Optimizing Cognitive Ad-Hoc Wireless Networks for Green Communications

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Abstract

This paper investigates the potential of smart routing in minimization of radio environment pollution in cognitive ad-hoc wireless networks. A wireless ad-hoc sensor network based on the IEEE 802.11b standard is used as a simulation testbed to determine statistical distribution of interference levels. Three different routing methods are used – flood routing, location aware routing (LAR) and a simultaneous localization and radio environment mapping based routing (SLAM routing). Results show that LAR partially reduces interference by limiting number of transmissions for a single packet resulting in lower interference. SLAM based routing causes significantly lower interference throughut the network by both lowering the number of transmissions and reducing the radiated power close to the minimum required for a successful transmission, resulting in an interference noise floor 19.7 dB below the flood routing protocol.

Keywords: smart routing, ad-hoc networks, cognitive networks, wireless networks, SLAM, interference, throughput.

1 Introduction

Today's telecommunications are witnessing an explosion in data traffic, with an increasing part of population expecting on-demand access to multimedia

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and information services whether they may find themselves on the bus watching videos, at a coffee shop checking their e-mail, or walking down the street and looking at online city maps. This expectation results in two problems:

1. providing the required services, and
2. dealing with increased interference from the large volume of data traffic.

These problems cumulatively increase the mobile device battery drain and require the operators to set up a large number of data access points to meet the user demands which then results in radio environment pollution and energy waste. A research report by Ericsson [1] states that more than half of a mobile operator's operating expenses come from energy costs.

Radio networking solutions that can improve energy-efficiency and reduce radio resource waste ('green communications') reduce also network operation costs and at the same time benefit the global environment. One of the solutions promising great improvement is location aware smart routing for ad-hoc networks. Ad-hoc networks can be implemented anywhere to either create a new communication network or extend an existing network's coverage area without new investments into infrastructure which makes them a good candidate for both local and global communications. Use of smart routing in such networks has the potential to both improve their throughput and reduce the caused intra- and inter-system interference. Efficient smart routing, however, requires mobile devices with sensing options and independent decision making.

Cognitive radios fulfill the requirements needed for such smart routing by incorporating sensing of outside stimuli (environment awereness), interpreting them via reasoning and learning (decision making) and act on these decisions through transmission parameter changes [2, 3].

This paper presents a distributed 'green communications' [4] approach for cognitive ad-hoc sensor networks [5] by using location and environment aware smart routing. Such networks can be used for remote sensing, environment mapping, localization or communication support (Figure 1) and many other applications where energy conservation or interference levels are critical factors in network's operation [6].

Three routing protocols have been simulated and tested under different load conditions to determine their positive and negative sides and offer an optimization scheme for future cognitive ad-hoc wireless networks in accordance with 'green communications' directives. The simulations are performed using 'Environment Visualization Office – EnVO', a network simulator developed in MATLAB at the Faculty of Electrical Engineering and Computing,

Figure 1 A surface monitoring sensor network deployed on Mars

University of Zagreb, Croatia, and Center for TeleInfrastruktur, Aalborg University, in Denmark. Each simulated cognitive radio device senses events, listens to the radio environment, exchanges mapping and localization data and makes decisions regarding its own packet transmissions. Devices use collected information and transmission experiences to optimize local network traffic using peer-to-peer services, transmission power control and routing control. Final result is a statistical analysis of smart routing methods on data packet transfer, throughput and interference levels.

2 Related Works

Our goal is to find an efficient smart routing algorithm for cognitive ad-hoc wireless sensor network using simultaneous localization and mapping (SLAM) based on network communication and received signal strength measurements (RSS). The key factors in efficient wireless routing are location and environment awareness, combination of which enables network devices to use packet forwarding schemes based on current mobile positions and channel states. This type of packet forwarding promises more efficient routing methods in terms of both energy use and interference reduction and theoretically comes closest to optimal routing. This opens the question of mobile device localization and radio environment mapping.

Various localization methods exist today: GPS [7], optical [8, 9], ultrasound [10], and inertial [11]. Additional methods relying on network communications signals include measurements of received signal strength (RSS) [12–15], angle of arrival (AoA) and time difference of arrival (TDoA) [16–19].

