CLSR: Cognitive Link State Routing for CR-based Tactical Ad Hoc Networks

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Abstract

The Cognitive Radio (CR) paradigm in tactical ad hoc networks is an important element of future military communications for network-centric warfare. This paper presents a novel Cognitive Link State Routing protocol for CR-based tactical ad hoc networks. The proposed scheme provides prompt and reliable routes for Primary User (PU) activity through procedures that incorporate two main functions: PU-aware power adaptation and channel switching. For the PU-aware power adaptation, closer multipoint relay nodes are selected to prevent network partition and ensure successful PU communication. The PU-aware channel switching is proactively conducted using control messages to switch to a new available channel based on a common channel list. Our simulation study based on the ns-3 simulator demonstrates that the proposed routing scheme delivers significantly improved performance in terms of average end-to-end delay, jitter, and packet delivery ratio.

Keywords: Tactical ad hoc networks, Cognitive radio ad hoc networks, Link state routing, Multipoint relay (MPR), Location information

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1. Introduction

The demand for new wireless connections between military entities for ad hoc communication is increasing sharply, making the radio spectrum a crucial resource for the future proliferation of wireless communication in network-centric warfare. However, similar to commercial networks, military wireless networks are likely to suffer from spectrum scarcity. Under such a limitation, the Cognitive Radio (CR) paradigm is a promising solution for achieving better spectrum utilization and improving the quality of wireless applications [1]. For this reason, the Defense Advanced Research Projects Agency (DARPA) is seeking to meet future military needs based on CR Ad Hoc Networks (CRAHNs) [2].

CRAHNs present new challenges due to the uncertain availability of the spectral resources of Mobile Ad Hoc Networks (MANETs). This is due to the network topology being highly influenced by the Primary User (PU). Conventional MANETs were considered promising in demanding tactical scenarios because of their recognized advantages (e.g., absence of infrastructure, mobility management, traffic relaying) [3]. However, CRAHNs have intrinsic limitations resulting from dynamic spectrum-changing features brought about by location-varying spectrum availability. This makes the selection of a stable route much more difficult when using a routing protocol. Traditional routing protocols for MANETs, especially proactive link state routing protocols such as Optimized Link State Routing (OLSR) [4], are considered more suitable for tactical environments in terms of reliability and immediacy [5][6][7]. However, OLSR would not be able to properly cope with selection of a stable route with PU activity because they have never been designed to be CR-aware.

In this paper, we propose a CR-aware Cognitive Link State Routing (CLSR) protocol for tactical CRAHNs. As its name implies, CLSR is based on the OLSR protocol, but has been significantly modified to incorporate certain CR features. Transmitter detection techniques [3] are utilized to distinguish signals from different networks. The aim is to detect the presence of PU signals by obtaining their features from local spectrum knowledge. Modified Hello and Topology Control (TC) messages are utilized to promptly notify neighbors of spectrum holes and to discover neighbors for underlay spectrum sharing. The main contributions of the proposed scheme are summarized as follows:

(1) A Cognitive Node (CN) is employed as a Secondary User (SU) to adaptively exchange control messages (P-Hello and P-TC) via Common Control Channel (CCC), which is the licensed portion of the spectrum, to share backup CCC and PU-aware information.

(2) CLSR has two PU-aware procedures to provide reliable and prompt routes. Using the geometric distance and existence of sent data packets, CLSR relieves hidden PU problems via power adaptation. The reduced power range is dependent on newly selected MultiPoint Relays (MPRs), which are defined as Closer-MPRs (C-MPRs).

(3) For delay-sensitive applications, CNs conduct proactive channel switching to re-establish a route and resume communication according to spectrum availability in response to PU activity. To share a new backup CCC based on spectrum information for channel switching, a Common Channel List (CCL) of TC messages is utilized according to the Available Channel List (ACL) of Hello messages.

2. Background and Related Work

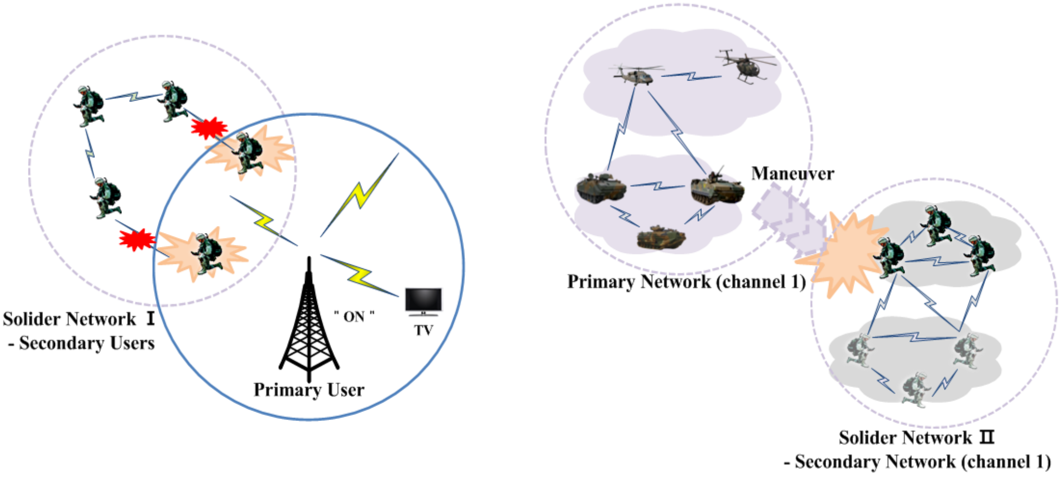
OLSR is a proactive routing protocol that is mainly aimed at delay-sensitive applications [4]. It provides knowledge of every current route to other nodes. Routing information is maintained within each node, and routing updates are continuously propagated to other nodes within MANETs via periodic control packets (Hello and TC messages). OLSR is an optimized pure link state routing protocol based on the concept of MPRs, which decrease the number of retransmissions of broadcast control messages.

