A Practical Approach for Channel Problem Detection and Adaptation in Tactical Radio Systems

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Abstract—Soldier-based tactical radio systems in the battlefield have tendencies to be severely affected by various phenomenon such as signal jamming and environment deterioration. This is because many types of wireless handheld and manpack devices carried by soldiers may not have efficient algorithms or the hardware for adapting the device to these conditions. Taking on the advantage that most of these devices use software-defined radios but do not fully utilize its functionalities, we present channel quality estimation and channel adaptation algorithms that can solve the problems of these devices. We utilize simple and practical channel problem detection methods by constantly monitoring the channel quality parameters such as signal-to-interference-noise ratio and clear channel assessment value while inducing low overhead. Furthermore, we propose efficient channel adaptation methods that can quickly sense and avoid deteriorated channel conditions. Via the experimental studies, we implement our proposed scheme on actual testbeds and show that it can improve the performance and mission-criticality of the tactical networks.

Keywords- Tactical Radio Systems; Channel Quality Estimation; Channel Adaptation

I. INTRODUCTION

Joint Tactical Radio Systems (JTRS) is being designed and planned to become the primary tactical wireless communication system for the U.S military [1]. It defines the usage of various software-defined radio (SDR) systems that can be integrated with both existing civilian and military networking systems. One particular aspect of JTRS is that it defines the Handheld, Manpack & Small Form Fit (HMS), which has the objectives of equipping field soldiers with dismounted radio systems that are efficient in portability, complexity, and durability. The HMS especially can also conform to the Soldier Radio Waveform (SRW), which defines the wireless communications requirements needed for the efficient communication support of ground soldiers. All added up, the SRW based HMS JTRS system is considered as a potential system for the formation of soldier based networks in the Warfighter’s Information Network-Tactical (WIN-T) [2].

A well-known problem in the area of tactical networks is that the wireless environments in the battlefield are prone to various channel noise factors, such as channel deterioration from obstacles, weather conditions, or signals from other networks. Jamming attacks on specific frequencies [3] may also interfere with the communication between tactical devices. Even though heavily equipped devices such as vehicles and other platforms may have the capabilities to efficiently prevent or heal from these problems, it is likely that HMS devices for soldiers may not be able to do this. This is because as seen in various HMS solutions [4, 5], these devices are more focused on being simple and lightweight, limiting the hardware functionalities of these systems. As a result, channel deterioration factors can severely affect the transmission of data packets traversing the soldier network, degrading the mission-criticality, quality of service, and reliability. Even though the software-defined radios installed in these military devices can provide means for alleviating this problem, they are not fully utilized to alleviate these problems.

We are inspired from the motivation that if the decision of selecting efficient frequency channels is well made, then these environmentally affected channels can be avoided and the network can maintain high level of efficiency. To achieve this goal, dynamic channel selection methods can be the ideal solution, which selects its frequency channel according to the status of the network. If the deteriorated channels can be quickly sensed in real-time and avoided by switching to better conditioned channels, the performance of the network can be maintained even under serious network conditions. The proposed scheme tries to achieve this goal by utilizing the SDR to enable the concept of cognitive radios [6].

To cope with the limitations that soldier nodes cannot sense the channel quality and transmit data simultaneously with a single network interface, channel monitoring and adaptation decisions are made by the gateway node that can utilize multiple radios. We also utilize opportunistic feedback methods from the soldier nodes to increase the accuracy of the gateway’s channel sensing method, while maintaining the overhead of soldier nodes low. We utilize simple parameters such as signal to interference and noise ratio (SINR) parameter to detect the condition of the currently used channel, and at the same time use the clear channel assessment (CCA) parameter to keep track of the conditions of other alternative channels. When it is determined that the current channel is deteriorated, the scheme adaptively chooses another channel that has the best quality among the alternative channels. The overall design of the algorithm induces low complexity to the soldier nodes, keeping the system practical and lightweight. The performance of the proposed scheme is evaluated via testbed implementation to prove that it can improve the performance of mission critical services, nearly providing up to 7 times more performance increase by utilizing the proposed scheme in tactical environments.