Environment information is usually stored in a form of a map or table. A definition of radio environment map (REM), as given in [20], is “an approach that allows ‘knowledge’ of the radio frequency (RF) signal environment, policy, historical performance, and network or node limitations to be shared throughout the region serviced by the wireless network”. This includes spectrum regulatory rules and user-defined policies, spectrum opportunities, where the radio is and where it is heading, the appropriate channel model to use, current and expected pathloss and signal-to-noise ratio, hidden nodes present in the neighbourhood, usage patterns of primary users and secondary users, and interference or jamming sources.

An already implemented infrastructure based REM with Manhattan propagation model was used to predict pathloss and signal-to-noise ratio (SNR) in order to reduce the interference from a secondary cognitive radio network to primary users and avoid the hidden node problem [37].

If both the transmitting and the receiving device know their positions in the environment, they can measure channel characteristics and map radio environment characteristics [21–26]. Use of the cooperative method and a distributed knowledge base can ensure that the devices slowly create a full environment map, improve it over time and use it for accurate prediction.

Examples include vehicle mapping using GPS for positioning and radar for terrain mapping [27], robot mounted with a laser rangefinder and a trinocular stereo vision system [28] or incremental vehicle map building [29]. SLAM implementations use one system or technology for positioning and another system based on a different technology for environment mapping, depending on which environment characteristics are mapped.

To the best of the authors’ knowledge, there have been no documented attempts to construct the entire REM database from the network communication alone by using known positions and a learning algorithm to extract physical environment data, nor implementations of SLAM algorithm where the devices use the same radio signal (regular communication) to perform both positioning and radio environment mapping.

Ad-hoc mobile wireless routing protocols can generally be categorized as either table-driven, or source-initiated [30]. Table-driven routing protocols keep routing information between all nodes in one or more tables and keep them up-to-date by transferring information on network topology changes through the network. Source-initiated routing protocols create routes only when a route discovery procedure between two specific nodes is initiated.

If a location of nodes is known, more advanced routing algorithms can be implemented by reducing the network load and improving battery life, as described in [31]. Usage of smart antennas offers even more possibilities [32] by reducing interference in unwanted directions and boosting the signal in the direction of the destination node. A comparison study between omnidirectional and directional protocols for ad-hoc networks can be found in [33].

3 Methodology

We propose a smart routing scheme based on a cooperative distributed SLAM algorithm developed for ad-hoc cognitive radio mesh networks. The main difference between the sensor network simulated here and the previous SLAM research is the use of ad-hoc radio communication signals for both mapping (using an RSS algorithm) and localization process (through radio fingerprinting and radio channel modelling). In order to test the proposed SLAM smart routing on network data traffic and interference minimization we use EnVO wireless network simulator. The RSS mapping algorithm, radio fingerprinting, radio modelling algorithm, and EnVO simulator were developed at Faculty of Electrical Engineering, University of Zagreb, Croatia, in cooperation with Center for TeleInfrastruktur, Aalborg University, Denmark. Communication between sensor nodes inside the network is based on WLAN 802.11b protocols.

Each of the sensor devices has the following properties:

- Packet generation.
- Ability to send and receive packets of data.
- Basic collision avoidance protocols (Carrier Sense Multiple Access and Collision Avoidance).
- Ability to change the radiated power within certain limits (software defined transmission).
- Ability to measure the incoming signal strength.
- Routing and packet registry.
- Memory and processing power comparable to the current personal computers.

The main task of simulated network devices is to detect outside events using sensors, generate reports carrying unique identifiers and then forward these report data to the point of interest inside the network (a randomly chosen destination device) to the best of their ability. The devices use their REM and location knowledge obtained through SLAM to find routes which require lowest energy input to forward the packet. Network load can be modified by changing the rate at which these random events occur. Generating a single event in the entire network's area puts the network under ideal unloaded conditions so that single packet routing and interference generation can be observed. Repeatedly generating events through the network area at a rate of several hundred events per second put the network into heavily loaded or even overloaded condition where it becomes theoretically impossible to report all the events. For the implemented network this limit is reached at 250 events per second as this data rate equals a continuous stream of event reports under ideal network operating conditions.

An example of importance of this kind of simulation are WLAN 802.11b systems. While the declared throughput is 11 Mbps, the achievable throughput in loaded network conditions with multiple users is actually a little over 6 Mbps with few users and falls down as the number of users increases which is significantly lower from the theoretical maximum [34, 35].

Three different smart routing methods are used to transmit packets; a flooding scheme, location aware directed flood routing (LAR) and the simultaneous localization and radio environment mapping based routing (SLAM routing). Main decision algorithms for each of the three methods are given in Figure 2. They show the device's transition from the transmission state (Tx) into idle state (Idle).