Several CR routing studies have been proposed using reactive, geographical, and learning algorithm-based routing schemes. For example, [8] presents a cognitive ad hoc on-demand distance vector routing. This scheme utilizes channel diversity to avoid interference with PUs during both route formation and data forwarding. However, [8] does not consider both path and channel diversity, meaning that PU activity can still affect network performance. The system proposed in [9] uses global knowledge of the network topology to exploit the availability of multiple channels and improve the overall performance. Although [9] can exploit the advantage of reactive CRAHN schemes by eliminating the need to construct routing tables, it is also prone to the route-request storming that occurs when frequent broadcasting is employed to avoid the PU. In [10], a geographical protocol for mobile CRAHNs was proposed. To avoid regions of PU activity, the geographical protocol jointly conducts several paths and channel selections during route formation, and adapts to newly discovered and lost spectrum opportunities during route operation. Reference [11] minimizes the interference to PU communications by utilizing knowledge regarding the position of both CNs and PUs for route maintenance. A Primary exposed/hidden node Aware Routing Scheme (PARS) has also been presented [12]. SUs have priority lists and select a channel depending on PU activity. PARS considers the Spectrum Opportunities (SOP), and places the active frequency bands in common priority list based on the channel usage ratio of the PU. Although PARS removes the hidden PU problems based on Ad hoc On-demand Distance Vector(AODV), it only considers certain scenarios.

Some proactive schemes have been proposed based on centralized infrastructure and learning algorithms to achieve overall performance [13]. This paper uses a generic approach to developing CRs based on the Radio Environment Map (REM). However, such methods cannot be deployed in self-organized multi-hop networks, where both the CN positions and the channel distribution are difficult to determine because of high computational overheads. Although studies on CRAHNs are ongoing, work related to cognitive link state-based routing has been limited. Unlike previous studies, we exploit the link state routing approach to reduce the end-to-end delay and provide more stable routing information. Based on these features, we believe that link state routing is suitable for multi-hop CR networks in highly changeable topologies to ensure CN performance.

3. Problem Statements

Although OLSR is a potential candidate for tactical MANETs, it has certain intrinsic problems when applied to CRAHNs. Assume that a CN is an equipped Solider Radio Waveform (SRW) that has CR capabilities to alleviate spectrum scarcity using SOPs in the time and space domain [14]. **Fig. 1** depicts the assumed network scenarios in the tactical space. In scenario 1, each CN has different available channels because of appearance of a PU. When a PU becomes active, CNs around the PU should stop broadcasting and surrender their operating channels in SOP through an in-band sensing mechanism [15].



(a) Scenario 1 (b) Scenario 2

Fig. 1. Assumed tactical network scenarios.

Such a reaction from CNs might cause unexpected disruption in a currently operating multi-hop route, or even a network partition.

In scenario 2, when emergency response forces or higher-priority mission forces are deployed as an overlay network on top of the soldier network, all networks suffer from performance degradation in the same tactical area of responsibility. Although channel availability is shared among SUs, they might select SOP in a limited spectrum independently of adjacent forces. Under this scenario, all CNs within the area will mutually induce significant collisions and backoff delay while simultaneously attempting to send packets over the same channel. If the transmitted data is survival information (e.g., demands immediate action to attack the enemy and/or prevent fratricide) that must be delivered within some Information Exchange Requirement (IER), the threshold requirement might not be met [24]. Consequently, the lack of spectrum knowledge makes it difficult to maintain ongoing communication. Thus, CNs with CR abilities must continue exchanging control messages with new coordinates for route reselection and spectrum decisions.

To evaluate the limitations of the OLSR protocol based on the scenarios described above, we measure its performance in a CR environment using the network simulator ns-3. All CNs are assumed to be equipped with a single IEEE 802.11a interface that uses 10 MHz bandwidth [25] to model an SRW with a low data rate of 3 Mbps [22]. We set the transmission range to 300 m. PUs run the *ON-OFF* stage with a transmission range of 500 m. Fifty SUs are randomly distributed across an area of 1000 m × 1000 m. In this scenario, six CNs generate 40 Kbyte/s of Constant Bit Rate (CBR) traffic to different CNs. **Fig. 2** shows the Packet Delivery Ratio (PDR) of CNs that is applied for OLSR in the CR environment. We observe that the PDR of CNs decreases as the PU activity rate increases. This is because, when the PU is active, source or relaying CNs that sense the PU must stop communication and wait for SOP. This limitation will cause serious packet losses because of buffer overflows. In addition, this radio environment severely affects the route stability in multi-hop networks because of the hidden primary node problem and the lack of spectrum knowledge [16]. These concerns require new design approaches to joint channel decisions and route reconfiguration with PU awareness to avoid performance degradation.

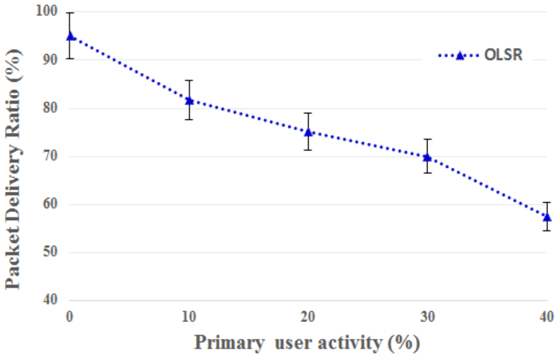


Fig. 2. Packet delivery ratio of the OLSR protocol with increasing PU activity.

