Overhead Analysis for Radio Environment Map-enabled Cognitive Radio Networks

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Abstract— **This paper presents a novel and general approach to *cognitive radio* (CR) networking based on the *Radio Environment Map* (REM). REM is envisioned to be an *integrated database* that consists of comprehensive multi-domain information for CR, such as geographical features, available services, spectral regulations, locations and activities of radio devices, policies, and past experiences. Disseminating and sharing REM information offers a proper vehicle of CR *network support*, which can be exploited by *cognitive engine* (CE) for most cognitive functionalities such as situation awareness, reasoning, learning, planning and decision support. Tradeoffs have to be made between the performance gain and the cost of overhead. This paper focuses on analyzing the overhead associated with REM dissemination under various scenarios. With analytical models and network simulations, it is shown that the overhead of REM dissemination can be significantly reduced by extending the optimized link state routing protocol (OLSR). Application-specific ad hoc methods have also been proposed and can be employed to further reduce the overhead. Simulations are presented, comparing the overhead of REM dissemination for different network size, topology, node density and mobility. Preliminary results show that the speed of wireless nodes has little impact to the load of overhead if the REM dissemination rate is fixed. The size of REM information element is estimated for the emerging cognitive wireless regional area networks (IEEE 802.22 WRAN).**

Keywords- Cognitive Radio Networks, Radio Environment Map (REM), Overhead Analysis

I. INTRODUCTION

As an emerging inter-disciplinary research topic, cognitive radio (CR) has received considerable attention recently from government, radio spectrum regulation authorities, military agencies, academia, and industry. The term CR was first coined by Dr. Joseph Mitola III in late 1990's [1]. Generally speaking, CR works by gaining situation awareness, and adapting to its radio environment to reach its goal(s) through a cognitive engine (CE). CE is the "brain" of the CR, which essentially is a software system that enables or supports various cognition functionalities. Being a relatively new research area, there have been various interpretations on CR in the literature. For example, the US Federal Communications Commission (FCC) views CR as "a radio that can change its transmitter parameters based on interaction with the environment in which it operates" [2]. Virginia Tech CR research group's view on CR is as follows [3]: A cognitive radio is an adaptive radio that is capable of the following:

- Awareness of its environment and its own capabilities.
- Goal driven autonomous operation.
- Understanding or learning how its actions impact its goal.
- Recalling and correlating past actions, environments, and performance.

Although there could be different views and expectations on CR, it is generally believed that CR has great potential of increasing spectrum utilization by enabling dynamic spectrum access, offering more personal, reliable, flexible and situation-aware communication services to end users, and bridging various wireless networks. Software radio provides an ideal platform for the realization of CR, and it is expected that most (if not all) cognitive radios are software defined radios [1]. Currently CR research is still at the very beginning stage. Many challenging technical issues are yet to be solved before making CR practical. The overarching problems include, but are not limited to the following:

- How is comprehensive situation awareness obtained at a network node?
- How is fast wide-band spectrum sensing achieved?
- How can the hidden node problem be mitigated?
- How can primary users and secondary users coexist with each other with interference management?
- How does one test the performance of CR network?

Generally, the performance of a CR network highly depends on how much information about the radio environment is available at each node. As illustrated in Figure 1, the Radio Environment Map (REM) is envisioned as an integrated database that consists of comprehensive multi-domain information of the radio environment, such as geographical features, available services, spectral regulations, locations and activities of radios, policies of the user and/or service providers, and past experiences [4]. In this paper, we present a novel and general approach to CR networking, i.e., REM-based CR networking, and focus on analyzing the overhead associated with REM dissemination in CR networks. The rationale to disseminate

REM information among CR nodes is to provide powerful network support to CR nodes via sharing global REM or distributed local REMs. With the help of REM dissemination, individual CR can know better about its radio environment by "seeing" far beyond its own horizon, which helps to coexist with primary users (PU), the ones with first rights to the spectrum, and/or other secondary users (SU), mitigate hidden node problem, and improve the overall network performance. The REM-enabled CR can relax the requirements on individual CR node by exploiting the REMs in an intelligent way. Disseminating REM in CR networks is also important for enabling cooperative (distributed) learning. However, careful tradeoffs need to be made between the performance gain and the associated costs, since disseminating REM also consumes power and bandwidth. This is the main motivation of this research.

