Cognitive routing optimization protocol based on multiple channels in wireless sensor networks

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Abstract

With the development of modern communication, available spectrum resources are becoming increasingly scarce, which reduce network throughput. Moreover, the mobility of nodes results in the changes of network topological structure. Hence, a considerable amount of control information is consumed, which causes a corresponding increase in network power consumption and exerts a substantial impact on network lifetime. To solve the real-time transmission problem in large-scale wireless mobile sensor networks, opportunistic spectrum access is applied to adjust the transmission power of sensor nodes and the transmission velocity of data. A cognitive routing and optimization protocol based on multiple channels with a cross-layer design is proposed to study joint optimal cognitive routing with maximizing network throughput and network lifetime. Experimental results show that the cognitive routing and optimization protocol based on multiple channels achieves low computational complexity, which maximizes network throughput and network lifetime. This protocol can be also effectively applied to large-scale wireless mobile sensor networks.

Keywords

Multiple channels, cognitive routing, optimization protocol, network throughput, network lifetime

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Introduction

With the development of modern communication, available spectrum resources are becoming increasingly scarce, which reduce network throughput. Moreover, the mobility of nodes results in the changes of network topological structure. Hence, a large amount of control information is consumed, which causes a corresponding increase in network power consumption and exerts a substantial impact on network lifetime. Recent studies have showed that the network lifetime is one of the most essential issues in large-scale wireless mobile sensor networks, whereas network throughput is considered the most important resource in such networks.\(^1\)

The extensive use of wireless communication technology has promoted the development of cognitive radio (CR) technology\(^2\) and the dynamic spectrum access mechanism. Moreover, opportunistic spectrum access (OSA) can effectively improve spectrum efficiency and communication quality.\(^3\)

The latest researches show that the dynamic adjustment of node transmission power and data transmission rate can increase the lifetime and throughput of wireless mobile sensor networks, and shorten the delay of end-to-end communication. Moreover, a suitable OSA can effectively solve the conflicts caused by a large number of nodes in the network.\(^4,5\) However, in these scenarios, multiple users shared the same subcarriers,
which made the traditional orthogonal frequency division multiplexing (OFDM) inferior to CR technology. Solving conflicts among channels is becoming increasingly popular. Interestingly, spectral selection may effectively improve the transmission performance of a neighbor sensor node. The distributed subcarriers and power control algorithms aim to minimize the power consumption of each bit information from subcarriers, and the simulation results demonstrated that the performance of the proposed approach is close to that of the centralized optimal solution. However, the authors only considered the data transmission rate and power consumption of a neighbor sensor node and disregarded the performance of the entire route. Inspired by biological systems, Son et al. proposed a bio-inspired scheduling algorithm that reduces the energy consumption and delay for wireless sensor networks (WSNs), in which the energy-efficient routing path and the energy consumption are investigated using multiple channels for data transmission. Simulation experiment showed the effectiveness of the proposed method.

Several OSAs based on MAC (medium access control) schemes in CR networks are discussed in detail in Sultana et al. The differences between the conventional MAC protocols and OSA-based MAC protocols were investigated. Palma proposed a new communication protocol, named as energy efficiency protocol (EFP), is based on a hop-by-hop transport scheme and is especially devised to simultaneously solve the network energy consumption and the performance of the closed-loop system. The proposed protocol can be implemented by means of three heuristics, basically using distinct rules to control the maximum number of retransmissions allowed in terms of the voltage level of the batteries of the network nodes. El Mougy et al. presented two routing approaches for WSNs; these approaches apply the concepts of node cooperation and information exchange to achieve cognition across multiple network layers. Hanefi proposed a new multichannel allocation approach, named hybrid multichannel allocation for WSNs, named as HMCA in our study, based on hybrid time division multiple access (TDMA) and frequency division multiple access (FDMA) techniques and using dual radio with multichannel communication. Simulation experiment showed the proposed method assured steady and high packet delivery ratios in large-scale networking environments even with hundreds of sensor nodes. Spachos and Hatzinakos presented a real-time cognitive WSN for carbon dioxide monitoring at a complex indoor environment. Experimental results validated the effectiveness of the proposed method.

Although many studies have considered route protocols based on spectrum choice, certain disadvantages require attention. First, some studies cannot be applied to large-scale wireless mobile sensor networks. Second, network lifetime and throughput are not considered (or only one of them is considered) when making route choices. To address these issues, a multiple-channel cognitive routing optimization protocol is proposed in the current work for selecting spectrum while maximizing network lifetime and throughput in large-scale wireless mobile sensor networks. Our proposed method based on the model of signal-to-interference plus noise ratio (SINR) can effectively solve the dynamic spectrum allocation, data transmission rate, and power control problems. The rest of this article is organized as follows. Section “Related work” summarizes system model, protocol assumption, performance analysis, and so on. Section “Results and discussion” is about simulation parameters, simulation results, and experimental analysis. Finally, conclusion of this study along with the future work is mentioned in section “Conclusion.”

Related work

A three-layer network topology is typically used in large-scale wireless mobile sensor networks, in where the information collected by a cluster head will be transmitted to the base station in multiple hops. In this study, a corresponding clustering process of Deng et al. and Hadi et al. is adopted to analyze multiple hops transmission between cluster heads and base stations.

System model

Assume that primary users (PUs) and secondary users (SUs) represent cluster nodes in large-scale wireless mobile sensor networks. The multiple address access technology of OFDM is used in PUs, and they possess user authority. Moreover, PUs can only transmit in their allocated spectra. This access technology is only controlled by the destination nodes and is not affected by the non-authoritative users. However, SUs have not any authorized spectrum and only transmit data with the help of the idle spectrum of PUs.

