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Benefits of sensor mobility when creating a radio environment map

Stephanie Faint, Geoffrey Colman and Tricia Willink

Defence R&D Canada – Ottawa

Technical Memorandum
DRDC Ottawa TM 2011-189
December 2011

Canada

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Abstract

Operating in a heterogeneous radio environment requires knowledge of the frequency occupancy for a given region of interest. To assist spectrum managers in allocating frequencies dynamically, the topography of radio frequency (RF) energy can be detailed in a radio environment map (REM). The generation of the REM may be supported by sensors spread over the region to obtain power measurements. Collecting measurements from many sensors incurs a large network overhead, resulting in lost or delayed measurements which can degrade the quality of the REM. It is shown through simulations that if the sensors are mobile, their movement can be used to improve the accuracy of the REM, reducing the number of sensors and networking overhead required. As the sensors' speed increases, or the observation window lengthens, the effective area covered by each sensor also increases, further improving the REM accuracy.

Résumé

Le fonctionnement dans un environnement radio hétérogène nécessite que l'on connaisse l'utilisation des fréquences pour une région d'intérêt donnée. Afin d'aider les gestionnaires du spectre à attribuer les fréquences dynamiquement, la topographie de l'énergie des radiofréquences peut être détaillée dans une carte d'environnement radio (REM). La REM peut être produite avec des capteurs dispersés dans une région donnée pour mesurer la puissance. La collecte de mesures à l'aide de nombreux capteurs engendre un surdébit considérable dans le réseau, ce qui peut causer un retard ou une perte des mesures et, conséquemment, miner la qualité de la REM. Des simulations ont démontré que les mouvements des capteurs mobiles peuvent améliorer la précision de la REM et ainsi réduire le nombre de capteurs nécessaires et le surdébit du réseau. La superficie couverte par chaque capteur s'étend également avec l'augmentation de la vitesse des capteurs, ce qui améliore la précision de la REM.

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Executive summary

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Defence R&D Canada – Ottawa; December 2011.

Background: Radio environment maps (REM) contain information about radio frequency (RF) environments that can be used by spectrum managers to determine the geographic areas where emitters can access frequency spectrum without suffering or causing unacceptable interference. In modern wireless communication networks, with an increasing demand on the available spectrum, radios need to function in heterogeneous environments, which require the sharing of limited spectrum resources over a large area while minimizing interference. The REM facilitates dynamic spectrum management by supporting the assignment of frequencies based on a user's location and the current spectrum usage.

To create a REM for the region of interest, mobile sensors are spread throughout the region to obtain local RF power measurements, which are then forwarded to a central location. The accuracy of the REM generated is limited by the amount of data able to reach the central location. As the number of sensors is increased, the accuracy of the REM would be expected to improve, but in fact this is offset by the increase in network congestion and collision rates which hamper network connectivity. Therefore, there is a need to improve the REM quality with a small number of sensors.

In networking, mobility is often seen as an obstacle to network connectivity, as maintaining a network where the links between network members can change requires ongoing communication between nodes, which increases the amount of traffic in the system, and therefore, the number of collisions. However, this same mobility can actually be beneficial to the creation of a REM, as each time a moving sensor senses a transmission, additional information about that transmission's source is obtained.

Principal results: To study the benefits of sensor mobility when creating a radio environment map, a series of simulations was performed in the OMNeT++ discrete event simulation engine using a varying number of mobile sensors. Additionally, these simulations were performed using a fixed number of static, non-sensor collection nodes that forwarded data from the sensors to a central location using the optimized link state routing (OLSR) protocol. Each simulation took place over several time intervals so that data could be collected over time windows of varying length (number of time intervals), L, for each of four sensor speeds. A flat-earth propagation model and a simple interpolation algorithm for REM generation were used.

As expected when sensors were stationary, increasing L made very little difference. As sensor speed increased, increasing L had more effect on the REM quality, with the most significant gain being made as L increased from one to two, as the number of sensors effectively doubled.

Increasing the speed of the sensors can compensate, over time, for a lower number of sensors. For example, 10 sensors can produce approximately the same results as 15 when window length L is four, and as 25 when L is 10. In this way, reducing the number of sensors, thereby decreasing the financial cost, can be offset by increasing the window length, at the expense of delayed results.

Significance of results: Using mobile sensors to support the generation of a REM has been seen to have many advantages. In addition to lower capital costs associated with fewer sensors, the bandwidth overhead required to support the routing protocol is reduced when there are fewer nodes, decreasing collision rate and allowing a more accurate REM to be computed.

As the speed of the sensors is increased, and the length of the time window is increased, fewer sensors are required to create an accurate REM. In a low density, swiftly moving sensor environment, the benefits to the accuracy of the REM are particularly great, with speed obviating the need for additional sensors.

Future work: Static collection nodes have been considered in this work to-date; as the OLSR protocol is proactive, i.e., sends topology control messages to establish routes in advance of demand, it is expected that the observations are representative of the case in which they are mobile. Increases in overhead due to node mobility must be traded off against the improvement in REM generation.

Static transmitters have also been considered herein, but in many cases of interest, the transmitters may also be mobile. In this case, there would be a trade-off between sensor coverage and the timeliness of the collected observations. The benefit to the REM in this case would depend on both the speed of the sensors, and of the transmitters; these benefits can be quantified using the same simulation tools developed and used in this work. The gain in REM accuracy seen as L increases from one to two could provide robustness in this case, as the change in transmitter geography would likely be minimal over a single time interval.

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Benefits of sensor mobility when creating a radio environment map

Stephanie Faint, Geoffrey Colman, Tricia Willink ; DRDC Ottawa TM 2011-189 ;
R & D pour la défense Canada – Ottawa ; décembre 2011.

Contexte : Les cartes d'environnement radio (REM) comportent des renseignements, au sujet des environnements de radiofréquence (RF), que les gestionnaires de spectre peuvent utiliser pour cerner les zones géographiques où des émetteurs peuvent avoir accès au spectre de fréquences sans qu'il y ait d'interférence inacceptable. Sur les réseaux modernes de communication sans fil, où il y a une demande accrue pour le spectre disponible, les radios doivent fonctionner dans des environnements hétérogènes, ce qui nécessite le partage des ressources spectrales limitées sur une vaste zone tout en minimisant l'interférence. La REM facilite la gestion dynamique du spectre en facilitant l'attribution des fréquences en fonction de l'emplacement d'un utilisateur et de l'utilisation actuelle du spectre.

