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

\[ \text{SINR} = \frac{B_i h_i^2 P_t}{N_0 + j\lambda h_i^2 P_t} \]

Where \( B_i \) is a binary indicator which is 1 if node i sends an RTS in that handshake phase, and 0 otherwise. \( N_0 \) is the power of the additive noise at the BS, \( h_i \) is the channel gain between node i and the BS. We assume that \( |h_i|^2, i = 1 \ldots n \) 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 is

\[ \text{Proposition 1: Assuming that the capture ratio is } b, \text{ and there are } n \text{ nodes in the network having the request probability vector } p = (p_1 \ldots p_n), \text{ then in a handshake phase, node } i \text{ is granted data transmission with probability } G_i = e^{-b N_0 P_t / \sum_j i=1 \lambda j P_t} \]

\[ G_i = e^{-b N_0 P_t / \sum_j i=1 \lambda j P_t} \]

where \( \lambda_j = \frac{P_i (T_i) G_j T_j}{T_0 \sum_j G_j T_j} \) and \( T_0 \) is the actual duration of an RTS packet.

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 \( p = (p_1 \ldots p_n) \) determines the average throughput and power consumption of each node.

**Analysis of the Network**

**A. Throughput Region**

**Definition 1:** A throughput vector \( (\lambda_1 \ldots \lambda_n) \) is achievable if there is a solution \( p = (p_1 \ldots p_n) \) to (9). The union set of all achievable throughput vectors is called the throughput region, denoted by \( \Omega(T[1 \ldots T_n]) \).

**Proposition 4:** \( \Omega(T[1 \ldots T_n]) = \Omega(T_1 \ldots T_n) \)

**Proof:** Assume \( (\lambda_1 \ldots \lambda_n) \) are arbitrary, i.e., there is a request probability vector \( (p[0] \ldots p[n]) \)

We will start from the request probability vector \( (p[0] \ldots p[n]) \), and successively update the request probability vector to \( (p_1 \ldots p_n) \) such that \( T_0 \lambda_i T_i = \sum_j i=1 \lambda_j P_j T_j \).

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

\[ \lambda_i = \frac{P_i (T_i) G_i T_i}{T_0 \sum_j G_j T_j} \]

where \( G_i = e^{-b N_0 P_t / \sum_j i=1 \lambda j P_t} \) and \( T_0 \) 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 \( P_r \) 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

\[ P_r (T_0 - T_0) / T_0 \sum_j G_j T_j \]
transmission period. Theorem 2: Assuming that the capture ratio \( b > 2 \) and all nodes use the same data transmission period \( M T_0 \) and the same channel code, then for any \((\lambda_1,...,\lambda_n) \in \Omega \) \((M T_0,...,M T_0)\), the total average transmission power consumption \( i \) \( S_i \) (pop) at the optimal operating point is upper bounded. In this case, let the maximum of the total average transmission power consumption \( i \) \( S_i \) (pop) at the optimal operating point maximized over \( \Omega \) \((T_1,...,T_N)\) be \( S_i \).

B. Power Consumption

The following proposition gives the average power consumption at an operating point \( p \) for an achievable throughput vector \((\lambda_1,...,\lambda_n)\)

Proposition 5: The average transmission power consumption of node \( i \) at an operating point \( p_{\text{opt}} \) \(= (p_1,...,p_n) \) for the achievable throughput vector \((\lambda_1,...,\lambda_n)\) is given by \( S_i = \lambda_i + T_0 (1-\lambda_t) p_i \), where \( T_0 < T \) is the actual duration of an RTS packet, \( \lambda_i = \lambda_i P_s i (T_i) \), and \( \lambda_t = \lambda_t P_s i (T_i) \). Proof: In each time slot, the channel is in either the handshake phase or the transmission phase. Hence, for the achievable throughput vector \((\lambda_1,...,\lambda_n)\), the fraction of time slots node \( i \) transmits data equals to \( \lambda_t \) (since the average frame success rate is \( P_s i (T_i) \)), and the RTS/CTS handshake phase occupies a fraction 1 - \( \lambda_t \) of the total time slots. With node \( i \)'s request probability \( p_i \), the fraction of time in which node \( i \) transmits RTS packets is \( (1-\lambda_t) p_i T_0 \). 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 \( 1-T_0 \). 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 \( S_i \) (pop) over the throughput region \( \Omega \) \((T_1,...,T_n)\) at the optimal operating point is equal to that over the region \( (p_1,...,p_n) \) \( i \) \( p_i \leq b+1 \) \( b \), \( 0 \leq p_i \leq 1 \). 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.

\( \beta(i p_i) + m \) \( G_j + 1 + m \) \( G_j \). 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 $\beta (b + 1) \geq 1$ and $\beta (1 pi) \leq 1$ 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 $b = 5$, $\beta (1 pi) = 1$, $T_1/T_0 = 3$, $T_2/T_0 = 10$, and $PT /N_0 = 10$

Fig. 4 shows the 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 with unequal data transmission periods, where the capture ratio $b = 5$, $\beta (1 pi) = 2$, $T_1/T_0 = 3$, $T_2/T_0 = 10$, and $PT /N_0 = 10$. It can be seen that the bound is tight except when the RTS fraction $\beta$ is large and the upper bound in (15) assumes the minimum $T_i$ which increases the portion of time occupied by the handshake phase that has a high total transmission power consumption $\beta (i pi)$.

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 $\alpha = b + 1 + b$ and $\alpha = T_0 i Ps / Ti (1 - \lambda i Ti)$, 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 $(pi 1, ..., pn)$ satisfying $\lambda i = pi j = 1 - \alpha pi j$. In addition, we need to show that if a solution exists, there is exactly one solution with $1 pi \leq b + 1$. Without loss of generality, assume $\lambda i = \max j \{ \lambda j \}$ and $\min j \{ \lambda j \} > 0$ (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 $S_1 (pi 1)$ can be obtained by using (3) and (5). And it is straightforward to see that the maximum of $S_1 (pi 1)$ occurs when $pi 1 = 1$. We will prove for the $n \geq 2$ case in the following. By (7) and (9), we have the following relation when data transmission periods $Ti = MT_0$ for all $i Gi = pi j i = b - 1$ and $\forall i$, where $Gi = \lambda i b N_0 PT M (1 - \lambda i Pt) = Gieb N_0 PT$ 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 $0 \leq pi \leq 1$ and $C \leq b + 1 b$, then the minimum of $\forall i = 1$ $Gi$ 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 $C \leq 1$: $(p* 1, ..., p* n) \in \{ (C, 0, ..., 0) \}$ and its permutations 2) when $C > 1$: $(p* 1, ..., p* n) \in \{ (1, C - 1, 0, ..., 0), (1, C - 1, 2, C - 1, 2, 0, ..., 0), ..., (1, C - 1, n - 1, ..., C - 1, n - 1, )$, and their permutations) For the maximum of $n i = 1$ $Gi$, we know that it must occur on the boundary of the region $(pi 1, ..., pn) = n i = 1 pi = C, 0 \leq pi \leq 1$ 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 \((p^* 1 \ldots p^* n)\). It is straightforward to see that their permutations are also solutions.

References