A spectrum is divided into two separate channels: data channel (DC) and common control channel (CCC). DC consists of a series of discrete sub-bands, which are marked as \( f_{\text{min}}, f_{\text{min} + 1}, \ldots, f_{\text{max}} \). The band of each sub-band is marked with a discrete subscript \( \omega \). CCC\( f_{\text{sc}} \) is used to consult with the spectrum access of SUs. \( f_{\text{sc}} \notin \{ f_{\text{min}}, f_{\text{max}} \} \) is generated by the interaction information from the control channels.

Destination nodes are assumed to be fixed cognitive infrastructure that permits access from PUs and SUs. Transmitters are adjusted to a series of discrete bands according to a variable carrier set by all users including PUs and SUs. PUs directly communicate with SUs with a single hop through the base stations, and SUs
transmit sensor data to the base stations with multiple hops. A multiple wireless network is typically modeled as a directed communication graph \( G = (C, E) \), where \( C = \{ c_1, \ldots, c_M + K \} \) denotes the limited set of PUs, \( |C| = M + N \); \( PU = \{ c_1, \ldots, c_M \} \) and \( SU = \{ c_M + 1, \ldots, c_M + K \} \) represent the sets of PUs and SUs, respectively; and \((c_i, c_j) \in E\) indicates the directed wireless links between \( c_i \) and \( c_j \).

**Protocol assumptions**

For convenience, the following protocol assumptions are used in this study:

1. All SUs have the same physical characteristics.
2. The location and velocity of all SUs are known.
3. All SUs can calculate the time of packet transmission, which is defined as the ratio of the size of a packet to the transmission rate.
4. To satisfy the requirements of different communication power and data transmission rates, each SU may be permitted to select multiple subcarriers. Data transmission rate, communication power, and subcarrier may be assigned with the corresponding algorithms.

**Definitions**

Prior to designing the cognitive routing and optimization protocol based on multiple channels (CROMC) in large-scale mobile WSNs, we first present the relevant definitions used in this study.

**Spectrum hole.** Spectrum hole is an important parameter in cognitive wireless technology. It represents the opportunity possessed by a spectrum. The frequency point is adopted as the spectrum hole of a user \( c_i \). The communication power of \( c_i \) should ensure the need of the bit error rate (BER) from the receiving terminal and the interference excluded from those of the PUs and SUs in this work. This formula is mathematically described as follows

\[
\frac{P_y(f)A_y(f)G}{N_y(f) + \sum_{v_j \in C, k \neq i} P_k(f)L_k(f)} \geq \lambda_{SU} \quad (1)
\]

\[
\frac{P_y^o(f)}{N_l(f) + \Delta l(f)} \geq \lambda, \quad \forall v_j \in C \text{ ongoing} \quad (2)
\]

In equation (1), \( P_y(f) \) means the communication power of the link \((c_i, c_j)\) within the frequency of \( f \), \( A_y(f) \) means the transmission loss from point \( c_i \) to point \( c_j \), \( G \) means the processing gain, \( N_y(f) \) presents the noise of the receiver within the frequency of \( f \), and \( \lambda_{SU} \) represents the threshold of SINR that ensures the BER of SU destination. In equation (2), \( P_y^o(f) \) means the signal power received from user \( c_i \), \( N_l(f) \) represents the noise and interference of \( c_i \) before transmitting from the user of \( c_i \), \( \Delta l(f) \) means the interference generated from the user of \( c_i \), and \( \lambda \) presents the threshold of SINR derived from the PUs or SUs according to the type of \( c_i \).

According to equations (1) and (2), we can calculate the available minimum and maximum transmission power of every frequency point from each SU, respectively. The corresponding formulas are defined as follows

\[
p_{y}^{\min}(f) = \frac{\lambda_{SU} \cdot \left( N_y(f) + \sum_{k \in C, k \neq i} P_k(f)L_k(f) \right)}{A_y(f)G} \quad (3)
\]

\[
p_{y}^{\max}(f) = \min_{l \in C} \left\{ \frac{P_y^o(f)/\Delta l(f)}{\lambda_{SU}} \right\} \quad (4)
\]

where \( p_{y}^{\min}(f) = \{ p_{y}^{\min}(f) \} \) and \( p_{y}^{\max}(f) = \{ p_{y}^{\max}(f) \} \), which represent the sets of minimum and maximum communication power in the link \((c_i, c_j)\) respectively.

If \( p_{y}^{\min}(f) < p_{y}^{\max}(f) \), then the frequency point \( f \) may be regarded as a spectrum hole by the SU of \( c_i \).

**Latency.** Latency is a time delay between the source node and the destination node in a WSN. It is presented as follows

\[
T_{av} = T_i + T_p + T_q \quad (5)
\]

where \( T_{av} \) means the average latency, \( T_i \) presents the transmission latency, \( T_p \) denotes the process latency, and \( T_q \) means the queuing delay. The data \( N_0 \) is assumed to be divided into \( K \) packets, where \( K \) is a parameter determined from the transmission rate, transmission power, and route. Hence, every factor in equation (5) is represented as follows

\[
T_i = \sum_{i=1}^{n} \frac{N_0/K}{R_{i-1,i}} \quad (6)
\]

\[
T_p = \sum_{i=1}^{n} \frac{N_0/K}{R_p} \quad (7)
\]

\[
T_q = \sum_{i=1}^{n} \left( \frac{N_0(K-1)}{2 \times K} + Q_i \right) \times \left( \frac{1}{R_{i-1,i}} + \frac{1}{R_p} \right) \quad (8)
\]

In equations (6)–(8), \( N_0 \) denotes the data in the source node, \( K \) denotes the number of data packets, \( Q_i \) represents the data that will be sent to the queue, \( R_{i-1,i} \) represents the transmission rate in the link \((i-1, i)\), \( R_p \) denotes the data process rate, and \( n \) means the number of hops between the source node and the destination node.

