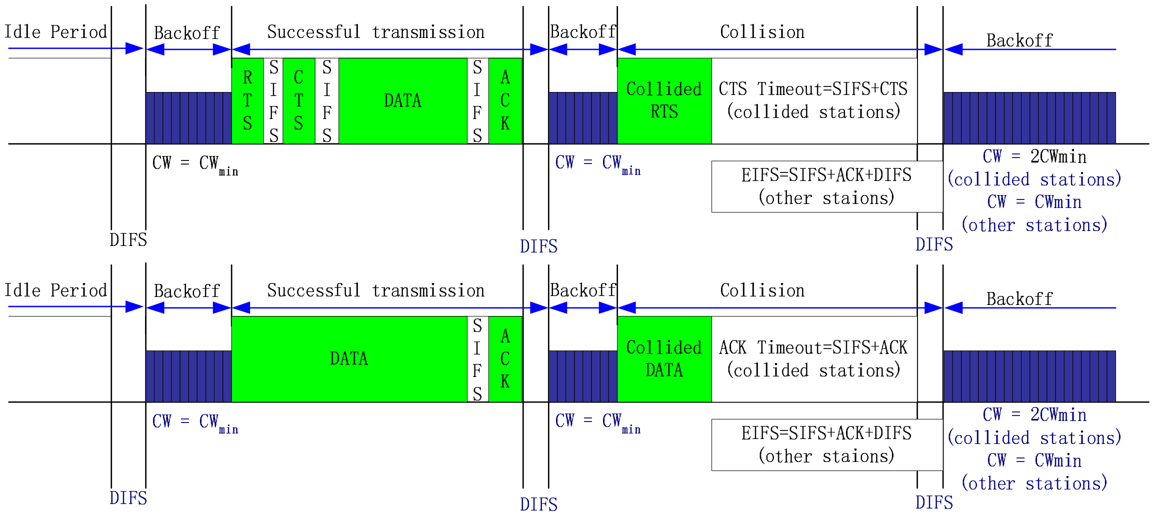

Fig. 1. RTS/CTS mechanism and basic access mechanism of IEEE 802.11

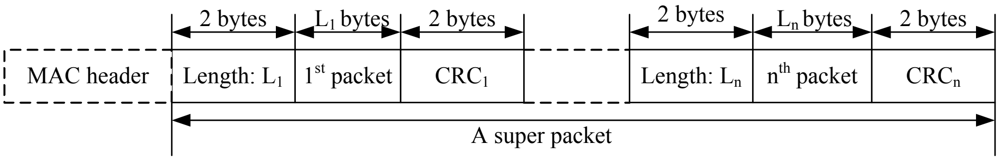

Fig. 3. The super packet structure

The transmission time t_{sp} of a super packet includes the transmission time of the physical and MAC layer overhead and the transmission time for the super packet itself. And t_{sp} must be less than or equal to t_{cc}. Thus we have

$$L_{th} = r_{data} \times (T_{cc} - T_{Hphy} - T_{HMAC} - T_{ACK} - sifs) \tag{1}$$

for the case that there is no RTS or CTS, where r_{data} is the data rate of the DATA frame, and T_{Hphy} and T_{HMAC} are respectively the transmission times of the physical and MAC headers of a DATA frame, and

$$\begin{aligned} L_{th} = r_{data} \times (&T_{cc} - T_{Hphy} - T_{HMAC} - T_{RTS} \\ &-T_{CTS} - T_{ACK} - 3sifs) \end{aligned} \tag{2}$$

for the case that RTS and CTS are used, where T_{RTS}, T_{CTS} and T_{ACK} are respectively the transmission times of the RTS, CTS and ACK frames.

Each time when the MAC layer picks up DATA packets from the interface queue and starts channel contention, APC concatenates the packet at the head of queue with several other packets that have the same next hop. These packets appear in the super packet in the order that they appear in the queue. The concatenation ends when concatenating one more packet will make the length of the super packet exceed L_{th}.

