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Optimization of MAC algorithm based on IEEE 802.15.4 in indoor positioning system①

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Abstract

The mobility of the targets asks for high requirements of the locating speed in indoor positioning systems. The standard medium access control (MAC) algorithm will often cause lots of packet conflicts and high transmission delay if multiple users communicate with one beacon at the same time, which will severely limit the speed of the system. Therefore, an optimized MAC algorithm is proposed based on channel reservation to enable users to reserve beacons. A frame threshold is set to ensure the users with shorter data frames do not depend on the reservation mechanism, and multiple users can achieve packets switching with relative beacon in a fixed sequence by using frequency division multiplexing technology. The simulation results show that the optimized MAC algorithm proposed in this paper can improve the positioning speed significantly while maintaining the positioning accuracy. Moreover, the positioning accuracy can be increased to a certain extent if more channel resources can be obtained, so as to provide effective technical support for the location and tracking applications of indoor moving targets.

Key words: medium access control (MAC) algorithm, indoor positioning, multi-channel, fingerprint identification, IEEE 802.15.4

0 Introduction

The establishment of indoor positioning system has greatly promoted the development of location-based service industry. The infrastructure of the system includes the beacons with known locations, and the users need to determine their locations quickly and exactly to satisfy the corresponding needs. Therefore, the positioning speed and accuracy of indoor location system design are of great significance. Some current studies, however, usually need to sacrifice some accuracy to achieve advancements in the performance of positioning speed[1-2]. Generally, users and beacons have to obtain received signal strength indicator (RSSI) values by exchanging packets to achieve location. The transceiver integrated on the beacon node conforms to the IEEE 802.15.4 standard[3], which defines the medium access control (MAC) layer specification. Carrier sense multipath access with collision avoidance (CSMA/CA) protocol[4] is the most typically used MAC algorithm in wireless local area networks (WLAN). The principle of channel allocation in this algorithm is that nodes listen to the channel before sending data, and randomly wait for the corresponding time period when the channel is busy. This process, however, often leads to a large number of packet conflicts, resulting in severe limitations of the algorithm based on competition in terms of maximum bandwidth and network throughput[5-6]. Time division multiple access (TDMA) MAC algorithm divides channels into time slots with specific nodes to avoid the contention period and packet conflicts, but it requires strict clock synchronization[7]. Ref. [8] proposed that assigning a separate channel and time slot to each node would cause a huge number of delays in a complex network environment. Ref. [9] described a frequency-hopping technique based on contention packet transmission, but it is difficult to estimate the appropriate length of the schedule. Ref. [10] proposed that allocating channels by using partially overlapping channels, but it will cause lots of packet loss as crosstalk between frequency bands. Ref. [11] proposed a novel scheduling method for autonomously enhanced beacon to reduce the collision probability of packets. In Ref. [12], different channels were used to achieve conflict-free time schedu-

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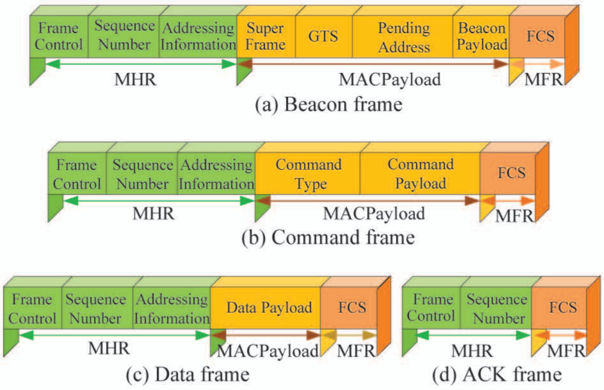
ling with introducing some complex algorithms. Ref. [13] split the tree network into multiple small networks using dedicated channels. However, the network topology cannot consider moving nodes. The work in Ref. [14] built a tree allowing nodes of the same level in the tree to compete for packets transmitted within a shared time slot. A special MAC algorithm was designed to realize the indoor positioning system in Ref. [15].

Frequent packet conflicts, high delay, and low network throughput, are induced when multiple users communicate with the same beacon in indoor positioning system, which gives rise to seriously attenuation in speed and accuracy of positioning. To this end, this paper will combine request-to-send and clear-to-send (RTS/CTS) mechanism, and adopt frequency division multiplexing technology to optimize the standard MAC algorithm. Furthermore, users with shorter data frames do not need to use the reserve mechanism by setting the frame threshold, so as to speed up the RSSI sampling process in indoor positioning system.

The chapters of this paper are arranged as follows: Section 1 makes an in-depth study and analysis on the delay and other performance parameters of the standard MAC algorithm based on IEEE 802.15.4. In Section 2, an optimized MAC algorithm is provided. Simulations and the performance analysis will be carried out in Section 3. Finally, Section 4 summarizes this paper.