Assume that \( K \) packets are under the same condition. Then, the total latency transmitting \( N_0 \) bits may be represented as follows
\[
T_{\text{total}} = K \times (T_i + T_p + T_q)
\]
\[
= K \times \left( \sum_{i=1}^{n} \left( \frac{N_0}{R_{i-1,j}} + \frac{N_i/K}{R_{i,j}} \right) + \sum_{i=1}^{n} \left( \frac{N_i(K-1)}{2R_{i,j}} + Q_i \right) \times \left( \frac{1}{R_{i-1,j}} + \frac{1}{R_{i,j}} \right) \right)
\]

In general, when a vast amount of data are required to be transmitted in the large-scale mobile sensor networks, the value of \( K \) is extremely large. Then, equation (9) is typically approximated as follows
\[
T_{\text{total}} = K \times \sum_{i=1}^{n} \left( \frac{N_0}{2} + Q_i \right) \times \left( \frac{1}{R_{i-1,j}} + \frac{1}{R_{i,j}} \right)
\]

**Network lifetime.** The maximization of network lifetime can be divided into the following aspects: the minimization of path energy consumption and the realization of load balancing, which needs to consider the residual energy of each node and the amount of queuing data, that is, energy standard deviation. In this section, we discuss only the power consumption in spectrum allocations, no more network lifetime. The load balancing of route is discussed in the following sections.

Power consumption is modeled as the sum of the consumption of transmission and processing. For an \( H \) hop route with \( N_0 \) data, the total power consumption is described as follows
\[
E_{\text{total}} = K \times \sum_{i=1}^{H} \left( \frac{P_{i-1,j} \times (N_0/K)^2}{R_{i-1,j}} + E_p \times N \right)
\]

where \( P_{i-1,j} \) denotes the power consumed by 1 bit data and \( E_p \) represents the average power required to process 1 bit data, including decoding and coding.

**Route capability.** The topology of an SU is usually changed because of the following reasons: First, PU access forces the spectrum withdrawal of an SU. Second, the mobility of an SU also changes its topological structure. That is, if the two nodes associated with a link are in their transmission range without affecting the communication of PUs in the network, then the link is accessible. However, changes in topology will result in broken links and packet loss. Therefore, only a limited number of data can be successfully transmitted over a limited route lifetime. Notably, route capability means that those data can be transmitted in links, and route lifetime represents the time that those data can be successfully transmitted.

Recent research shows several spectrum prediction methods based on history information, which can not only provide effective spectrum utilization but also predict the spectrum stability of links. However, Hanefi believed that route capability is more important than simple route stability for on-demand routing. For example, when the data are transmitted to node \( c_i \), the links before \( c_i \) are broken, but data remain accessible. Although spectrum prediction methods are used to predict spectrum stability, broken links with spectrum withdrawal should still be addressed. For simplicity, when analyzing route capability and lifetime, the mobility of SUs is only considering. The route capability of \( N_0 \) may be expressed as
\[
\sum_{i=1}^{h+1} (N_0 + Q_i) \left( \frac{1}{R_{i-1,j}} + \frac{1}{R_{i,j}} \right) \leq t_{h-1,h}, 1 \leq h \leq H
\]

From equation (12), it can be obtained that
\[
N_0 = \min_{1 \leq h < H} 2 \times \left( \frac{t_{h-1,h}}{K} - \sum_{i=1}^{h+1} Q_i \left( \frac{1}{R_{i-1,j}} + \frac{1}{R_{i,j}} \right) \right)
\]

where \( t_{h-1,h} \) denotes the prediction connection time of the link \( (c_{h-1}, c_h) \), which satisfies the following inequation
\[
\left( x_{h-1}(t_1) + v_{h-1}(t_1) \cdot \cos \theta_{h-1}(t_1) \cdot t_{h-1,h} \right)^2
\]
\[
\left( -x_{h-1}(t_1) - v_{h-1}(t_1) \cdot \cos \theta_{h-1}(t_1) \cdot t_{h-1,h} + y_{h-1}(t_1) + v_{h-1}(t_1) \cdot \sin \theta_{h-1}(t_1) \cdot t_{h-1,h} \right)^2
\]
\[
\left( -y_{h-1}(t_1) - v_{h-1}(t_1) \cdot \sin \theta_{h-1}(t_1) \cdot t_{h-1,h} \right)^2
\]

where \( t_1 \) represents the reference start time and \( R_{h-1,h} \) indicates the maximum connected distance between \( c_{h-1} \) and \( c_h \), which is determined with transmission power, total noise interference, and SINR threshold value.

**Protocol design**

Given the current spectrum environment and hardware constraints, CROMC aims to maximize network throughput and lifetime. Figure 1 shows the overall frame of CROMC. Hence, the following assumptions are presented. First, the node with the largest residual energy in the cluster is selected as the cluster head. Second, information in the network is transmitted through every cluster head with multiple hops. Therefore, the network lifetime is maximized through path loss and energy balance according to equations (3) and (4). The network throughput is inversely proportional to path transmission delay when data are transmitted simultaneously. Therefore, maximizing network lifetime and throughput is equivalent to minimizing path loss and delay and comprehensively considering
the load balancing problem. To minimize path power and delay, we first select the spectrum $F_{ij}$ and the corresponding transmission power of $P_{ij} = \{P_{ij}(f)\}_{f \in F_{ij}}$.

