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Improving Throughput and Reducing Power Consumption of Nodes Using RAN

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Abstract

A random access network that uses the request-to-send and clear-to-send (RTS/CTS) handshake for reservation of transmission time. In the network, nodes initiate data transmission to a common base station (BS) by sending an RTS packet according to a transmission probability. The RTS packet of a node specifies the length of the nodes requested data transmission interval, and will be successfully received by the BS if its signal to interference plus noise ratio (SINR) is higher than the capture ratio. The BS will then reply with a CTS packet to grant this node the requested data transmission interval and inform the other nodes not to interrupt. The transmission probabilities of RTS packets of all nodes will determine the average throughput and power consumption of each node. The set of all possible throughputs that can be achieved by the network is called the throughput region. Providing an upper bound on the total transmission power consumption over the throughput region at the optimal operating point depending on the fraction of time occupied by the RTS packets.

Keywords: Medium access control (MAC), Performance analysis, Power consumption, Reservation mechanisms, RTS/CTS, Throughput region..

Introduction

The performance of IEEE 802.11-based networks have been intensively studied, and some methods have been proposed to improve the efficiency of channel utilization and power consumption.. The difference there is in the selection of the bakeoff interval which is sampled from a geometric distribution with parameter p. It was shown that the p-persistent.IEEE 802.11 can closely approximate the standard protocol. In [9], Tay and Chua adopted a different modelling approach based on average values for analytical study. They derived closed-form approximations for the collision probability and maximum throughput. Recently, there have been some studies showing that the system performance of the earlier WLAN design based on the collision channel (i.e., packets collide when more than one node transmit) is not optimal and can be enhanced with the Multipacket reception (MPR) capability [9][10]. The system performance of WLAN can also be improved by utilizing multi-user diversity. The readers are referred to [11] and the references therein for this issue**.**

Consider a simple reservation-based random access network with the request-to-send (RTS)/clear-to-send (CTS) handshake mechanism which was introduced to solve s the hidden terminal problem. If a node's RTS packet is successfully received by the BS, the BS will respond with a CTS packet granting the use of the channel only to this node for a reserved period of time (requested in the RTS packet) to avoid collision of data packets.

The Network Model

Consider a wireless network where n nodes transmit data to a common BS over a shared channel. Time is slotted. Nodes intending to send data initiate transmission by sending an RTS packet to the BS attempting to reserve the channel for a number of the following slots specified in the RTS packet. If an RTS packet is successfully received by the BS, the BS will respond with a CTS packet granting the use of the channel to the corresponding node for the duration requested, and informing the other nodes not to transmit in the reserved time slots. Let the total duration of this two-way handshake be T0 slots. If no node is granted the permission to send data, the two-way handshake is repeated for the next T0 slots. If node i is granted the permission, it can send its data without the interruption from the other nodes for a duration of Ti slots, where Ti is specified in the RTS packet sent by node i. The transmission power is PT for all nodes, for the RTS as well as the data packets. Without loss of generality, the throughput is measured in the number of successfully received data packets per

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slot, with the assumption that each data packet occupies one slot and contains the same amount of data. Independent Rayleigh fading channels between nodes and the BS are assumed. The period of exchanging RTS and CTS is called the handshake phase, and the period of data transmission is called the transmission phase. In general, the RTS packets from different nodes will not be perfectly time- aligned when they arrive at the BS. We assume that the time misalignment between RTS packets is negligible for the simplicity of the interference expression. The reservation-based random access model with the RTS/CTS handshake mechanism.. The request probability vector p =(p1,...,pn) determines the average throughput and power consumption of each node.

Reception model: In each handshake phase, the BS can successfully receive the RTS packet with SINR larger than the capture ratio b, and grant the permission to the corresponding node. We assume that b>1 (which is common for most systems except the spread spectrum systems), so at most one node is granted the permission.

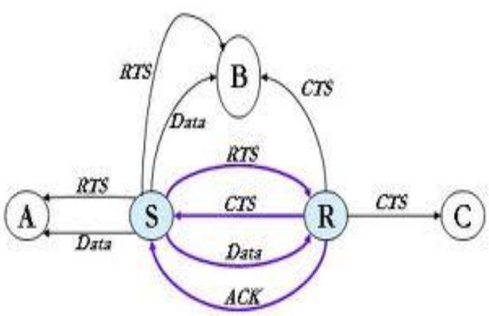

Fig. 1 Illustration of the reservation-based random access model by the RTS/CTS handshake mechanism

In a given handshake phase, the SINR of node i's RTS packet is given by

SINR = Bi|hi|Pt / N0 +j=i Bj|hj|PT

Where Bi is a binary indicator which is 1 if node i sends an RTS in that handshake phase, and 0 otherwise. N0 is the power of the additive noise at the BS, hi is the channel gain between node i and the BS. We assume that |hi|2, i =1... n, are independent, exponentially distributed random variables with mean one. When s nodes simultaneously transmit RTS packets to the BS, the probability of data transmission granted to a particular node.

