Markov Chain-Based Channel Access Mechanism for Packet Loss Prevention in 802.15.4 Networks (Postprint)

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Abstract

To reduce the packet loss rate of 802.15.4 MAC layer data frames, a channel contention mechanism model based on Markov chain is proposed upon analyzing the causes of packet loss. Through mathematical derivation of the steady-state probabilities of network transmission, backoff, and channel detection states, analytical expressions for channel collision and data frame packet loss rate are investigated; finally, the impacts of parameters including packet arrival rate, number of nodes, bit error rate, backoff exponent, and number of backoff waiting times on collision probability and packet loss rate are studied. Experimental results demonstrate that, compared with 802.15.4 networks without node sleep states, the node packet loss rate is reduced by an average of 23.7%, the model accurately describes the proposed MAC layer channel access mechanism, reasonable network parameter settings can optimize the data frame packet loss rate, and the research findings provide a reference for reliable transmission optimization in wireless sensor network applications.

Full Text

Preamble

Title: Research on Channel Access Mechanism for Anti-Packet-Loss in 802.15.4 Networks Based on Markov Chain

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Abstract: To reduce the packet loss rate of data frames in the 802.15.4 MAC layer, this paper proposes a channel competition mechanism model based on Markov chain by analyzing the causes of packet loss. Through mathematical derivation of the steady-state probabilities of network transmission, backoff, and channel detection states, the paper investigates analytical expressions for channel collision and data frame packet loss rates. Finally, it examines the influence of parameters including packet arrival rate, number of nodes, bit error rate, backoff exponent, and number of backoff attempts on collision probability and packet loss rate.

Experimental results show that, compared with 802.15.4 networks without node sleep states, the node packet loss rate is reduced by an average of 23.7%. The model accurately describes the proposed MAC layer channel access mechanism, and reasonable network parameter settings can optimize the data frame packet loss rate. The research findings provide a reference for reliable transmission optimization in wireless sensor network applications.

Keywords: 802.15.4 MAC; Markov chain; collision probability; packet loss rate

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0 Introduction

Wireless sensor networks are self-organizing networks with low-power, short-range communication capabilities. The IEEE 802.15.4 protocol, which serves as the media access control (MAC) layer standard for wireless sensor networks, is a low-cost, low-complexity, and low-power specification that defines both the MAC and PHY layer standards for such networks. Research on its MAC layer has attracted widespread attention in the industry, particularly the use of mathematical modeling methods such as Markov chains for protocol performance optimization, which has become a hot research topic.

Since nodes in the network use the time-sharing slotted CSMA/CA (carrier sense multiple access with collision avoidance) algorithm to compete for channel access, packet loss phenomena in the MAC layer have become one of the important issues that 802.15.4 networks need to address. Previous studies have several limitations: some have modeled the 802.15.4 protocol MAC layer channel access mechanism and investigated network performance metrics such as energy consumption and throughput, but without detailed description of the node backoff mechanism. Others have considered node idle states and modeled the channel competition mechanism, but did not account for node sleep states, lacking accuracy in protocol performance analysis. Some studies did not comprehensively analyze the superframe structure nor consider node sleep periods, resulting in cumbersome performance analysis of data frame average service time. While adaptive duty cycle mechanisms have been used to optimize network lifetime, they did not balance the impact of multiple protocol parameters. Research on packet loss rate performance of wireless LAN MAC layers under Rayleigh fading channels has analyzed the influence of packet length and modulation schemes on packet loss rate, but did not thoroughly study the impact of protocol parameters such as payload length, bit error rate, and backoff window on collision probability and packet loss rate. Nonlinear testing methods have revealed balanced relationships between data transmission rates and packet loss rates in wireless sensor networks under different experimental environments with obvious nonlinear characteristics, but such methods cannot provide accurate mathematical analysis of wireless sensor network MAC protocols. Markov modeling methods have been used to analyze the collision probability of 802.15.4 MAC layers in single-hop communication modes, but packet loss rate issues were not studied in detail.