During flood routing scheme each event report is broadcast to all the neighbouring nodes. The transmission power is set to the maximum allowed by the transmitting device and the report is sent to all the devices within the range. The transmitting device then saves the packet ID in its routing table to avoid retransmissions of the same packet. All the nodes which managed to receive that transmission correctly in turn forward the data packet by broadcasting it to all of their neighbours. This continues until all the nodes receive the packet or the packet exceeds its lifetime. Flood routing is the most commonly used routing protocol in ad-hoc sensor networks.

In the LAR case devices are aware of their relative or absolute position in space and use that knowledge to create links and forward packets. Each device transmits at maximum available transmission power to all of its neighbours that are closer or equally far from the destination as the last device. This

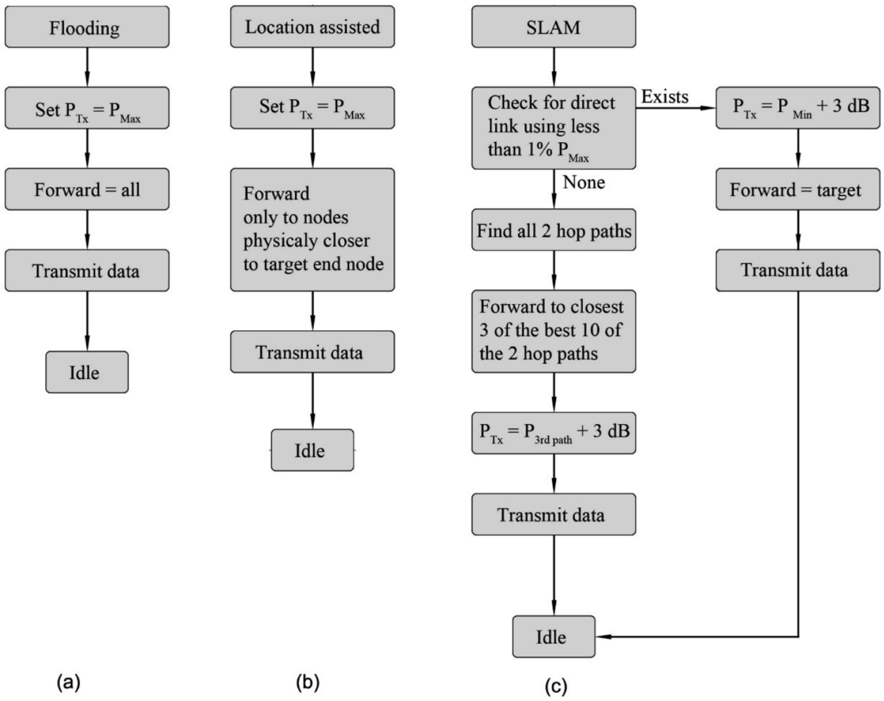

Figure 2 Smart routing sensor network diagram for the data packet transmission state showing implementation of the three routing protocols: (a) flood routing, (b) location assisted routing, and (c) SLAM routing in forward table and transmission power decisions

algorithm continues until each of the packet copies reaches the destination or exceeds its lifetime. This type of restricted directional flood routing is most similar to the distance routing effect algorithm for mobility (DREAM) [36].

In the SLAM case each of the mobile devices is also aware of the exact environment (knowledge obtained through radio environment mapping) and the devices use that knowledge to create dynamic routing tables on demand and find optimal paths in regards to delay, battery use, intereference and chance of successful packet transmission.

The routing algorithm first checks if the destination can be reached using less than 1% of maximum transmission power (20 dB below the maximum) and transmits the packet directly with the minimum required power increased by a 3 dB safety margin to account for possible fading and erroneous data (decisions are based on 'delayed' knowledge which may contain small errors). If no such path exists, the device constructs all possible two hop paths

Table 1 Power consumption for simulated wireless sensor devices during various communication activities

Batery usage during device operation	
Activity	Power consumption
Transmission	$\leq$ 100 mW
Reception	3 mW
Backoff wait	1 mW
Idle/sensing	1 mW

with ten closest devices, chooses from them the three best paths and forwards the event report data packet along these paths using minimum transmission power required to reach all three chosen destinations, increased by a 3 dB fading safety margin. This procedure is repeated until each of the packet copies reaches the destination or exceeds packet lifetime.

