MSF-MAC: A Multi-Channel MAC Protocol for Long-distance and Anti-interference in Wireless Sensor Networks

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Abstract. On-site monitoring in the energy industry such as photovoltaic power stations is one of the main application areas of wireless sensor networks, with long distances, many nodes, long deployment cycles, and large communication interference. Aiming at these data collection characteristics, we propose a multi-channel MAC protocol which is capable of optimizing the allocation of multiple users for parallel transmission at a low data rate based on the SFs, named MSF-MAC. Based on the channel characteristics and flow characteristics of the data distribution of the acquisition nodes, the traffic adaptive slot allocation and the rate-based multi-spread-spectrum channel allocation algorithm are used to perform real-time coordinated scheduling of network nodes. At the same time, the protocol combines CSMA / polling mechanisms to design a multi-channel MAC protocol for long-distance and anti-interference in WSNs. Simulation experiments in NS2 confirm that the MSF-MAC has similar characteristics to 802.11 in the case of single-channel, and has a better system throughput and a lower average delay than 802.11 in the multi-channel scenario, which reduces the overhead of collisions and retransmissions, and improves the interference immunity of intra-cluster communication.

1. INTRODUCTION
On-site monitoring in the energy industry such as photovoltaic power stations is one of the main application areas of wireless sensor networks (WSNs), with the characteristics of long distances, lots of nodes, long deployment cycles, short data and large communication interference. Furthermore, over long distances, there are often shelters such as trees, hills, and electromagnetic interferences which caused by human factors are influencing the performance of wireless network. Compared with the traditional protocols using TDMA in cluster-based WSNs, such as the LMAC[1], many MAC protocols have been proposed for making effective communications under the single transceiver and multi-channel environment like the proposed application scenario, and we describe it in details in Section 2.

In the long-distance and anti-interference WSNs, the spread-spectrum communication is often used to avoid narrow-band interference effectively. The spread-spectrum modulation uses multiple information chips to represent each bit of payload information, which is called chips, so as to avoid the interference. The transmitting rate of spreading information is called symbol rate (Rs). The ratio of chip rate and the symbol rate is called the spreading factor (SF, spreading factor), which indicates the number of symbols that per bit of the spreading information need to be sent. These SFs are orthogonal to each other, which means that these same frequency channels with different SFs is equivalent to those parallel channels without interfering with each other. The spreading factor is proportional to the communication distance and anti-interference, and is inversely proportional to the transmission rate.
In this paper, in order to achieve a higher throughput and a lower latency of the multi-channel WSNs, we propose a hybrid CSMA and scheduled access multi-channel MAC protocol which is capable of optimizing the allocation of multiple users for parallel transmission at a low data rate in spread spectrum WSNs. The results of performance evaluation in NS2 confirm that our proposed MAC protocol have a higher throughput and a lower latency than 802.11 in multi-channel scenarios.

2. RELATED WORKS

Most of the existing multi-channel MAC protocols are generally optimized from the aspects of improving network throughput, robustness, or simplicity of node protocols. They always include at least one of the following four aspects.

- Control/data information exchange through a dedicated channel.
- Control/data information exchange through a dedicated phase.
- Strict global clock synchronization of the network.
- Synchronous/asynchronous channel frequency hopping using a pseudo-random sequence.

CCR-MAC[2], which is a communication channel recommendation MAC protocol in multi-channel WLANs, have been discussed in many papers. It uses one control channel (CCH) and multiple parallel data channels (CH). The nodes negotiate the channel with each other on the CCH and transmit on the selected CH. However, the overall throughput is limited by the CCH. HER-MAC[3][4] uses both TDMA and CSMA schemes to improve reliability in broadcasting messages and efficiency in service channel utilization, but when the number of nodes increases, the probability of collisions caused by single channel still limits its throughput and rises its latency. Similarly, the iQueue-MAC[5], which also uses a hybrid CSMA and TDMA scheme, allocates time slots from the perspective of node traffic queues to reduce the burst traffic latency effectively, but it requires accurate time synchronization and ignores unbalanced collisions in the multi-channel scenario.