The capability and the level of situation-awareness greatly impact the CR performance. As depicted in Figure 2, network support to CR can be realized through disseminating and leveraging global REM and/or local REMs. In this figure, the CR is symbolized as a "brain"-empowered radio. The global REM maintained on the network keeps an overview of the radio environment, while the local REM stored at the user equipment only presents a more specific view to reduce memory footprint and communication overhead. The local REMs and global REM may exchange information in a timely manner so as to keep the information stored at different entities current. Common control channel can be employed for disseminating REM information between nodes. Leveraging both internal and external network support through the REMs presents a practical approach to implementing CR networks in a reliable, flexible, and cost-effective way. The REM-based CR networking is also a future-proof approach for dynamic spectrum management in the sense that it allows regulators or service providers to modify or change their rules or policies simply by updating the REMs.

In this paper, we evaluate the performance of REM dissemination in CR networks with various network topologies, sizes, density and mobility. We also discuss about the avenues to improve the efficiency of REM dissemination. As an example, we estimate the size of REM information element for cognitive wireless regional area network (WRAN) [6], which will be the first commercial application of CR technology to efficiently share the broadcast TV bands.

The remainder of this paper is organized as follows. Section II first discusses the typical CR network scenarios, several performance metrics considered for REM dissemination, and the related work. Section III discusses REM dissemination schemes, implementation issues, and applications to 802.22 WRAN. Section IV presents a simple analysis of the overhead associated with REM dissemination. Section V compares the overhead for various scenarios with network simulations. Section VI summarizes the main contributions of this paper and discusses the future work.

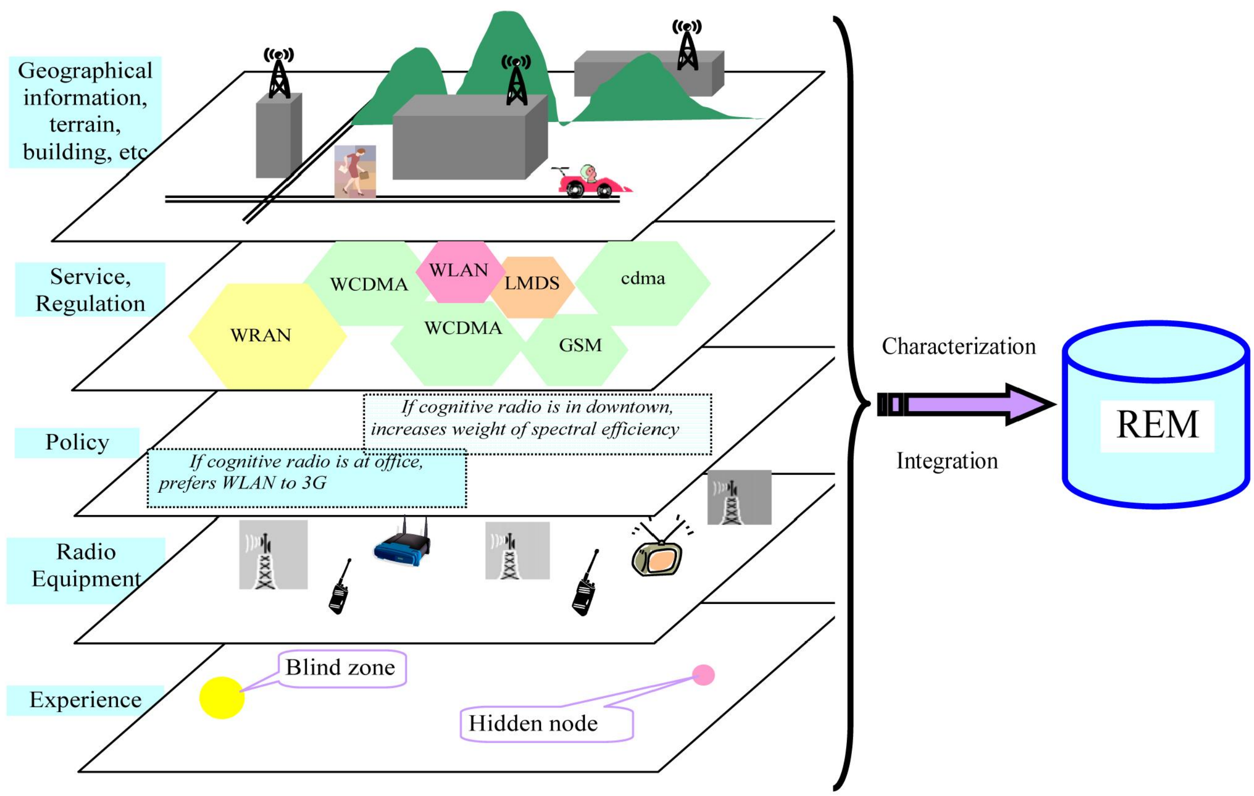


Figure 1. REM is envisioned as an integrated database characterizing the real-world radio scenario [5].