Building upon the above research foundation, this paper analyzes the key algorithms of the 802.15.4 MAC protocol, accurately describes the various states of nodes during channel access and their characteristics, and proposes a Markov chain-based channel access mechanism model for the 802.15.4 protocol. Based on this model, node collision problems and packet loss performance are analyzed in detail.

The IEEE 802.15.4 protocol is primarily applied in environments with small data volumes and low rates, where networks generally operate under non-saturated load conditions. Based on this characteristic, the states of nodes that fail to compete for the channel can be appropriately adjusted to improve network collision and packet loss issues. This paper studies the 802.15.4 MAC layer protocol with beacon-enabled mode, where all nodes are synchronized with the coordinator through superframe timing. The superframe consists of an active period and a sleep period. The active period comprises beacon time and contention access period, while the contention access period consists of backoff period and data transmission period. All nodes compete for the channel according to the slotted CSMA/CA algorithm, thereby achieving time-sharing of the channel. Based on precise setting of the superframe structure, nodes can enter the sleep period under the following conditions: (a) after waiting for the maximum number of backoff attempts without successfully entering the data transmission period during the contention access period; (b) when the node load is empty during the contention access period; (c) after the arrival of superframe sleep period slots.

Assuming that the non-saturated load of all nodes in the 802.15.4 network follows a Poisson process with rate , and that the load arrival processes of each node are independent, the dynamic random process of all nodes accessing the channel according to the slotted CSMA/CA algorithm exactly matches the characteristics of discrete state space analysis objects in Markov chains. Therefore, Markov theory can be used to model the dynamic state change process of nodes in the channel, and the relevant performance of the 802.15.4 network MAC layer can be studied through this model, as shown in [Figure 1: see original paper].

In the model, A represents the state where a node checks the channel, S represents the state where a node successfully accesses the channel and sends data, and DO represents the sleep state of a node. Ri,k represents the waiting state of the k-th slot after the i-th channel access failure (i [0, NB], k [0, Wi-1]). NB (number of backoff) is the maximum number of backoff attempts. The initial waiting time W0 when a node first backs off is 2minBE, and the waiting time at the i-th backoff is Wi = W02i, where maxBE-minBE i maxBE. BE (backoff exponent) has maximum and minimum values represented by maxBE and minBE, respectively. s and t are the probabilities that a node fails to succeed after the two channel checks Ai,1 and Ai,2. g1 represents the probability that a node' s load is empty after completing one transmission, and g2 represents the probability that a node's load remains empty after waking from the sleep period. Based on the division of superframe periods and calculations from reference [1], g1 = e- Tservice and g2 = e- W0, where Tservice is the average packet service time.

1 Packet Loss Rate

Nodes in IEEE 802.15.4 networks use DC battery power, making energy consumption optimization an important research focus. Many factors contribute to network node energy consumption, such as packet loss, retransmission, and idle listening. Like most MAC layer protocols, data frame collisions severely affect overall system performance, potentially increasing node energy waste, reducing throughput, and increasing data frame packet loss rates. Therefore, reducing MAC layer data frame collisions and packet loss rates has become an important measure to improve protocol energy consumption performance. Compared with wired channels, wireless channels experience more severe packet loss, and collision is a very important factor causing packet loss. However, collision phenomena in IEEE 802.15.4 networks are unavoidable because the 802.15.4 MAC uses the CSMA/CA random access mechanism to compete for channel access. Nodes use a shared wireless channel and cannot listen to the channel while transmitting signals, resulting in data frame collisions. Generally, data frame collisions occur when two or more nodes simultaneously enter the channel monitoring state. After detecting the channel as idle through two CCA (clear channel assessment) checks, nodes begin transmitting data simultaneously. When multiple data frames arrive at the destination node, collisions will occur.

For the IEEE 802.15.4 protocol, this paper analyzes the influence of parameters PER, collision probability, bit error rate, number of nodes, minBE, and NB on packet loss rate. By optimizing the settings of key network parameters, collision probability can be reduced, thereby further reducing network packet loss rate and improving and balancing key network performance metrics.