1 Standard MAC algorithms

IEEE 802.15.4 protocol is committed to implementing a low-complexity, low-cost, low-power, and low-rate wireless connection technology, which defines 4 types of frames with their types and formats shown in Fig. 1. The protocol facilitates network management and promotes the advance of synchronous communication by introducing the concept of beacon frame in MAC layer.



(a) Beacon frame

(b) Command frame

(c) Data frame (d) ACK frame

Fig. 1 Frame types and formats defined by the IEEE 802.15.4 protocol

In view of the unslotted nature of the IEEE 802.15.4 protocol, the process of media access is shown in Algorithm 1, where, N is the number of channel visits by nodes, B is the retreat index, Max$B$ is the maximum number of retreats, and CCA represents clear channel assessment.

Algorithm 1 Carrier sense mechanism

```
Initialize $N = 0$, $B = \text{Min}B$
Begin
1. Delay for random $(2^B - 1)$ Backoff periods;
2. Perform CCA;
3. If Channel is idle, then success,
      Else $N = N + 1$, $B = \text{Min}(B + 1, \text{Max}B)$;
      End If
4. If $N > \text{macMax}B$, then Failure,
      Else repeat 1;
      End If
End
```

1.1 Transmission delay

The total delay can be divided into 7 items during packet transmission, and the specific division is shown in Eq. (1). The time to be considered is inter frame space (IFS), the length of which depends on the length of the transmitted packet.

$$T_{TD} = T_B + T_{CCA} + T_{TA} + T_P + T_{TA} + T_{ACK} + T_{IFS} \tag{1}$$

where, T_{TD} is the total delay of the transmission process, T_B is the retreat time, T_{CCA} is the time to perform CCA, T_{TA} is the switching time of the transceiver mode, and T_P is packet transmission time, T_{ACK} is the time for the transmission of an ACK packet, T_{IFS} is the time interval of frame transmission. In general, the value of T_B obtained as Eq. (2) is larger than the value of the other items, which cannot be determined in advance for its randomness.

$$T_B = B_S \cdot T_S \tag{2}$$

where, B_S is the back-off time of the node before sending the packet, T_S is the duration of a single time slot.

A certain amount of delay is also generated in the operating system (OS) in addition to the above delay. The OS needs to deal with sending and receiving packets. There will be two additional periods of time, namely sending time and receiving time. Therefore, the transmission generates two delays at the start and end.

1.2 Network throughput

Network evaluation is extremely crucial for complex indoor locating systems since it can estimate the maximum bandwidth and packet exchange rate that the system can achieve. This experiment uses the simulator Matlab and the operating system TinyOS[16] to measure the maximum network throughput. The network topology is set as a star, the receiver and transmitter are located in the same broadcast domain, the sender continuously sends packets with a fixed length of 23 bytes to the receiver at a constant transmission rate. All nodes are located in the same broadcast domain and share the same channel. The retreat time valuation method of TinyOS distributed CC2530 transceiver is shown in Eq. (3).

$$B_S = \text{rand mod}(31 \times \text{CC2530\_Backoff\_Period}) + \text{CC2530\_Min\_Backoff}) \quad (3)$$

where, the values of the constants CC2530 _ Backoff _ Period and CC2530 _ Min _ Backoff introduced are both 10 ms. The valuation method of retreat delay in case of busy channels is shown in Eq. (4).

$$B_S = \text{rand mod}(7 \times \text{CC2530\_Backoff\_Period}) + \text{CC2530\_Min\_Backoff}) \quad (4)$$

where, the value range of B_S is 0.3125 – 2.5 ms.

Network throughput is defined as the percentage of time it takes to send a packet to the total time successfully spent in the positioning process in this experiment. The network throughput can be obtained by different numbers of users at different packet transmission rates. The simulation result is shown in Fig. 2, where U is the number of users.

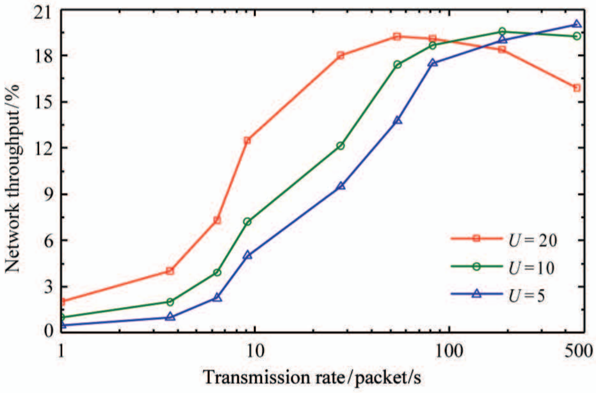


Fig. 2 Network throughput for nodes at different packet transmission rates

The result shows that the throughput will increase with the number of users at a low transmission rate. However, there will be a large number of packet collisions when the rate of packet transmission is fast, especially exist lots of users, which resulting in a decline in throughput. Besides, the throughput cannot exceed 21% in any of the scenarios. It can be concluded that the MAC algorithm using the CSMA protocol is not applicable when multiple users are trying to communicate with the same receiver in a scenario requiring high-speed transmission.