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II. BACKGROUND AND RELATED WORKS

A. HMS JTRS system environment and Interference Model

The basic structure of the soldier based networking system belonging to the WIN-T can be observed in Fig. 1. The soldiers carrying SRW based HMS JTRS devices form a multi-hop wireless network between each other. As stated in [4, 5], the HMS devices that soldiers carry are designed to be simple and lightweight, utilizing only one or at maximum two wireless channels at the same time. On the other hand, vehicles are capable of equipping more interfaces, supporting the soldier network as the backbone gateway to other WIN-T Domains. From the formation of the network, we can observe that majority of the data transmission in the soldier-based network are either transmitted from the soldier node to a gateway, or vice versa. This form of network naturally causes data traffic to concentrate near the gateway.

The causes of channel deterioration that may affect the performance in these tactical environments are jamming attacks, obstacle interference, and signals from other networking devices. We assume spot jamming attack and barrage jamming attack that sustains the attack on specified frequencies over a period of time [3]. Also, obstacle interference from physical structures are considered sustained deterioration factors as they locate themselves in a specific region of the network and interfere with wireless transmission. Multimedia streaming sessions and other real-time applications generated from different network sources can also cause sustained interference. These sustained interferences can degrade the performance of specific channels for a long period of time. The initial design of our channel problem detection and adaptation algorithm will be focused on coping with these interference models.

B. Related Works on Channel estimation and adaptation

There has been active research on estimating the quality of channels by using various parameters, such as SNR, SINR, and CCA. [7] shows methods of accurately estimating the quality of channels using the SNR value. It considers the effect of fading channels for establishing a new channel quality estimating index. This may be efficient for sensing the quality of the currently used channel, but cannot be an efficient solution for also sensing other unused channels, because actual packets that are needed to decode the SNR and SINR values may not be transmitted in these channels. Instead, quality of other unused channels can be estimated by using the CCA value. Methods such as [8] and [9] propose methods for using various CCA parameters to sense the channel quality. However, they lack the algorithm for adapting the network to different channels when there is a problem in the current channel.

Works such as [10] and [11] propose methods for channel adaptation in multi-channel networks. [10] proposes various methods for maximizing the total channel utilization for all nodes in the network. Nodes may utilize different channels between different source/destination pairs to allow better channel utilization. However, this network model may not be efficient in the tactical network environments where most of the data communication can be concentrated to the vehicle node. Also, it does not propose solutions for channel adaptation when problems occur. Even though works such as [11] considers various channel selection methods such as random selection, lowest channel available selection, and soft channel reservation, none of these are based on the channel status of the current channel or the conditions of other available channels.

Much research has also been focused on channel selection issues for multi-channel multi-interface networks. Protocols such as [12] maximize bandwidth utilization by selecting non-overlapping channels between neighboring nodes. However, we like to point out that the focus of these works is more based on graph-coloring problems. On the other hand, our work is based on estimating the quality of various channels and dynamically adapting the entire network based on this estimation. Also, it would be inefficient to adapt these multi-interface algorithms in our assumed environment as they require installation of additional interfaces that may affect the portability of these tactical devices.

III. PROPOSED SCHEME

The network environment for the proposed scheme consists of a single vehicle node that will act as a gateway for the soldier nodes. The primary wireless interface is used for communicating with the soldier nodes, while the secondary wireless interface is used for constantly sensing the current condition of all tunable channels. The soldier node will maintain a single transceiver interface that is used to communicate with the gateway and nearby soldier nodes. All of the interfaces are assumed as SDRs, and have the ability to switch the frequency of the communication interface.

In our scheme, we utilize the SINR for detecting the problem of the currently used channel. As an alternative, other popular parameters such as the Bit Error Ratio (BER) can also be used to detect the same problem. As shown in [13], there are high relations between these parameters, and both are expected to show identical outcome when applied to our scheme. For sensing the channel status of all other candidate channels, we utilize the CCA parameter. The reason that we choose the CCA value over the popular Received Signal Strength Indicator (RSSI) is that the calculation of RSSI is only made after the reception of a packet. Also, RSSI calculation is thought to be inaccurate when it is acquired from high transmission data rate environments [14], which is a requirement in tactical networks.