Afin de produire une REM pour la région d'intérêt, des capteurs mobiles sont répartis dans l'ensemble de la région dans le but d'obtenir des mesures locales de puissance de RF, qui sont ensuite transmises à un emplacement central et combinées sous forme de cartes (REM). La précision de la REM ainsi produite est limitée par la quantité de données qui atteint l'emplacement central et par le retard de transmission de ces mêmes données. À mesure qu'on augmente le nombre de capteurs, on pourrait s'attendre à ce que la précision de la REM s'améliore, mais elle est en fait perturbée par l'accroissement de la congestion du réseau et le taux de collisions qui nuit à la connectivité de ce même réseau. Par conséquent, il faut améliorer la qualité de la REM en utilisant un petit nombre de capteurs.

Par ailleurs, la mobilité est souvent perçue comme un obstacle à la connectivité d'un réseau, puisque le fait d'entretenir un réseau où les liens entre les éléments peuvent varier, nécessite une communication permanente entre les nœuds. Cela augmente la circulation sur le système et ainsi, le nombre de collisions. Toutefois, cette même mobilité peut en fait être avantageuse pour la production d'une REM, étant donné que chaque fois qu'un capteur en mouvement détecte une transmission, on obtient plus de renseignements au sujet de la source de cette transmission.

Résultats principaux : Dans le but d'étudier les avantages de la mobilité des capteurs pour la création d'une REM, on a mené une série de simulations à l'aide du moteur de simulation d'événements discrets OMNeT++ et d'un nombre variable de capteurs mobiles. On a également fait ces simulations avec un nombre fixe de nœuds de collecte immobiles sans capteurs qui acheminaient les données provenant des capteurs vers un endroit central à

l’aide du protocole de routage OLSR (Optimized Link State Routing). On a fait chaque simulation pour différents intervalles de temps afin de recueillir des données sur des périodes de durée variée *L* pour chacune des quatre vitesses de capteur. On a utilisé un algorithme d’interpolation simple et un modèle de propagation de terre plate pour produire la REM.

Comme on s’y attendait avec les capteurs fixes, l’augmentation de *L* a fait peu de différence. À mesure que croissait la vitesse des capteurs, l’augmentation de *L* améliorait visiblement la qualité de la REM. Le gain le plus important a été observé pour une hausse de *L* de un à deux, puisque le nombre de capteurs avait effectivement doublé.

L’augmentation de la vitesse des capteurs peut compenser, au fil du temps, la diminution du nombre de capteurs. Par exemple, 10 capteurs peuvent produire environ les mêmes résultats que 15 capteurs sur une période *L* de 4 et que 25 capteurs sur une période de 10. Ainsi, on peut compenser la réduction du nombre de capteurs pour un coût financier moindre en augmentant la durée de la période, mais les résultats seront produits avec du retard.

Portée des résultats : On a constaté que l’utilisation de capteurs mobiles pour faciliter la production d’une REM comporte de nombreux avantages. Outre les coûts d’immobilisation moindres associés à un nombre réduit de capteurs, on parvient à diminuer le surdébit de la bande passante requise pour soutenir le protocole de routage quand il y a moins de nœuds, ce qui abaisse le taux de collision et permet un calcul plus précis de la REM.

À mesure qu’augmentent la vitesse des capteurs et la durée de la période, il faut moins de capteurs pour produire une REM précise. Dans un environnement à faible densité où l’on trouve des capteurs mobiles rapides, les avantages s’avèrent particulièrement importants pour la précision de la REM, et la vitesse permet d’utiliser moins de capteurs.

Recherches futures : On a considéré les nœuds de collecte immobiles jusqu’à présent dans ces travaux. Étant donné que le protocole OLSR est proactif, c’est-à-dire qu’il envoie des messages de contrôle de la topographie pour déterminer les voies avant les demandes, on s’attend à ce que les observations soient représentatives d’un scénario dans lequel ces nœuds seraient mobiles. Il faut comparer l’augmentation du surdébit causée par la mobilité des nœuds et l’amélioration de la production des REM.

On a également tenu compte des émetteurs fixes dans le présent document, mais, dans bien des cas d’intérêt, les émetteurs peuvent aussi être mobiles. Dans un tel cas, il faudrait mettre en parallèle la couverture des capteurs et le caractère actuel des observations recueillies. Dans pareil cas, les avantages pour la REM dépendraient de la vitesse des capteurs et des émetteurs. On peut quantifier ces avantages en utilisant les mêmes outils de simulation mis au point et utilisés dans le cadre des travaux. L’amélioration de la précision de la REM observée lors du passage de *L* de un à deux peut s’avérer un élément probant dans un tel cas, car la modification de la géographie des émetteurs s’avérerait vraisemblablement minimale au cours d’un intervalle

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1 Introduction

Radio environment maps (REM) [1],[2, Ch. 11] contain information about radio frequency (RF) environments that can be used by spectrum managers to determine the geographic areas where emitters can access frequency spectrum without suffering or causing unacceptable interference. In modern wireless communication networks, with an increasing demand on the available spectrum, radios need to function in heterogeneous environments, which requires the sharing of limited spectrum resources over a large area while minimizing interference. The REM facilitates dynamic spectrum management by supporting the assignment of frequencies based on a user's location and the current spectrum usage.

To create a REM for the region of interest, static and mobile sensors are spread throughout the region to obtain local RF power measurements. The sensors are able to transmit their location as well as the power level at the output of an omni-directional antenna. These data are collected at a single location, referred to here as the headquarters (HQ). It was shown in [3] that the accuracy of the REM generation is limited by message collisions, which result in sensor measurements not being received by HQ. As the number of sensors is increased, the accuracy of the REM would be expected to improve, but in fact this is offset by the increase in network congestion and collision rates. Therefore, there is a need to improve the REM quality with a small number of sensors.

In networking, mobility is often seen as an obstacle to network connectivity, as maintaining a network where the links between network members can change requires ongoing communication between nodes, which increases the amount of traffic in the system, and therefore, the number of collisions. However, this same mobility can actually be a benefit to the creation of a REM, as each time a moving sensor senses a transmission, additional information about that transmission's source is obtained.

The objective of this work is to study the benefits of sensor mobility on REM generation. To achieve this, a series of simulations has been performed to evaluate the quality of a REM by estimating the locations where interference would be unacceptable, using a variable number of sensors travelling at a range of speeds in a flat-earth scenario. The scenarios simulated are introduced in Section 2 of this paper and results are given in Section 3. A brief summary, as well as suggested areas of further study, is given in Section 4.

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2 Simulations

2.1 Scenarios

To measure the benefits of sensor mobility to the creation of the REM, scenarios with different numbers of sensors travelling at different speeds were used. Each scenario contained three transmitters, eight collection nodes, and N sensors, one of which functioned as the HQ node, all placed in a 15 km square flat area. The three transmitters were located at (6000 m, 1000 m), (1000 m, 11000 m) and (14000 m, 4000 m). The eight collection nodes were placed in a regular pattern as shown in Figure 1. The HQ node was placed in the lower right corner of the square, while the $N-1$ remaining sensors were each given a random starting location and a random direction in which to travel.