2 Optimization of MAC algorithm

Users and beacons, generally, are required to perform the exchange of packets at different power levels in multiple channels during the RSSI collection process. The exchange of packets is defined as the continuous transmission of packets in two directions, namely users to beacons and beacons to users. The total number of packets exchanged depends on the number of channels K used, the number of power levels L, and the number of retransmissions N in a set of channels and levels. In general, the higher accuracy the system can achieve if more information can be obtained, which will often result in greater delay. The values of K, L and N that are set during system initialization will perform a good trade-off between the locating accuracy that can be realized and the acquisition delay. Therefore, an optimized MAC algorithm is provided in this section to accelerate the collection process of RSSI values.

2.1 Initial assumptions

A dedicated channel is set up by the optimized algorithm for beacons to announce their availability by sending broadcast packets. The RTS/CTS is adopted by users to reserve beacons for subsequent transmission after receiving the broadcast data packets. Beacon determines whether the users require using the reservation mechanism after it receives the RTS frame by determining the length of data frame in the queue of the upper interface. The user's fixed transmission sequence including the list of channels and levels used in the process of data exchange is also defined by optimized algorithm in advance. Additionally, the sequence must be followed by all users.

The remaining users and beacons must quit using the radio for a certain time to ensure that the users who reserve the beacon successfully can complete all packets switching on the first channel. The user immediately enters the next channel after achieving packet exchange with the beacon on this channel. The channel used is released for use by other users, who also enter the next channel after the exchange is accomplished, and so on.

2.2 Design of optimized MAC algorithm

The set scenario contains a certain number of users and beacons that periodically broadcast their available packets on a specific channel (Ch1) in the optimized algorithm. The first user who uses the RTS/CTS frame to reserve a beacon will be set aside some time to achieve packet transmission at all levels in the first channel of the K channels used. Other users and beacons located in the same radio range will not be able to transmit during the period.

Algorithm 2 Channel resource allocation

```
Initialize $K$ $L$ $N$
Begin
1. $B_i$→Broadcast packet(availability) at Ch1;
2. User $m$ receive packet & retain Message ($B_i$);
3. Others (User & Beacon) start a timer;
4. If Time(wait) > Time(reserved), then U&B overflow,
       Else Beacon stop transmit packets (Broadcast Data);
       End If
5. User $m$ exchange Packet ($B_i$) use Ch$n$ ($PL$ from $P_1$ to $P_L$);
6. User $m$ pass to next _ Ch;
7. If $n < K$, then $n = n + 1$; repeat 2,
       Else User $m$ complete exchange (Data);
       End If
End
```

The user enters the next channel immediately after achieving the packet exchange on a certain channel. User can access the channel without using the CSMA algorithm in this process, the used channel is released at this time, and the beacons use Ch1 to broadcast its availability. Besides, the channel reservation timer starts, and the remaining users and the beacon restart the transceiver. The process is shown in Fig. 3.

The algorithm will use the system's frequency division multiplexing capability to allow different users to exchange packets in parallel with corresponding beacons on diverse channels if multiple users attempt to exchange packets with different beacons. The sequence of access is the same to reduce the complexity of the algorithm. The user and the beacon have a fixed period of time in each different channel to complete the packet exchange process. They must move from the current channel to the next one at the end of this period, the sequence of channel access is shown in Fig. 4.

The RTS/CTS protocol will increase the transmission delay provided that the length of data frame (L_D) is less than the length of control frame in the phase of channel reservation. The optimized algorithm determines whether the user sending data needs to use the reservation mechanism by setting the RTS frame threshold (L_T), as shown in Algorithm 3, where F is the feedback frame of the beacon, L_F is the length of F, F_S is data frames less than L_T in length.

In this case, T_{TA} and T_{ACK} will not exist in Eq. (1) because no confirmation is required to send packets for transmission, which reduces the transmission delay greatly. Reducing the delay and increasing the transmission efficiency can be achieved by using control frames to transmit data. The possibility of collisions is reduced and throughput is improved since the user node with F_S is transmitted when the beacon is idle.