Therefore, the multi-objective optimization expression is established and load balancing is discussed in subsection “Routing.” For simplicity, we assume that the spectrum of $F_{ij}$ may be discrete sub-band sets and the transmission power of $P_{ij}$ at each frequency point exhibits no difference. The mathematical expression is described as follows:

P1:
Given: $(c_i, c_j), I_j, N_j, A_{ij}, P_{ij}^{\min}, P_{ij}^{\max}, P_{Bgt}^b, \Delta f_{Bgt}$
Find: $F_{ij}, P_{ij}, \psi, K$
Minimize: $T_{\psi}, E_{\psi}$

\[
\begin{align*}
\text{s.t. max} \{P_{ij}^{\min}(f)\} &\leq P_{ij}(f) \leq \text{min} \{P_{ij}^{\max}(f)\}, \forall f \in F_{ij} \\
P_{ij} &\leq P_{ij}(f)w\Delta f_{ij} \leq P_{Bgt}^b \\
N_{\psi} &\geq N_0
\end{align*}
\]  
(15)

where $\Delta f_{ij} = |F_{ij}|$ means the number of sub-bands, $I_j = [I_j(f_{\text{min}}), I_j(f_{\text{min}} + 1), \ldots, I_j(f_{\text{max}})]$ denotes the interference vector at the receiver of $c_j$, $N_j = [N_j(f_{\text{min}}), N_j(f_{\text{min}} + 1), \ldots, N_j(f_{\text{max}})]$ represents the noise vector at the receiver of $c_j$, $A_{ij} = [A_{ij}(f_{\text{min}}), A_{ij}(f_{\text{min}} + 1), \ldots, A_{ij}(f_{\text{max}})]$ means the transmission loss vector, and $c_i, c_j \in SU$. The first constraint condition shows the existence of spectrum holes, whereas the other two conditions indicate the constraint from the user’s hardware. The last constraint emphasizes that routing capability should be larger than the amount of data to be transferred. However, such routes are occasionally not found in networks, thereby showing that the constraint conditions are too strict to satisfy. Therefore, when we solve the aforementioned optimization problem, the constraint condition can be ignored and applied only to the route selection standard.

Evidently, the solution for P1 is the minimization of finite multiple target vectors. Therefore, the multi-objective optimization problem can be transformed into a single-objective optimization problem by using the weight factor, which is described as follows:

P2:
Given: $(c_i, c_j), I_j, N_j, A_{ij}, P_{ij}^{\min}, P_{ij}^{\max}, P_{Bgt}^b, \Delta f_{Bgt}$
Find: $F_{ij}, P_{ij}, \psi, K$
Minimize: $\Phi_{\psi} = \lambda_1 T_{\psi} + \lambda_2 E_{\psi}$

\[
\begin{align*}
\text{s.t. max} \{P_{ij}^{\min}(f)\} &\leq P_{ij}(f) \leq \text{min} \{P_{ij}^{\max}(f)\}, \forall f \in F_{ij} \\
P_{ij} &\leq P_{ij}(f)w\Delta f_{ij} \leq P_{Bgt}^b \\
\Delta f_{ij} &\leq \Delta f_{Bgt} \\
N_{\psi} &\geq N_0
\end{align*}
\]

(16)

where $\lambda_1 \in \Lambda$ means the importance of each target, and

\[
\lambda_1 > 0, \sum \lambda_i = 1
\]
(17)

$\Phi_{\psi}$ is described in detail as follows

\[
\Phi_{\psi} = \lambda_1 K \cdot \sum_{i=1}^{H} \left(N_0/2 + Q_i\right) \left(\frac{1}{R_{i-1,i}} + \frac{1}{R_p}\right) + \lambda_2 K \cdot \sum_{i=1}^{H} \left(\frac{P_{i-1,i}(N_0/K)^2}{R_{i-1,i}} + E_p N_0/K\right)
\]
(18)

Given that the condition of equality is obtained from an inequality, we set

\[
K = \sqrt{\frac{\lambda_2 \sum_{i=1}^{H} \left(N_0/2 + Q_i\right) \left(\frac{1}{R_{i-1,i}} + \frac{1}{R_p}\right)}{\lambda_1 \sum_{i=1}^{H} \left(N_0/2 + Q_i\right) \left(\frac{1}{R_{i-1,i}} + \frac{1}{R_p}\right)}}
\]
(19)

Then, $\Phi_{\psi}$ may achieve the minimization value, it is that

\[
\Phi_{\psi} = 2\sum_{i=1}^{H} \left(N_0/2 + Q_i\right) \left(\frac{1}{R_{i-1,i}} + \frac{1}{R_p}\right) \sum_{i=1}^{H} \left(P_{i-1,i}N_0^2/R_{i-1,i}\right) + \lambda_3 HE_p N_0
\]
(20)

Furthermore, considering the condition of the Cauchy–Schwarz inequality, we set

\[
\frac{\lambda_2 N_0^2 P_{i-1,i}}{\lambda_1(N_0/2 + Q_i)(1 + R_{i-1,i}/R_p)} = \eta
\]
(21)
where \( \eta \) is a given constant, of which the dimension with \( P_{i-1, i} \) can be defined as the Cauchy–Schwarz power. We further obtain the minimization of \( \Phi_{p_{ij}} \), and the corresponding mathematical expression is presented as follows

\[
\Phi_{p_{ij}} = 2 \cdot \sum_{i=1}^{H} \sqrt{\lambda_1 \lambda_2 N_0^2 (N_0/2 + Q_i) \rho_{i-1, i} + \lambda_2 H E_{pi} N_0}
\]

where \( \rho_{i-1, i} = \frac{P_{i-1, i}}{E_{pi, i}} \left( \frac{1}{\rho_{i, i}} + \frac{1}{E_{pi, i}} \right) \).

**Spectrum allocation and routing**

To obtain the maximum network lifetime and throughput according to the goal of the protocol design, we achieve only the optimization problem of P2 and consider the energy equilibrium and the fourth constraint condition (i.e., routing capability) in P1. According to equations (21) and (22), the process may be executed in two steps: minimizing the spectrum allocation of \( \rho_{i-1, i} \) and the routing of \( \Phi_{p_{ij}} \).