Each scenario comprised 10, 15, 20, or 25 sensors travelling at 0, 10, 20, or 30 m/s. An example of these initial placements for 20 sensors is shown in Figure 1, and the corresponding coverage obtained for five time intervals as these sensors move at 20 m/s is shown in Figure 2. The mobility model used for the sensors is similar to the random direction model given in [4], where each sensor chooses a random direction to travel along until reaching the simulation boundary. However, in this simulation, instead of choosing a new random direction at the boundary, the sensor moves away from the edge at its reflection angle.

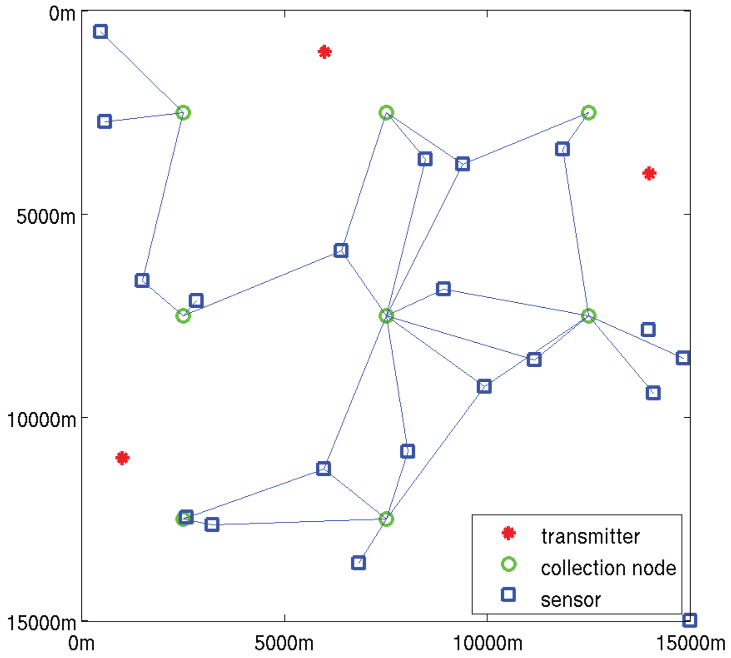


Figure 1: *Locations of transmitters, sensors and collection nodes, 20 sensors case.*

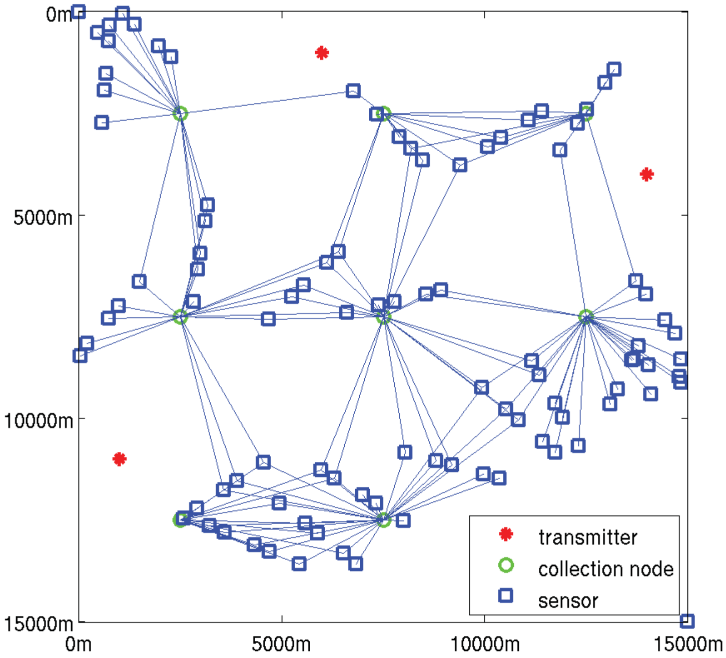


Figure 2: *Sensor movement with 20 sensors at 20 m/s, over 5 time intervals.*

Each transmitter had a transmission power of 100 W and a 512 MHz carrier frequency. To reduce the collision rate noted in [3], the mobile sensors used low power, 5 W transmitters to report their power measurements to static collection nodes. These nodes then collected and forwarded the observations to HQ, using 100 W transmitters. The sensors and collection nodes operated at a 508 MHz carrier frequency.

A simple path loss model [5, Ch. 4] was used, such that the received power at a distance d from the transmitter was

$$P_R = P_T \left(\frac{\lambda}{4\pi}\right)^2 (d^{-\alpha}) \tag{1}$$

where P_T is the transmitted power, λ is the wavelength and the path loss exponent was $\alpha = 3$. Note that this flat-earth propagation model omits the effect of shadowing, which is expected to be a significant factor in REM generation accuracy.

In each scenario, the three transmitters broadcast their signals omni-directionally. If any signal energy was detected by a sensor, the total received power and the sensor location were sent to any collection nodes in range of the sensor. The collection nodes would then forward the data to HQ, using the optimized link state routing (OLSR) protocol [6], as recommended in [7] for networks where timeliness is a priority over connectivity. Once HQ received the data from the collection nodes, a REM was created.

2.2 Implementation

Each of the sixteen scenario combinations described in Section 2.1 was run 1000 times, with new random sensor placement and mobility direction, using the OMNeT++ discrete event simulation engine [8]. The INET framework [9], a communication networks simulation package for OMNeT++, was incorporated into the simulations. In particular, the code for the OLSR routing protocol was used.

The use of this discrete event simulator prevented the correct handling of simultaneous signals. Thus, each type of event (transmitter broadcast, sensor report to collection nodes, and collection node report to HQ) was given a block of time in which to occur. The total time to complete all three stages (a time interval) was 30 s, and thus a simulation length of 300 s was chosen to allow ten time intervals. Throughout each simulation, the collection nodes continued to send their routing messages.

To simulate the signals broadcast from the three transmitters, data messages were sent from each transmitter. Again, the discrete event simulator required a workaround, and thus the transmitters each broadcast a single data message at the beginning of each time interval, with a delay interval of 0.5 s. In this way, all of the signals from one transmitter were able to reach all of the sensors in range before the next transmitter started to broadcast. Once the sensors received all three transmissions, the sum of the three received power values was calculated, to simulate simultaneous transmissions.

At a randomly chosen time between 5 s and 8 s from the start of the time interval, each sensor forwarded the received power value, along with the sensor location, to any collection nodes within range. Figure 2 shows examples of the communication links between the sensors and the collection nodes.

Between 10 s and 24 s from the start of each time interval, the collection nodes forwarded all their collected data to the HQ node, using the OLSR protocol. Because the measurements from some sensors had been received by more than one collection node, there was some redundancy in the data sent to HQ. However, the small cost of redundancy was balanced by increased robustness to congestion and lost packets as described in [3].

At the completion of each run, the total received power at, and location of, each of the sensors was output. These data were then imported into Matlab to create the REM and for further analysis.