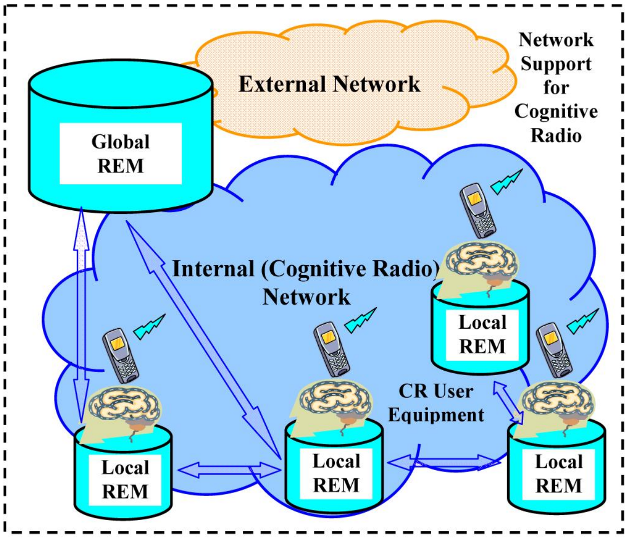


Figure 2. Internal and External Network Support for Cognitive Radio. REM provides cognitive services to both the associated internal networks and a useful awareness of external networks [4].

II. Network scenarios, performance metrics, and related work

A. Typical network scenarios for REM dissemination

For REM dissemination in CR networks, we may consider the following two typical scenarios:

Case 1: REM information sharing or exchanging between a central node and distributed nodes in infrastructure-based (centralized) CR networks;

Case 2: REM information sharing or exchanging between distributed nodes in ad hoc (infrastructure-less) CR networks.

For the first case, it is fairly straightforward to disseminate REM with broadcasting (from central node to distributed nodes) or request/report messages (from distributed nodes to central node); for the second case, the REM information can be disseminated in a similar way as how topology information is passed for routing table construction. Therefore, analyzing the overhead of REM dissemination in ad hoc CR networks is the focus of the remainder of this paper.

For example, by sharing the TV broadcast bands between 54 MHz and 862 MHz, 802.22 WRAN systems are initially aimed to offer fixed wireless access services in a centralized mode, whereas supporting mobility in an ad hoc network (or a mesh network) mode will be the natural evolution of 802.22 standards in the near future. For cognitive WRAN systems, the primary users include incumbent TV stations, TV receivers, wireless microphones, and public safety systems. 802.22 system subscribers are secondary users, and therefore, should avoid generating harmful interference to the primary users.

B. Performance metrics of REM dissemination

To evaluate the performance of various REM dissemination schemes, there could be multiple performance metrics to consider, such as load of overhead, latency, reliability, reachability, correctness, and convergence time.

Load of overhead indicates the efficiency of REM dissemination algorithm. Latency refers to the time delay from the REM information source to its destination, which can be estimated with maximum delay or average delay. The overall delay may consist of propagation delay, processing delay, queuing delay, and transmission delay. REM information could be static (e.g., terrain features) or dynamic (e.g., RF spectrum usage). The latency can affect the freshness and utility of REM information, since some dynamic REM information required for real-time adaptation could become useless if the dissemination delay is too big. Reliability is a measure of REM packets received without error by network nodes whereas reachability refers to the total number of unique nodes reached by the dissemination process. Correctness can be evaluated with the deviation between the original REM from the source node and the recovered REM at the destination node. Decision fusion or data fusion is made by each individual node independently based on the distributed observations embedded in local REMs, the error propagation problem can be avoided. Therefore, convergence time is not considered in this paper.

Note that there may be different considerations for REM dissemination, as compared to the control message flooding in ad hoc networks. For example, we may not require the REM information originated from one node reach all other nodes in the CR network, since only some nodes actually need such information. How often CR node needs to disseminate REM may depend on the characteristics of the radio environment as well as the specific application of CR.