On the other hand, in order to be suitable for the field data collection in WSNs, the protocol needs to improve the anti-interference performance. Due to the frequency-hopping communication network has a strong anti-interference and pseudo-randomness performance, it is one of the most common communication anti-interference strategies. The M-MAC[6] was firstly proposed to negotiate the data channel through the synchronous switching of the control channel between nodes, but an entire network time synchronization is required, so the DSMMAC[7] used a multi-user asynchronous frequency hopping sequence to form WSNs without control channel. But the disadvantage is that continuous frequency hopping works will make a huge node’s energy consumption, so it does not fit for sensor nodes which are often powered by batteries. Similarly, CoCH-CSMA/CA MAC[8] used cooperative control feedback in channel-hopping cognitive radio network, and CQM[9] MAC utilized quorum systems in mobile ad hoc networks, they are also need to keep channel hopping to achieve network transmissions.

3. DESIGN OF MSF-MAC PROTOCOL

3.1. Net Model

We propose a new multi-channel MAC protocol for long-distance and anti-interference in WSNs, named MSF-MAC. MSF-MAC is destined for improving the performance of anti-interference in WSNs by DSSS and channel allocation algorithm.

![Figure 3.1 The cluster network topology in WSNs](image-url)
The net model includes three parts: sensor nodes, clusters, and gateway. We assume that every cluster is far away from each other, so our net model is a cluster’s star topology in Fig 3.1. Every sensor node has a different q, a hopping sequence for requesting data transmission as shown in TABLE I. Assuming that the topology has these following properties:

1) Each topology supports \( \{f_1, f_2, ... , f_m\} \) and \( \{s_{f_1}, s_{f_2}, ... , s_{f_n}\} \) as \( m \times n \) matrix channel number. The channel is named as \( L_{i,j} \), assembled by \( f_i \) and \( s_{f_j} \).
2) Hopping sequence \( \{q_1, q_2, ... , q_n\} \) are only used to request transmission by sensor nodes in CSMA period, the channel to transmit long data is assigned by its cluster.
3) The two clusters next to each other should use a different frequency sequence, and divide communication distances and anti-interference performances through different spread factors inside their cluster.
4) Each cluster head plays the part of coordinator to coordinate node’s data transmission and channel assignment.

TABLE I. The different hopping sequence in MSF-MAC

| Sequence | CH1  | CH2  | CH3  | CH4  | CH5  |
|----------|------|------|------|------|------|
| q1       | L_{2,1} | L_{3,2} | L_{3,1} | L_{1,1} | L_{2,2} |
| q2       | L_{3,1} | L_{2,2} | L_{4,2} | L_{3,2} | L_{2,1} |
| q3       | L_{3,2} | L_{1,1} | L_{2,2} | L_{3,1} | L_{4,2} |
| q4       | L_{2,2} | L_{4,2} | L_{3,2} | L_{2,1} | L_{3,1} |

3.2. Traffic Adaption
MSF-MAC protocol adopts the super-frame structure as Fig3.2 shows. It includes beacon period, vTDMA with SA period, vCSMA with SA period, and PA protected period.

Figure 3.2 The super-frame structure in MSF-MAC

During the beacon period(B), the coordinator broadcast the beacon frame on each channel simultaneously. In addition to the fixed MAC frame header, the beacon frame contains current time, the remain CSMA slot, and channel indexes with a highest probability of idle. The current time is used to synchronize the sensor nodes on this channel. The CSMA slot provides an accurate access to these nodes who have data to send. The predicted idle channel indexes are purposed to reduce the access latency of failed nodes.

Because of the vTDMA and vCSMA periods are dynamic, the coordinator will allocate these time slots based on the transmission time slots requested by the nodes in the previous super-frame.

During the scheduled access period(vTDMA), the coordinator uses a short scheduling frame to schedule node’s transmission in the allocation table. In order to achieve a lower delay and greater throughput, every data frame contains the remaining number of data packets in the node’s FIFO. After the reserved slot is arrived, if it still remains data in FIFO, the coordinator will consider whether to continue transmitting. In single channel case, we continue to transmit until the end, while in the multi-channel case, we stop transmitting and assign the channel number for the next transmission. However, it will cause extreme collisions with application nodes in CSMA period if continue transmitting. Therefore, the coordinator will broadcast the data ACK in the CSMA period to avoid the hidden terminals. Furthermore, if the data transmission fulfills the whole super-frame, the last ACK in super-frame will contain the channel index for the next transmission and turn to PA period.