Proposition 1: Assuming that the capture ratio is b, and there are n nodes in the network having the request probability vector p =(p1,...,pn), then in a handshake phase, node i is granted data transmission with probability Gi(p1,...,pn) ≡ Pr (BS grants node i data transmission)

≡ e−b N0 PT pi ∏ j=i1− bpj 1+b.

Proposition 2: The average throughput of node i is given by

λi =Pi (Ti)GiTi T0 /T0 ∑GjTj

Where Gi = e−b N0 PT pi J =i (1− bpj 1+b), Ps i (Ti) is the average frame success rate of node i when the data transmission period is Ti slots, and we have used j to denote n j=1 for simplicity. Let Si (p) denote the normalized average transmission power consumption of node i (normalized by the transmission power PT). Then Si (p) is equal to the fraction of time in which node i transmits either RTS or data packets. In the sequel, we will simply call Si(p) the average transmission power consumption of node i for brevity. By defining T0 <T 0 as the actual duration of an RTS packet, the following proposition can be easily obtained from Proposition 2

Proposition 3: The (normalized) average transmission power consumption of node i is given by Si (p) =pi GiTi T0 +j GjTj, (5) where T0 <T 0 is the actual duration of an RTS packet. Remark: With or without sending an RTS packet, each node always needs to receive the CTS packet in the handshake phase to perform virtual carrier sensing (i.e., to know the length of the following transmission phase and whether it can transmit or not). Let PR be the average power consumption when a node is in the receiving mode. The average power consumption for each node due to receiving CTS packets is

PR (T0− T0) /T0∑jGjTj

Analysis of the Network

A. Throughput Region

Definition 1: A throughput vector (λ1... λn) is achievable if there is a solution p = (p1... pn) to (9). The union set of all achievable throughput vectors is called the throughput region, denoted by Ω (T1...TN).

Proposition 4: Ω(T1,...,Tn) Ω(T 1,...,T n) if T i ≥ Ti,

.Proof: Assume (λ1,...,λn) Ω(T1,...,Tn), i.e., there is a request probability vector (p(0) 1 ,...,p(0) n)

We will start from the request probability vector (p(0) 1 ,...,p(0) n), and successively update the request probability vector to (p 1,...,p n) such that T0 λi T i(1−λt) = p i j=i1− bp j 1+b, i. (10) Note that λi = λi Ps i (Ti) , and Ps i (T i) ≥ Ps i (Ti) when T i ≥ Ti. If we choose (λ 1... λ n) such that λi = λi Ps i (Ti) = λ i Ps i (T i), then we will have λ i ≥ λi. If a solution (p 1... p n) to (10) exists, we can conclude that (λ 1... λ n) Ω (T1... TN). Since the average through- put λi is increasing in pi, it can be easily proved that (λ1... λn) Ω (T 1... TN). We now prove (10). Assume that Ti <T i for some i (otherwise, we are done since Ti = T i for all i).

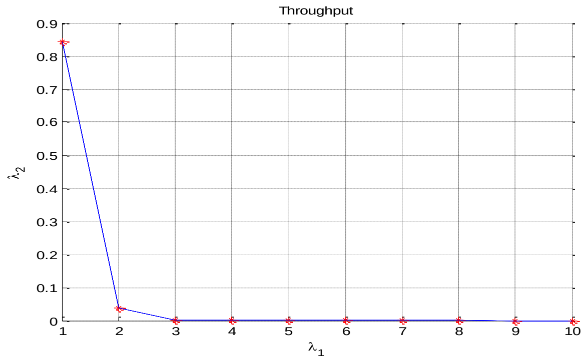

Fig. 2 The throughput region of a two-node network. The solid line is the analytical result and the asterisks are the simulation results.