C. Related work

Little work has been reported explicitly on overhead analysis for CR networking in the literature yet, partially because of the very early stage of CR research and development. It is also difficult to find well-defined CR scenarios and baseline simulations in the literature for comparison purpose, though some papers simulate the network capacity, throughput, spectrum efficiency for various CR network scenarios. For example, reference [7] presents some simulation results on normalized throughput for a CR network consisting of 30 nodes. In [8], the authors present optimization algorithms to minimize the required network-wide spectrum via local information exchange among neighboring nodes. In [9], the authors present models for estimating the performance of flooding in multi-hop ad hoc networks, and investigate the performance of flooding in terms of its reliability and reachability in delivering packets. Reference [10] explains the importance of global knowledge of mobile ad hoc networks for making cross-layer decisions and optimizations, and provides some simulation results on the correctness of global knowledge, which is obtained by collecting "local views" from the distributed nodes.

In this paper, we focus on the load of overhead and reliability of REM dissemination in mobile ad hoc CR networks. The load of overhead directly reflects the efficiency of REM dissemination and the price we need to pay for implementation. High overhead may consume too much precious bandwidths and energy, and it also can congest the control channel. Reliability is also important, since unreliable REM information may cause wrong decision making and degrade network performance.

III. REM DISSEMINATION SCHEMES, DEPLOYMENT ISSUES, AND EXAMPLE APPLICATIONS

A. REM dissemination schemes

REM information can be disseminated in various methods. In this paper, we consider the following three schemes and compare their performance in the next section.

A first, and naïve scheme is to periodically broadcasts REM information to the entire network via plain flooding. This approach is straightforward while it tends to be prohibitively costly in terms of energy and spectrum consumption. The merit of this scheme is that it is simple, easy to implement, does not require any specific protocol support. It may be still good for small CR networks consisting of a limited number of nodes.

Motivated by the analogous between routing information dissemination in link state-based routing protocols and REM dissemination in CR networks, we propose to extend the optimized link state routing protocol (OLSR) [11] for REM dissemination. More specifically, REM dissemination in ad hoc networks can be viewed as setting up a "generalized routing table" in CR networks. Considering that OLSR is a proactive protocol and uses the link-state scheme in an optimized manner to diffuse topology information, we may adapt or extend the HELLO message and Topology Control (TC) message in OLSR to support other dimensions of REM information in addition to topology; TC messages are broadcast and retransmitted by the multipoint relays (MPRs) in order to diffuse the messages in the entire network.

The OLSR protocol developed for mobile ad hoc networks is an optimization of the classical link state algorithm tailored to the requirements of a mobile wireless LAN. The key concept used in the protocol is MPRs, which are selected nodes which forward broadcast messages during the flooding process. This technique substantially reduces the message overhead as compared to a classical flooding mechanism, where every node retransmits each message when it receives the first copy of the message [11]. In OLSR, link state information is generated only by nodes elected as MPRs. Thus, a second optimization is achieved by minimizing the number of control messages flooded in the network. OLSR provides optimal routes (in terms of number of hops). The protocol is particularly suitable for large and dense networks as the technique of MPRs works well in this context. Figure 3 illustrates the MPR employed in OLSR and how it works. As we can see from this figure, MPRs are selected in a way such that message from current node cane reach *all* of its 2-hop neighbors via retransmissions by MPRs *only*.

Finally, application-specific ad hoc methods can be used to further reduce the control overhead. For example, the REM dissemination rate can be adaptively adjusted according to the features of the incumbent primary users or interference; and we may also only disseminate the selected REM information (rather than complete map) in an "on-demand" mode; a clustered approach may also be effective in optimizing the cooperative CR network performance while keeping the overhead to a minimum [12].

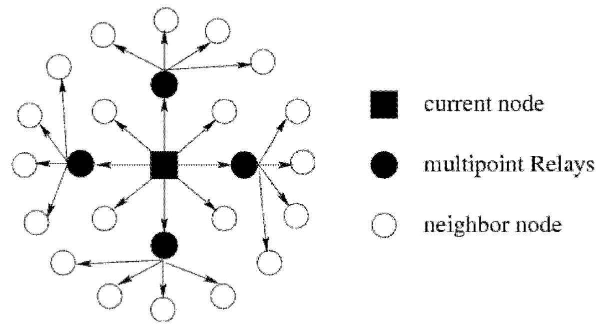


Figure 3. Illustration of MPRs employed in OLSR protocol

In summary, in order to minimize the traffic load of REM dissemination, we may try to minimize the number of retransmissions, to reduce the message size of REM, and to limit the sources of REM (i.e., the number of overhead originators).

