A Study on Throughput of Slotted 802.15.4 Networks Based on Hidden Terminals (Postprint)

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Date: 2018-06-19T00:00:00+00:00

Abstract

To improve the throughput performance of 802.15.4 networks, an improved node state transition process was designed, and a node channel access model considering hidden terminal problems and retransmissions was proposed and analyzed. Based on the calculation results and channel state model analysis, the data collision probability, packet loss rate, and network throughput considering hidden terminal problems were derived. Finally, the effects of packet arrival rate, backoff exponent, and hidden terminals on network throughput performance were investigated. Experimental results demonstrate that the model accurately describes the node channel access process and enables precise dynamic analysis of network throughput. Compared with 802.15.4 networks without a retransmission mechanism, the network throughput increased by approximately 83.9%. Furthermore, compared with the partial conditional sleep method, the network throughput increased by an average of 13.3%, indicating that the proposed model can effectively enhance network throughput performance.

Full Text

Abstract

To improve the throughput performance of 802.15.4 networks, this paper designs an improved node state transition process and proposes a node channel access model that considers both the hidden terminal problem and retransmission, followed by analytical calculations of the model. Based on the computational results and channel state model analysis, we derive the data collision probability, packet loss rate, and network throughput while accounting for hidden terminal issues. Finally, we investigate the impact of packet arrival rate, backoff exponent, and hidden terminals on network throughput performance.

Experimental results demonstrate that the model accurately describes the node channel access process and enables precise dynamic analysis of network throughput. Compared with 802.15.4 networks without retransmission mechanisms, the network throughput increases by approximately 83.9%. When compared with partial conditional sleep methods, the network throughput improves by an average of 13.3%, indicating that the proposed model can effectively enhance network throughput performance.

Keywords: hidden terminal; throughput; channel access; packet arrival rate; modeling

0 Introduction

Wireless sensor networks have been widely deployed in most distributed sensing applications, with the majority constructed based on the IEEE 802.15.4 protocol. Consequently, performance research and optimization of the 802.15.4 standard protocol have become critical issues, with mathematical modeling emerging as an important approach for protocol analysis and optimization.

Literature [1] proposed a simple protocol model based on a backoff non-persistent CSMA algorithm with theoretical analysis. Literature [2] designed a model without considering node sleep states, and its calculations for average service time and throughput were relatively cumbersome. Literature [3] designed a channel contention method considering node sleep states, but its description of the node backoff process was imprecise, and its modeling of non-saturated load lacked depth. Literature [4] modeled unsaturated load using queuing theory, but the described dynamic state transition process of nodes did not match the actual operational characteristics of 802.15.4 networks. Literature [5] modeled and analyzed the contention access period of the 802.15.4 MAC layer protocol, proposed an improved collision avoidance method, and analyzed throughput performance, but did not consider the hidden terminal phenomenon. Literature [6] proposed a single-hop communication IEEE 802.15.4 MAC model based on hidden terminals and analyzed certain network performance metrics. Literature [7] modeled the MAC layer channel for standard star-topology 802.15.4 networks with node grouping, analyzing the impact of frame length and data arrival rate on throughput under hidden terminal conditions, but without optimizing or improving the MAC layer protocol. Literature [8] designed a priority-based 802.15.4 MAC model but did not model channel access delay performance. Literature [9] proposed a distributed adaptive algorithm for delay and energy consumption performance optimization, modeling the average delay performance for received data but without analyzing channel contention delay performance.

Existing performance modeling work on the 802.15.4 MAC protocol is highly significant, yet the relevant models and methods require further improvement. Among the primary performance metrics of wireless sensor networks, throughput represents one of the main design objectives for the 802.15.4 network MAC layer protocol. Current research on network throughput generally performs throughput analysis based on the standard 802.15.4 protocol or fails to consider the impact of hidden terminals on network throughput performance. Building upon MAC layer mechanism optimization for the 802.15.4 protocol, this paper mathematically models the slotted 802.15.4 MAC layer protocol based on retransmission mechanisms and hidden terminals, investigates the influence of protocol parameters on network throughput, and explores effective methods for improving network throughput performance.

1 Throughput Performance Based on Hidden Terminals

In wireless sensor networks employing the 802.15.4 protocol, nodes compete for the MAC layer channel through time-sharing methods, making hidden terminals inevitable in the network. The hidden terminal problem significantly impacts data packet collisions, thereby affecting primary network and node performance.

To effectively improve 802.15.4 network throughput performance, addressing data packet collision issues in the MAC layer constitutes an important approach. Data collisions in the 802.15.4 MAC layer primarily result from two causes: channel access conflicts and collisions caused by hidden terminals. Therefore, analyzing the impact of hidden terminals on network throughput performance and improving channel contention access mechanisms hold significant importance for 802.15.4 protocol applications.

This paper conducts an in-depth analysis of key 802.15.4 protocol algorithms considering hidden terminals, proposes an optimized node media access control mechanism, establishes mathematical models for its key algorithms and throughput, analyzes the impact of network and protocol parameters on throughput through experiments, and investigates effective methods for improving network throughput performance.