2.3 Analysis

As in [3], the accuracy of the REM is measured by comparing an estimated REM, calculated from the collected sensor data, and the true REM, calculated using the actual transmitter locations and the flat-earth propagation model. As only the total area of interference from the transmitter matters, not the variations of the strength of the interference inside that area, contours are used in this comparison, rather than the function inside the contour.

The true REM was calculated in Matlab using (1) with a 100 m measurement resolution. The estimated REM was created through interpolation of the measurement data using Matlab. Note that a more sophisticated REM generation algorithm would be required in practice, as shadowing effects in real environments result in a true REM that is much more complex than considered here. Contours of these REMs were then calculated at -75 dBm. Figure 3(a) shows an example of a contour comparison for a single time interval, with 20 sensors at 20 m/s, where the contours enclose regions with power above -75 dBm.

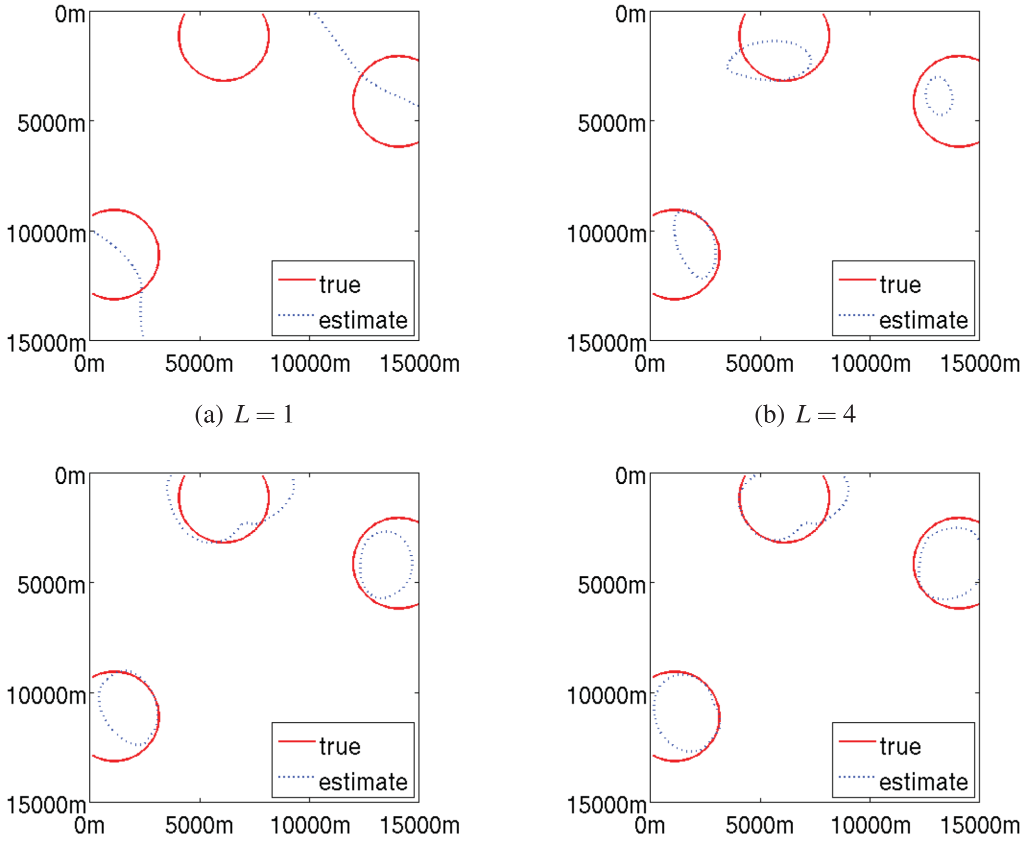
To determine the benefit of mobility, the estimated REMs and contours were then calculated for multiple consecutive time intervals. Power measurements from each sensor were stored over a time window of length L, and combined in the REM generation. Figure 3 shows the improvement in REM accuracy as the time window length is increased, for 20 sensors at 20 m/s. For $L = 1$, the estimated contour shows little similarity to the true contour, and would give no useful information about the emitter environment to a spectrum manager. Some improvement can be seen with $L = 4$. With $L = 7$, the estimated and true contours are similar, and the estimated regions are refined as L increases to 10.

As stated in [3], there are three areas to consider when comparing the true to the estimated REM contours: the correct detection zone (CDZ), the false alarm zone (FAZ), and the missed detection zones (MDZ). These are illustrated in Figure 4, where $T1$ is the true contour, and $E1$ and $E2$ are the estimated contours. Here, only the FAZ, the area where the estimate falsely shows transmitter activity, and the MDZ, the area where transmitter activity is missed, will be considered. The CDZ, the area where the the estimate correctly identifies the true contour, was used only in the calculations of the MDZ and the FAZ.

In Figure 3, the true contour area is 14% of the total area. This is true of all simulations, as the transmitter locations are the same for all scenarios. The values for CDZ, MDZ and FAZ are given in Table 1.