**Spectrum allocation.** The spectrum allocation algorithm is implemented by every distributed SU with the given spectrum environment, which is described as follows:

**P3:** Given: \((c_i, e_i), I_j, N_j, A_{ij}, P_{ij}^\text{min}, P_{ij}^\text{max}, f_{\text{Bgt}}, \Delta f_{\text{Bgt}}\)  
Find: \(F_{ij}, P_{ij}\)  
Minimize: \(\rho_{ij}\)

\[
\text{s.t. } \max\{P_{ij}^\text{min}(f)\} \leq P_{ij}(f) \leq \min\{P_{ij}^\text{max}(f)\} \quad \forall f \in F_{ij} \\
P_{ij} = P_{ij}(f)w \Delta f_{\text{Bgt}} \leq f_{\text{Bgt}} \\
\Delta f_{ij} \leq \Delta f_{\text{Bgt}}
\]

\[
\frac{\lambda_2 N_0^2 p_{ij}}{\lambda_1 (N_0/2 + Q_i)(1 + R_{ij}/R_p)} = \eta
\]

From the fourth constraint condition, we can obtain

\[
P_{ij} = \frac{\lambda_1 \eta (N_0/2 + Q_i)(1 + R_{ij}/R_p)}{\lambda_2 N_0^2 R_{ij}}
\]

We set \( R_{ij} = M w \Delta f_{ij} \), where the value of \( M \) is determined with the selected modulation and encoding. According to equations (23) and (24), we can obtain the following expression

\[
P_{ij}(f) = \frac{\lambda_1 \eta M (N_0/2 + Q_i)(1 + R_{ij}/R_p)}{\lambda_2 N_0^2 R_{ij}}
\]

To obtain the solution for P3, the spectrum environment should be evaluated to find the optimal transmission power at each frequency point. Then, the transmission sub-band sets are selected based on the optimization results. From \( \rho_{i-1, i} = P_{i-1, i}/R_{i-1, i} \), the optimization of P3 is equivalent to the maximization of \( R_{ij} \), that is, \( \Delta f_{ij} \). Therefore, we can obtain \( R_{ij1}, R_{ij2} \), and \( R_{ij3} \) from the last three constraints of P3. The corresponding mathematical expression is defined as follows

\[
R_{ij1} = \left( \frac{\lambda_2 N_0^2 p_{\text{Bgt}}}{\lambda_1 \eta (N_0/2 + Q_i)} - 1 \right) R_p
\]

\[
R_{ij2} = M \cdot w \Delta f_{\text{Bgt}}
\]

\[
R_{ij3} = \frac{\lambda_1 \eta M (N_0/2 + Q_i)}{\lambda_2 N_0^2 \max\{P_{ij}^\text{min}(f)\} - \lambda_1 \eta M (N_0/2 + Q_i)/R_p}
\]

Then, the transmission sub-band sets of \( \Delta f_{ij}(f) \) and the optimal transmission power of \( P_{ij}(f) \) are obtained at each frequency point, which are

\[
\Delta f_{ij}(f) = \begin{cases} 
\max\{P_{ij}^\text{min}(f)\}, & f \in F_{ij} \\
\min\{P_{ij}^\text{max}(f)\}, & f \in F_{ij}^\text{null}
\end{cases}
\]

\[
P_{ij}(f) = \frac{\lambda_1 \eta M (N_0/2 + Q_i) - \lambda_1 \eta M (N_0/2 + Q_i)/R_p}{\lambda_2 N_0^2 R_{ij}}
\]

where \( \lfloor \cdot \rfloor \) indicates the lower bound integer of the number of sub-bands. According to equations (29) and (30), the selection of the spectrum of \( F_{ij} \) should satisfy the following sub-band sets. First, the optimization transmission power of each sub-band should be as small as possible. Second, the number of sub-bands should match the optimization of the transmission power thereby determining the spectrum allocation and the number of sub-bands of each link. Finally, the optimal transmission power of each link can be calculated using equation (30). If no spectrum resource based on the negotiation result is available, then the message will not be transmitted temporarily. The corresponding algorithm is described in Table 1.

**Routing.** The goal of spectrum allocation is the minimization of \( \rho_{i, i} \). After determining spectrum and
transmission power among all links, a route is selected to minimize $\Phi_\Psi$ in equation (20). Then, the solution for P2 is completed. Each link should be assigned a link cost of $\omega_{ij}$ according to the system model described in subsection “System model.” Therefore, $\Phi_\Psi$ denotes the total cost of the routing plus factor of $\lambda_2 HE_p N_0$. The link cost of $\omega_{ij}$ can be defined as follows:

$$\omega_{ij} = \sqrt{\lambda_1 \lambda_2 N_0^2 (N_0/2 + Q_i) \rho_j}$$

When $Q_i = 0$, $\Delta_{ij} = \Delta R_{bg}$, the minimum value of $\omega_{ij}$ may be obtained using equation (31), that is

$$\omega_{ij} = \frac{1}{2} \lambda_1 N_0 \left( \frac{1}{M_{\nu}} + \frac{1}{R_{\text{proc}}} \right) \cdot \sqrt{\eta} \tag{34}$$

For route capability, we should select the route that comprises the link with the maximum route capability and can guarantee $N_0 \geq N_0$. From equation (13), we can draw the following conclusion. For a given possible route, that is, $t_{h-1, h}$, $Q_i$, $h$, and $R_p$, the maximization of routing capability is equivalent to the maximization of each $R_{e-1, i}$. Therefore, route capability will not be handled, only when $N_0 \geq N_0$. However, if no link exists in which route capability is more than $N_0$, then the source node can only transfer data in real time by using the current optimal routing.