To support multiple channel rates, APC calculates L_{th} using the current transmission rate of the MAC layer. There are basically two methods to determine the transmit rate r_{data}. First, it can be determined by the history. The transmitter determines r_{data} according to the received power P_r of the last ACK frame from the next hop if the last transmission is successful. Otherwise it uses a lower rate or the lowest available rate. In the second method, the transmit rate r_{data} is determined by the received power P_r of the CTS frame from the next hop. The first method depends on the result of previous transmission and may conclude with a wrong channel quality because a transmission failure can result from a collision as well as poor channel quality. The second method uses the short RTS/CTS frames to probe the channel quality before the DATA transmission and has a more accurate channel information. Although the second method requires RTS/CTS frames, RTS/CTS are also useful to shorten the collision periods. Therefore, APC uses the second method to determine r_{data}.

To utilize multiple channel rates, we must notice that different channel rates have different requirements of the received power threshold RX_{thresh} and the signal to interference plus noise ratio (SINR). The widely used IEEE 802.11b support 1, 2, 5.5, and 11Mbps. In

$$r_{data} = \begin{cases} 1Mbps\ (RX_{thresh1} \le P_r < RX_{thresh2} \text{ and } SINR \ge CP_{thresh1}) \\ 2Mbps\ (RX_{thresh2} \le P_r < RX_{thresh3} \text{ and } SINR \ge CP_{thresh2}) \\ 5.5Mbps\ (RX_{thresh3} \le P_r < RX_{thresh4} \text{ and } SINR \ge CP_{thresh3}) \\ 11Mbps\ (P_r \ge RX_{thresh4} \text{ and } SINR \ge CP_{thresh4}) \end{cases} \tag{3}$$

Equation (3), $RX_{threshi}$ and $CP_{threshi}$ ($1 \le i \le 4$) are the thresholds required by the hardware to correctly decode the received signals. For example, the requirements of a PCMCIA Silver/Gold card by Orinocco are that $RX_{thresh1} = -94dBm$, $RX_{thresh2} = -91dBm$, $RX_{thresh3} = -87dBm$, $RX_{thresh4} = -82dBm$, $CP_{thresh1} = 4dB$, $CP_{thresh2} = 7dB$, $CP_{thresh3} = 11dB$, and $CP_{thresh4} = 16dB$.

B. Performance Analysis of the Network Throughput in the Single Hop Case

In this subsection, we analyze that how much improvement APC can achieve for the saturated throughput and the maximum throughput in the case that the IEEE 802.11 MAC protocol is used in a single hop network.

Let R_s denote the ratio of the time periods with successful transmissions to the total time. Then, following the techniques in [5] [6], we have

$$\begin{array}{l} R_s = \frac{p_s T_s}{p_i \sigma + p_s T_s + (1 - p_i - p_s) T_c} \\ p_i = (1 - p_t)^n \\ p_s = n p_t (1 - p_t)^{n-1} \\ p = 1 - (1 - p_t)^{n-1} \end{array} \tag{4}$$

where T_s is the average successful transmission time, T_c is the average collision time, σ is a MAC layer idle slot time, p_t is the transmission probability of each node in any slot, n is the total number of nodes in the network, and p is the collision probability that a node encounters collision whenever transmitting. And from [7],

$$\begin{array}{l} T_s = T_{RTS} + T_{CTS} + \overline{T_{data}} + T_{ACK} + 3sifs + difs \\ T_c = T_{RTS} + sifs + T_{CTS} + difs \end{array}, \tag{5}$$

for the case where the RTS/CTS mechanism is used, and

$$\begin{array}{l} T_s = \overline{T_{data}} + T_{ACK} + sifs + difs \\ T_c = \overline{T_{data^*}} + T_{ACK\_timeout} + difs \end{array}, \tag{6}$$

for the case where there is no RTS/CTS mechanism, where $\overline{T_{data}}$ and $\overline{T_{data^*}}$ (please refer to [6] [9] for derivation of $\overline{T_{data^*}}$) are the average length, in seconds, for the successful transmission and collision of the data packets, respectively. If the average packet length is L_p, then

$$\overline{T_{data}} = \frac{L_p}{r_{data}} + T_{Hphy} + T_{HMAC} \tag{7}$$

Now the network throughput S can be expressed as R_s multiplied by the DATA transmission rate r_{data} excluding the physical and MAC layers' overhead, i.e.,

$$S = R_s \times \frac{\frac{L_p}{r_{data}}}{T_s} \times r_{data} = \frac{p_s L_p}{p_i \sigma + p_s T_s + (1 - p_i - p_s) T_c} \tag{8}$$