Table 1: *CDZ, MDZ, and FAZ percentage of total area for Figure 3.*

	$L = 1$	$L = 4$	$L = 7$	$L = 10$
CDZ	3.8	4.5	10.0	11.3
MDZ	10.2	9.5	4.0	2.7
FAZ	5.8	0.5	1.5	0.7



(a) $L = 1$ (b) $L = 4$

(c) $L = 7$ (d) $L = 10$

Figure 3: *Example of contours at -75 dBm, with 20 sensors at 20 m/s.*

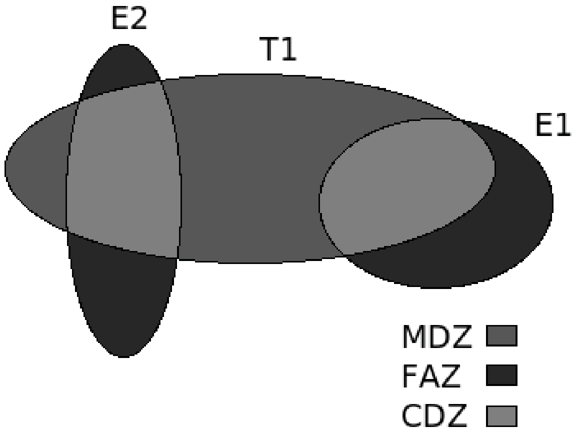


Figure 4: *False alarm, missed detection and correct detection zones [3].*

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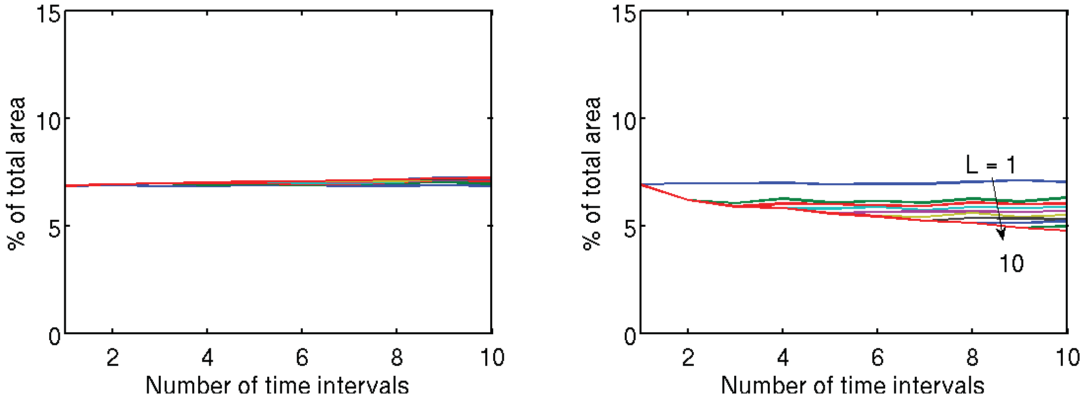
3 Results

In order to study the effect of sensor mobility on the accuracy of a REM, the REM quality is analyzed as a function of speed, number of sensors, and time. Section 3.1 gives the results in the 20 sensor case over all values of L as sensor speed is varied. Section 3.2 gives the results at a sensor speed of 20 m/s over all values of L as the number of sensors is varied. Finally, Section 3.3 gives the results of speed versus number of sensors at $L = 5$.

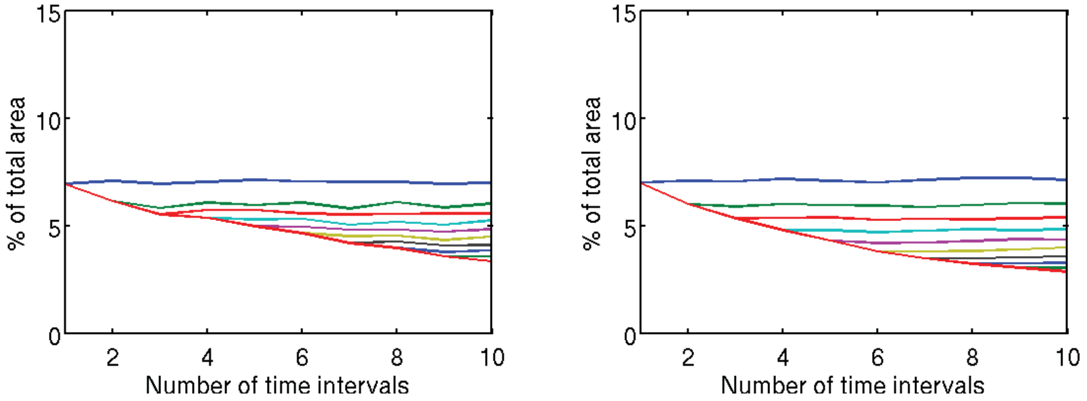
3.1 Speed over time for 20 sensors

Figure 5 shows the change in the average MDZ as a percentage of the total area as L is increased from 1 to 10, and as the speed of the sensors is increased, for the 20 sensor case. As expected, when the sensors are stationary, increasing L makes almost no difference, as the power levels measured in each time interval are the same as those before it. Note that there is a small improvement as L increases, as transmitted data lost to collisions have more opportunities to arrive at the HQ. As the sensor speed increases, increasing L has more effect on the MDZ, as the power measurements in each subsequent time interval are from sensors further from their previous locations. The most significant gain is made as L increases from one to two, as the number of sensors has effectively doubled.

Figure 6 shows the change in the average FAZ as a percentage of the total area as L is increased from 1 to 10, and as the speed of the sensors is increased, in the 20 sensor case. As with the MDZ case, the stationary case shows almost no change as L increases, but the change in L has more effect on the FAZ as the speed of the sensors increases, the most significant increase again occurring between $L = 1$ and $L = 2$. However, while the $L = 1$ case has approximately the same value for all speeds for both MDZ and FAZ, the effect of L is greater for FAZ than for MDZ. This is because the MDZ has a fixed ceiling of 14%, the area of the true contour, while the FAZ is limited only by the size of the total area.

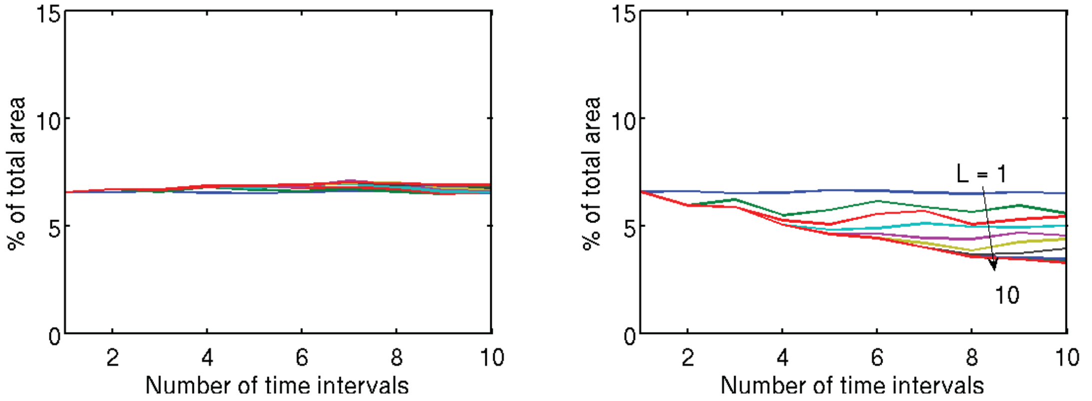


(a) 0 m/s (b) 10 m/s

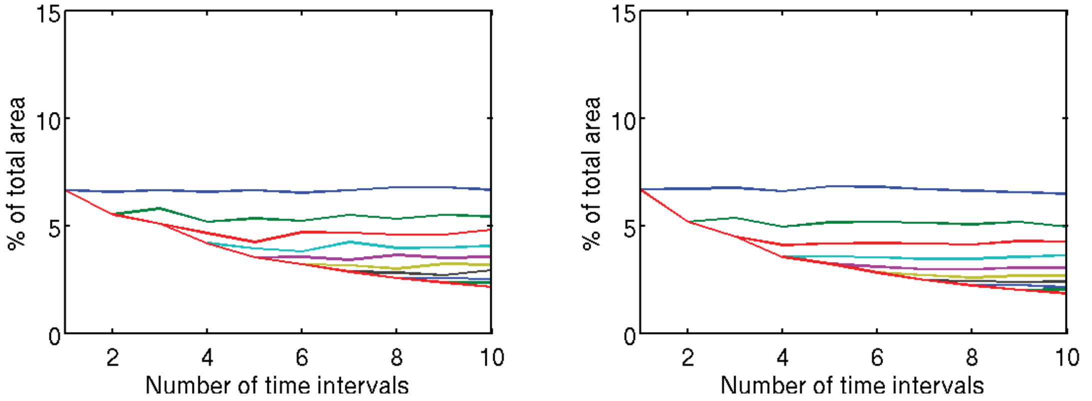


(c) 20 m/s (d) 30 m/s

Figure 5: *Average MDZ as percentage of total area, 20 sensors. Window length* $L = 1, \ldots, 10$.