Based on the above transition probabilities and steady-state probability formulas, the steady-state probability R0,0 of the initial backoff state can be analyzed as:

$$\pi_{R_{0,0}} = \frac{1}{[(1-s)(1-t)]/(1-g_1) + \sum_{i=0}^{m}\sum_{k=0}^{W_i-1}\pi_{R_{i,k}} + \sum_{i=0}^{m}\pi_{A_{i,1}} + \sum_{i=0}^{m}\pi_{A_{i,2}} + \pi_S + \pi_{DO}}$$

$$\times \frac{1}{[(1-s)(1-t)]/(1-g_1) + \sum_{i=0}^{m}\sum_{k=0}^{W_i-1}[(1-s)(1-t)]^i/(W_i) + \sum_{i=0}^{m}[(1-s)(1-t)]^i s + \sum_{i=0}^{m}[(1-}$$

$$+ \frac{1-g_1}{g_1} + \frac{1-g_2}{g_2} + L_D$$

Additionally, the total steady-state probability formulas for channel check state, data transmission state, and backoff state in the model are:

$$\pi_{A_{i,1}} = \frac{(1-s)(1-t)}{1-g_1}\pi_{R_{0,0}}, \quad (i \in [0,m])$$

$$\pi_{A_{i,2}} = \frac{(1-s)(1-t)}{1-g_1}\pi_{R_{0,0}}, \quad (i \in [0,m], k \in [0,1])$$

$$\pi_{R_{i,k}} = \frac{(1-s)(1-t)}{1-g_1}\pi_{R_{0,0}}, \quad (i \in [0,m], k \in [0,W_i-1])$$

$$\pi_S = \frac{(1-s)(1-t)}{1-g_1}\pi_{R_{0,0}}$$

$$\pi_{DO} = \frac{g_1}{1-g_1}\pi_{R_{0,0}} + \frac{g_2}{1-g_2}\pi_{R_{0,0}}$$

3 Packet Loss Rate Experiments

Based on the theoretical analysis of network data frame collisions and packet loss issues above, experiments are conducted to study the impact of 802.15.4 network protocol parameters on MAC layer data frame collision and packet loss performance, and to validate the proposed node state transition model.

The experimental parameters are set as follows: network node quantity N ranges from 5 to 60, beacon order (BO) value is 6, superframe order (SO) ranges from 4 to 5, backoff exponent (BE) value ranges from 2 to 5, number of backoff attempts (NB) ranges from 4 to 5, and data packet length L is 6 slots. The beacon interval (BI) value is 960×0.016×2BO, and the superframe active period is 960×0.016×2SO. The beacon frame reception time is Tb = 0.3 slot. One superframe slot width is 20 symbol periods, each symbol period is 0.016 ms, and one slot value in the superframe period is 0.32 ms. The following sections analyze the MAC layer data packet collision probability and data frame packet loss rate performance.

3.1 Collision Probability

According to the mathematical analysis and probability calculations from model [Figure 1: see original paper], the data frame collision probability of a single network node is analyzed. If two nodes simultaneously detect the channel as idle and then send data to the receiver, the collision probability at the receiver is expressed as: pC = 1 - (1 - r)N-1, where r is the probability of a node sending a data frame, and N is the number of nodes.

[Figure 2: see original paper] shows the trend of steady-state probability of node sending state. As the number of nodes increases, the probability of nodes sending data shows a decreasing trend. Moreover, the larger the backoff exponent (BE) value, the smaller the sending probability. This is because a larger initial BE value results in relatively longer initial backoff time, causing nodes to spend more time in the backoff state and reducing the probability of sending data frames.

[Figure 3: see original paper] illustrates the trend of collision probability after nodes send data. Clearly, as N gradually increases, the collision probability gradually increases and channel conflicts intensify. Protocol parameter BE has a significant impact on collision probability; under larger BE values, network collision probability is smaller. This is because the node' s initial backoff slot number is relatively large, placing more nodes in the backoff state and reducing the probability of attempting to detect the channel for data transmission, naturally decreasing the probability of conflict. Meanwhile, larger protocol parameter NB helps reduce channel conflicts and thus reduces MAC layer collisions, because increased backoff attempts extend node backoff waiting time, reducing collision phenomena to a certain extent.