For the saturated case where each node always has a packet contending for the shared wireless channel, Bianchi [6] derived the formula for the transmission probability p_t at any slot in terms of p. Considering a finite retransmission limit followed by the packet dropping, we further derived p_t in [9] as

$$p_t = \left\{ \begin{array}{ll} \frac{2(1-p^{\alpha+1})}{1-p^{\alpha+1}+(1-p)W(\sum_{i=0}^{\alpha}(2p)^i)} & ,\alpha \le m \\ \frac{2(1-p^{\alpha+1})}{1-p^{\alpha+1}+pW\sum_{i=0}^{m-1}(2p)^i+W(1-2^m p^{\alpha+1})} & ,\alpha > m \end{array} \right\} \tag{9}$$

where α is the maximum allowed retransmission times, W is the minimum contention window size, and $2^m W$ is the maximum contention window size. By Equations (8) and (9), we can derive the value for p, p_t and S for the saturated case, referred as $\tilde{p}$, $\tilde{p_t}$ and $\tilde{S}$.

For the non-saturated case where not all the nodes are contending for the channel, the collision probability p is smaller than $\tilde{p}$ and hence may achieve a larger throughput. From Equation (4) and (8), S can be expressed as the function of p. S is equal to 0, $\tilde{S}$ and 0 when $p = 0$, $\tilde{p}$ and 1, respectively. To obtain the maximum value of S, denoted by S^*, and the corresponding value of p, denoted by p^*, let

$$\frac{d}{dp} S = 0 \tag{12}$$

Let $\hat{p}$ be the root of the Equation (12). Then

$$p^* = min(\hat{p}, \tilde{p}) \tag{13}$$

In the APC scheme, the network throughput S_{APC} can be calculated with the Equation (11), which is obtain by excluding the APC overhead in Equation (10). Here L_{spl} is the average total length of the concatenated packets in a super packet. For the case that the packet length L_p is fixed, we have

$$\begin{array}{l} L_{spl} = \lfloor \frac{L_{th}}{L_p + 4} \rfloor L_p \\ L_{sp} = \lfloor \frac{L_{th} - 1}{L_p + 4} \rfloor (L_p + 4) \end{array} \tag{14}$$

$$S = \frac{n(1-p)(1-(1-p)^{\frac{1}{n-1}}) \times L_p}{(1-p)^{\frac{n}{n-1}}\sigma + n(1-p)(1-(1-p)^{\frac{1}{n-1}})T_s + (1-n(1-p)(1-(1-p)^{\frac{1}{n-1}}) - (1-p)^{\frac{n}{n-1}})T_c} \tag{10}$$

$$S_{APC} = \frac{n(1-p)(1-(1-p)^{\frac{1}{n-1}}) \times L_{spl}}{(1-p)^{\frac{n}{n-1}}\sigma + n(1-p)(1-(1-p)^{\frac{1}{n-1}})T_s + (1-n(1-p)(1-(1-p)^{\frac{1}{n-1}}) - (1-p)^{\frac{n}{n-1}})T_c} \tag{11}$$

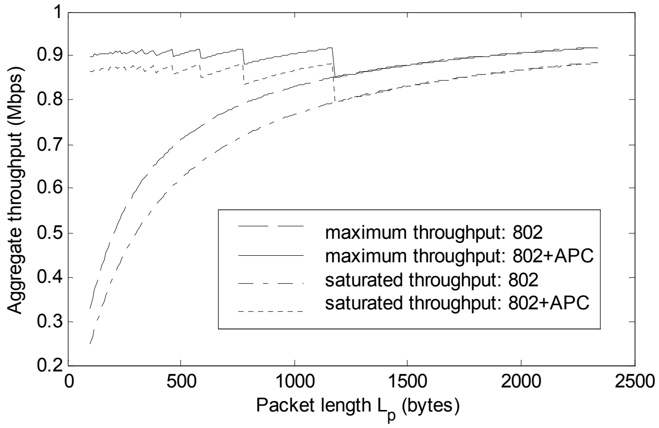

Fig. 4. Throughput when channel rate is 1Mbps, $L_{th} = 2346$bytes and RTS/CTS mechanism is used.