B. Deployment issues

REM can be implemented with any kind of data structure as long as it can present the desired radio environment information. When deployed in CE, we may implement REM with a C++ structure, or a multi-dimension matrix, or a multi-dimensional database.

The REM information can be disseminated through a common control channel, which could be implemented with one of the following four options:

(1) A (narrowband) channel in licensed band
(2) A channel in license-free ISM or UNII band
(3) A ultra wideband (UWB) channel
(4) Sharing with the traffic channel

The attributes and memory footprint of REM will highly depend on the specific application of CR networks. For 802.22 WRAN, a REM information element is illustrated in Table 1. For this example, the size of one REM information element is about 65 bytes. However, in many cases, there is no need to disseminate the entire REM, we only need to update partial REM information that changed over the last update, which will further reduce the overhead. For example, we can just update the interference temperature, which can significantly reduce the load of REM dissemination overhead by more than 30 times (from 65 bytes to 2 bytes).

C. *Example applications*

REM and REM dissemination will play an important role for cognitive WRAN systems, since it can provide the WRAN nodes not only the radio environment information (such as the location, antenna height and the transmit power of nearby TV stations, the local terrain, the Grade B service contours of TV station, the forbidden spectrum used by local public safety radios, the demographical distribution of TV receivers), but also the spatio-temporal spectrum usage and the variation of interference temperature. Such information helps the WRAN nodes choose the best spectrum opportunity to use at the optimal transmission power. Smart antenna techniques can be more efficiently employed with the radio environment information provided by the REM.

REM dissemination is also very important for mobility support, hidden node detection and protection. The RTS/CTS mechanism employed in 802.11 MAC cannot completely eliminate hidden node problem, due to the interference range is larger than the reception range [13]. REM-based dynamic spectrum access can address this problem, which will estimate the interference range of CR and transmit only if none of primary users falls into its interference range based on the radio environment information. In such a way, the performance of CR networks and incumbent primary user networks can be further improved by reducing the mutual interference between primary users and secondary users.

For spectrum sharing applications, interference temperature (IT) is an important metric to be employed by CR nodes. IT can be part of REM information (see Table 1) and disseminated throughout CR networks, which allows the transmitting CR node knows the interference margin at other nodes (e.g., incumbent primary users), in such a way CR nodes can adjust their transmission power or antenna pattern to avoid harmful interference to primary users or hidden nodes.

IV. ANALYTICAL MODELS

In [14], the authors present a theoretical analysis on the performance of OLSR multipoint relay-based flooding, and develop two graph models for indoor and outdoor scenarios, respectively. Interested readers can refer to [14] for more details. These analytical models can also be used for REM dissemination overhead analysis for the scheme based on OLSR, and are summarized below.

Case I: Random graph model for indoor ad hoc networks. It is shown that the average overhead of OLSR for topology broadcast in random graph model is $O((logN)^2)$ for each node. This is a great reduction in overhead as compared to $O(N^2)$ associated with plain link state algorithm. Note: N is the number of wireless nodes in the network.

Case II: Random unit graph model for outdoor ad hoc networks. It is shown that the overhead of OLSR for topology broadcast in random unit graph model is $O((N)^{1/3})$ for each node when N tends to infinity.

Table 1: An illustrative example of REM Information Element for 802.22 WRAN systems

Attribute index	Syntax	Size	Notes
1	CR_ID	2 bytes	Unique ID for each radio device
2	CR_Location	12 bytes	GPS coordinates (such as longitude, latitude, and altitude), or the relative position in a CR network.
3	Time stamp	4 bytes	The time when this observation is made.
4	Spectrum usage map	16 bytes	Observed spectrum usage at this location.
5	Geographical environment Type	1 byte	Type of local geographical environment, e.g., indoor; mountainous; open rural; suburban; dense urban, etc., which indicates the appropriate channel model to apply.
6	Detected primary user (PU) profile	6 bytes per PU entry	PU profile may include the type of PU, channel in use, and usage pattern of PU (e.g., the likelihood of presence).
7	Secondary user (SU) profile	6 bytes per SU entry	SU profile may include the type of SU, channel in use, and usage pattern of SU (e.g., the likelihood of presence).
8	Interference temperature	2 bytes	The interference temperature which is estimated by the wireless node at this location.
9	Forbidden channels	16 bytes	The spectrum that is not allowed to use at this location by regulation.