A. Channel Monitoring Phase

The monitoring phase of the channel status is initiated by the gateway node. Since soldier nodes only utilize one wireless interface, it would be inefficient for these nodes to periodically sense the conditions of other channels that can be used in the
network. This is because while a soldier node switches its channel to calculate the quality of another channel, it cannot receive any data that other nodes are transmitting through the originally used channel. If high level of synchronization between each node were made, this can be possible by each node tuning to the same channel at the exact same time while also sensing the channel quality. However, this is extremely difficult and unrealistic to achieve in dynamic tactical environments. To make the design of our network more practical, soldier nodes will initiate channel sensing only when it is queried by the gateway.

The gateway node utilizes its primary interface to sense the SINR value of the packets received from the currently used channel. The SINR moving average value of the currently used channel \( k \) is recorded by the gateway as shown in formula (1),

\[
\text{SINR}_{\text{avg}}(ch_k, t) = \frac{1}{T} \sum_{i=1}^{T} \text{SINR}(ch_k, i)
\]

where \( T \) equals the number of packets that will be accounted for the calculation of SINR moving average. \( t \) is the identifier of the received packets, where \( t = 1 \) represents the most currently received packet. Therefore, \( \text{SINR}(ch_k, t) \) represents the \( t \)-th SINR value of channel \( k \). Based on the value of \( T \), more historical SINR values from older packets can be used for configuring the SINR calculation. Each recently calculated SINR moving average acquired from (1) will be compared with a threshold value to see if there is a problem with the current status of the channel, as seen in (2),

\[
N(ch_k, t) = \begin{cases} 
1 & \text{if } \text{SINR}_{\text{avg}}(ch_k, t) < \text{SINR}_{\text{threshold}} \smallskip 
0 & \text{otherwise}
\end{cases}
\]

where \( \text{SINR}_{\text{threshold}} \) is the pre-defined threshold for detecting the problem in the recently acquired SINR values. Even though acquiring a SINR value from a packet means that the packet has actually been transmitted successfully, it does not necessarily mean that the successfully transmitted packet has also met the transmission requirements of a specific application. To cope with this, \( \text{SINR}_{\text{threshold}} \) value can be controlled depending on the application to react to these certain requirements that the application demands. For example, [15] states that the required bit error rate for audio streaming service and conversational voice is lower than 10^-2. According to [13], the SINR value of 64QAM modulation that is equivalent to 10^-2 bit error ratio is approximately 20dB. If we can configure the \( \text{SINR}_{\text{threshold}} \) to 20dB, equation (2) can easily realize whether the packet transmissions are meeting the requirements of real time streaming audio applications, by checking whether the SINR of each packet is over or under 20dB. Depending on the type of environment or the requirement of the applications, the setting of \( \text{SINR}_{\text{threshold}} \) may vary dynamically.

If the \( N(ch_k, t) \) from (2) returns the value of 1 in succession of \( N_{\text{threshold}} \) times, it is decided that the currently used channel is problematic. The value of \( N_{\text{threshold}} \) can also be configured based on the dynamicity of the network. The \( N_{\text{threshold}} \) Should be high enough in our assumed environment to ignore sudden transient decrease in the SINR level. In environments where transient interferences occur more frequently, this value should be lower to cope with these interferences.

The secondary interface of the gateway node is in charge of sensing the quality of all channels that can be used in the network. This is done by switching the channel of the secondary interface in a round-robin fashion and periodically recording the condition of each channel. However, in this case, the SINR value cannot be calculated from other channels using the secondary interface. This is because there are no data transmissions occurring at these unused channels, while SINR value can only be acquired when a destined signal is received. To solve this problem, we will instead use the CCA value, which samples the current pure energy level of a channel and return a Boolean value depending on the channel’s idle/busy status. The CCA value of each channel is periodically analyzed (1ms taken for sampling each channel) and values derived from sampling are stored by the gateway and utilized when the problem is triggered from the channel monitoring phase.

### B. Channel Adaptation Phase

Upon problem trigger, the channel adaptation phase is initiated to adapt the network to a more efficient channel. To do this, we firstly derive the CCA False Ratio (CFR) from the periodically measured CCA value. The CFR of each channel is acquired by calculating the CCA sampling failure count (the samples that returned busy status) in relation to the overall sampling count per second. This ratio is recorded periodically in a moving average for all the channels, including the one that is currently being used.