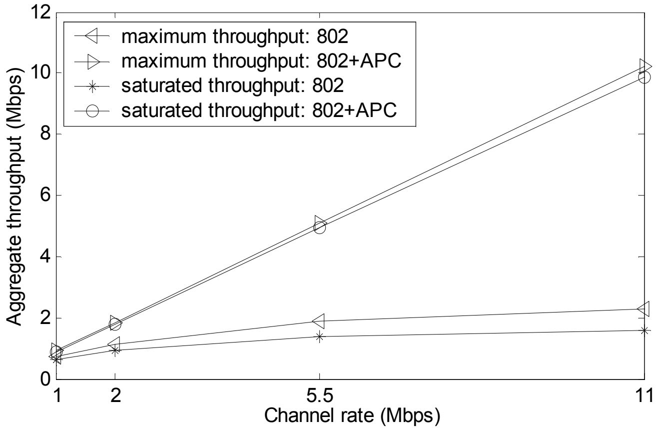

Fig. 5. Throughput when channel rate is 1, 2, 5.5 and 11Mbps and RTS/CTS mechanism is used.

where $\lfloor \frac{L_{th}}{L_p+4} \rfloor$ is the greatest integer less than or equal to $\frac{L_{th}}{L_p+4}$, and L_{sp} is the average length of a super packet. In Equation (11), T_s and T_c are calculated by Equations (5) (6) and (7) according to the average super packet length L_{sp}, while in Equation (10), T_s and T_c are calculated according to the average packet length L_p.

Now the network throughputs for the IEEE 802.11 protocol with and without the APC scheme can be calculated by Equations (10) and (11) using p^* and $\tilde{p}$. The numerical results are shown in Fig. 4 where $n = 200$. The parameter values of the IEEE 802.11 system are shown in Table I.

TABLE I

IEEE 802.11 SYSTEM PARAMETERS

Channel Bit Rate	1 Mbit/s
PHY header	192 bits
MAC header	224 bits
Length of RTS	160bits + PHY header
Length of CTS	112bits + PHY header
Length of ACK	112bits + PHY header
Initial backoff window size (W)	32
Maximum backoff stages (m)	5
Short retry limit	7
Long retry limit	4

From Fig. 4, we have two important observations. First, the APC scheme can greatly increase the throughput when the packet length is smaller than a half of the concatenation threshold L_{th}. For the saturated case, the throughput of APC scheme is up to 3.5 times of that of the IEEE 802.11 protocol when the data packet length is equal to 100bytes. And the maximum throughput of APC scheme is up to 2.7 times of that of the IEEE 802.11 protocol. Second, a smaller collision probability is desired to obtain a larger throughput since the maximum throughput is always larger than the saturated throughput. Specifically, the maximum throughput of the IEEE 802.11 protocol is much larger than the saturated throughput of the IEEE 802.11 protocol especially when the data packets are short. The improvement ranges from 4% to 32% when the packet length decreases from 2346 to 100 bytes. When the APC scheme is used, the improvement ranges from 4% to 7%. In addition, a smaller collision probability is also required to achieve a shorter delay and a better energy efficiency. It is desired to design a scheme to support small collision probability while achieving or approaching the maximum throughput. One such scheme can be found in [10].