In conclusion, for given the non-negative weight subgraph $G_0$, the positive constant $\xi$, and the node pair $(s, t)$, the problem becomes seeking the shortest route from $s$ to $t$, which are arranged in ascending order according to total weight.

The $\xi$ shortest path problem is a classic shortest path problem that seeks multiple paths based on weight in ascending order. Many researchers have proposed a series of algorithms, which uses the distributed algorithm to search for a route. That is, each SU can update and send route information to its neighbor nodes in the spectrum negotiation stage. Then, the base station makes a decision based on the received routing information according to the sum weight in ascending order based on the received routing information. If the negotiation indicates that no link exists between two given users, then the users will neither update nor transmit routing information. The existence and uncertainty of the shortest path is described as follows.

**Lemma 1 (existence).** The shortest route exists in a feasible route that satisfies the route selection method.

**Proof.** From the preceding description, SU’s update and transmit routing information only in negotiations with available links. Therefore, we can draw the following conclusions. First, the route information reaching the base station represents a feasible route. Second, the transmission time is exceedingly long for all available information to reach the base station. The shortest route is a feasible route with the sum of the minimum weight, which satisfies the route selection method. Thus, Lemma 1 is proven.

**Lemma 2 (deterministic).** The shortest route can be determined.
weights compose a finite element set, which is called as mechanism when transmission error occurs. In
transmission power. It also boots the routing maintenance rate, and transmission power. Finally, each node
the allocated spectrum, data transmission rate, and transmission power. Each node receives the corresponding parameters and adjusts 
transmission rate, and transmission power, are transmitted to all the nodes along the selected route. Each node receives the corresponding parameters and adjusts 
transmission rate, and transmission power. Therefore, Lemma 2 is proven.

Protocol description

Various on-demand routes have been proposed. For example, dynamic source routing (DSR)\textsuperscript{21} and ad hoc on-demand distance vector routing (AODV)\textsuperscript{22} are classic on-demand route protocols when users need to transmit data. Similar to the DSR and AODV protocols, the CROMC protocol is also divided into two stages: the establishment stage of route and the steady state of data transmission to the base station. Figure 2 presents the procedure of CROMC protocol.

During the establishment phase, source nodes broadcast a routing request (RREQ), and SUs negotiate the spectrum, data transmission, and transmission power with each neighbor node. Then, the negotiation results and route information are transmitted to the next hop until they reach the base station. With the aid of the received information, the base station selects the route with the smallest weight that satisfies the routing capacity. Then, parameters, such as spectrum, data transmission rate, and transmission power, are added to the routing records. After calculating the link weight using equation (32), each node updates the route weights and broadcasts them. If no negotiation spectrum is available, then the RREQ is discarded.

When the base station receives all route information, a suitable route that satisfies the routing capability and possesses the sum of the minimum routing weight will be selected as described in subsection “Routing.” A routing response will also be sent to the routing initiator. The routing response is composed of the following information: the selected route records, data transmission rate, transmission power, and packet number. After receiving the response, the root initiator will send the packet series via the selected route and channel in the steady transmission stage. All negotiation information and control packets are transmitted using CCC.

Steady transmission. The routing establishment stage, which is simpler than the steady-state stage, has two parts: data transmission and routing maintenance. All packets in the steady-state transmission phase are transmitted through DC.

Prior to transmitting data, the source node first divides the data into $K$ packets and then sends the packets according to the allocated spectrum, data transmission rate, and transmission power. If the data cannot be received completely, then the packet is considered lost.
due to the delay in packet transmission. The possible reasons include a change in node speed or direction, PU access, network congestion, and hardware failure in the course of transmission. Therefore, confirmation information should be added during the data transfer process. When a packet is successfully received, the node will send an acknowledgment (ACK) message to the parent node, which confirms whether the packet has been sent successfully. After completing the data transmission process, the link is disconnected and the spectrum resource is released. Subsequently, the packets are transmitted through each node according to the selected routing, determined spectrum, data transmission rate, and transmission power until the base station.

When a route is broken, route maintenance is activated and the corresponding node acts as a new source node and rebuilds the route according to the aforementioned method, thereby continuing data transmission. All negotiation information and the control packet are retransmitted via CCC.

**Performance analysis of CROMC**

**Computational complexity analysis.** We analyze the proposed protocol to evaluate the computational complexity of CROMC. The SUs and the base station play different roles. Hence, computational complexity should be discussed separately.

For each SU, spectrum negotiation, including determining the optimal transmission power and the number of sub-bands of the available spectrum for every frequency point in the spectrum environment, will be executed among its neighbor nodes. For a given spectrum, the computational complexity of the optimal transmission power is $\Theta(1)$ if the number of subcarriers is $|F|$. Meanwhile, on the basis of the spectrum selection and sub-band determination algorithm, we can draw the conclusion that the computational complexity of the available spectrum depends mainly on the variety of selected algorithms. The computational complexity of the fast classification algorithm is $\Theta(|F| \cdot \log (|F|))$. If each SU possesses neighbor node, then the total computational complexity is $\Theta(|S| \cdot |F| \cdot \log (|F|))$.

After receiving route information, the base station should rank the routing weights in ascending order and select a suitable route as the data transmission path. Therefore, in determining the appropriate route, the computational complexity of the base station is also dependent on the complexity of the classification algorithm. Assume that $\eta$ reachable routes are available. Then, the computational complexity of the base station is also $\Theta(\eta \log \eta)$.

In summary, the computational complexity of the CROMC protocol is effective in polynomial time.

**Effect of mobility.** The impact of node mobility is inevitable in large mobile WSNs. For the proposed protocol, node mobility will affect the change in link weights. Consequently, the sum of possible route weights obtained during the route establishment stage will change over time. In this study, we analyze the impact of mobility on the change in link weight between two points.