Expected results from the implemented SLAM smart routing algorithm include reduction in interference levels, lower power consumption and higher network throughput over the existing ad-hoc wireless sensor network routing algorithms.

4 Simulation Setup and Results

An environment map of 200 m by 200 m size is used for the simulation. A total of 100 sensor devices are randomly placed on the map. Receiver sensitivity of the devices is set to -97 dBW as this falls within the typical range for WLAN 802.11b at speed of 11 Mbps. Omnidirectional antennas are used. Simulations are run until packet clears the network in one packet scenario, or over 10 minutes of simulated network time during loaded network tests. The chosen power consumption for simulated sensor devices in communication modes is given in Table 1. Maximum transmission power of the devices is set to -10 dBW (EU limit on transmission power for ISM 2.4 GHz band). Power consumption values during reception, backoff wait and sensing was arbitrarily chosen to better represent a realistic sensor network. Each sensor device is assigned a battery with 24 mWh energy capacity, enough for only 24 hours of idle time, in order to provide a better feedback on battery drain. A typical NiMH AA battery has approximately 3000 mWh energy capacity which is enough for 4 months of idle time at 1 mW power drain.

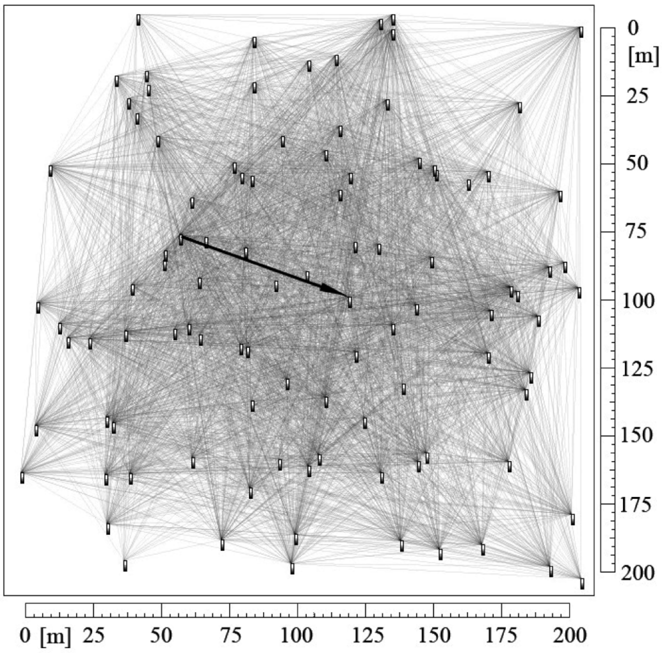

Figure 3 Simulation results for one packet transmission using flood routing algorithm. All network devices (small rectangles), packet transmission paths (thin lines) are shown, as well as the path connecting origin of the event report packet to the final destination device (thick arrow)

4.1 One-Event Report Simulation

In the first scenario the network generates a single event at a random device and chooses another as report destination. It transmits the report using implemented modification of 802.11b protocol and the chosen routing scheme. Simulation is terminated after the packet finishes its path through the network and all the nodes go back to idle state (none of the nodes has a packet waiting to be transmitted). The goal of this simulation is to see how each of the implemented algorithms handles packet transmission in an ideal unloaded condition.

The routing map for one packet simulation using flood routing algorithm is shown in Figure 3. Routing map shows all the network devices as small rectangles, an arrow connecting origin and destination devices, as well as all the individual links along which the packet was transmitted (thin lines). Each packet transmission is represented by a thin line connecting the transmitting

Table 2 Simulation data for single packet forwarding

Batery usage during device operation		
Routing	Hops	Mean interference
Flood	1	−62.7 dBW
LAR	1	−71.9 dBW
SLAM	4	−82.6 dBW

and receiving nodes. Intense lines represent a heavy traffic connection while very thin or pale lines represent very light traffic (the density of the lines is scaled linearly with the traffic). The thick arrow in the middle connects the device where the packet originated to the final destination device. As shown, the packet was sent through the entire network in order to ensure that it will reach its destination. This excessive packet transmission is the main downside of the flood routing protocols [31].

Sensor network is forced to send the packet to every single device operating in the network due to ignorance of backbone infrastructure or actual network topography. Only in this way, there is assurance that the destination is reached. Since the devices have no knowledge of propagation channels, no power control is used and the packet is always forwarded with maximum power. This combination uses a lot of battery energy (every node in the network will have to transmit every packet at maximum power usage) and creates an average interference level of −62.7 dBW to other systems, but requires the least (only one in this example) number of hops (Table 2).