From the above transition probabilities and steady-state probability formulas, the steady-state probability R0,0 of the initial backoff state can be derived. [Figure 4: see original paper] shows the trend of MAC layer collision probability varying with data packet arrival rate. Clearly, as non-saturated load gradually increases, collision probability gradually increases. The impact of NB and BE on collision probability is significant; smaller BE leads to larger collision probability, indicating that when the initial backoff exponent is small, nodes have shorter backoff time before detecting the channel, increasing the probability of detecting the channel as busy and intensifying MAC layer collisions.

Additionally, when network non-saturated load data traffic is small (< 71), smaller NB results in more severe collision probability. This is because with small NB, nodes have fewer backoff rounds, increasing the probability of attempting to compete for the channel and naturally increasing the probability of conflict. When non-saturated load is large (> 71), larger NB results in more severe collision probability. This is because after the load increases, increasing backoff attempts has limited effect on alleviating data frame collisions.

3.2 Packet Loss Rate

Based on the above analysis of collision probability, the MAC layer packet loss rate issue is analyzed below. Packet loss is primarily caused by channel bit errors and collisions. The probability P1 of data frame errors during channel transmission is: 1 - (1 - BER)LD, where LD is the data packet length (set to 400 bits). BER is the wireless network channel bit error rate, i.e., the probability of error occurring during transmission of 1-bit information. According to reference [3], the multipath fading characteristics of wireless sensor network channels are described through Rayleigh fading channels, where BER is related to path loss exponent and transmission distance. This paper sets BER values between 7×10-4 and 3×10-3. The packet loss rate without retransmission can be expressed as: pd = 1 - (1 - P1)(1 - pC).

[Figure 5: see original paper] shows the trend of data frame packet loss rate varying with the number of nodes. As the number of nodes increases, the data frame packet loss rate gradually increases. This is because with larger network scale, more nodes compete for MAC layer channel access, increasing the probability of node transmission failure. Additionally, smaller NB leads to larger data frame packet loss rate because reduced node backoff time intensifies channel conflict probability. Moreover, larger minimum backoff exponent (minBE) results in longer node backoff time, weakening channel conflicts to a certain extent and reducing data frame packet loss rate. [Figure 5: see original paper] reflects that in larger-scale networks, BE and NB have significant impact on packet loss rate.

[Figure 6: see original paper] demonstrates that as channel transmission conditions deteriorate, the data frame packet loss rate increases with the increase of packet error rate, reflecting that channel quality has a relatively large impact on the MAC layer. Additionally, larger NB results in smaller data frame packet loss rate because larger NB extends the waiting time before nodes monitor the channel, thereby reducing channel conflicts. Larger minimum backoff exponent (minBE) leads to longer node backoff waiting time, reducing data frame collisions to a certain extent and decreasing packet loss rate. [Figure 6: see original paper] reflects that under the same channel quality conditions, BE and NB have noticeable influence on packet loss rate.

[Figure 7: see original paper] shows the trend of data frame packet loss rate varying with data frame arrival rate. As gradually increases, the data frame packet loss rate slowly increases, reflecting that non-saturated load has relatively small impact on MAC layer packet loss rate when the load is small. Additionally, smaller number of backoff attempts (NB) leads to larger data frame packet loss rate because shorter backoff time before channel checking intensifies channel conflicts. Smaller minimum backoff exponent (minBE) results in larger variations in packet loss rate. [Figure 7: see original paper] reflects that under the same load conditions, BE has greater impact on packet loss rate than NB.

Through comparative analysis of protocol collision probability, packet loss rate, and parameters based on the model, the proposed model can effectively analyze the data frame transmission performance of the 802.15.4 protocol MAC layer in sleep mode. Moreover, the model enables more precise study of the impact of network parameter configuration on MAC layer data frame transmission, providing performance optimization references for practical applications of the 802.15.4 standard.

Experimental results also show that the packet loss rate of the model without node sleep in reference [1] is significantly higher. The superframe period mechanism with node sleep state reduces data frame packet loss rate by 23.7%, demonstrating that adding sleep states reduces MAC layer collision phenomena and significantly improves data transmission reliability.