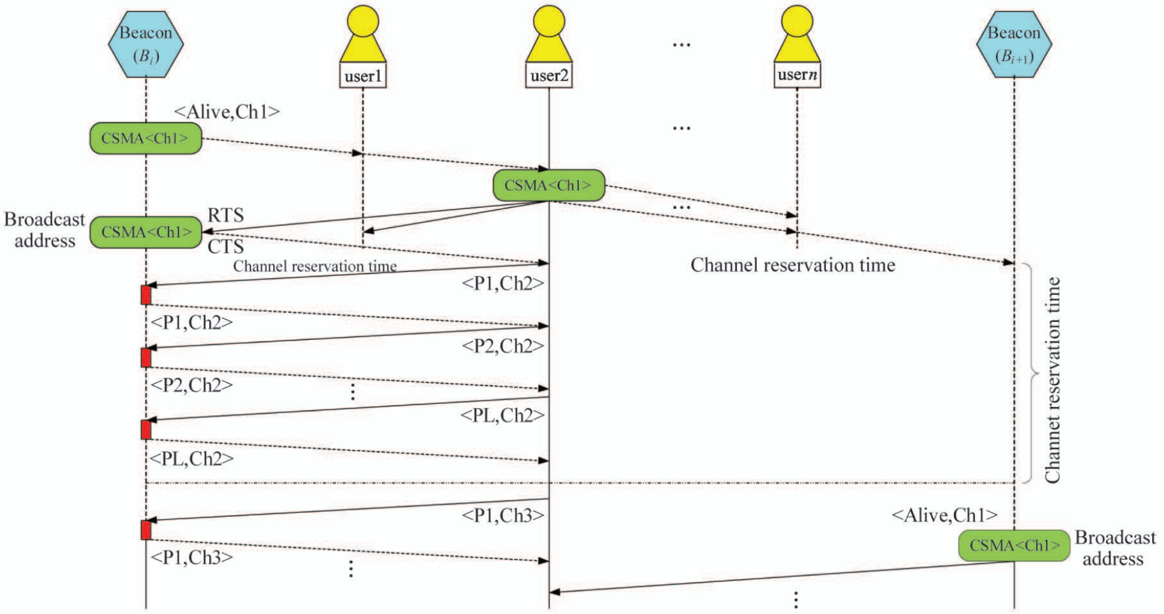


Fig. 3 Access channel sequence for users in the optimized MAC algorithm

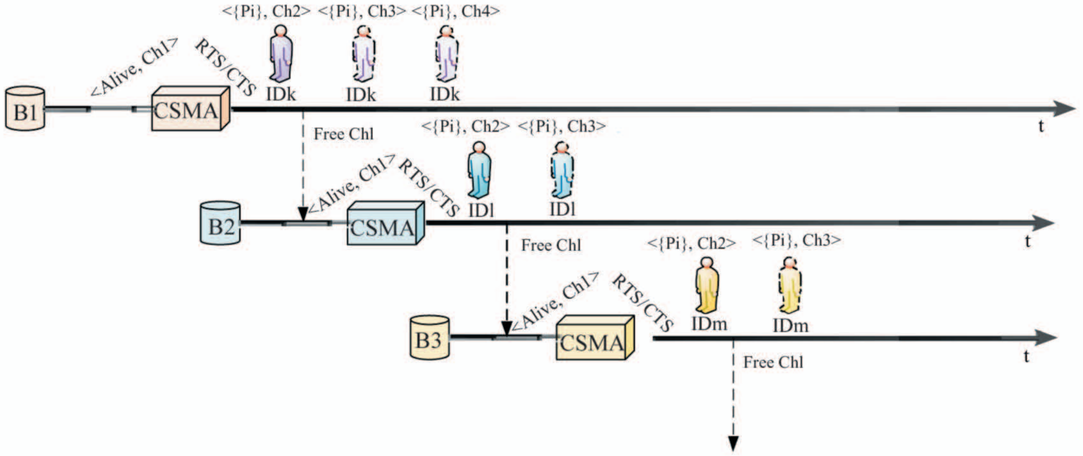


Fig. 4 Access sequence for multiple users exchanging packets on multiple groups of channels in parallel

Algorithm 3 Channel reservation

```
Initialize $L_T$
Begin
1. $B_i$→Broadcast packet (availability) at Ch1;
2. User nodes ($U_i$):
        2.1 $U_i$ sends RTS & waits for $F$;
        2.2 $U_i$ identify $L_F$ (length of $F$);
            If $L_F \geqslant L_T$, then send data to $B_i$,
            Else dormancy;
            End If
        2.3 $U_i$ (dormancy) send data directly to $B_i$ (no task)
3. Beacon node ($B_i$);
        3.1 $B_i$ receives RTS & checks $L_D$ in the upper sequence;
        3.2 If there exists $F_S$, then $B_i$ send CTS to $U_i$,
            Else $B_i$ send ACK ($L_{ACK} < L_{CTS}$) to $U_i$;
            End If
        3.3 $B_i$ takes out $F_S$ from sequence (exist $F_S$) &
            sends $F_S$ to U$_i$ according to the original path;
End
```

2.3 Energy consumption

Energy consumption is a significant issue in the design of positioning system. The optimized algorithm stipulates that the node will always be in the receiving mode except that the node is sending packets, which will effectively reduce the large amount of energy consumption caused by idle listening. The user can easily replace the battery of the node and connect the beacon to the main power source in a general indoor positioning system. However, compared to other similar algorithms, using the MAC algorithm based on IEEE 802.15.4 standard can flexibly arrange beacons at low power consumption and low cost in some complicated scenes that cannot provide the power supply. The node will always be in receiving mode by default except when it is sending packets. Therefore, the energy consumption of the node can be accurately calculated by judging the time taken by the node to receive and send packets. The energy consumption will change with the power level used in the packet transmission process. The energy consumption by the user to collect all RSSI values is shown in Eq. (5).