Average power level for a map tile I_{tile} is calculated as the sum of all received transmission powers at the tile's coordinates where $P_{Rx,\text{tile},i}$ is the ith transmission and N the total number of transmissions that occurred during the simulation time period T:

$$I_{\text{tile}} = \frac{1}{T} \cdot \sum_{i=1}^{N} P_{Rx,\text{tile},i} \tag{1}$$

This average map tile power level is seen as interference by all the other systems and networks operating in the same area. Mean interference level I_{mean} for the entire map can then be calculated as

$$I_{\text{mean}} = \frac{1}{M} \cdot \sum_{\text{tile}=1}^{M} I_{\text{tile}} \tag{2}$$

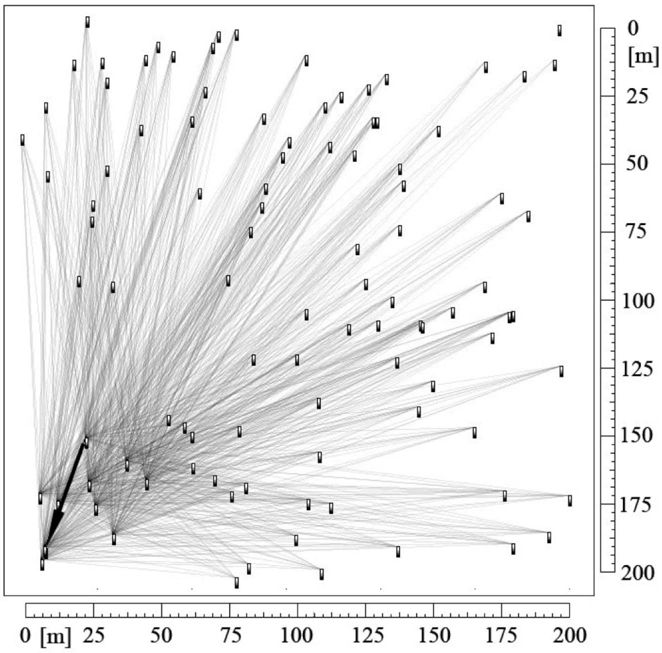

Figure 4 Simulation results for one packet transmission using location aware routing algorithm. Shown here are all packet transmission paths (thin lines) as well as the direct path (thick arrow)

where M is the total number of map tiles. The good side of this approach is that the packet will reach its destination in the shortest possible time and have the best success rate.

Figure 4 shows results using LAR approach. The transmissions are now limited only to the area between the device where event originated and the destination device which requires knowledge of mobile device positions. Position information is obtained using radio fingerprint localization. The mobile devices still use full transmission power during routing transmission as they have no knowledge of propagation channels between two devices. The negative side of this approach is that it still causes an average interference level of -71.9 dBW (Table 2) within a very large area (typical maximum range is over 100 m) which forces a lot of neighbour devices to enter reception mode (99 out of 100 devices placed on the map) before discarding their received packets. As shown in Figure 4, these one way transmission paths reached all nodes except for one in the farthest corner of the map (top right). It is still a

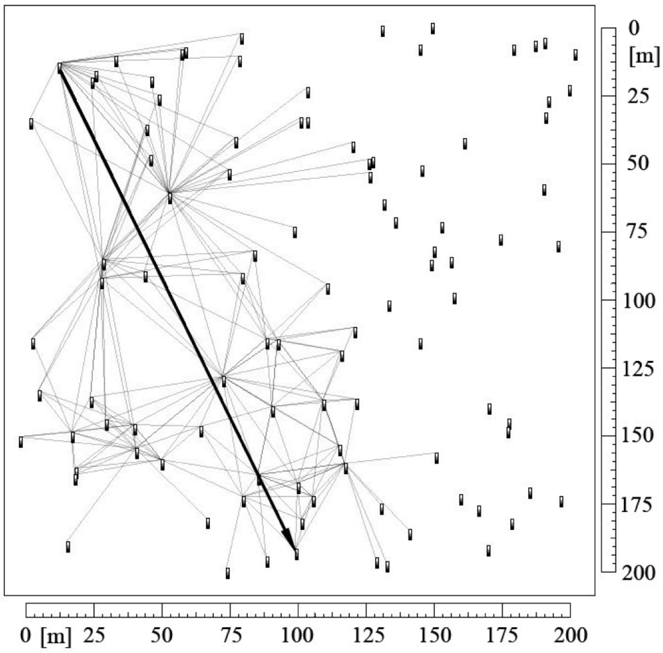

Figure 5 Simulation results for one packet transmission using SLAM routing algorithm. Shown here are all packet transmission paths (thin lines) as well as the direct path (thick arrow)

clear improvement over the flooding algorithm as the interference level was reduced by 9.2 dB.