4. The Proposed Scheme

4.1 System models

In this sub-section, we explain the proposed node and channel models in detail. First, we assume that CNs are supported by an underlying channel coordination mechanism in the link layer that provides spectrum sensing information based on the feature detection techniques described in [17]. CNs are assumed to have a Global Positioning System (GPS) installed. The distance between nodes can be calculated based on the coordinates that are exchanged through control messages and stored in a routing table [18]. It is also assumed that the activity pattern of the PU that affects the communication of CNs varies according to a two-state *ON-OFF* switching cycle. The *ON* period T^k_{on} denotes the duration of PU activity on channel k. The *OFF* period T^k_{off} denotes the duration of PU inactivity. The activity ratio of PU on channel k is defined as

$$P^k_{on} = \frac{T^k_{on}}{T^k_{on}+T^k_{off}} \times 100\,\% \tag{1}$$

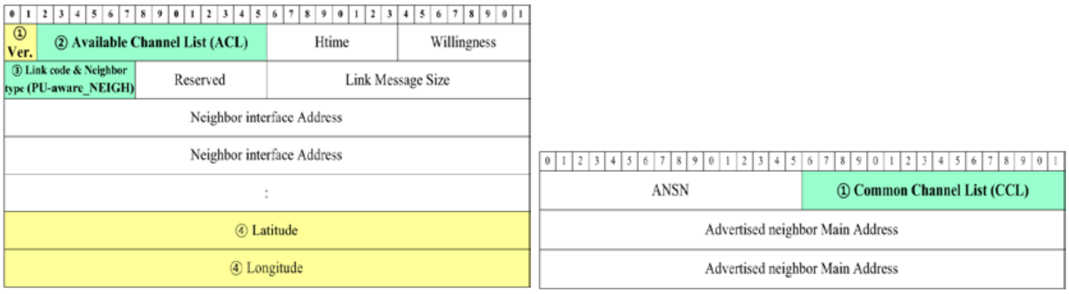
In CR networks, a CCC is imperative for cooperation methods such as PU awareness, neighbor discovery, channel access negotiation, and routing information updates among CNs. As the proposed scheme only exchanges control messages on the licensed band, it does not depend on a dedicated out-of-band channel. We assume that there is a CCC available among the CNs and PU transmission range is wider than CN transmission range. Although spectrum availability distribution might be quite different between the CNs, they periodically exchange their local spectrum knowledge via Hello messages. The available channel information for the CCC is periodically recalculated by updating the ACL, where $ACL(x) = \{Ch_1, Ch_2, Ch_3, \ldots, Ch_n\}$ is a set of SOP in CN x. The ACL is periodically broadcast by each Hello message. Based on the ACL, a CN floods sensed channels via TC messages to generate new CCCs for PU-aware channel switching.

4.2 The Design Concept

CLSR is a proactive routing protocol based on OLSR, but is modified to operate properly in CRAHNs. Based on the assumed system models, our CLSR uses two control messages: PU-aware Hello (P-Hello) and PU-aware TC (P-TC). The differences between the control messages in OLSR and CLSR are described in **Table 1**.

Table 1. Control messages in CLSR.

Type	Control messages	Additional fields based on default control messages
CLSR	P-Hello	①Version infromation ②Available Channel List (ACL) ③Neighbor type (PU-aware_NEIGH) ④Location information (Latitude and Longitude)
	P-Topology Control	①Common channel list (CCL)



(a) P-Hello message (b) P-TC message

Fig. 3. Modified Hello and TC message in CLSR.

Fig. 3 illustrates modified Hello and TC messages based on OLSR control messages. A P-Hello message contains additional version, PU detection, ACL, and location information based on general Hello messages. Note that the original Hello message in OLSR also has three types of neighbors: *SYM_NEIGH*, *MPR_NEIGH*, and *NOT_NEIGH*. In CLSR, a new neighbor type of *PU-aware_NEIGH* is additionally defined. When a CN senses a PU, a P-Hello message is broadcast with PU information. In addition, a P-TC contains a CCL based on the original TC messages.

In CLSR, the transmission power is considered to avoid interference to the PU and attain on-going communication. The ACL and CCL denote binary mappings for channel information. Each CN has a maximum transmission power P^k_{max} that is utilized during normal operation, which means that a CN does not sense the PU over channel k. P^k_{min} is used as the adapted transmission power without affecting PU communication. The transmission power P^k_{min} of the CN over channel k is also defined by the assumed propagation model. P_{thr} denotes the receiving sensitivity threshold, and indicates that a received packet can be successfully decoded. The adjusted transmission power P^k_{min} can be modeled as [19]:

$$P^k_{min} = d_0\left(\frac{P}{P_{thr}} \cdot \frac{\lambda}{4\pi d_0}\right)^{\frac{1}{\alpha}} \tag{2}$$

where parameters d_0 and α represent the Line-of-Sight distance reference and path-loss exponent, respectively, and λ is the wavelength. Furthermore, an arbitrary CN might only selectively adjust its transmission range for route recalculation via power adaptation when the PU is sensed. CLSR has PU-aware procedure schemes based on the geometric distance between a CN and PU. $D^k_{X,C}$ denotes a distance between a PU and CN x when CN x detect a PU on channel k. The distance condition for power adaptation is defined as follows:

$$D^k_{X,C} \leq D^k_{X,S} \text{ and } D^k_{X,C} \geq D^k_{X,T} \tag{3}$$

where $D^k_{X,S}$ means sensing range of CN x. $D^k_{X,T}$ denotes transmission range of CN x. The distance condition between the PU and the PU sensed CN is described in **Fig. 4**.