Fig. 5 shows the throughput at different channel rates where the packet length $L_p = 512$ bytes and the channel coherence time T_{cc} is the same with that in

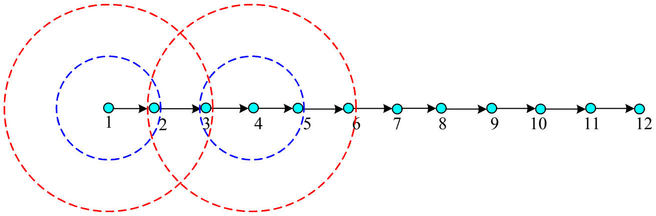

Fig. 6. Chain topology.

Fig. 4. In the APC scheme, the throughput approximately linearly increases along with the channel rate. However, the throughput of the IEEE 802.11 protocol does not increase much along with the channel rate. This is because the relative protocol overhead is much larger for a higher channel rate in the IEEE 802.11 protocol. The improvement of the APC scheme is up to 6.2 and 4.5 times when the channel rate is 11Mbps for saturated throughput and maximum throughput, respectively.

C. Performance Analysis of the Network Throughput in a Multihop Network

In a multihop wireless network, the collision probability is not easy to derive. As in the single hop network, each node has to contend for the channel with the nodes in its own carrier sensing range. Furthermore, the hidden terminals of one transmitter, which may be two-hop away and can not sense the transmission, may initiate a new transmission which introduces a collision at the intended receiver of the ongoing transmission. This kind of collision depends on the network topology and is difficult to be characterized.

In this section, we derive the maximum throughput that the IEEE 802.11 protocol and APC scheme can achieve instead of their exact throughput which is different for different network deployment. Then we will discuss how to approach this maximum throughput in a wireless multihop network. We first study a multihop flow which travels through a chain topology as shown in Fig. 6 where small circles denote the transmission range and large circles denote the carrier sensing range.

Maximum throughput of a multihop flow is achieved when the packet scheduling fully utilizes the space resource, i.e., scheduling as many as possible concurrent transmissions with a SINR that is high enough for a correct decoding at the receivers. At another hand, nodes will not initiate any new transmissions if they sense a busy channel due to the requirement of carrier sense procedure in the IEEE 802.11 protocol. Thus we have two requirements for maximum spatial reuse. First, there is only one transmission in the carrier sensing range of each node. Second, the power ratio of the received signal to the interferences from other transmissions must be larger than or equal to a certain threshold as shown in Equation (3). Let γ denote the path loss exponent, then the power level P_r of the received signal equals

$$P_r = P_o(\frac{d_o}{d_h})^\gamma \tag{15}$$

where d_o is the distance between the transmitter and a reference point, P_o is the power level of the signal received at the reference point and d_h is the distance between the transmitter and the intended receiver. In the regular chain topology in Fig. 6, d_h is also the hop distance.

In the chain topology, the strongest interference comes from the concurrent transmission which is closest to the receiver. Other interference can be neglected for a much smaller power level. Let d_i denote the distance between two concurrent transmitters in the chain topology. For example, if transmitter-receiver pair (1,2) and (5,6) can be scheduled to transmit at the same time, then $d_i = 4d_h$. Let P_i denote the power level of the interference signal. Given a certain requirement of SINR, we have

$$SINR \leq \frac{P_r}{P_i} = (\frac{d_i - d_h}{d_h})^\gamma \Rightarrow d_i \geq d_h(SINR^{\frac{1}{\gamma}} + 1) \tag{16}$$

Thus the minimum hop distance N between two concurrent transmitters equals

$$N = \lceil SINR^{\frac{1}{\gamma}} \rceil + 1 \tag{17}$$

where $\lceil x \rceil$ is the ceiling function and equals the largest integer larger than or equal to x. Thus the maximum end-to-end throughput S_{chain} of a multihop flow in a regular chain topology is

$$S_{chain} = \frac{L_p}{T_s} \times \frac{1}{N} = \frac{L_p}{T_s(\lceil SINR^{\frac{1}{\gamma}} \rceil + 1)} \tag{18}$$

where $\frac{L_p}{T_s}$ is the maximum throughput at each hop and N is the spatial reuse ratio. For the APC scheme, the maximum end-to-end throughput S_{chain_APC} is obtained by using a super packet instead of a data packet:

$$S_{chain\_APC} = \frac{L_{spl}}{T_s(\lceil SINR^{\frac{1}{\gamma}} \rceil + 1)} \tag{19}$$

where T_s is calculated according to the length of L_{sp}.