4 Conclusion

Addressing the optimization of data frame packet loss in the 802.15.4 MAC layer, this paper focuses on analyzing data frame collision problems and their impact on MAC layer packet loss. Based on modeling and analysis of the MAC layer channel access mechanism, the steady-state probabilities of node states such as data transmission probability during channel competition are derived. Then, according to the mathematical analysis formula for packet loss rate, the influences of network protocol parameters NB and minBE, network load , network scale N, and BER on collision probability and packet loss rate are analyzed.

The analysis results demonstrate that the proposed analytical model can accurately analyze relevant network performance metrics. Network state parameters and protocol parameter settings can optimize data frame packet loss rate. Future work will further improve the core algorithm of the protocol, establish mathematical models that better match actual networks, propose new optimization strategies, and enable the protocol to have broader application prospects.

References

[1] Ramachandran I, Das A K, Roy S. Analysis of the contention access period of IEEE 802.15.4 MAC. ACM Trans on Sensor Networks, 2007, 3(1): 4:1-4:22.

[2] Wen Hao, Lin Chuang, Chen Zhi Jia, et al. An improved Markov model for IEEE 802.15.4 slotted CSMA/CA mechanism. Journal of Computer Science and Technology, 2009, 24(3): 495-504.

[3] Fang Mei, Lu Yang, Guan Junming. Modeling and analysis of non-saturated 802.15.4 network throughput. Journal of System Simulation, 2010, 22(4): 1037-1041.

[4] Park P, Ergen S C, Fischione C, et al. Duty-cycle optimization for IEEE 802.15.4 wireless sensor networks. ACM Trans on Sensor Networks, 2013, 10(1): 12:1-12:32.

[5] Cheng Yuan, Zhang Yuan, Gao Xiqi. Performance analysis of packet loss rate for wireless LAN under error channels. Journal on Communications, 2007, 28(5): 53-56.

[6] Li Zhihua, Lian Bin, Wei Zhongcheng, et al. Performance analysis of energy efficiency and delay in wireless sensor networks. Computer Application Research, 2014, 31(8): 2473-2476.

[7] Zhou Xiangyun, Qian Hui, Yu Lun. Research on S-MAC protocol for low packet loss rate wireless sensor networks. Computer Science, 2011, 38(10A): 367-369.

[8] Prasad Y, Pachamuthu R. Analytical model of adaptive CSMA-CA MAC for reliable and timely clustered wireless multi-hop communication. Proc of IEEE World Forum on Internet of Things. Piscataway, NJ: IEEE Press, 2014: 212-217.

[9] Hussein O, Sadek N M, Elnoubi S, et al. Analytical model of multihop IEEE 802.15.4 with unslotted CSMA/CA. International Journal of Computer and Communication Engineering, 2014, 3(3): 226-230.

[10] Du Wan, Navarro D, Mieyeville F. Performance evaluation of IEEE 802.15.4 sensor networks in industrial applications. International Journal of Communication, 2015, 28(10): 1657-1674.

[11] Hussein O, Sadek N M, Elnoubi S, et al. Analytical model of multihop IEEE 802.15.4 with unslotted CSMA/CA. International Journal of Computer and Communication Engineering, 2014, 3(3): 226-230.

[12] Cheng Hongbin, Wang Xiaonan, Liang Wei. Research on energy saving of 6LoWPAN network with node sleep state enabled. Computer Engineering & Science, 2012, 34(10): 53-56.

[13] Kim T O, Baek S, Choi B D. Performance analysis of IEEE 802.15.4 superframe structure with the inactive period. Performance Evaluation, 2016, 106: 50-69.

[14] Patel N R, Kumar S. Enhanced clear channel assessment for slotted CSMA/CA in IEEE 802.15.4. Wireless Personal Communications, 95(4): 4063-4081.

[15] Park P, Di Marco P, Fischione C, et al. Modeling and optimization of the IEEE 802.15.4 protocol for reliable and timely communications. IEEE Trans on Parallel and Distributed Systems, 2013, 24(3): 550-564.

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