Algorithm 1: CCL Generation

```
Input: ACL(x), N(x)=N, n = number of channels  // Update ACL upon receiving Hello messages

CCL(x)={Ø}← Common Channel List at node x
 For j=1 to n
    SUM ($ch_j$)= $\sum_{i=1}^{N} ACL(i)_j$ // Sum ACL degrees of channel j
   If SUM ($ch_j$)==N then,
       Add  j in CCL(x) and remove from ACL(x)
       Sort CCL by ascending order according to channel usage rate
   End if

Output: CCL(x)={$ch_1$,$ch_2$, $ch_3$, …, $ch_n$}
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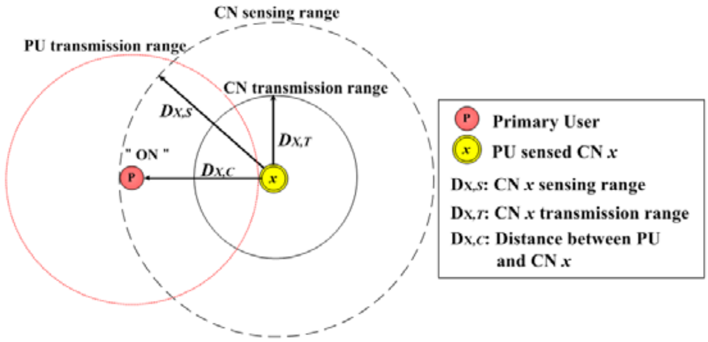


Fig. 4. The distance condition between the PU and the PU sensed CN.

Upon sensing the PU, $D^k_{X,C}$ is used to determine PU-aware procedures by comparing $D^k_{X,S}$ and $D^k_{X,T}$. When a CN's $D^k_{X,C}$ is less than $D^k_{X,S}$ and greater than $D^k_{X,T}$ from the PU, the CN conducts power adaptation using P^k_{min} for route recalculation. Thus, a sensed CN can utilize channel k, while its current transmission range is adapted by P^k_{min}. On the other hand, if $D^k_{X,C}$ is less than $D^k_{X,T}$ from the PU, the CN might affect PU communication. Although the CN reduces its power according to P^k_{min}, it cannot avoid interfering with PU communication. Thus, when $D^k_{X,C}$ is less than $D^k_{X,T}$, the CN vacates the current CCC and moves to a new CCC.

4.3 Common Channel List

As mentioned in the previous section, the intrinsic underperformance of OLSR is caused by an impossible neighbor discovery process via CCC following a PU request for the use of the licensed channel. Thus, CNs should employ a proactive channel coordination mechanism by exchanging control messages without a central coordinator. CNs must have local and global knowledge about CCCs, because the provision of backup channels is essential to a proactive routing scheme. In CLSR, a CN creates the ACL from sensing information based on local radio observations. The CCL generated from the ACL is described in *Algorithm 1*, where *ACL(x)* is a set of channels that are sensed at node *x*. *N(x)* is the set of CN *x*'s 1-hop symmetric neighbors, and *CCL(x)* is used to determine whether to select a new backup CCC for channel switching at node *x*.

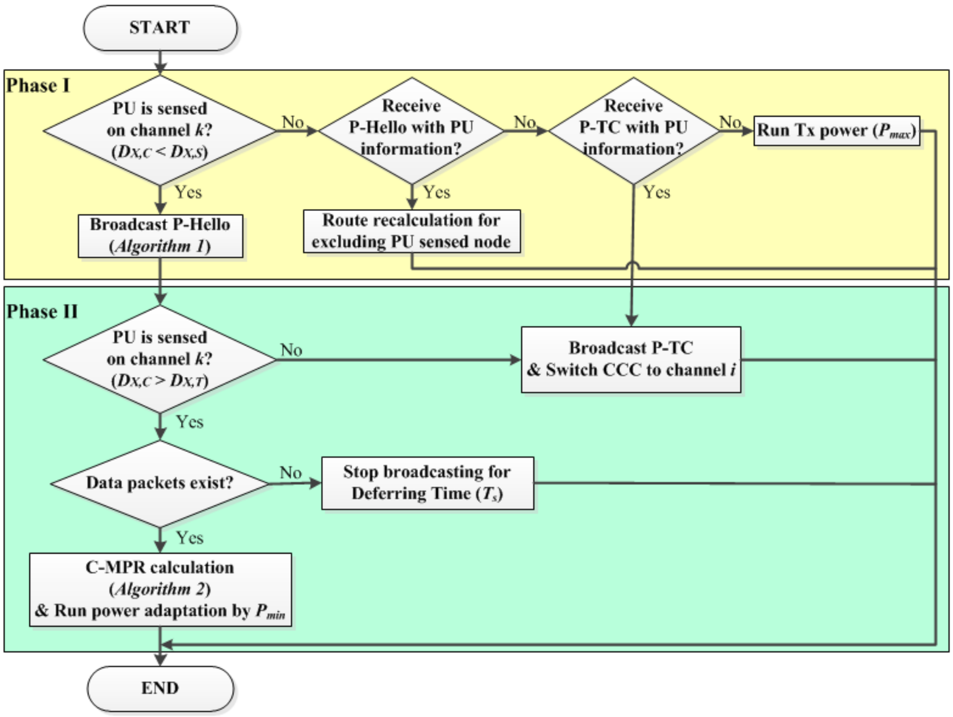


Fig. 5. The CLSR flowchart.

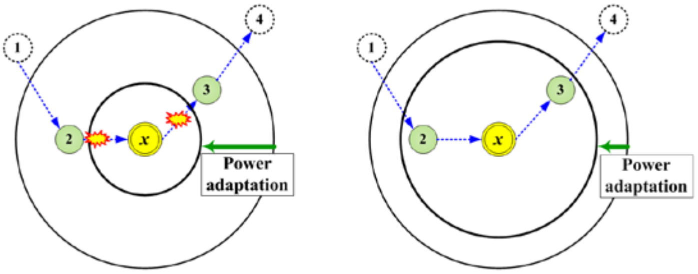
$CCL(x) = \{ch_1, ch_2, ch_3, \ldots, ch_n\}$ is sorted in ascending order based on the PU channel usage ratio. When the first priority channel ch_1 is not available because of PU activity, node x is aware of this and moves to the second priority channel in the CCL.

4.4 Cognitive Link State Routing

When no PU is sensed, CLSR runs in OLSR mode and proactively maintains paths by broadcasting control messages on the CCC that is free from the PU. However, upon detection of PU activity, two scenarios may occur. First, the CN may become aware of PU activity indirectly by receiving P-Hello or P-TC messages containing *PU-aware_NEIGH* information from its neighbors. Second, the CN may be directly aware of the PU through sensing mechanisms from an underlying layer.

The CLSR flowchart in **Fig. 5** illustrates these two cases. As mentioned in sub-section 4.2, when CNs sense a PU with $D^k_{X,C}$ less than $D^k_{X,S}$, the CN broadcasts a P-Hello message. When a CN receives a P-Hello message with PU information from its 1-hop neighbors, the CN recalculates its route to avoid relaying data packets through the PU-sensed node. This is because a CN that senses a PU and broadcasts a P-Hello message instead of a P-TC might conduct power adaptation. When the PU-sensed node is not the destination node, route recalculation enables the PU-sensed node to prevent packet relay using the current CCC. If the CN receives a P-TC with PU information from its neighbors, the CN prepares to switch to a new channel according to the CCL independently of the current status.

In the second phase, although a PU has been sensed, CNs should verify how much the PU communication will be affected with regard to the space between the sensed CN and the PU. On broadcasting a P-Hello message due to the PU, the sensed CN checks the geometric distance between itself and the PU.



(a) Case 1 (b) Case 2

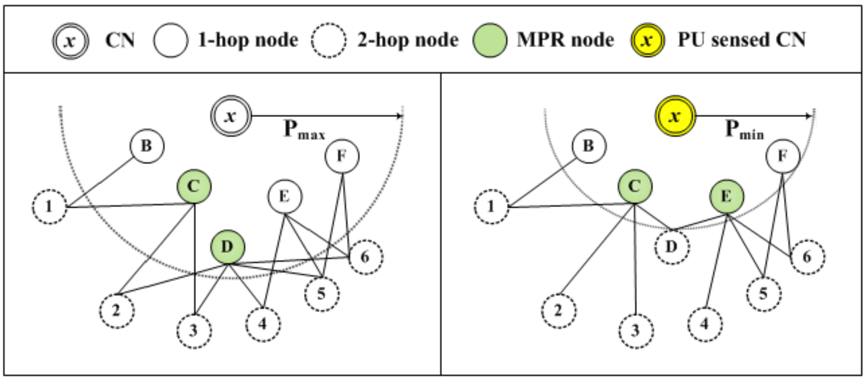
Fig. 6. PU-aware power adaptation case study.

Algorithm 2: C-MPR selection