$$E = \sum_{b} ((T_{\mathrm{d}} - \sum_{L} T_{\mathrm{txL}}) \cdot P_{\mathrm{rx}} + \sum_{L} T_{\mathrm{txL}} \cdot P_{\mathrm{txL}}) \qquad (5)$$

where, E is the energy consumed to collect all RSSI values, b is the number of beacons, T_{d} is the total delay in the RSSI collection process, T_{txL} is the time it takes to transmit a packet when the power level is L, P_{rx} is the power consumption of the node in the receiving mode, and P_{txL} is the power consumption of the node in the transmitting state when the power level is L.

3 Experimental testing and simulation analysis

In this section, the Matlab simulation environment is used to perform the analysis of the optimized algorithm about delay and other performances based on Section 2. Then, experimental tests are conducted on factors that affect positioning accuracy in the laboratory building. The improvement in the positioning speed is always achieved at the expense of sacrificing precision. Therefore, the last experiment relates the RSSI collection delay to the localization error, in order to study the optimized algorithm's trade-off effect between the speed and accuracy.

3.1 Simulation and analysis of performance

The simulation scenario of this simulation includes one user and one beacon, who exchange packets to obtain RSSI values. Users and beacons are implemented using Telosb nodes[17], and the software used is TinyOS.

3.1.1 Delay

This experiment is aimed at the total delay incurring during the collection of RSSI values. Different K and L are used in the course of the RSSI sampling process, and the retransmission number remains the same ($N = 10$). The case of using the MAC algorithm with CSMA (MAC) and the optimized MAC algorithm (OMAC) are used to compare in the experiments. The simulation result is shown in Fig. 5.

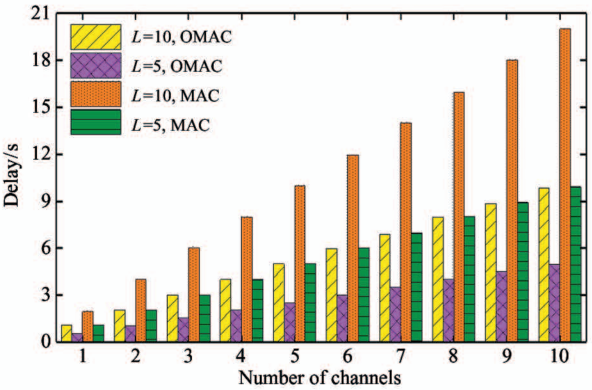


Fig. 5 Delays in collecting RSSI values at different numbers of channels and power levels

The result shows that the total delay is reduced in the optimized algorithm distinctly compared with the MAC algorithm using CSMA in the RSSI collection process. The total delay is reduced by about half, which as a result of the back-off time it contains takes up approximately half of the total time consumed in the entire transmission process when the algorithm with CSMA is implemented.

3.1.2 Network throughput

This experiment is intended at the network throughput that the system can achieve during packet transmission. The network throughput achieved is tested using different L and N, the number of channels used is fixed at 1 ($K = 1$). The simulation result is shown in Fig. 6.

The simulation result shows that the throughput of the overall network is improved significantly because less time is taken to access the channel. Additionally, the maximum network throughput that can be obtained by the optimized algorithm is not exactly the same when the number of senders is different, because the stage of channel reservation is mainly based on the RTS/CTS handshake mechanism, which still uses the CSMA algorithm. Besides, the effect of the stage of reservation on the overall consequence will be decreased when more packets and levels are used in the RSSI collection process.

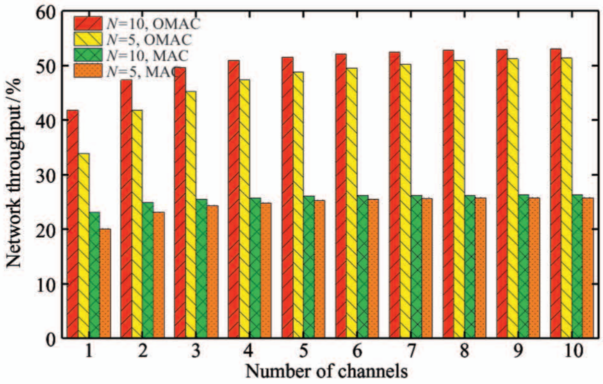


Fig. 6 System throughput achieved at different power levels and number of retransmissions

3.1.3 Energy consumption

This experiment is mainly for the analysis of energy consumption. The analysis is intended at the current consumption of the CC2530 wireless transceiver with different operating conditions. The current consumed in the receiving mode and the transmitting mode with different power levels is shown in Table 1.