Figure 5 shows simulation results for one packet transmission using SLAM routing. In this case the event report packet is forwarded only by nodes close to the most efficient path (energy wise). Each forwarding node sends the packet to a maximum of three new nodes and all of these transmissions are power controlled. The packet in the example arrived after four hops, with both a lower total radiated power and a smaller number of nodes entering reception mode compared to flood routing or LAR simulations. An average interference level of −82.6 dBW was observed.

While the packet is transmitted using SLAM routing, only some of the nodes along the way are able to hear the transmissions (67 out of 100) and even fewer are involved in the forwarding scheme (12 out of 100). The rest of the network nodes are oblivious to this exchange as the signal levels at their positions fall below the sensitivity (−97 dBW) of their receivers. This

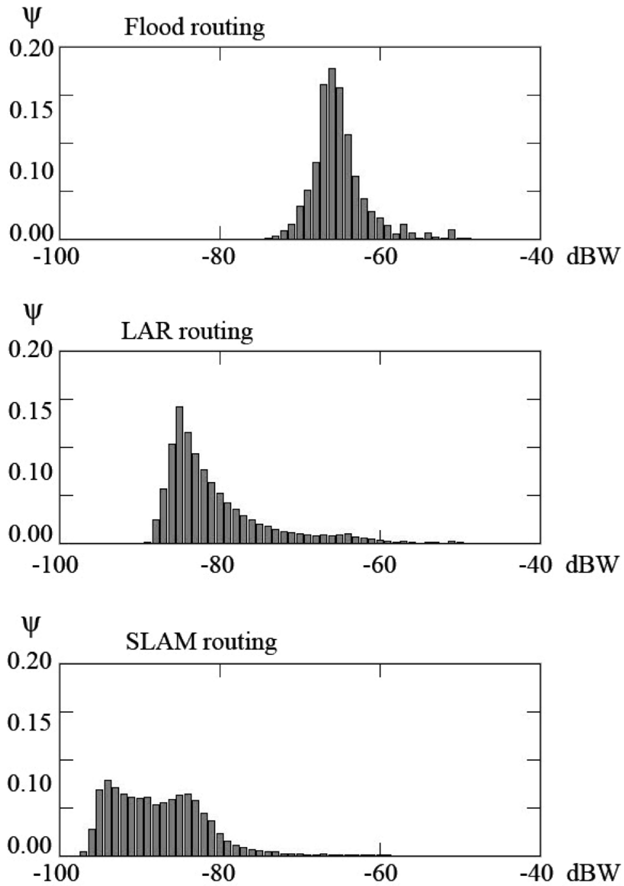

Figure 6 Interference histograms for one packet routing simulation showing probability (ψ) of interference levels for map tiles for: flood routing (top), location aware routing (middle) and SLAM routing (bottom)

means that they are free to perform other transmissions at the same time and spatially reuse the channel at ranges much smaller from the maximum.

Figure 6 displays interference histograms for the three presented one-event simulation scenarios. These histograms show the distribution of interference levels over the entire map area (40000 m^2). Horizontal axis shows the levels of interference in dBW, and the probability ψ of a map tile (size of a map tile is 1 m^2) to have that interference is plotted as a bar in the vertical direction. Probability ψ for a given interference level I_B represents the chance that a map tile's interference level I_{tile} will fall between I_B and $I_B + \delta$, where δ is the histogram's resolution (1 dB for Figure 6).

Probability ψ is calculated as the number of map tiles n having interference levels in that range divided by the total number of map tiles M:

$$\psi(I_B) = \frac{n(I_B \leq I_{\text{tile}} < (I_B + \delta))}{M} \tag{3}$$

The top histogram shows interference for the flood routing scenario from Figure 2, middle histogram shows reduced interference levels obtained by LAR and the third histogram the interference distribution for SLAM routing. Flood routing had the highest chance of finding interference values around -65 dBW and 95% of the map tiles had interference levels between -72 and -58 dBW. LAR routing had the highest chance of finding interference values around -87 dBW and 95% of the tiles had interference levels between -88 and -64 dBW, a significant improvement over flood routing. SLAM routing did not have a single significant interfence level, but 95% of the map tiles had between -96 and -80 dBW with an almost uniform probability distribution for ψ around 0.06.