```
Input: x, N(x) = N, $N_2(x) = N_2$
  STEP 1.  C-MPR ={Ø}← The closet 1_hop neighbor from x
  STEP 2.  Find covered the symmetric 2_hop_neighbor set in $N_2(x)$ through C-MPR
  STEP 3.  Remove all 2_hop_neighbors found by STEP 2 from $N_2(x)$
  STEP 4.  C-MPR Set ← C-MPR
  STEP 5.  Remove C-MPR node  from 1_hop neighbor in N(x)
  STEP 6.  If ($N_2(x)$!=null), Goto Step 2
Output: C-MPR(x, N, $N_2$)
```

If $D^k_{X,C}$ is less than $D^k_{X,T}$, the sensed CN broadcasts a P-TC message, and then switches to a new CCC. If $D^k_{X,C}$ is greater than $D^k_{X,T}$, the current CCC can continue to be utilized. In this case, two functions are applied depending on whether the CN has data packets to be sent. If the CN has no data packets, it stops broadcasting control messages for some *deferring time* (T_s) that is set to a period equal to the P-Hello message (2 s by default). The *deferring time* is limited to three consecutive P-Hello message periods (6 s by default), which we call the *Neighbor_holding_time*, because neighbor information is valid before new TC messages are received. Thus, even when a CN does not receive a P-Hello, 2-hop neighbor information is still available.

When a CN has data packets, it runs the power adaptation mechanism. Due to the broadcasting nature of wireless transmissions, power control is a promising technique to avoid interference with the PU. However, any unbalanced transmission power between CNs results in asymmetric links, causing performance degradation [20]. We provide an example to show the necessity of limited power control using the case study shown in **Fig. 6**. Suppose that CN *1* establishes a route to CN *4* (case 1). OLSR might provide a route (1-2-*x*-3-4) with the minimum hop count. In **Fig. 6-(a)**, when node *x* senses a PU, it broadcasts a P-Hello message and adapts its transmission power. Thus, the path is disconnected by power adaptation, because the links from *x* to both CN *2* and *3* are broken. On the contrary, **Fig. 6-(b)** illustrates properly controlled power adaptation by CN *x* to retain the on-going communication session and avoid network partition.



(a) MPR selection in OLSR (b) C-MPR selection in CLSR

Fig. 7. C-MPR selection case study.

Table 2. Comparison of MPR selections between OLSR and CLSR.

Type	CN	1-hop neighbors	2-hop neighbors	MPR node
OLSR standard [4]	*x*	B, E, F	1, 2, 3, 4, 5, 6	C, D
CLSR		B, F	1, 2, 3, 4, 5, 6, D	C, E

Based on this case study, we propose the C-MPR selection algorithm, which utilizes the distance concept to apply PU-aware power adaptation. The objective of the revised MPR selection algorithm is to prevent network partitioning caused by unbalanced power transmission prior to PU-aware power adaptation. Basically, MPRs are intermediate CNs between an MPR selector node and the 2-hop neighbor nodes. Because an MPR selector node has a minimum number of MPRs located within a certain geographical distance and is connected to all 2-hop neighbors, partitioning the network can be avoided by reducing the transmission power to cover only the C-MPR set. The C-MPR selection algorithm is described in *Algorithm 2*, where x is a CN, $N(x)$ is the set of 1-hop symmetric neighbors, and $N_2(x)$ is the set of 2-hop symmetric neighbors, excluding any CN in $N(x)$. CN x selects one of the closest CNs as the C-MPR node in $N(x)$. The C-MPR node is only selected when it has 2-hop neighbors. In addition, the 2-hop neighbors of C-MPR are removed from the 2-hop neighbor set $N(x)$. C-MPR selection continues until the remaining 2-hop neighbor set $N_2(x)$ is empty. Once the C-MPR set has been selected, CN x adapts the transmission power according to P^k_{min}, which is used to cover the outer C-MPR node.

Fig. 7 illustrates how the C-MPR selection algorithm works. **Fig. 7-(a)** shows a situation based on the results of MPR selection in the OLSR standard [4]. Because CNs C and D have more symmetrical 2-hop neighbors than other 1-hop neighbors of CN x under transmission power P^k_{max}, CN x selects nodes C and D as MPR nodes. A comparison of MPR selection under OLSR and CLSR is given in **Table 2.**