Figure 4 plots the average number of retransmissions per node for plain flooding and OLSR (in indoor networks and outdoor networks), respectively. As can be seen, the overhead of OLSR is significantly less than that of plain flooding, especially when the number of nodes gets larger. Furthermore, Figure 4b shows that the OLSR overhead for outdoor ad hoc networks is smaller than that for indoor networks according to the analytical models. It is expected that the overhead of realistic networks may lie somewhere between the two curves shown in Figure 4b.

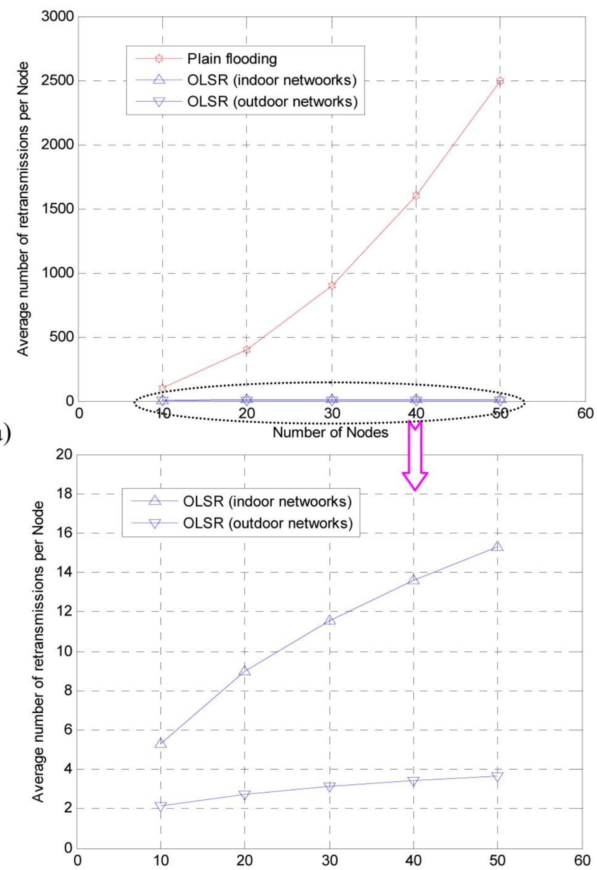
V. Network Simulations

In this Section, we use the ns-2 network simulator ([15], version 2.29) to simulate REM dissemination overhead with extended OLSR in various mobile ad hoc CR networks.

A. Simulation model

We used the UM-OLSR [16] model with the ns-2 network simulator and perform simulations with the parameters listed in Table 2. UM-OLSR complies with RFC 3626 [11] and supports all core functionalities of OLSR. For all of the simulations described in this section, wireless nodes comply with IEEE 802.11b PHY/MAC. The channel model used in ns-2 simulation is a two-ray ground reflection model. REM information packet is piggybacked as part of the TC message and HELLO message. The overhead of REM dissemination is estimated in terms of "average REM information packets to transmit at each node" by averaging the total number of TC and HELLO messages sent during the simulation period.

(a)



(b)

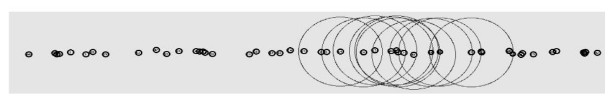
Figure 4. Overhead analysis on overhead of plain flooding vs. OLSR using analytical models (Note: Figure 4b is to zoom in and show the details of two overlapping curves in Figure 4a).

Table 2: Simulation parameters

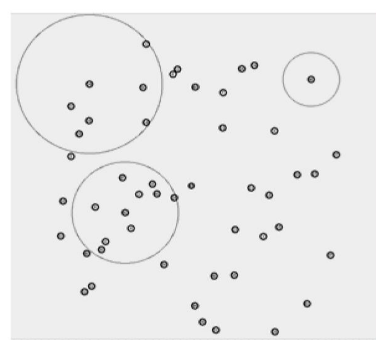
Parameter	Value
Communication range of wireless node	250 meters
Maximum moving speed of wireless node	10 m/s unless stated otherwise
Pause time in random waypoint mobility model	0
TC interval in OLSR	2 seconds
HELLO interval in OLSR	Same as TC interval
REM dissemination interval	Same as TC interval
Data rate of wireless channel	2 Mbps
Interface queue length	50 packets
CBR packet size	512 bytes
CBR traffic rate	1 CBR packet per second
Simulation period	100 seconds

B. Network topologies for overhead simulations

Figure 5 shows the network topologies used in our ns-2 simulations. Topology A shown in Figure 5(a) is to emulate a mobile ad hoc CR network deployed along a street; Topology B shown in Figure 5(b) is to emulate a mobile ad hoc CR network deployed in an open square area. Note: the circles in Figure 5 just show the instantaneous wavefront of radio waves from different nodes at the time of snapshot. The radius of these circles does not mean the transmission range of different nodes. In our ns-2 simulations, all wireless nodes use the same transmit power.