During the random access period (CSMA/CA), MSF-MAC uses RTS/CTS mechanism to achieve data interaction. In purpose to maximize the throughput and minimize the average delay, the nodes are allowed to send a unit packet after receiving CTS, and the coordinator replied ACK contained the channel number for the next transmission. In MSF-MAC, the performance of the random access period is similar to 802.11. As the number of requesting nodes increases, an imbalance occurs across multiple channels which causes to high latency in 802.11. In order to solve this problem in MSF-MAC,
as well as enhanced the performance of anti-interference, the nodes use different frequency hopping sequences which should follow the principle of low collisions to send RTS in the multi-channel scenario.

The protection period (PA) mainly includes the protected slot of the frequency switching and the time difference caused by different spreading factors, so as to protect MSF-MAC’s super-frame structure.

In MSF-MAC, when a sensor has a new transmission request, it will be waked up and change to the channel corresponding to the current moment in the hopping sequence, and start listening for the beacon frame to get current channel’s attribute. A typical example of node’s communication is shown in Figure 3.3 below.

When the sampling data period is arrived, the node (N1) generates a new transmission request and changes to Tx1(L(m1, n1)), which means \(f_{m1, SF_{n1}}\). After receiving the beacon frame, N1 gets the CSMA time slot and goes to sleep. When the time reaches, the node is waked up and turns to CAD mode (channel activity detection, a mode in lora modem). As the channel is idle, it sends an RTS request, after receiving the CTS, it transmits the maximum allowed length of unit data in the period. After receiving the ACK successfully which contained the channel Tx2 for the next transmission, N1 switches to Tx2 immediately and turns to sleep until receiving the beacon frame in Tx2. As receiving the short scheduling frame during the scheduled access period, N1 transmits the scheduled length of data in FIFO which allocated by the coordinator.

\[
\text{Tx1: } L(m_1, n_1) \quad \text{DATA} \quad \text{Arrived} \quad \text{LAST SUPERFRAME} \\
\text{Tx2: } L(m_2, n_2) \quad \text{LAST SUPERFRAME} \quad \text{RECEIVE} \quad \text{BEACON} \quad \text{TRANSMIT} \quad \text{END} \\
\text{OTHER TRANSMISSION} \quad \text{CHANGE} \quad \text{FREQ} \\
\text{CH: Tx1} \quad \text{CH: Tx2} \quad \text{SENSOR: N1}
\]

Figure 3.3 The example of the communication process

3.3. Multi-Channel Assignment by BFA

We adopt the DSSS spread spectrum communication in MSF-MAC because our protocol is oriented to long-distance and anti-interference scenarios. It transmits data with different spreading gains, which is called spreading factor(SF), and different SFs correspond to different communication distances. The SFs are orthogonal to each other, and they are directly proportional to communication distance and inversely proportional to communication speed. Through combining the characteristics of spread spectrum and greedy algorithm for multi-channel assignment based on BFA, the MSF-MAC allocates channels to nodes with different rates based on the nodes’ distances and traffic characteristics in order to maximize the system throughput.

Here we take Lora spread spectrum as an example of DSSS, (1) shows the data rate (DR) of Lora.

\[
DR = SF \times \left(\frac{BW}{2^SF}\right) \times CR \quad (1)
\]

\(BW\) represents the spread spectrum modulation bandwidth, \(SF\) represents the spreading factor, and \(CR\) represents the error correction rate. Due to \(BW\) and \(CR\) are normally constants, (1) could be converted as (2).

\[
y = C \times \frac{x}{2} \quad \left(SF_{min} \leq x \leq SF_{max}, C \text{ is positive integer} \right) \quad (2)
\]

At the same super-frame time \(T\), the transmission capacity (TC) of different DR channels is different too, and the formula could be described as (3). Moreover, the Table II shows the relationship in Lora between DRs and SFs.

\[
TC(SF_i) = T \times DR(SF_i)_{max} \quad (0 \leq i \leq N_{SF}) \quad (3)
\]
The DRs with different SFs in Lora

| SF | 6   | 7   | 8   | 9   | 10  | 11  | 12  |
|----|-----|-----|-----|-----|-----|-----|-----|
| $DR_{\text{max}}$ (bps) | 9380 | 5468 | 3125 | 1757 | 976 | 839 | 293 |

Taking the network model in Fig 3.1 as an example, after receiving the RTS request from node A in channel $(f_s, SF_i)$, the coordinator calculates the channel index $f_n$ and packet number $l$ of the node's next transmission through the following algorithm in TABLE III.