(a) 0 m/s (b) 10 m/s

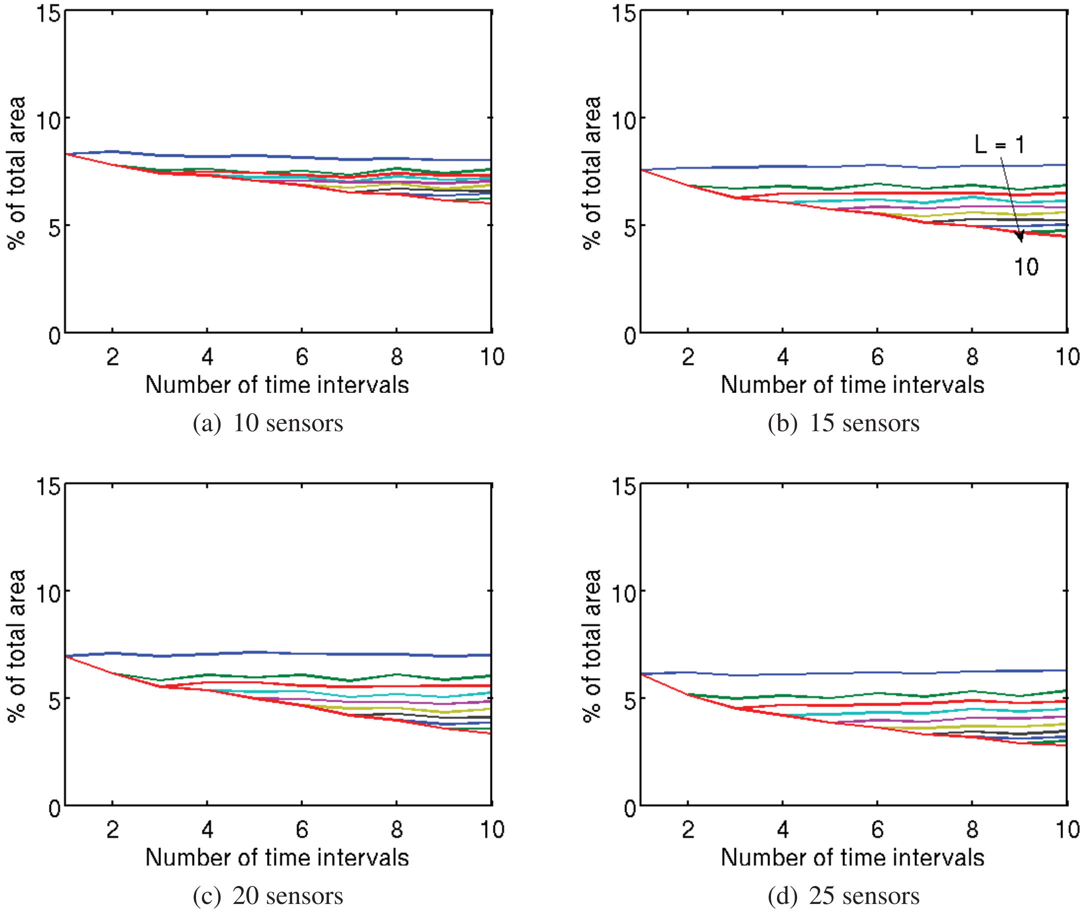


(c) 20 m/s (d) 30 m/s

Figure 6: *Average FAZ as percentage of total area, 20 sensors. Window length* $L = 1, \ldots, 10$.

3.2 Number of sensors over time at 20 m/s

Figures 7 and 8 show the change in the average MDZ and FAZ as a percentage of the total area as L is increased, and as the number of sensors is increased from 10 to 25, in the 20 m/s case. As in [3], the $L = 1$ case shows an improvement in MDZ as the number of sensors is increased. As in Figures 5 and 6, the largest gain occurs when L increases from one to two. Additionally, adding sensors has a more pronounced effect on the FAZ than it does the MDZ, as the MDZ is again bounded by the area of the true contour. However, in both cases, increasing L can compensate for the number of sensors. For example, increasing L to 10 in the 10 sensor case achieves the same results as the 25 sensor case with $L = 1$, and with L increased to only four approximates the $L = 1$, 15 sensor case. In this way, reducing the number of sensors for a smaller financial cost can be offset by increasing the window length, at the expense of delayed results.