B. Power Consumption

The following proposition gives the average power consumption at an operating point p for an achievable throughput vector (λ1… λn)

Proposition 5: The average transmission power consumption of node i at an operating point popt =(p1,...,pn) for the achievable throughput vector (λ1,...,λn) is given by Sip opt= λi + T0 (1−λt)pi, where T0 <T 0 is the actual duration of an RTS packet, λi = λi Ps i (Ti) , and λt =i λi. Proof: In each time slot, the channel is in either the handshake phase or the transmission phase. Hence, for the achievable throughput vector (λ1… λn), the fraction of time slots node i transmits data equals to λi (since the average frame success rate is Ps i (Ti)), and the RTS/CTS handshake phase occupies a fraction 1 λt of the total time slots. With node i's request probability pi, the fraction of time in which node i transmits RTS packets is (1 − λt) pi T0. The proposition follows since the average transmission power consumption equals to the fraction of time node i transmits RTS or data packets. Remark: It follows from the above proof that the average power consumption of node i due to receiving the CTS packet is 1−T0. Finally, we relate the total average transmission power consumption to an achievable throughput vector at the optimal operating point by the following proposition: Proposition 6: The maximum total average transmission power consumption Si (pop) over the throughput region Ω (T1,..., Tn) at the optimal operating point is equal to that over the region (p1,..., pn) i pi ≤ b+1 b, 0≤ pi ≤ 1. Proof: The result follows directly from Theorem 1 and its corollary. The following theorem gives an upper bound on the total average transmission power consumption when b>2, and all nodes use the same data transmission period.1 Theorem 2: Assuming that the capture ratio b>2 and all nodes use the same data transmission period MT0 and the same channel code, then for any (λ1,..., λn) ∈ Ω (MT0,..., MT0), the total average transmission power consumption i Si (popt) at the optimal operating point is upper bounded. In this case, let the maximum of the total average transmission power consumption i Si (pop) at the optimal operating point maximized over Ω (T1... TN) be Si.

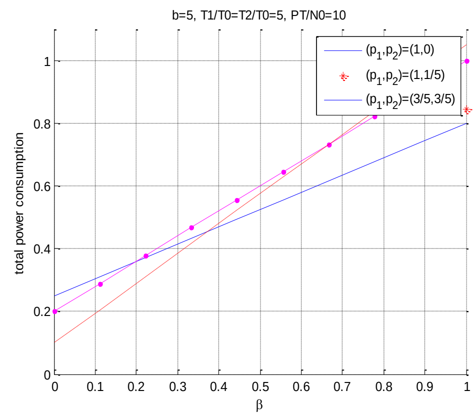

Fig. 3 The upper bound of the total average transmission powerconsumption of a two-node network with the capture ratio b =5 , Ps 1 (T1)= Ps 2 (T2)=1 , T1/T0 = T2/T0 =5, and PT/N0 = 10. The upper bound is achieved by one of the three request probability vectors (p1,p2) ∈ {(1, 0),(1,1/5), (3/5,3/5)}

Note that the right-hand side of the inequality equals to the maximum total average transmission power consumption at the optimal operating point of the case when all nodes use the same data transmission period mT0. By proposition 2, the first two inequalities in (15) can be obtained. When βb+1 b ≥1, both case (i) and case (ii) can happen. If β(i pi) ≤ 1 (i.e., case (i)), we know from the second inequality of (15) and the proof of Theorem 2 that i Si(popt) ≤ mΨb,n+β b+1 b m Ψb,n+1 ≤ mΨb ,n+β b+1 b Ψb,n+1 ≤ mΓ(n)+β b+1 b mΓ(n)+1 .

In the case when β(b+1 b) ≥ 1 and β(i pi) ≥ 1, again, let the maximum of the total average transmission power consumption i Si(popt) at the optimal operating point maximized over Ω(T1,...,Tn) be S. ByProposition 6, we have S ≤ max {(p1,...,pn):

β(i pi)+mj Gj 1+mj Gj . The right-hand side of the inequality equals to the maximum total average transmission power consumption at the optimal operating point of the case when all nodes use the same data transmission period mT0. By proposition 2 and together with the above result for the β (b + 1 b) ≥ 1 and β (I pi) ≤ 1 case, the last inequality in (15) can be obtained.

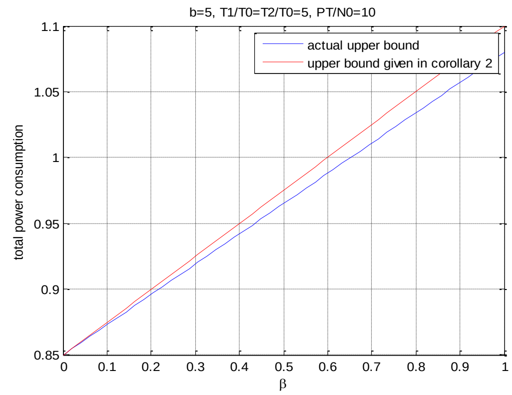

Fig. 4 Actual upper bound of the total average transmission power consumption, obtained by exhaustive search, and the upper bound given in Corollary 2 for a two-user network. The capture ratio b =5 , Ps 1 (T1)=Ps 2(T2)=1 , T1/T0 =3 , T2/T0 = 10, and PT /N0 = 10