2.1 Model and Derivation

This paper analyzes the working mechanism of the IEEE 802.15.4 network MAC layer protocol supporting beacon-enabled mode, where nodes compete for the MAC layer channel using the slotted CSMA/CA algorithm. Through analysis of sensor node state transitions, we design an 802.15.4 MAC layer channel contention mechanism that better aligns with the actual operational characteristics of wireless sensor networks, thereby optimizing node throughput performance.

Based on the features of non-saturated load and small data volume in wireless sensor networks, we enable the superframe inactive period and exclude the contention-free access period within the superframe active period. The node operating superframe cycle consists of both inactive and active periods. During node operation, possible states include active period states and inactive period states. According to the slotted CSMA/CA algorithm flow, active period states can be divided into four possible states: listening, idle, channel detection, and transmission. Both idle and listening states occur when nodes are in backoff waiting periods. Listening occurs when nodes receive broadcast data not intended for them during backoff. The node state transition diagram is shown in [Figure 1: see original paper].

Network nodes compete for channels according to the 802.15.4 media access control protocol. Their operational characteristics constitute a discrete random dynamic process, and the actual operational features of nodes align with the characteristics of Markov chain models. Therefore, we use a two-dimensional Markov chain model to simulate the node channel access process, as shown in the model [11~13] in [Figure 2: see original paper].

Based on the design of the node operating superframe cycle described above, the states in the channel access model are data packet transmission state T, backoff state G (including listening and idle states), channel detection state H, and inactive state. The single-step transition probabilities from transmission state, inactive state, and backoff state to inactive state are c1, c2, and c3, respectively. After completing a backoff period, the probabilities of node failure in two consecutive channel detection attempts are x and y, respectively. The maximum number of backoff rounds in a channel contention process is NB, where the duration of the ith backoff round is W02i, W0 is 2minBE, representing the initial backoff time value, and minBE is the protocol parameter representing the minimum backoff exponent value.

Additionally, this model considers the data packet retransmission mechanism. Once a data packet transmission collides, the node will retransmit the packet, reattempting transmission according to the channel access mechanism. j represents the probability of data transmission collision.

According to the characteristics of the Markov chain model, the proposed model has a stationary distribution. The main single-step state transition probabilities and steady-state probabilities of the node are:

发 送 信 道 检 测 非 活 跃 退 避 成 功 失 败 超 过 退 避 次 数 极 值 有 数 据 发 送 超 过 重 传 次 数 限 制 无 冲 突 冲 突 重 传 TI

2.2 Throughput

Based on the node channel access model and following the methodology in literature [10], we use a Markov chain model to mathematically model the network channel operation process. The MAC layer channel throughput in 802.15.4 networks is defined as the ratio of time consumed for successfully transmitting a unit data packet to the total channel time expended. The channel state transition process is shown in [Figure 3: see original paper].

According to the channel model, the working states of the channel during data transmission are divided into A, (A,A), Fa, and Tr. Where: A represents the channel idle state; (A,A) represents the channel being idle in two consecutive slots, with occurrence probability [MATH_EXPRESSION]; Tr represents the data transmission state, with transition probability from (A,A) to Tr state; Fa represents the channel collision state, with transition probability from (A,A) to Fa being 1-e-f.

Additionally, based on the model, we can derive the steady-state probability equations for channel states, thereby deriving the throughput expression for 802.15.4 networks as:

Tho=Lf/(1+(1+L)(1-e))

Where: Regarding the causes of network packet loss, this paper primarily considers packet loss due to node channel contention failure and data collisions caused by hidden terminals. The collision probability due to node channel contention failure can be expressed as:

P1 = 1-(1-)^(n-1)

Where: is the steady-state probability of a node being in data transmission state; n is the total number of network nodes.

Considering the existence of hidden terminal nodes in the network, the data transmission conflicts they cause exacerbate packet loss. Therefore, network throughput considering hidden terminal phenomena is expressed as:

Tho=Lf(1-p1)(1-p2)/(1+(1+L)(1-e))

3 Throughput Performance Analysis

We investigate the throughput performance of 802.15.4 networks based on hidden terminal phenomena through experiments. The experimental environment consists of a single-hop star network topology where nodes are within effective communication range. The load arriving at nodes is non-saturated, assuming a data packet arrival rate ranging from 0 to 20 packets/second and a total node count N within 25. The maximum number of retransmissions after failed data transmission is 3. In the node superframe cycle, the minimum beacon order SO is 6 and the superframe order BO is 4. The maximum node backoff rounds NB is 5, with a minimum backoff exponent of 2. We conduct experimental studies on network throughput performance below.