When channel adaptation is initiated, the gateway node will use equations (3) and (4) to analyze the amount of interference that is occurring at currently used channel \( k \), while excluding the effect of data transmission on the CFR value,

\[
\frac{\Delta \text{CFR}}{\Delta TP} = \max \left( \frac{\text{CFR}_{\text{prev}}(ch_k) - \text{CFR}_{\text{prev}}(ch_k)}{TP_{\text{max}} - TP_{\text{min}}} \right)
\]

where \( TP \) is the throughput value that is recorded at the time of the problem trigger. \( TP_{\text{max}} \) and \( TP_{\text{min}} \) each records the highest and lowest throughput values during the usage of channel \( k \). \( \text{CFR}(ch_k) \) is the current CFR value of channel \( k \) recorded by the gateway. \( \text{CFR}_{\text{prev}}(ch_k) \) is the CFR value that is recorded when the throughput during the usage of channel \( k \) was at its highest. \( \text{CFR}_{\text{prev}}(ch_k) \) on the other hand is the CFR value when the throughput was at its lowest.

Equation (3) represents the effect of the current data transmission on the CFR value. This is acquired by calculating the variation of the CFR from the lowest throughput to the highest throughput during the usage of channel \( k \). Then the result from (3) is used in equation (4) to exclude this result on the total CFR value of channel \( k \). The reason for this is that the effect of data transmission throughput on the CFR value will be moved on to another channel when channel switching is made, because data transmission is continued by the newly chosen channel. If the result from (3) is multiplied with the current throughput rate as seen in (4), the amount of CFR that the data transmission is inducing can be acquired and then excluded.

The results of (4) are then used in equation (5) to select the candidate channels that is more efficient than channel \( k \):
the packet is transmitted to only the neighboring nodes of the gateway. The values of the soldier node are then reported back to the gateway, which attempts to select the best channel among the candidates. The CFR of all the channels is acquired and also the CFR of a specific number of soldier nodes.

We consider this gateway-oriented centralized channel sensing method as a viable approach because majority of the data streams in the HMS/JTRS systems are directed to or from gateways. Since most of the data traffic is concentrated at the gateway, the channel conditions at the area of the gateway also become the most critical. However, we will not completely exclude the channel status of the soldier nodes by utilizing opportunistic methods to select certain number of soldier nodes for providing feedback data to gateway.

After the selection of the candidate channels, the gateway node will attempt to select the best channel among the candidates. If none of the channels were picked as candidates, the current channel will be maintained. If only one channel was selected, then that channel will be enforced in the network. If more than one channel was selected as candidates, then an election process is initiated to choose the best channel. The following formula is used to consider the CFR of the gateway and also the CFR of a specific number of soldier nodes.

\[
CH_{\text{Candidate}} = \{c_h | \text{CFR}(c_h) < \text{CFR}'(c_h), c_h \in CH \} \quad (5)
\]

When \( CH = \{c_h | c_h \text{ is all available channels} \} \), \( \text{CFR}(c_h) \) is the current CFR value of an available channel \( i \) calculated by the gateway. As seen in (5), the CFR values of all available channels \( i \) are compared with the \( \text{CFR}'(c_h) \). Only channels that have lower CFR than this value are chosen to be considered as candidate channels.

Once the new channel is selected, the information must be propagated to all nodes in the network. The gateway generates a \textit{Channel_switch} packet and broadcasts it to all the soldier nodes. The \textit{Channel_switch} packet will contain the information of the newly selected channel. Each node receiving this control packet will rebroadcast the packet to all other neighbors and then switch its channel according to the packet information.

C. Example of the Proposed Scheme Operation

The basic mechanism of our scheme operation is shown in Fig. 2. We can see in Fig. 2 (a) that the gateway node is calculating the moving average of SINR for channel 1, and also the CFR of all the channels. Node D is transmitting its data to the gateway via node B, and we assume that the SINR value calculated from data forwarding by node B has recorded 14 dB in succession and triggered a problem at the gateway. The gateway will realize that there is a problem in the network and try to discover a candidate channel.

In Fig. 2 (b), we can see that by comparing the CFR of each channel with CFR’ of channel 1 which is calculated as 25%, channel 6 and channel 11 are both considered as the candidate channel. The gateway will include this information in the \textit{Channel_request} packet and broadcast it to neighboring soldier nodes. Upon reception of \textit{Channel_request}, node A and node B will halt its transmission and switch its channels to 6 and 11 to acquire the CFR. Once the CFR is acquired, this information is included in \textit{Channel_report} packet and sent back to the gateway.