(a) Topology A: CR nodes located in a street-like area (2000m x 20m)



(b) Topology B: CR nodes located in a square area (1000m x 1000m)

Figure 5. Screen shot of ns-2 simulations for different network topologies

C. Overhead simulations under different network sizes, topologies and node densities

Simulations have been conducted to investigate the impact of network size, topology and node density on the overhead of REM dissemination. Figure 6 shows the REM dissemination overhead for various node densities, network sizes and topologies. In general, the simulation results are quite consistent with the analytical results shown in Figure 4b.

In addition, we can also make the following observations from Figure 6.

(i) If the network size is very small (e.g., 250m x250m) such that most nodes are within 1-hop range, the load of overhead is low and almost constant (close to 1 REM packet per node) regardless the node density, since no MPR is needed for such scenarios;

(ii) If the network has medium size (e.g., 1000m x1000m) such that most nodes can communicate with each other through relays, the load of overhead normally increases with the node density;

(iii) If the network size is very large (e.g., 2000m x2000m) such that many nodes cannot reach each other, the load of overhead becomes lower again due to the decrease of the number of MPRs.

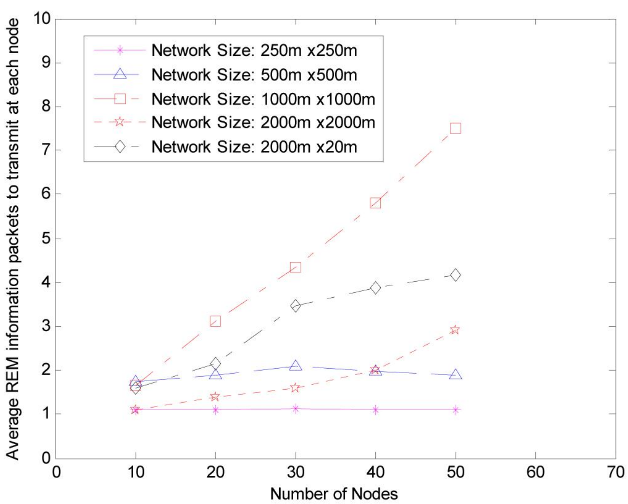


Figure 6. Overhead under various network sizes and node densisties

D. Impact of mobility on REM dissemination

Movements of the CR nodes can be determined by different mobility models, such as random waypoint mobility model, Manhattan model, and modified Manhattan model that takes dense urban radio propagation into consideration [17]. For simulations in this paper, random waypoint mobility model is employed. In this model, each node randomly chooses a destination within the specified network area and a random speed from within a given range and moves towards it. When it arrives at the destination, it pauses for a random period of time from a specified range, and then chooses another destination and moves on.

To investigate the impact of moving speed to the overhead, we simulate the REM dissemination with two different network topologies for comparison. For network topology A, the speed of each node varies from a low speed (1 m/s) to a very high speed (50 m/s); For network topology B, the speed of each node varies from a very low speed (0.1 m/s) to a medium high speed (10 m/s).

Figure 7 shows the simulation results. It can be seen that for both types of network topologies, the speed of wireless node has little impact to the load of overhead. This observation is reasonable since the load of overhead mostly depends on the number of REM retransmissions, supposing that the REM dissemination rate is fixed (as is the case for our simulations). However, in case that the REM dissemination rate need to change with the speed of wireless nodes, then the total load of overhead will be affected by the speed of nodes, too.