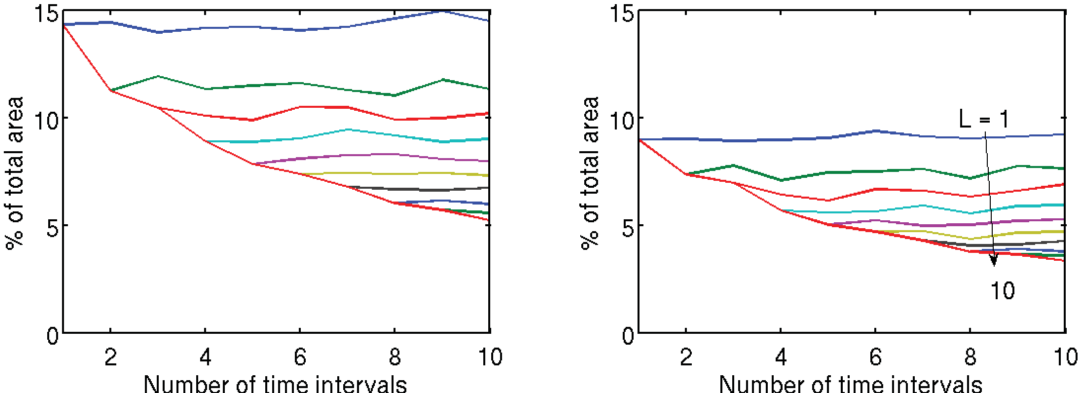
(a) 10 sensors

(b) 15 sensors

(c) 20 sensors

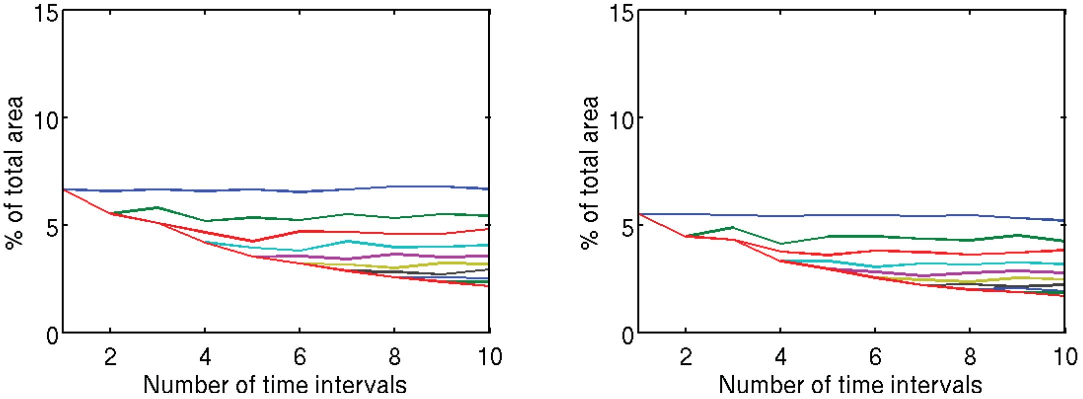
(d) 25 sensors

Figure 7: *Average MDZ as a percentage of total area, 20 m/s. Window length* $L = 1, \ldots, 10$.



(a) 10 sensors

(b) 15 sensors



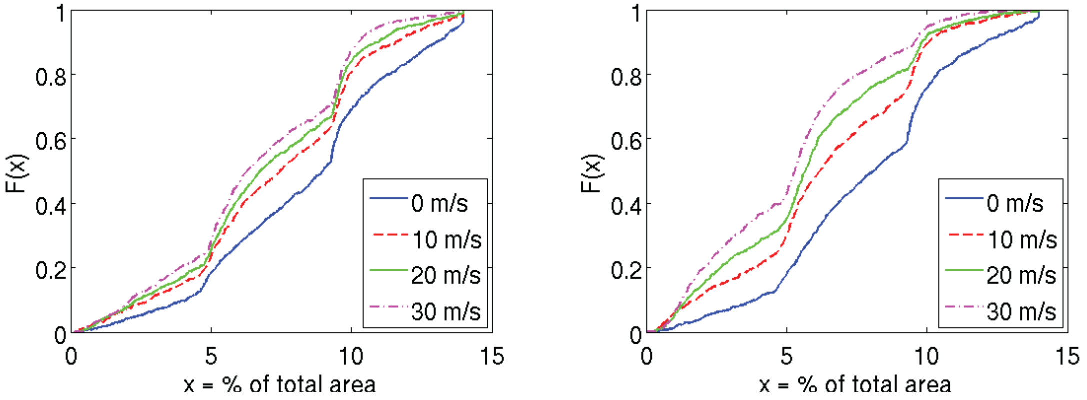
(c) 20 sensors

(d) 25 sensors

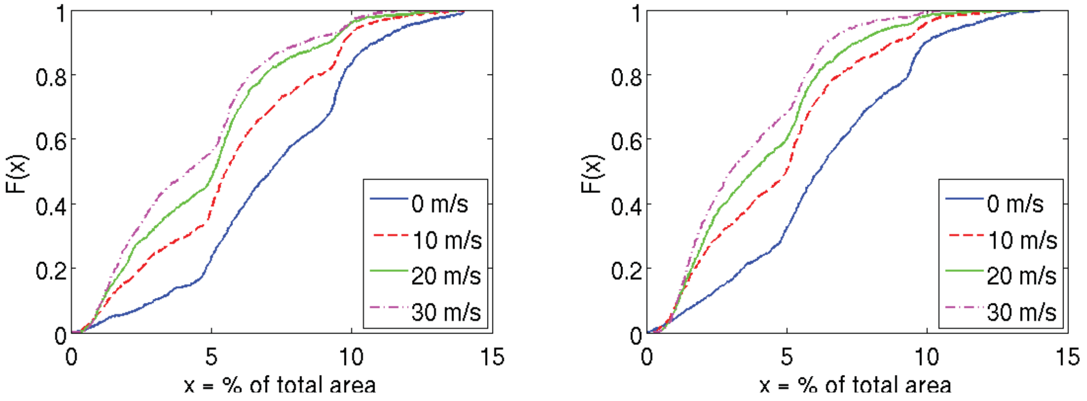
Figure 8: *Average FAZ as a percentage of total area, 20 m/s. Window length* $L = 1, \ldots, 10$.

3.3 Number of sensors over speed at L = 5

Figures 9 and 10 show the cumulative distribution of the MDZ and FAZ as a percentage of the total area at time interval 10, with $L = 5$. The non-smooth shape of the MDZ cumulative distributions are due to the fixed locations of the transmitters; each discontinuity in the line occurs approximately at the size of the area of the true contour around one transmitter. At some point in the data collection process, the estimation of the contour around one transmitter will not be significantly improved by increasing the sensor coverage so that reductions in MDZ can only be achieved by improving the other contours. As the estimated contours are random in size and shape, the FAZ cumulative distributions do not share this property.