Table 1 Current consumption of CC2530 transceiver at different modes

Mode	Current consumption/mA
reception	18.8
sending ($L = -25$ dBm)	8.5
sending ($L = -15$ dBm)	9.9
sending ($L = -10$ dBm)	11.2
sending ($L = -7$ dBm)	12.5
sending ($L = -5$ dBm)	13.9
sending ($L = -3$ dBm)	15.2
sending ($L = -1$ dBm)	16.5
sending ($L = 0$ dBm)	17.4

The number of channels and beacons is fixed at 1, the number of retransmissions is 5 and 10 respectively, and 8 different power levels are used (as shown in Table 1) in the experiment. The levels increase in order, namely the level of −25 dBm is used when only one power level is used. Levels of −25 dBm and −15 dBm are used for transmission provided that two power levels are used, and so on. The experimental result is shown in Fig. 7.

The simulation result shows that the listening time is reduced because of the elimination of the contention period, thereby eliminating the energy consumption of the listening, which makes the algorithm dramatically superior to MAC algorithm with CSMA about energy consumption. Besides, energy consumption will also increase as the number of retransmissions increases since the total number of packets and the total delay will continue to increase in the course of the RSSI collection process.

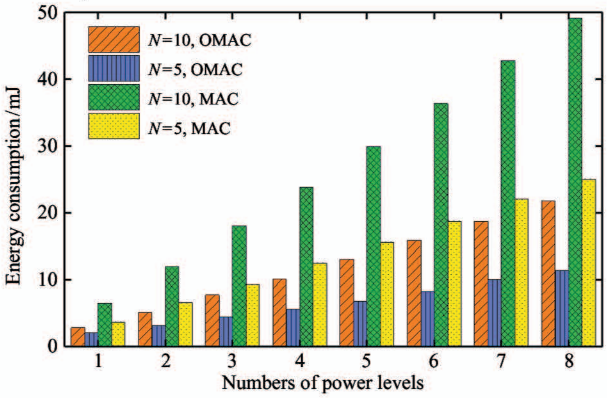


Fig. 7 Energy consumption of the system at different numbers of power levels

3.2 Test and analysis of positioning performance

The optimized algorithm is tested on the positioning accuracy in the laboratory building. The experimental environment mainly includes three laboratories, two offices, a corridor, and eight beacons deployed in different offices, laboratories and corridors. The specific distribution is shown in Fig. 8, where the squares indicate the specific locations of the beacons (consisting of Telosb nodes). The lines are the paths of the data collection device. Collection device is connected to another Telosb node, which is used to collect RSSI values at the spots. The collection device is required to collect RSSI values at each test point by using different channels and power levels, and exchanging packets with each beacon in the collection process.

A second round of RSSI values collection is performed to obtain the user's location information in the experimental area after the database has collected the data. The user's location can be estimated using the positioning algorithm proposed in Ref. [18] based on these data. The main feature of the algorithm is that it can make full use of all the information that appears in the collection process, and this additional information can improve the locating accuracy. In addition, the system delay will increase as the number of transmitted packets increases. Next, the effects of K and L on locating accuracy and the trade-offs made by the system in delay and accuracy of location will be analyzed.

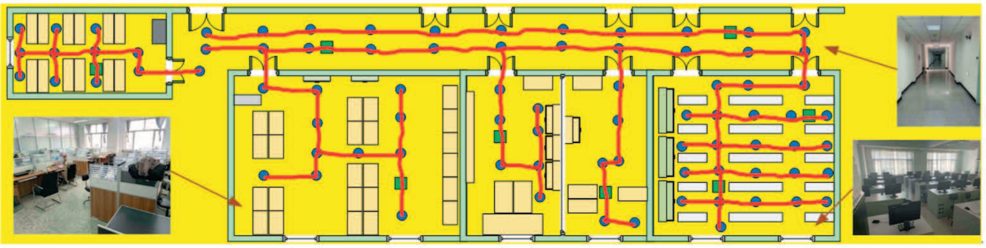


Fig. 8 Scenario model for deploying the experimental setup

3.2.1 Locating accuracy based on the number of channels

The effect of the number of channels on the locating accuracy is analyzed in this experiment. Each user needs to be placed on the test point and the positioning error is calculated. Packets with 8 beacons ($B = 8$) are exchanged by users to obtain RSSI values, and the process is repeated 5 times ($N = 5$). The power levels used are −10 dBm, −7 dBm, and −5 dBm. The method of location estimation is based on the algorithms proposed in Ref. [18] and Ref. [19]. The 2400 MHz frequency band defines 16 channels, the calculation method of its center frequency is shown in Eq. (6).

$$f = 2405 + 5(k - 11) \qquad (6)$$

where, f is the center frequency of the channel, and its unit is MHz, k is the channel number and its value range is 11 − 26.

The channels used in this experiment are 11 (2405 MHz), 13 (2415 MHz), 16 (2430 MHz), 19 (1445 MHz), 22 (2460 MHz) and 26 (2480 MHz). Channels are added in order during the experiment, that is, channel 11 is used when just one channel is included. Channels 11 and 13 are used when two channels are used, and so on. Positioning starts after all packets have been exchanged. Experimental result obtained is shown in Fig. 9 in the case of using one power level and different channel numbers.