Given a reference moment $t_0$, the weight of link $l_i$ is $w_{ij}(t_0)$, the weight of link $l_j$ is $w_{ij}(t_0 + \Delta t)$ over $\Delta t$, and the change in the weight of link $l_i$ is described as follows:

$$
\Delta w_{ij} = w_{ij}(t_0 + \Delta t) - w_{ij}(t_0)
$$

$$
= \left[ A_1 A_2 N_0^2 (N_0 + Q_i(t_0 + \Delta t)) \right] \left( \frac{1}{R_y(t_0 + \Delta t)} + \frac{1}{R_y(t_0 + \Delta t)} \right)
$$

$$
× \left( P_y(t_0 + \Delta t) - P_y(t_0) \right)
$$

$$
= A_1 A_2 N_0^2 (N_0 + Q_i(t_0)) \left( \frac{1}{R_y(t_0 + \Delta t)} + \frac{1}{R_y(t_0 + \Delta t)} \right)
$$

$$
× \left( \frac{\gamma_{LU NI_j}}{A_y(t_0 + \Delta t)} - \frac{\gamma_{LU NI_j}}{A_y(t_0)} \right)
$$

$$
= A_1 A_2 N_0^2 (N_0 + Q_i(t_0)) \left( \frac{1}{R_y(t_0 + \Delta t)} + \frac{1}{R_y(t_0 + \Delta t)} \right) \frac{\gamma_{LU NI_j}}{G}
$$

$$
× \left( \frac{1}{A_y(t_0 + \Delta t)} - \frac{1}{A_y(t_0)} \right)
$$

$$
= A_1 A_2 N_0^2 (N_0 + Q_i(t_0)) \left( \frac{1}{R_y(t_0 + \Delta t)} + \frac{1}{R_y(t_0 + \Delta t)} \right) \frac{\gamma_{LU NI_j}}{G \cdot 10^{\eta}}
$$

$$
× \left( \frac{1}{d_y(t_0 + \Delta t)^{2}} - \frac{1}{d_y(t_0)^{2}} \right)
$$

$$
= U \left( d_y(t_0 + \Delta t)^{2} - d_y(t_0)^{2} \right)
$$

(36)

where $NI_j$ denotes the noise and interference received by the node of $j$.

To clearly understand the equation, we convert it into polar coordinate. Let $c_i$ be located at the original
Therefore, the distribution of $V_{ij}$ can be described as

$$V_{ij} = \frac{f_r(v_i) f_r(v_j)}{\pi} \frac{|\partial f_r|}{\partial v_j} v_{ij}$$

(42)

For equation (41), it is difficult to directly obtain the numerical results. Therefore, the probability density function of $v_{ij}$ can be simulated to obtain the change range of $v_{ij}$. Existing research shows that the random variable of $v_{ij}$ is between 0 and 80 m/s when $v_{max} = 40$ m/s, in which the interval is set to $[0, 2 \times v_{max}]$. From the preceding analysis, we can obtain the following formula

$$E\left\{d_y(t_0 + \Delta t)^{-\frac{1}{2}}\right\} = \frac{1}{\pi} \int_0^{2v_{max}} \int_0^{2v_{max}} \left(\rho_j^2 + (v_{ij} \Delta t)^2 + 2 \rho_j v_{ij} \Delta t \cos \theta_{ij}\right)^{-\frac{1}{2}} f_r(v_i) f_r(v_j) d\theta_{ij} dv_{ij}$$

(43)

Evidently, the factor of $(\rho_j^2 + (v_{ij} \Delta t)^2 + 2 \rho_j v_{ij} \Delta t \cos \theta_{ij})$ is monotonically decreasing from 1 to 1, then

$$E\left\{d_y(t_0 + \Delta t)^{-\frac{1}{2}}\right\} < \frac{1}{\pi} \int_0^{2v_{max}} \int_{-1}^{1} (1 - x^2)^{-\frac{1}{2}} f_r(v_j) dxdv_{ij}$$

(44)

Considering $2 \alpha < 4$ and $\rho_j >> v_{max} \Delta t$, then

$$\approx 2 v_{max} \rho_j^{-\frac{1}{2}}$$

(45)

which can yield the following formula

$$E\left\{\Delta w_{ij}\right\} = U \cdot E\left\{d_y(t_0 + \Delta t)^{-\frac{1}{2}} - d_y(t_0)^{-\frac{1}{2}}\right\}$$

$$< U \rho^{-\frac{1}{2}} (2v_{max} - 1)$$

(46)
The preceding analysis shows that data are transmitted through the route that satisfies routing capacity. Moreover, the impact of node mobility on link weight is not particularly evident and can be disregarded. Therefore, the CROMC protocol can be preferably adapted to wireless mobile sensor networks.

Results and discussion

Simulation parameter

In this section, we describe the simulation parameters used in our experiment as shown in Table 2.

In addition, the parameters $R_\text{p}$, $E_\text{p}$, $\lambda_1$, $\lambda_2$, $k_1$, and $k_2$ are set to 100 Mbps, 10–5 J/bit, 0.5, 0.5, 0.5, and 0.5, respectively.

The Cauchy–Schwarz power of $\eta$ should be analyzed prior to accessing the CROMC protocol. Equations (29) and (30) show that the Cauchy–Schwarz power of $\eta$ is related to the transmission success rate and transmission power of the spectrum after negotiation. Figure 4 presents the detailed experimental results of the average transmission success rate with different $\eta$ values after 50 times.

As shown in Figure 4, the success rate value increases gradually with an increase in $\eta$ and exhibits a steady change trend when $\eta>6000$. Therefore, to obtain a high transmission success rate, the value of $\eta$ is set between 6000 and 7000 in this study.