In **Fig. 7-(b)**, once CN x senses the PU, it calculates $N(x)$, $N_2(x)$, and the distance to the PU. CNs C and E are selected as the C-MPR set. Note that D is not considered as a C-MPR node, because it is further away from CN x than B, C, and E, notwithstanding having more than 2-hop neighbor sets. CN x then adapts its power to cover CN E. Based on the distance information, the adapted transmission power is set to P^k_{min}. As a result, while CN x conducts PU-aware power adaptation after the C-MPR selection algorithm, each CN recalculates and updates its route to each known destination in the routing table upon receipt of the C-MPR information.

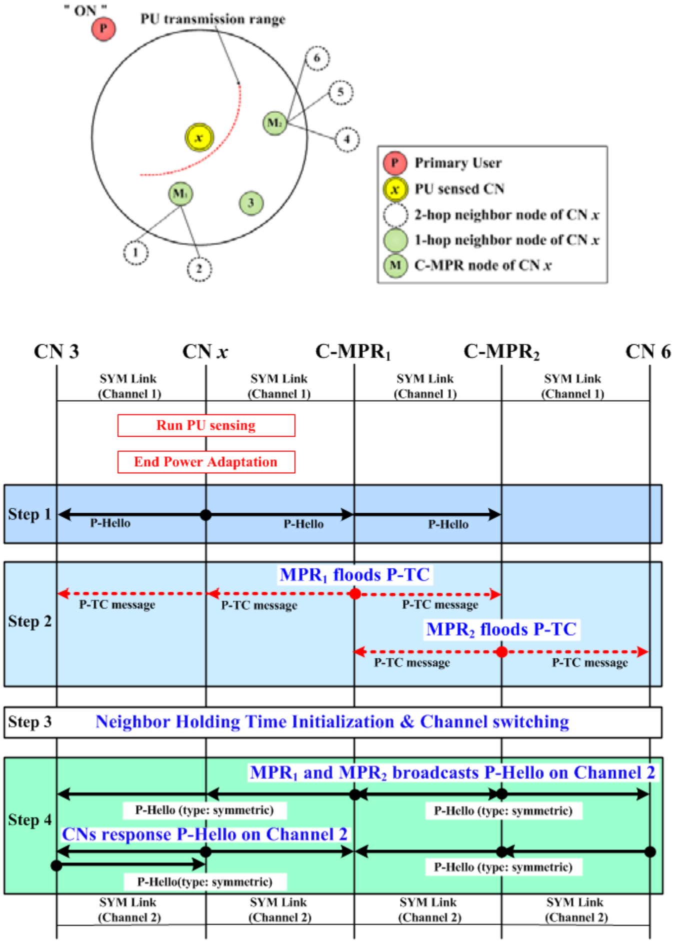


Fig. 8. PU-aware channel switching case study.

During power adaptation with the current CCC, the CN should continuously refer to the distance $D^k_{X,C}$ from the PU to avoid interference. When a CN becomes aware that $D^k_{X,C}$ is less than $D^k_{X,T}$, PU-aware channel switching is initiated by broadcasting a P-TC message. Upon receiving this, all CNs become aware of the impending channel switch. A P-TC contains recently updated PU information, the CCL, IP address of the node, and an incremented sequence number. As mentioned in sub-section 4.3, channel information is notified through a P-Hello message. The new CCC is selected by a C-MPR node in the CCL. Under OLSR, the MPR nodes play a crucial role as a temporary coordinator to broadcast P-TC messages with reduced control overheads. Thus, a C-MPR node leads to local Hello association and determines a new CCC. However, because MPR nodes mainly flood P-TC messages into the network, flooding P-TCs through MPR nodes might affect the PU performance. To cope with this interference to the PU, the PU-sensed CN does not flood P-TCs, although it is selected as an MPR node by the MPR selector nodes.

When the C-MPR node first receives a P-TC from a CN that senses the PU, it examines the sequence number. This is because the C-MPR node should verify whether there are new PUs in the network, and prevent unnecessary channel switching. In OLSR, if a neighbor set is not refreshed within a certain period, the neighbor entries in a CN's neighbor set recognize that the bidirectional connection to the neighbor is broken [4]. When a CN receives a P-TC for channel switching in CLSR, however, *Neighbor_hold_time* is initialized to maintain neighbor information without re-association. In addition, to reduce neighbor detection latency, an adaptive-interval Hello mechanism [21] is applied during channel switching. If topology changes occur through P-Hello messages containing new PU information, this adaptive Hello mechanism temporarily enables CNs to improve the reaction time. The PU-aware channel switching procedure is described with a case study.

The operation of the channel switching process is shown in **Fig. 8**. First, when CN *x* senses the PU, it broadcasts a P-Hello message over the current channel (Channel 1). Then, CN *3*, $C\text{-}MPR_1$, and $C\text{-}MPR_2$ become indirectly aware that there is a PU when they receive this P-Hello message. In step 2, MPR_1 broadcasts a P-TC message with new CCC information, because it is the closest to CN *x*. CN *3* and MPR_2 verify the P-TC received from CN *x* to determine whether the sequence number in a P-TC message is larger than the previous sequence number. If so, the new PU information is updated and forwarded. Otherwise, the P-TC message is discarded. In steps 3 and 4, after initializing *Neighbor_hold_time*, $C\text{-}MPR_1$ and $C\text{-}MPR_2$ resume the P-Hello association using the new channel (Channel 2). The 1-hop neighbor nodes of C-MPR nodes follow the new association by broadcasting the more recent P-Hello message using the new channel (Channel 2), and thus become neighbors.

5. Performance Evaluation

Table 3. Simulation Environment

Environment Parameters	Values