The experimental result shows that the location will be more accurate as the number of channels increases. There are a lot of obstacles in this scenario, which effectively avoids obstacle-free transmission between the users and the beacons. It can be concluded from this that higher power levels can provide better positioning results as these levels can cover larger radio range.

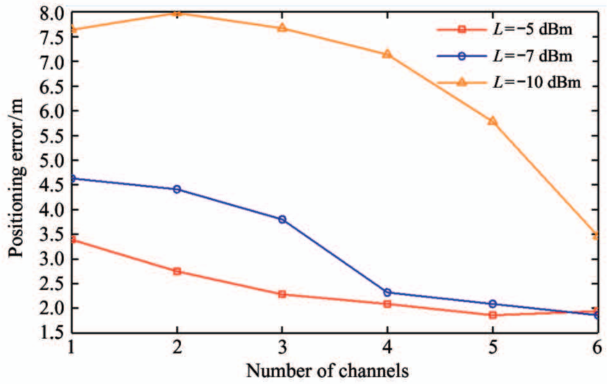


Fig. 9 Positioning error for different number of channels

3.2.2 Locating accuracy based on the number of power levels

This experiment focuses on the effect of the number of power levels on locating accuracy. The number of channels respectively used is 4 (11, 16, 20, 26), 6 (11, 13, 16, 19, 22, 26), 8 (11, 13, 16, 19, 20, 22, 24, 26) at each test point, which exchanges packets using different number of power levels ($L = 1, 2, \cdots, 6$), and each group is repeated 5 times. The levels used are 0 dBm, −1 dBm, −3 dBm, −5 dBm, −7 dBm, and −10 dBm, and the levels increase sequentially. Locating is carried out after all packets are exchanged, and the experimental result obtained is shown in Fig. 10.

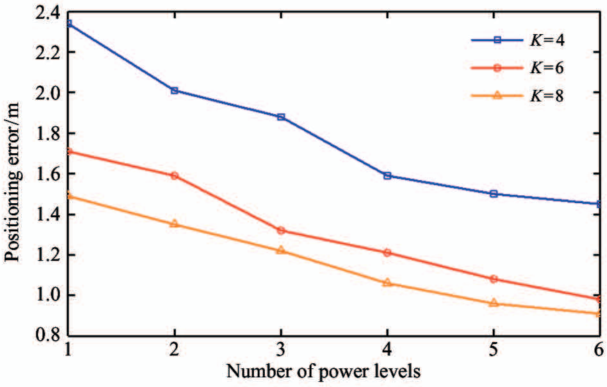


Fig. 10 Positioning errors for different number of power levels

The result shows that the number of RSSI values collected will increase with the number of power levels used increasing no matter what number of channels is used. Therefore, the positioning accuracy can increase effectively by increasing the number of power levels.

3.2.3 Locating accuracy and RSSI collection delay

This experiment will analyze the trade-off effect between the locating accuracy and RSSI collection delay. K, N, and B are fixed at 6, 5, and 8 respectively. The channels used are 11, 13, 16, 19, 22, 26, and the power levels used are 0 dBm, − 1 dBm, −3 dBm, −5 dBm, −7 dBm, and −10 dBm, and the levels increase in order. The delay is measured after all the packets included in one user and eight beacons are sent. The experimental result is shown in Fig. 11.

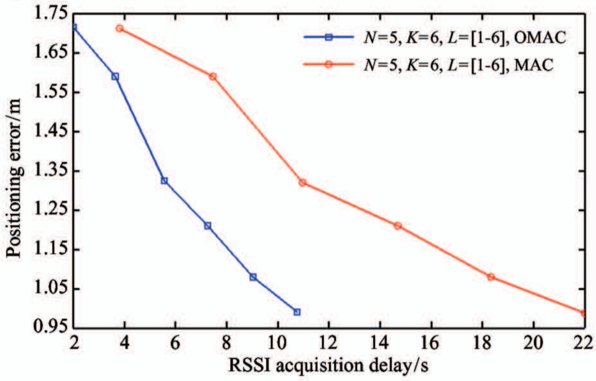


Fig. 11 Correlation image between RSSI collection delay and locating error

The result shows that the system has made a better tradeoff between the delay generated by the RSSI collection and the achievable positioning accuracy. Compared to the MAC algorithm with CSMA, the time required to collect the RSSI values is reduced by half, and the positioning accuracy is improved effectively on a specific combination of K, L, B, and N. Therefore, it can be concluded that the optimized algorithm can reduce the delay by half without changing the positioning accuracy.