Fig. 4 shows the actual upper bound of the total aver- age transmission power consumption, obtained by exhaustive search, and the upper bound given in Corollary 2 for a two- node network with unequal data transmission periods, where the capture ratio b =5 , Ps 1(T1)=Ps 2 (T2)=1 , T1/T0 =3 , T2/T0 = 10, and PT /N0 = 10. It can be seen that the bound is tight except when the RTS fraction β is large and the upper bound in (15) assumes the minimum Ti which increases the portion of time occupied by the handshake phase that has a high total transmission power consumption β(i pi).

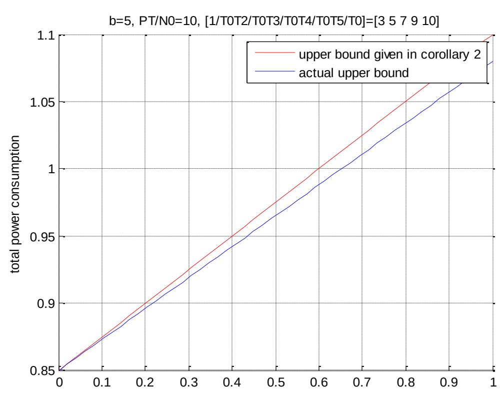

Fig. 5. Actual upper bound of the total average transmission power consumption, obtained by exhaustive search, and the upper bound given in Corollary 2 for a five-user network. The capture ratio b =5 , Ps i (Ti)=1 ,∀i,T 1/T0 =3 , T2/T0 =5 , T3/T0 =7 , T4/T0 =9 , T5/T0 = 10, and PT /N0 = 1

Conclusion

The throughput region and power consumption of a reservation-based random access network using the RTS/CTS handshake and provided an upper bound on the total power consumption over the throughput region at the optimal operating point. Specifically, the upper bound is satisfied by one of three points in the throughput region depending on the RTS fraction when the lengths of the data transmission periods for all nodes are equal. Extending the analysis to ad hoc networks is a challenging direction for future work.

Appendix

Proof of Theorem 1

Let α = b 1+b and λi = T0λi Ps i (Ti) Ti (1−λt), both being constants determined by the system parameters. To show that the system of equations in (9) have at most two solutions is equivalent to showing that there are at most two solutions of (p1,...,pn) satisfying λi = pi j=i (1−αpj), ∀i. (18) In addition, we need to show that if a solution exists, there is exactly one solution with i pi ≤ b+1 b . Without loss of generality, assume λi = max j{ λi} and minj{ λi} > 0 (note: the node with throughput 0 transmits RTS packets with probability 0, and can be excluded without affecting the proof).

Proof of Theorem 2

For the case n =1, the average power consumption S1 (p1) can be obtained by using (3) and (5). And it is straightforward to see that the maximum of S1 (p1) occurs when p1 =1. We will prove for the n ≥ 2 case in the following. By (7) and (9), we have the following relation when data transmission periods Ti = MT0 for all i Gi = pi j=i1− bpj 1 +b, ∀i, where Gi = λi b N0 PT M (1− λt) = Gieb N0 PT is defined to make the following proof concise. We first give some lemmas required to complete the proof. Lemma 1: Given fixed n i=1 pi = C with 0 ≤ pi ≤ 1 and C ≤ b+1 b , then the minimum of□n i=1 ˆ Gi can be achieved by (p∗ 1,...,p∗ n)=(C n ,...,C n) and the maximum of n i=1 Gi can be achieved by one of the following points 1) when C ≤ 1: (p∗ 1,...,p∗ n) ∈{ (C,0,...,0) and its permutations} 2) when C ≥ 1: (p∗ 1,...,p∗ n) ∈{ (1,C−1,0,...,0),(1 , C−1 2 , C−1 2 ,0,...,0),..., (1, C−1 n−1 ,...,C−1 n−1), and their permutations} For the maximum of n i=1 Gi, we know that it must occur on the boundary of the region {(p1,...,pn):n i=1 pi = C,0 ≤ pi ≤ 1} because there is only one critical point and the point is a minimum. Since the problem is symmetric with respect to the nodes, in the following, we will only consider the representative solutions of (p∗ 1... p∗ n). It is straightforward to see that their permutations are also solutions.

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