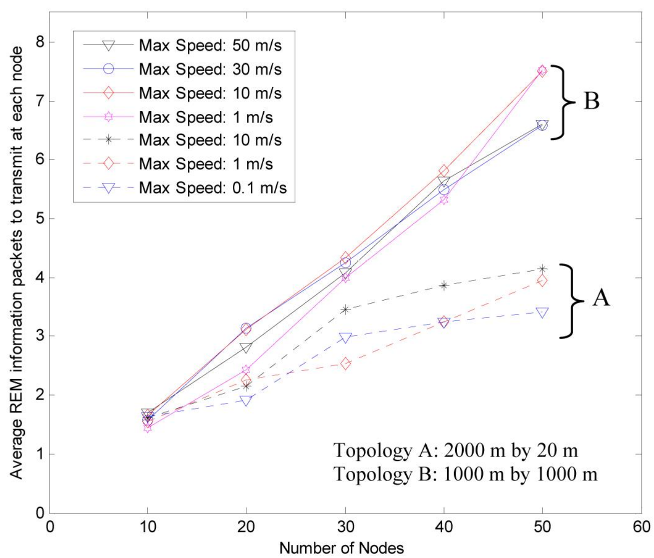


Figure 7. Overhead under various node moving speed

E. Reliability of REM dissemination

The reliability of REM dissemination is evaluated with REM packet drop ratio in the simulations. Figure 8 shows the simulated REM dissemination reliability under different network scenarios using the following two different implementation schemes:

(i) REM is disseminated through a dedicated control channel;

(ii) REM is disseminated by sharing a traffic channel with constant bit rate (CBR) stream.

Figure 8 shows that (i) REM dissemination is more reliable when using a dedicated control channel, compared to using a shared traffic channel; and (ii) REM packet drop ratio increases with the node density. This is mainly because REM packets are more likely to be dropped when REM dissemination is shared with other traffic or with increasing number of nodes due to the capacity limit of wireless channel and the finite queue at a node. Note that the bandwidth requirement is different for implementing these two schemes.

For example, if the bandwidth of traffic channel and dedicated control channel are BW_1 and BW_2, respectively, then the total required bandwidth for the first scheme is the sum of BW_1 and BW_2 (Note that BW_1 is used for REM dissemination and BW_2 for traffic data), whereas all traffic data and REM packets share the bandwidth of BW_1 in the second scheme.

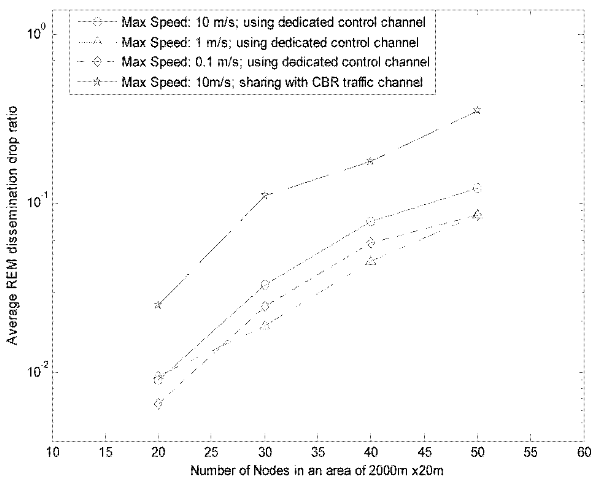


Figure 8. REM packet drop ratio under various conditions using different dissemination channels

VI. SUMMARY AND FUTURE WORK

The key feature of REM-enabled CR networks is that CR can be simple (low cost) while still obtain the needed situation awareness for optimal or reasonable adaptation by disseminating and leveraging the distributed REMs. In this paper, the performance of REM dissemination with various network topologies, sizes, node density and mobility are evaluated and compared. Some preliminary analytical and simulation results are presented. Several REM dissemination schemes have been proposed and discussed. It is shown that by extending the existing OLSR protocol, REM can be efficiently disseminated in mobile ad hoc CR networks. Simulations also show that the speed of wireless node has little impact to the load of overhead if the REM dissemination rate is fixed.

The main contributions of this work are three fold: first, we introduce the idea of REM-enabled CR networking and explain why timely and efficient REM dissemination is needed in CR networks; secondly, we quantitatively analyze the REM overhead under various network scenarios using different dissemination schemes with both analytical models and simulations; thirdly, we discuss about the avenues to improve the efficiency of REM dissemination.

The key remaining issue is to evaluate the performance gain of REM-enabled CR networks, which will help us to make proper tradeoff when implementing REM-enabled CR. It is also interesting to evaluate the robustness of CR networks to REM dissemination error and investigate how to protect the REM-enabled CR networks from unreliable or malicious REM dissemination.

ACKNOWLEDGMENT

Youping Zhao has been supported in part by the Electronics and Telecommunications Research Institute (ETRI) and the Army Research Office (ARO). Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the author(s) and do not necessarily reflect the views of ETRI or ARO. Youping Zhao would like to thank David Raymond, Ruffy Zarookian and Karthik Channakeshava for their help in ns-2 simulations.

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