4 Conclusions

An improved media access control algorithm is proposed for indoor positioning system based on the IEEE 802.15.4 to resolve the problems of frequent packet collisions and high delay when multiple users communicate with the same beacon. The proposed algorithm is mainly used to the RSSI values acquisition process in positioning systems, and realizes obvious achievements in indoor positioning systems using multiple power levels and channels. Compared to other similar algorithms, different channels are adopted to avoid the contention cycle of media access without using the algorithms with complex scheduling and strict clock synchronization. The optimized algorithm uses effective RTS/CTS mechanism to reserve beacons and channels for the medium. The system will generate a channel reservation period for the first user who reserves the channel successfully to ensure that the user can complete the exchange with all the packets on the first channel. The contention period is eliminated throughout the packet exchanging process since the process is not disturbed by the remaining users and beacons. Other users can use the channels that have been tested and released by previous users to cover their packets exchanging process to different beacons. Experimental results show that the algorithm can significantly accelerate the positioning speed by reducing packet collisions and transmission delays while maintaining the same positioning accuracy. Moreover, the system can even improve positioning accuracy with more channels and power levels.

References

[1] Zhou M, Qiu F, Xu K J, et al. Error bound analysis of indoor Wi-Fi location fingerprint based positioning for intelligent access point optimization via Fisher information [J]. *Computer Communications*, 2016, 86(15): 56-74

[2] Arsan T. Improvement of indoor positioning accuracy of ultra-wide band sensors by using big bang-big crunch optimization method [J]. *Journal of Engineering Sciences*, 2018, 24(5): 921-928

[3] Chandane M, Bhirud S G, Bonde S V. Performance analysis of IEEE 802.15.4 [J]. *International Journal of Computer Applications*, 2012, 40(5): 23-29

[4] Wang F, Li D, Zhao Y. Analysis of CSMA/CA in IEEE 802.15.4 [J]. *IET Communications*, 2011, 5(15): 2187-2195

[5] Uddin M F. Throughput performance of NOMA in WLANs with a CSMA MAC protocol [J]. *Wireless Networks*, 2019, 25(6): 3365-3384

[6] Latré B, Mil P, Moerman I, et al. Throughput and delay analysis of unslotted IEEE 802.15.4 [J]. *Journal of Networks*, 2006, 1(6): 20-28

[7] Ergen S C, Varaiya P. TDMA scheduling algorithms for wireless sensor networks [J]. *Wireless Networks*, 2010, 16(4): 985-997

[8] Zhou G, Huang C, Yan T, et al. MMSN: multi-frequency media access control for wireless sensor networks [C] // Proceedings of the 2006 IEEE International Conference on Computer Communications, Barcelona, Spain, 2006: 1-13

[9] Cao X L, Song Z X, Yang B. Multi-slot reservation-based multi-channel MAC protocol for dense wireless ad-hoc networks [J]. *IET Communications*, 2018, 12(10): 1263-1271

[10] Park P, Jung B, Lee H, et al. Robust channel allocation with heterogeneous requirements for wireless mesh backbone networks [J]. *Sensors*, 2018, 18(8): 2687-2699

[11] Karalis A, Zorbas D, Douligeris C. Collision-free advertisement scheduling for IEEE 802.15.4-TSCH networks [J]. *Sensors*, 2019, 19(8): 1789-1814

[12] Jovanovic M D, Djordjevic G L. TFMAC: multi-channel MAC protocol for wireless sensor networks [C] // Proceedings of the 2007 International Conference on Telecommunications in Modern Satellite, Cable and Broadcasting Services, Nis, Serbia, 2007: 23-26

[13] Wu Y, Stankovic J A, He T, et al. Realistic and efficient multi-channel communications in wireless sensor networks [C] // Proceedings of the 2008 Conference on Computer Communications, Phoenix, USA, 2008: 1867-1875

[14] Phan V V, Hoon O. Optimized sharable-slot allocation using multiple channels to reduce data-gathering delay in wireless sensor networks [J]. *Sensors*, 2016, 16(4): 505-520

[15] Fonseca J A, Bartolomeu P A. MAC protocol to manage communications in localization systems based on IEEE 802.15.4 [C] // Proceedings of the 34th Annual Conference of IEEE Industrial Electronics, Orlando, USA, 2008: 2717-2723

[16] Levis P, Gay D. TinyOS Programming [M]. Cambridge: Cambridge University Press, 2009: 116-143

[17] Polastre J, Szewczyk R, Culler D. Telos: enabling ultra-low power wireless research [C] // The 4th International Symposium on Information Processing in Sensor Networks, Boise, USA, 2005: 364-369

[18] Marti J, Sales J, Marin R, et al. Localization of mobile sensors and actuators for intervention in low-visibility conditions: the ZigBee fingerprinting approach [J]. *International Journal of Distributed Sensor Networks*, 2012: 12(26): 1-10

[19] Claver J M, Ezpeleta S, Martí J V, et al. Analysis of RF-based indoor localization with multiple channels and signal strengths [C] // Proceedings of the Wireless Internet: 8th International Conference, Lisbon, Portugal, 2014: 70-75

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