### TABLE III. The MSF-MAC’s channel assignment algorithm

1. while $i \leq N_{SF}$ do
2. if $l \leq M(f_s, SF_i)$ then
3. $f_n = \text{Index}(f_s, SF_i)$; return $f_n$;
4. else
5. while $j \leq N_f$ do
6. if $f_j$ is idle and $l \leq M(f_j, SF_i)$ then
7. $f_n = \text{Index}(f_j, SF_i)$; return $f_n$;
8. endif
9. end while
10. endif
11. $i++;$
12. end while
13. return $\text{Index_of_maxlen}$;

When $l$ is greater than the remaining transmission capacity ($TC$) of RTS’s channel which called $M(f_s, SF_i)$, it will search the other frequencies which have the same SF first. If the channels are also occupied, it will increase SF and repeat searching like the previous operation. In the end, if there is still no enough space for transmission $l$, the algorithm will return the packet number and the channel index which has the maximum $M$ in the searching process.

### 4. PERFORMANCE EVALUATION

In order to further test the actual performance of the MSF-MAC protocol, we conducted simulation tests on the system throughput and average delay in the NS2 (Version NS2.35) simulation environment. Based on the multi-channel network model which proposed by Professor Ramon for NS2 improvement simulation in the paper[10], we add the MSF-MAC protocol’s code and modify appropriately in the MAC layer to suitable for Lora WSNs, such as each SF channel has its own link bandwidth and control/data rate are equal to DR values, as well as modified the AODV adaptively into a clustering protocol and add channel allocation algorithm’s code in the network layer. The simulation uses the actual working parameters of the Lora spread-spectrum chip called Sx1278 as the source of our simulation parameters, including the spread factors, data rates, bandwidths, coding rates and so on as shown in TABLE IV.
### TABLE IV. Simulation parameters

| Parameter         | Value                          |
|-------------------|--------------------------------|
| Channel number    | 1-4                            |
| Node number       | 2-20                           |
| SF number         | 6-12                           |
| Bandwidth         | 125kHz                         |
| Control/Data rate | 293-9380 bps                   |
| Packet size       | 10-160 bytes                   |
| Range             | 1000*1000 m                    |
| Super-frame time  | 1020ms                         |
| CR                | 4/5                            |
| RTS size          | 46 bytes                       |
| CTS size          | 46 bytes                       |
| ACK size          | 40 bytes                       |
| MBCN size         | 72 bytes                       |
| MAC header        | 20 bytes                       |
| Simulation time   | 50 s                           |
| Sample rate       | 1 times/s                      |

In NS2.35, we mainly compare the performance of MSF-MAC and 802.11 in terms of system throughput and average latency, and show the graphs for single channel and multi-channel scenarios. We can conclude that as the number of nodes increases, the performance of MSF-MAC is significantly better than 802.11.

#### 4.1. single-channel 802.11 and MSF-MAC in system throughput

First of all, we consider the situation of SF=6. The length of data is 155 bytes. As can be seen from Figure 4.1, when there are 1 to 3 nodes in the cluster, the throughput of MSF-MAC is slightly higher than 802.11, however, when the number of nodes changes from 4 to 8, the MSF-MAC increases slower than 802.11, this is relevant to the control frame cost and protected period’s overhead. When it changes from 9 to 16, MSF-MAC’s throughput is a little higher than 802.11 about 100bps, and both gradually become stable.

In the case of SF=7, because the data rate is lower than SF=6, it will cause an increase in transmission time. Therefore, the protection slot time at SF=7 should be set longer than that at SF=6 to avoid collisions when the transmission time is not enough for one data transmission. The length of data is 140bytes in this case.