Topology	Grid topology (5 by 10)
MAC/PHY	IEEE 802.11a 3Mbps (Bandwidth: 10MHz)
Frequency (Channel)	5 GHz (11 orthogonal channels)
Data payload size	1Kbyte [23]
The number of Data Sessions	6
The number of nodes	PU: 4, CN: 50
Transmission Range	CN (300 m), PU (500 m)
Nodal moving speed	0 – 5 m/s
Mobility model	Random Waypoint
Simulation time	500 s
Defering time (T_s)	2 s
Propagtion model	Rayleigh model

5.1 Simulation Setup

In this section, we evaluate the performance improvement attained by CLSR in comparison with OLSR and PARS [12]. We use the ns-3 simulator under different network conditions and PU activity. Our aim is to prove that CLSR can meet its design goal and achieve reasonable performance results under random PU activity. We consider the CNs and PUs to be distributed with a grid topology within the network area. The CNs employ the IEEE 802.11a MAC interface as the SRW, because tactical radios tend to have narrow bandwidth and deliver a much lower link rate. The CNs generate CBR traffic according to periodic data whose size is based on variable message formats [22]. The source CN traffic is initiated 30 s after the start of the simulation, and continues until 500 s. Each simulation scenario is conducted 30 times, and the results are averaged. The simulation parameters are listed in **Table 3**.

We evaluate the proposed scheme using three metrics [24]: PDR, end-to-end delay, and jitter. PDR is the ratio of the number of packets received at the destination to the number of packets transmitted by sources. The delay is the sum of delays from the source to the destination for successfully transmitted packets. Moreover, when a CN generates a periodic packet, two successive data packets will be transmitted in a defined interval. Jitter is defined as the variability of packet latency over time. These metrics represent the importance of information delivery by considering survival information features that are exchanged by military forces for command & control and situation awareness.

5.2 Simulation Results

Fig. 9 shows the simulated PDR as PU activity increases. CNs generate 40 data packets per second as CBR traffic to random destination CNs. We can observe that OLSR has a lower PDR, caused by the high occurrence of link failures under PU activity. PARS gives a lower PDR than CLSR because while it should re-discover the routing path during waiting for SOP between source and destination. In contrast, because CLSR conducts power adaptation and moves to another CCC to resume communication when the PU is active, it attains better PDR results, regardless of PU activity. **Figs. 10** and **11** illustrate the end-to-end delay and jitter results with regard to successfully transmitted packets under increasing PU activity. The CNs again generate 40 data packets per second as CBR traffic to random destination CNs. Basically, when the PU is not active, all schemes produce similarly low delay and jitter values. When the PU activity increases, however, CLSR exhibits higher delay and jitter. This is because the CNs adaptively recalculate routes through PU-aware procedures such as reducing transmission power, and change the CCC in response to PU activity. Such reactions result in queuing and switching delays at the source and relay CNs. On the contrary, because certain CNs in OLSR are affected by sudden PU interruption, OLSR has uniform delay and jitter with respect to successfully received packets. PARS has lower delay jitter than CLSR without CN mobility because re-route establishment time is low because of local switching channels. Although OLSR and PARS maintain lower delay and jitter, the much higher PDR of CLSR means that the proposed method is more reliable than OLSR and PARS.