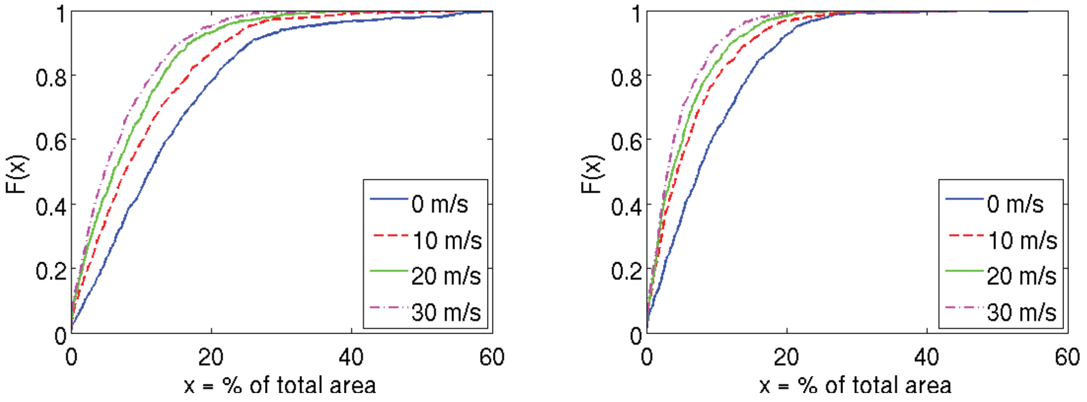
(a) 10 sensors (b) 15 sensors



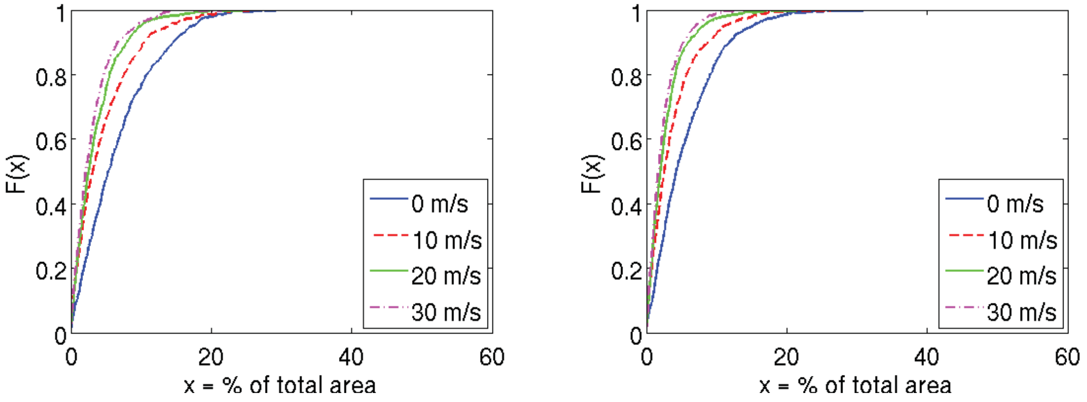
(c) 20 sensors (d) 25 sensors

Figure 9: *Cumulative distribution of the MDZ as a percentage of the total area at time interval 10,* $L = 5$.

It should be clear that when $L = 1$, all 4 sensor speeds are equivalent to the case where the sensor speed is 0 m/s, for any value of L. Thus, as L increases, and as the sensor speed increases, both forms of estimation error decrease. Also, as expected, since the MDZ is



(a) 10 sensors (b) 15 sensors



(c) 20 sensors (d) 25 sensors

Figure 10: *Cumulative distribution of the FAZ as a percentage of the total area at time interval 10,* $L = 5$.

bounded by the area of the true contour, while the FAZ is bounded only by the total area, the improvement over sensor number for the FAZ is much more pronounced than for the MDZ.

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4 Conclusions

Using mobile sensors to support the generation of an REM was shown to have many advantages. In addition to lower capital costs associated with fewer sensors, the bandwidth overhead required to support the routing protocol is reduced when there are fewer nodes, decreasing collision rate and allowing a more accurate REM to be computed.

As the speed of the sensors is increased, and the length of the time window, L, is increased, fewer sensors are required to create an accurate REM. In a low density, swiftly moving sensor environment, the benefits to the accuracy of the REM are particularly great, with speed obviating the need for additional sensors.

Static collection nodes have been considered in this work to-date; as the OLSR protocol is proactive, i.e., sends topology control messages to establish routes in advance of demand, it is expected that the observations are representative of the case in which they are mobile. Increases in overhead due to node mobility must be traded off against the improvement in REM generation.

Static transmitters have also been considered herein, but in many cases of interest, the transmitters may also be mobile. In this case, there would be a trade-off between sensor coverage and the timeliness of the collected observations. The benefit to the REM in this case would depend on both the speed of the sensors, and of the transmitters; these benefits can be quantified using the same simulation tools developed and used in this work. The gain in REM accuracy seen as L increases from one to two could provide robustness in this case, as the change in transmitter geography would likely be minimal over a single time interval.

References

[1] Zhao, Y., Raymond, D., da Silva, C., Reed, J. H., and Midkiff, S. F. (2007), Performance Evaluation of Radio Environment Map-Enabled Cognitive Spectrum-Sharing Networks, In *Proc IEEE MILCOM 2007*, pp. 1–7.

[2] Fette, B. A. (2009), Cognitive Radio Technology, Second ed, Academic Press.

[3] Faint, S. M., Ureten, O., and Willink, T. J. (2010), Impact of the Number of Sensors on the Network Cost and Accuracy of the Radio Environment Map, In *Proc IEEE CCECE 2010*, pp. 199–203.

[4] Royer, E. M., Melliar-Smith, P. M., and Moser, L. E. (2001), An analysis of the optimum node density for ad hoc mobile networks, In *Proc IEEE ICC*.

[5] Molisch, A. F. (2005), Wireless communications, John Wiley & Sons Ltd.

[6] Jacquet, P., Muhlethaler, P., Clausen, T., Laouiti, A., Qayyum, A., and Viennot, L. (2001), Optimized link state routing protocol for ad hoc networks, In *Proc IEEE INMIC 2001*, pp. 62–68.

[7] Faint, S. (2011), Impact of AODV and OLSR routing protocols on the network cost of the Radio Environment Map, (DRDC Ottawa TM 2011-001) Defence R&D Canada – Ottawa.

[8] Varga, A., OMNeT++ users manual: OMNeT++ version 4.0 (online), `http://www.omnetpp.org/doc/omnetpp/manual/usman.html` (Access Date: June 2011).

[9] INET Framework for OMNeT++/OMNEST (online), `http://inet.omnetpp.org/doc/INET/neddoc/index.html` (Access Date: June 2011).

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1. ORIGINATOR (The name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Centre sponsoring a contractor's report, or tasking agency, are entered in section 8.) Defence R&D Canada – Ottawa 3701 Carling Avenue, Ottawa ON K1A 0Z4, Canada	2. SECURITY CLASSIFICATION (Overall security classification of the document including special warning terms if applicable.) UNCLASSIFIED (NON-CONTROLLED GOODS) DMC A REVIEW: GCEC June 2010

3. TITLE (The complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S, C or U) in parentheses after the title.)

Benefits of sensor mobility when creating a radio environment map

4. AUTHORS (Last name, followed by initials – ranks, titles, etc. not to be used.)

Faint, S.; Colman, G.; Willink, T.

5. DATE OF PUBLICATION (Month and year of publication of document.) December 2011	6a. NO. OF PAGES (Total containing information. Include Annexes, Appendices, etc.) 32	6b. NO. OF REFS (Total cited in document.) 9

7. DESCRIPTIVE NOTES (The category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

Technical Memorandum

8. SPONSORING ACTIVITY (The name of the department project office or laboratory sponsoring the research and development – include address.)

Defence R&D Canada – Ottawa
3701 Carling Avenue, Ottawa ON K1A 0Z4, Canada

9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.) 15bx	9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.)
10a. ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.) DRDC Ottawa TM 2011-189	10b. OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.)

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Operating in a heterogeneous radio environment requires knowledge of the frequency occupancy for a given region of interest. To assist spectrum managers in allocating frequencies dynamically, the topography of radio frequency (RF) energy can be detailed in a radio environment map (REM). The generation of the REM may be supported by sensors spread over the region to obtain power measurements. Collecting measurements from many sensors incurs a large network overhead, resulting in lost or delayed measurements which can degrade the quality of the REM. It is shown through simulations that if the sensors are mobile, their movement can be used to improve the accuracy of the REM, reducing the number of sensors and networking overhead required. As the sensors' speed increases, or the observation window lengthens, the effective area covered by each sensor also increases, further improving the REM accuracy.

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