Once the gateway receives all the feedback from neighboring nodes, it will try to calculate the best channel among the candidate channels. As seen from Fig. 2 (c), the CFR from the gateway, node A, and node B are added up and compared. Even though channel 6 had better quality than channel 11 from the calculation of the gateway, bad condition from node A enlightens channel 6 to be worse than channel 11. The results of this calculation may vary depending on value of weight we give as seen in (6), but for this example, we configure even weights for each node and the gateway. The gateway will choose channel 11 as the next channel to use and broadcast this information in the \textit{Channel_switch} packet to all the nodes in the network. All nodes that receive this information will record the information of channel 11, rebroadcast the \textit{Channel_switch} packet, and then switch its currently used channel to 11.
we assume real time streaming audio data in the tactical environment. Our first evaluation results can be observed in Fig. 3. This environment with no interference will be the point of data congestion. At the initialization of the network, channel 1 is statically configured for all the nodes in the network. However, FCA cannot adapt its network to other environments. Therefore, the performance is seriously degraded when the number of connections increases. The performance of all the environments tends to decrease when the number of UDP connections also increase. This is because the 802.11g based network starts lacking transmission capacity when more than 22 connections are made simultaneously.

Fig. 3 (b) shows the aggregated goodput of each network environment. The aggregated goodput is calculated by adding all the successful transmissions to the gateway per second. The performance saturation point of FCA scheme is reached when there are only 14 UDP connections in the network. On the other hand, the proposed scheme has managed to successfully service twice more connections, providing nearly 600% performance increase when at its maximum. Even though 54Mbps is supported by 802.11g, the performance saturation of the upper bound is just over 8Mbps, which is mostly due to multi-hop transmissions and overheads from various layers of the network.

Fig. 3 (c) looks into the detail of the proposed scheme and the FCA by evaluating the Playout Continuity Index (PCI) [17] of each connection. We focus on a scenario of when 18 connections are generated and transmitted in the network. PCI calculates the percentage of the playback time (overall play time minus the pause time duration) that occurred in the streaming multimedia in relation to its overall play time. The PCI can be used as an important indicator for evaluating the performance of multimedia applications, and this can also be a critical factor in tactical networks where streaming audio data or live footages to/from soldiers of the current battlefield must be timely delivered. As seen in Fig. 3 (c), the PCI for each connection in FCA only record about 60% PCI, as failure in packet delivery and longer transmission latency causes the pause time of each connection to increase. On the other hand, our proposed scheme guarantees more than 90% PCI for every connection generated in the network. Every single data connection generated in the proposed scheme provided better streaming service than the data connections generated in the FCA scheme.

IV. EXPERIMENTAL STUDY

To evaluate the performance of the proposed scheme, we implemented it on the actual 802.11 based testbeds, notes that IEEE 802.11 is compliant with SRW based HMS solution and Wideband Networking Waveform (WNW) in JTRS system [16]. The gateway is a Linux 2.6.31 kernel based notebook equipped with one primary interface using 2.4GHz Ralink RT73 wireless USB interface card and a secondary interface also using 2.4GHz frequency. The wireless interface operates IEEE 802.11g utilizing up to 54Mbps transmission rate. Each soldier node is also a Linux based notebook that equips one Ralink interface card as its lone SDR. We have installed 6 soldier nodes in the network, with two nodes neighboring the gateway, two nodes in the two hop range and the other nodes in the three hop range. 3 orthogonal channels, 1, 6, and 11, will be used in the 2.4GHz frequency. As explained in section 3, the SINR_{Threshold} for our proposed scheme is fixed to 20dB, because we assume real time streaming audio data in the tactical networks. The N_{Threshold} is empirically measured and configured to 5.

UDP multimedia streaming connections equaling 300Kbps per connection are used in the network, and the number of connections was increased to evaluate the performance of each network environment. The destination of all connections is the gateway, meaning that the location near the area of the gateway will be the point of data congestion. At the initialization of the network, channel 1 is statically configured for all the nodes in the network. All nodes will transmit their data using channel 1, while channel 6 and channel 11 remain idle. During the evaluation, heavy interfering signal created by outer network source of approximately 10Mbps is generated to channel 1 at the 50 second interval. This interference will act as the noise factor and is expected to deteriorate the conditions of channel 1. The evaluation has been made 5 times for each experiment set, with each set lasting for 100 seconds.