To investigate the effect of CN mobility on performance, we evaluate CLSR by comparing the PDR and delay with that of OLSR as CN mobility increases at random way points. In this simulation, CNs generate 60 data packets per second as CBR traffic to random destination CNs. The PU activity is set to 20%. In **Fig. 12**, we see that CLSR maintains a PDR of above 83%, whereas OLSR maintains a level of around 70%. Because of PU-aware procedures for packet forwarding, CLSR maintains a higher PDR regardless of mobility. For OLSR, higher CN mobility has a substantial effect, similar to when low PU activity exists along a path. Increased velocity with PU activity leads to an interruption in packet forwarding and higher reselection of designated neighbor CNs. Thus, OLSR attains a worse PDR than CLSR. Because PARS must repair the end-to-end routing path when a path is broken by node mobility, it consistently achieves a lower PDR than CLSR. In **Fig. 13**, all routing protocols show an increased delay when the CN mobility rises. The end-to-end delay increases when packets are queued and CNs are unable to send data freely because of PU activity. Although PARS and OLSR attain lower delay in the static condition (**Fig. 10**), the queue delay in OLSR is higher than CLSR's switching delay while the PU is active and the CN is mobile.

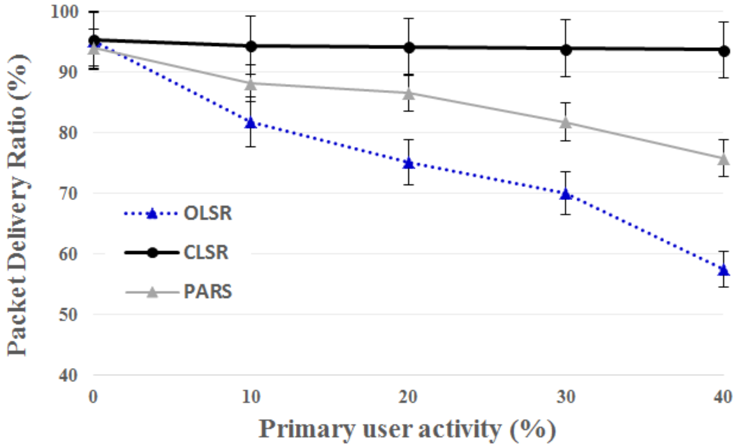


Fig. 9. PDR comparison with increasing PU activity.
(Amount of Traffic: 40 packet/s, No CN mobility)

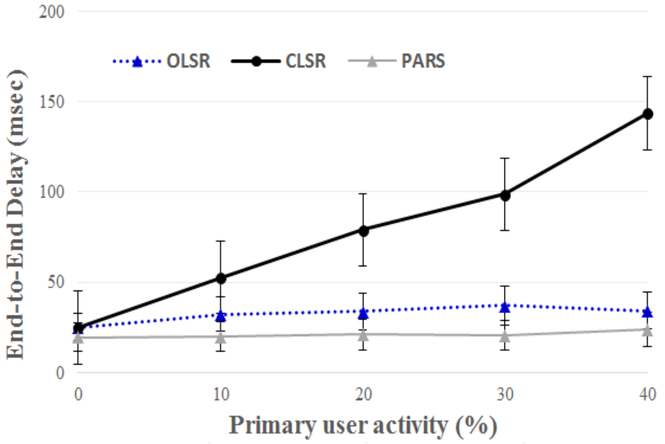


Fig. 10. Delay comparison with increasing PU activity.
(Amount of Traffic: 40 packet/s, No CN mobility)

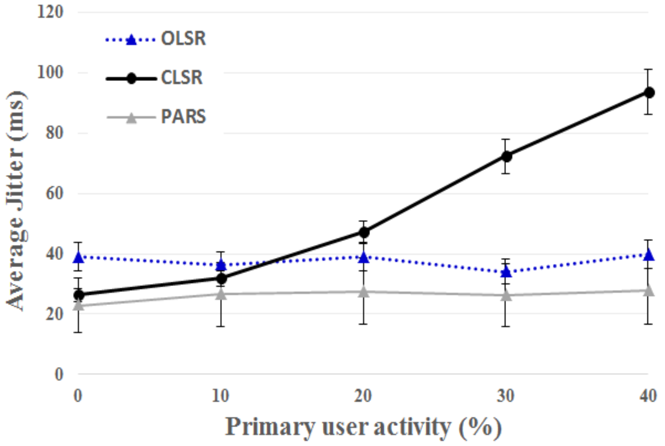


Fig. 11. Jitter comparison with increasing PU activity
(Amount of Traffic: 40 packet/s, No CN mobility)

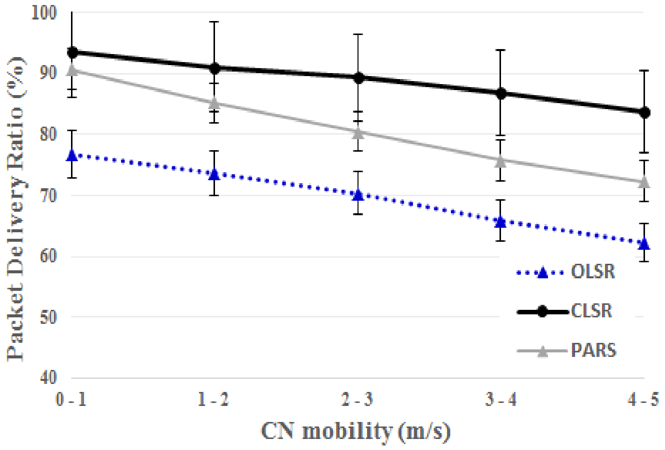


Fig. 12. PDR comparison with increasing CN mobility. (Amount of Traffic: 60 packet/s, PU activity: 20%)

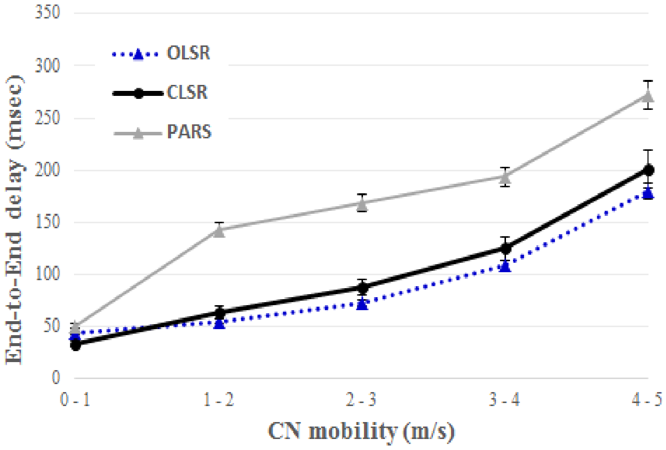


Fig. 13. Delay comparison with increasing CN mobility (Amount of Traffic: 60 packet/s, PU activity: 20%)

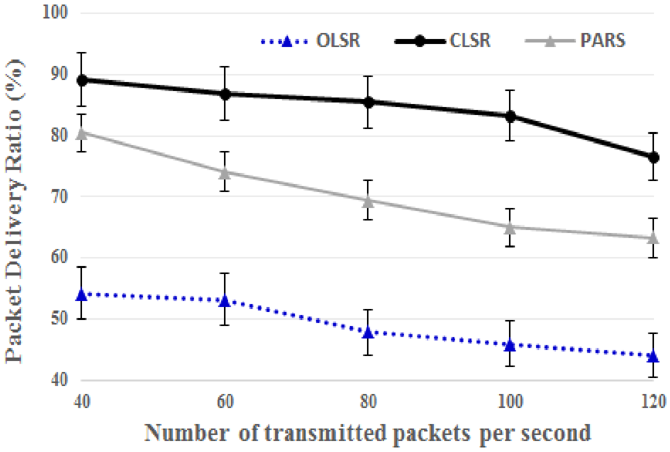


Fig. 14. PDR comparison with increasing number of transmitted packets. (CN mobility: 1m/s, PU activity: 40%)

Thus, CLSR manages nearly 85% of its transmitted packets with slightly higher delay than OLSR because of the CCC switching delay. PARS has a lower PDR than CLSR due to the frequent end-to end rerouting procedure.

The results in **Fig. 14** show the PDR with respect to the number of transmitted data packets at a CN mobility of 1 m/s. When CBR traffic increases with PU activity to 40%, each CN in OLSR and PARS should cease transmission and wait for the CCC to become available. This is because the PU request prevents OLSR from using new routes, causing more packets to be sent via the current CCC. In contrast, CLSR provides a higher PDR, even under conditions of high congestion, because new routes are selected using the proposed PU-aware procedures.

Overall, the performance of OLSR is decreased by high transmission interruptions and an unstable CCC when PUs exist in the network, as there is no function for avoiding PU interference. PARS exhibits lower performance when the CN's become mobile because of the false positive route decision errors caused by PU activity. In contrast, CLSR has PU-aware functions that can adapt power and switch the CCC to a spectrum hole that the PU does not use. Therefore, CLSR provides higher PDR and lower delay for tactical traffic applications, even under increasing mobility and PU activity.

6. Conclusion

In this paper, we proposed the CLSR protocol for tactical CRAHNs. To ensure compatibility and relevance, we utilized control messages and schemes already presented in OLSR standards. CLSR requires a novel route construction phase via PU awareness mechanisms. To share and select a vacant CCC in CRAHNs, CNs incorporate local and network channel information using the ACL and CCL. PU-aware procedures during neighbor discovery and a route establishment process allow for timely route recalculation, thus providing reliable routing paths immediately after PU activity occurs. Simulation results indicate that the proposed scheme achieves enhanced performance compared to OLSR and PARS.

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