Fig. 7 shows the maximum end-to-end throughput of a multihop flow with at least four hops in the regular chain topology where we set $d_o = 1m$, $P_o = 0dBm$, $\gamma = 4$ and the data packet length is 512 bytes. The requirement of SINR adopts the values discussed at the end of Section III-A. The maximum end-to-end throughput of the APC

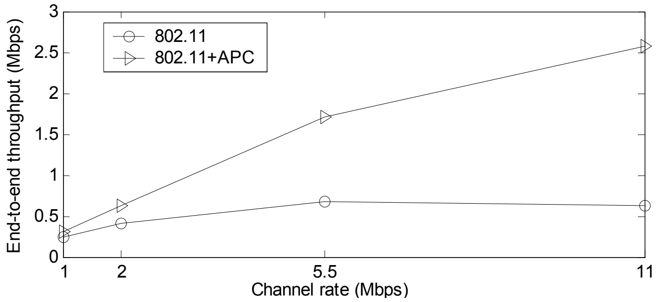

Fig. 7. Maximum end-to-end throughput of a multihop flow.

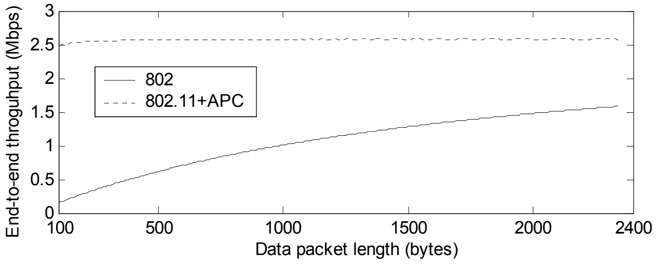

Fig. 8. Maximum end-to-end throughput of a multihop flow.

scheme is 1.24, 1.53, 2.52 and 4.08 times of that in the IEEE 802.11 protocol when the channel rate is equal to 1, 2, 5.5 and 11Mbps, respectively. Fig. 8 where the channel rate is 11Mbps shows that the APC scheme can achieve a stable and much higher end-to-end throughput at different packet length. The throughput of the APC scheme is 1.62 to 16.50 times of that of the IEEE 802.11 protocol when the packet length decreases from 2246bytes to 100bytes.

To achieve the maximum end-to-end throughput, we must alleviate the hidden terminal problem as much as possible. In the chain topology, to avoid a node becoming a hidden terminal and introducing a collision, the carrier sensing range must be large enough to includes the nodes which can introduce enough interference to corrupt the ongoing transmission. Thus the radius of the carrier sensing range d_c must satisfy

$$d_h(SINR^{\frac{1}{\gamma}}+1) \le d_c \le d_h(\lceil SINR^{\frac{1}{\gamma}} \rceil+1) \qquad (20)$$

where the left inequation prevents the collision from the hidden terminal problem and the right inequation makes it possible for the maximum spatial reuse ratio.

Besides the hidden terminal problem, we also need to address the unfair medium access probability at each forwarding node to maximize the end-to-end throughput. One such scheme can be found in [11], which addresses both medium contention and network congestion and can well approach the above maximum end-to-end throughput. For a multihop flow in a more general topology, the maximum end-to-end throughput depends on the bottleneck location where there are the poorest spatial reuse and the most interference from other flows. We leave the analysis of such topology to the future work.

IV. CONCLUSION

In this paper, we propose a distributed adaptive concatenation scheme for the sensor and wireless ad hoc networks. It adaptively concatenates several short data packets into a large super packet according to the current channel quality and queue status. It effectively reduces the relative protocol overheads especially when multirate capability of the IEEE 802.11 protocol is considered and the data packet is short, which are the case for many applications. We also derive the throughput of the proposed scheme in both single hop networks and multihop networks. The analytical results show that this scheme can improve the throughput by up to 4 to 16 times.

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