For comparison, the proposed scheme is compared with the typical Fixed Channel Assignment scheme which we abbreviate to FCA. FCA chooses the channel with the best quality at the initialization of the network and maintains it till the end of the experiment. Also, the upper bound performance is also analyzed by creating an ideal environment that does not generate any interference nor change the channel during transmission. This environment with no interference will be the near-optimal result that can be achieved when single interface is used throughout the network. Our first evaluation results can be observed in Fig. 3.

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**Fig. 3** Performance Evaluation of our Proposed Scheme via Testbed Implementation

- **(a) Comparison of Delivery Ratio**
- **(b) Aggregated Goodput**
- **(c) PCI Performance**

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**Table 1**

<table>
<thead>
<tr>
<th>Number of Connections</th>
<th>FCA Scheme</th>
<th>Proposed Scheme</th>
<th>Ideal Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>90.0%</td>
<td>95.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>14</td>
<td>85.0%</td>
<td>92.0%</td>
<td>97.0%</td>
</tr>
<tr>
<td>18</td>
<td>80.0%</td>
<td>90.0%</td>
<td>95.0%</td>
</tr>
<tr>
<td>22</td>
<td>75.0%</td>
<td>85.0%</td>
<td>90.0%</td>
</tr>
<tr>
<td>30</td>
<td>70.0%</td>
<td>80.0%</td>
<td>85.0%</td>
</tr>
</tbody>
</table>

**Figure 3**

(a) Comparison of Delivery Ratio
(b) Aggregated Goodput
(c) PCI Performance

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Fig. 4 further evaluates the performance of our proposed scheme in relation to time. During the evaluation of 100 seconds, 18 UDP connections are statically initiated at the 20 second interval. The network utilizes channel 1 in the beginning of the network, and the 10Mbps of interference is also generated to channel 1 in the 50 second interval. In Fig. 4(a), we can observe that CFR of channel 1 increases from 40% to more than 70% when FCA is used. This is due to the 10Mbps interference that uses more bandwidth and causes the CCA sampling to fail more. Even though the CFR of channel 1 is increased, the network does not make any changes to the network and maintains the usage of channel 1. We can also observe that channel 6 and channel 11 maintains a very low CFR, because they are not utilized at all.

On the other hand, we can observe in Fig. 4(b) that when the increase in CFR of channel 1 is detected in the proposed scheme, the primarily used channel is instead switched to channel 11, which maintains the lowest CFR among the candidate channels. Therefore, when channel 11 is utilized, its CFR is increased. However, the CFR of channel 11 is lower than the status of channel 1 shown in Fig. 4(a), meaning that our proposed scheme has selected a more efficient channel and the interference from the used channel is less. Fig. 4(c) shows the variations of aggregated goodput in relation to the CFR. When FCA is used, the aggregated throughput is rapidly degraded to about 3.5 Mbps at the 50 second interval. In the proposed scheme, the performance also decreases just before channel switching occurs, but after the channel switching, we can see that the aggregated goodput is raised again to over 5.5 Mbps for the remainder of the experiment.

In overall, we have proved through our implementation results that using fixed channels may pose big problems in the dynamic environment of tactical networks. We have shown that our scheme can guarantee performance near the upper-bound by adaptively selecting the most efficiently channel only when it is decided that the current channel is deteriorated.

V. CONCLUSION

The wireless environments in the tactical network systems can be severely affected by various phenomenon. Although simple and lightweight, HMS devices used by soldiers may not have enough functions to cope with these problems. To alleviate these problems, we utilize the functionalities of the software defined radios installed in these devices and present novel channel detection and channel adaptation method for tactical networks. We believe that more research is needed to polish the proposed scheme. For example, we have observed through our experiment that when there are enough data connections that cause the SINR value of the gateway to be near the boundary, the performance may decrease a little. To solve this problem, we may need to include additional SINR problem trigger algorithms to suppress excessive channel switching. Also, when calculating formula (6), weighting parameters should be researched to select different soldier nodes for calculating the CFR. Finally, testbed experiments based on more complex scenarios are needed to prove that our proposed scheme can function reliably in realistic conditions.

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