Simulation results

Figure 5 illustrates the detailed results with different $\eta$ values. As shown in Figure 5, the total energy consumption of $\eta$ decreases sharply with a gradual increase in average throughput. The possible reason for this result is that a low throughput leads to a poor spectrum condition of communication, which consumes more power. In addition, a large power of $\eta$ requires more power with the same throughput.

To study the routing capability of CROMC, different hops of CROMC are presented in Figure 6. Notably, the average distance between the source node and the base station in the stimulation scenario is approximately 3000 m, and the maximum distance of one hop is less than 1000 m. Four hops are executed from the source station to the base station under this scenario. Therefore, our proposed method has fewer hops.

To evaluate the performance of CROMC, we investigated the average throughput and the total power

| Parameter                  | Value                                      |
|----------------------------|--------------------------------------------|
| Network size               | $5000 \times 5000 \text{m}^2$              |
| Source node region         | $[0, 1000] \times [0, 1000]$               |
| PU                        | 25                                         |
| SU                         | 50                                         |
| Spectrum                   | 3.5–3.75 GHz                               |
| Bandwidth of carrier       | 0.5 MHz                                    |
| Bandwidth of common channel| 2 MHz                                      |
| Noise spectrum density     | $-180 \text{dBm/Hz}$                      |
| Subcarrier of PU           | 10                                         |
| Subcarrier of SU           | $<5$                                       |
| SNR of PU                  | 10 dB                                      |
| SNR of SU                  | 5 dB                                       |
| Maximum power of PU        | 0.1 W                                      |
| Maximum power of SU        | 0.05 W                                     |
| Data                       | 500 kbit                                   |
| Arrival rate of PU         | 6/h–50/h                                   |
| Service time of PU         | 120 s                                      |

PU: primary user; SU: secondary user; SNR: signal-to-noise ratio.

Figure 4. Values of success rate for different values of $\eta$.

Figure 5. Values of total energy consumption for different values of average throughput with a threshold of $\eta$ between 6000 and 7000.
consumption of the user with an increment of 50 between 100 and 500. Figures 7 and 8 present the different values of $h$ for the effects of average throughput and total power consumption, respectively. As shown in Figures 7 and 8, the average throughput and total consumption change slightly with an increase in $h$. Figure 7, the average throughput is 200 Kbps because the multi-hop is a continuous transmission system. The average throughput can be calculated based on transmission rate per hop and hops. Compared with the transmission route with an average of 4–5 hops, the transmission rate of each hop is approximately 1 Mbps.

The maximum number of subcarriers in each hop cannot exceed 5 according to the simulation parameters. The maximum transmission rate modulated by $M = 1/2$ is 1 Mbps. Hence, the transmission rate of each hop can basically reach the maximum number of subcarriers in the simulation scenario, that is, the proposed protocol can achieve the maximum average throughput.

As shown in equations (31) and (32), the corresponding link weights present energy consumption balance and unbalance, which indicates the corresponding simulation results in Figures 7–9. From these figures, we can clearly see that the average throughput of the system will be reduced and the total power consumption will be increased. The primary reason is that the routing with the better spectrum is skipped when energy consumption balance is considered. Moreover, the standard deviation of energy (as shown in Figure 9) is relatively small after transmission under this circumstance, that is, the residual energy of all SUs in the network is basically equal.

To evaluate the performance of CROMC, we further compare the results of CROMC with the two other latest methods on multichannel sensor networks. The first one is EFP, which is based on a hop-by-hop transport scheme and seeks the minimum power consumption, the other one is HMCA, which is based on hybrid TDMA techniques and seeks the maximum throughput under the premise of delay control. Similar to the above analysis, $\eta = 6500$ is used. The detailed descriptions are presented in Figures 10 and 11, respectively.

From Figure 10, we can clearly see that our proposed method achieved a high proportion of fewer hops, when the number of hops is 3 and 4. Especially, the highest percentage of the number of hops is obtained when the number of hops is 4, which is 54.5%. And, the highest percentage of the number of hops of EFP and HMCA is obtained when the number of hops is 5, which is 36% and 42.2%, respectively. It
shows that CROMC is superior to the two methods on the number of hops. This is because one of the goals of CROMC is to minimize the number of transmission hops.

In Figure 11, we study how the method behaves in terms of total energy consumption and let average throughput from $1.15 \times 10^5$ to $2.0 \times 10^5$ bps with a $0.1 \times 10^5$ increment. With the gradual increase of average throughput, the total energy consumption decreases. With the gradual increase of average throughput, the total energy consumption decreases. HMCA achieves the larger energy consumption value, because HMCA is mainly used to solve the problem of maximum throughput within the allowable range of delay, and the percentage of the number of large hops is more than that of CROMC, as shown in Figure 10; therefore, the higher value of power consumption is achieved. EFP obtains the higher power consumptions value than that of CROMC, the reason is that the mobility of nodes increases the power consumption. Notably, the ratio of the number of large hops of EFP is higher than that of CROMC, as shown in Figure 10. CROMC considers the minimum number of hops and the minimum power consumption from the perspective of global network, so it achieves the minimum energy consumption with the increase of throughput, which is as shown in Figure 11.

**Conclusion**

Spectrum selection plays an important role in the research on routing protocols. Realizing on-demand information transmission with limited spectrum resources in large-scale wireless mobile sensor networks has always been a popular topic among researchers.

To maximize the throughput and lifetime of a network for on-demand data transmission under spectrum resource and hardware constraints, CROMC, which is based on the cross-layer design, was proposed. Our proposed protocol can effectively select the communication spectrum between links via spectrum negotiations among cluster heads, determine data transmission rate and transmission power between links, and transmit data by selecting minimum weight routing from the base station. The experimental result shows that our proposed method can effectively maximize network throughput and lifetime with lower computational complexity, which is also widely applied to large-scale wireless mobile sensor networks.

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