It can be seen in Figure 4.1 that when SF=7, the throughput will reach a stable value after the number of nodes is 4, which is mainly limited by the bandwidth. After that, as the number grows, the difference between MSF-MAC and 802.11 is always about 200bps, which is mainly due to the increase in the cost of guard slots and the proportion of control expenses.

![Figure 4.1 The system throughput in single-channel](image-url)
4.2. single-channel 802.11 and MSF-MAC in packet delay

We first talk about the performance in the case of SF=6, from Figure 4.2, we could conclude that before the number of nodes reaches 11, the average delay of MSF-MAC is still slightly higher than 802.11, and from 9 to 16, the MSF-MAC is basically unchanged, but 802.11 still increases steadily, due to the 802.11’s delay is proportional to the number of nodes’ collisions. However, with the number of nodes increasing, the most time of MSF-MAC are assigned to the scheduled access period, the nodes who have data transmission request have to wait until the beacon frame is monitored and free CSMA time slots are available, this is a fundamental difference between the two protocols. Furthermore, the delay of MSF-MAC is mainly caused by the sequence of data requests, the number of request packets, and the scheduling priorities. The simulation result shows that the delay of data packets in each node is changed from high to low, while the 802.11’s latency is almost high. Therefore, MSF-MAC is more suitable for distributed WSNs which have processing priority.

It can be seen from Figure 4.2 that compared with SF=6, the delay is much higher at SF=7, because the lower transmission rate increases the transmission time. On the other hand, the delay of 802.11 continues to increase due to the increase in collision probability, while the delay of MSF-MAC remains basically stable after the number of nodes exceeds the transmission capacity (TC), since it is always in the scheduling stage.

![Figure 4.2 The average packet delay in single-channel](image)

4.3. multi-channel 802.11 and MSF-MAC in system throughput

As shown in Figure 4.3, both 802.11 and MSF-MAC protocol are now SF=7 and the transmission byte is 140 bytes. The throughput difference between the two protocols on average access is about 1000 bps, and this is caused by the excessive proportion of control expenditures at low data rates. Therefore, higher SF channels such as SF=11 and SF=12 are not suitable as control channels. At this time, they can only be used as data channels.

![Figure 4.3 The system throughput in multi-channel](image)

When the number of channels is 4, two new channels with SF = 6 are added to the original two channels with SF = 7. Because nodes use random access in 802.11, when the number of nodes
increases, collisions caused by the uneven access number of each channel will occur. This phenomenon is more obvious in low-rate channels, such as when the number of nodes is 5–8 and 13–14 in Figure 4.3. Due to MSF-MAC uses a channel allocation method, nodes will be allocated to idle channels according to priority and request order. As the number of nodes increases, the idle channels are gradually filled, and there will be no such imbalance case, but this uneven random access will seriously affect the system throughput of 802.11.

4.4. multi-channel 802.11 and MSF-MAC in packet delay

As shown in Figure 4.4, when the number of channels is 2, the latency of 802.11’s nodes is increasing rapidly. However, the average delay of MSF-MAC always remains low after reaching the transmission capacity (TC), because it is always in the scheduling stage at this time. With the continuous increase of access nodes and the sampling data coming in cycles, the amount of data requested for transmission exceeds the DR value that can be transmitted in a unit time, so MSF-MAC is always in the busy process of scheduling the requested nodes for data transmission.

When the number of channels is 4, it can be seen that the average delay of both protocols is significantly reduced. In short, MSF-MAC rises slowly and always keeps low latency, because the channels are allocated based on the node traffic, while the delay of 802.11 rises rapidly to a small peak when the number of nodes is 5–8, because newly added nodes all access the same channel and cause congestion collision, and after more now nodes access the idle channel, the overall average delay is reduced to a certain extent.

![Figure 4.4 The average packet delay in multi-channel](image)

5. CONCLUSION

In this paper, we proposed a hybrid CSMA/polling scheme multi-channel protocol. We mainly discussed the clustering model of MSF-MAC, the adaptive CSMA / polling super-frame structure, and the pseudo-codes of the spread-spectrum channel allocation algorithm. Finally, we conducted a comparative test on the MSF-MAC and 802.11 protocols in the NS2 simulation environment from a single-channel and multi-channel perspective, proving the feasibility of the MSF-MAC protocol.

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