[Figure 4: see original paper] describes the relationship between throughput and when considering hidden terminal phenomena, showing how protocol parameters BE and NB affect channel throughput as network load varies. Clearly, network throughput exhibits an initial increase followed by a decrease as increases. When is small, throughput increases with due to more transmission tasks. At this stage, smaller minimum backoff exponent BE values result in lower network throughput because the extended node backoff period causes nodes to spend more time in backoff waiting, consequently reducing throughput. After reaching maximum throughput, as continues to increase, network throughput gradually decreases because increased data transmission tasks lead to more transmission conflicts due to hidden terminals and channel contention. At this point, larger minimum BE values result in lower network throughput because larger BE values increase the node backoff window. Under non-saturated load conditions, nodes experience longer equivalent channel waiting times, reducing the probability of data transmission and decreasing network throughput.

[Figure 4: see original paper] also reflects the impact of the maximum backoff count NB on throughput. The results show that NB has relatively little effect on network throughput, with smaller NB values yielding better throughput performance. Once the network load becomes saturated, network throughput decreases further and tends toward saturation. This occurs because after channel throughput peaks, the network enters a saturated state where increasing load only intensifies channel conflicts, causing throughput to continuously decline.

[Figure 5: see original paper] illustrates the impact of hidden terminal count on throughput. Assuming the number of hidden terminals is Nh, following the derivation methodology in literature [14,15], the data packet collision probability caused by hidden terminals is expressed as:

$$p2 = 1 - (1 - psend)^{((Nh * Th)/Ds)}$$

Where: Th is the data conflict probability interval caused by hidden terminals, expressed as (-z, z+SIFS+B), with z being a data packet transmission time, B the MAC layer channel propagation delay, and SIFS the minimum inter-packet spacing; Ds is the length of a time slot.

Based on the analysis of data collision probability, the MAC layer packet loss rate in networks without retransmission mechanisms is expressed as:

$$p\_no\_retransmission = 1 - (1-p1)(1-p2)$$

Additionally, in networks with retransmission mechanisms, assuming a maximum retransmission count m, the network packet loss rate is expressed as:

$$p\_with\_retransmission = p^{(m+1)}$$

Based on the derivation of packet loss rate and throughput models, network throughput considering hidden terminals is expressed as:

$$Tho = Lf/(1+(1+L)(1-e))$$

As the number of hidden terminals in the network increases, throughput decreases substantially, indicating that hidden terminal count significantly impacts throughput. Moreover, larger minimum backoff exponent BE values result in lower throughput. This occurs because with the same number of hidden terminals, nodes spend more time in the backoff period, thereby reducing the probability of channel detection and data transmission states and consequently decreasing throughput.

[Figure 6: see original paper] compares throughput with and without considering hidden terminals. As increases, network throughput without considering hidden terminals is significantly higher, demonstrating that hidden terminals have a clear negative impact on network throughput performance.

[Figure 7: see original paper] compares the throughput of our model with that of literature [10]. Our model considers the single-step probability c3 of nodes transitioning from backoff state to inactive state, where nodes end channel contention and enter inactive state upon discovering insufficient remaining superframe time for two channel detections and one data frame transmission after completing the current backoff period, thereby waiting for the next superframe to recontend for the channel. The purpose of considering c3 is to reduce the probability of data transmission failure. Experimental results show that our model' s throughput improves by 13.3% compared to literature [10]' s model.

[Figure 8: see original paper] shows experimental results on the relationship between retransmission mechanisms and network throughput. The figure demonstrates that after incorporating the retransmission mechanism, our model increases network throughput by approximately 83.9% compared to 802.15.4 networks without retransmission mechanisms. This is because in protocols without retransmission mechanisms, nodes enter inactive state once data transmission collisions occur. Our model incorporates retransmission, allowing nodes to recompete for the channel according to the slotted CSMA/CA algorithm after data collisions, thereby effectively increasing opportunities for data transmission, reducing network packet loss rate, and improving network throughput performance.

[Figure 9: see original paper] presents experimental results on the relationship between throughput and node count. As the number of nodes increases, throughput gradually rises due to more data transmissions in the channel. Under the same network scale, the hidden terminal problem has relatively less impact on network throughput. Additionally, with the same node count, larger minBE values yield better network throughput performance. This is because under fixed network scale conditions, longer node backoff periods reduce channel conflicts, increase the probability of successful data transmission, and consequently improve throughput.

Through experimental studies on network throughput, data collision probability, and packet loss rate based on the improved model, the proposed model effectively reflects the throughput performance of slotted 802.15.4 networks based on hidden terminals. Our model enables more precise investigation of the impact of protocol parameter configuration and hidden terminals on media access control layer data packet transmission, providing theoretical support for the practical application of the 802.15.4 protocol in wireless sensor networks.

4 Conclusion

To address throughput performance optimization in 802.15.4 networks with hidden terminals, this paper proposes a node channel access model for the slotted CSMA/CA algorithm based on a retransmission mechanism. Combined with mathematical analysis and calculation of the channel state model, we analyze data collision and packet loss issues to derive a network throughput performance analysis model. Extensive experimental studies demonstrate that the proposed analytical model can effectively analyze network throughput performance, and optimal configuration of key protocol parameters can improve throughput performance to a certain extent. Future work will involve designing relevant protocol optimization strategies to establish analysis models that better reflect reality and make the protocol more suitable for practical application requirements.

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Note: Figure translations are in progress. See original paper for figures.