4.2 Loaded Network Simulation

In this scenario the performance of the sensor network under load is observed by generating 25 events per second within the network area for 10 minutes (a total of 15000 events). All of the detected events are reported using 40 kb packets (this was the report size chosen for the simulation) which require approximately 9.6% of the maximum IEEE 802.11b channel capacity (11 Mbps). Without infrastructure for optimal organization of communication and with devices outside single hop range, it can be expected that the network will have difficulty handling this amount of communication. Additionally, while participating in communication by either sending or receiving data, or waiting in a backoff state (waiting for the communication channel to open so they can forward the packet they're holding), the devices are not sensing events causing some of them to go undetected. Results of these simulations are given in Table 3.

The number of events detected by the devices is given in the 'Detected' column. For each detected event a report was generated and sent using the routing protocol. The number of detected events is directly proportional to the time spent in 'Idle' mode by the devices in the network. Not all of the

Table 3 Simulation data for an ad-hoc sensor network opearting under 9.6% maximum channel load (25 events per second)

10 minute simulation						
Routing	Detected	Received	% of total	Avg. hop	Avg. delay	Mean interference
Flood	1697	1654	11.0%	1.7	6.1 ms	−58.8 dBW
LAR	2494	2419	16.1%	1.4	6.5 ms	−58.8 dBW
SLAM	11764	10545	70.3%	3.1	14.5 ms	−72.2 dBW

packets are successfully received – their number is given in the 'Received' column.

Percentages of the total generated events that were reported by each network are given in third column labeled '% of total'. Much larger number of detected events using SLAM routing indicates that, on average, the devices spent much less time transmitting the reports and more time sensing the events. This indicates that the SLAM routing scheme uses much less of the total network resources for communication. Average number of hops required for flood routing was 1.7, for LAR 1.4 and for SLAM 3.0. The associated delay including the backoff times is given in the 'Avg. delay' column. The results show that SLAM offers a more efficient routing method at the cost of increased delay in communication (14.5 ms compared to 6.1 ms with flood routing and 6.5 ms with LAR) and a higher number of average hops to reach the destination.

Mean interference levels caused by network operation using each of the routing algorithms are given in the last column of Table 3. While flood routing and LAR had nearly identical mean interference levels – LAR caused lower interference per each event report, but reported nearly 50% more events compared to flood routing, SLAM routing had the lowest spectrum interference footprint by a margin of 13.3 dB and reported 10545 events – more than four times the number of events as LAR (2419 reported events) and six times more than flood routing (1697 reported events).

5 Conclusion

This study concludes that SLAM based smart routing can be used with cognitive ad-hoc wireless sensor networks to improve their throughput (10545 packets received) by a factor of six when compared to flooding algorithms (1654 packets received) or directed flood routing (2419 packets received) used in most networks. At the same time the devices spend much less time transferring the information and more time performing their sensing duties which can be seen from the number of detected and reported events. 70.3% of the time was spent detecting when using SLAM routing, and 16.1% for LAR and 11% for flood routing. The SLAM routing also reduces mean interference level to other systems operating in the area by 13.3 dB while utilizing this increased network throughput.

References

[1] Ericsson Press Release, June 2008, http://www.ericsson.com/ericsson/press/facts_figures/doc/energy_efficiency.pdf.
[2] J. Mitola. Cognitive radio. Ph.D. Dissertation, Royal Institute of Technology (KTH), Stockholm, Sweden, 2000.
[3] R. Prasad and K.-Ch. Chen. *Cognitive Radio Networks*, John Wiley & Sons, 2009.
[4] R. Prasad, S. Ohmori and D. Simunic. *Towards Green ICT*, River Publishers, 2010.
[5] R. Prasad. *Globalisation of Mobile and Wireless Communications: Today and in 2020*, Springer Verlag, 2010.
[6] R. Prasad and A. Mihovska. *New Horizons in Mobile and Wireless Communications: Ad HOC Networks and PANs*, Artech House, 2009.
[7] E. Kapplan. *Understanding GPS Principles and Applications*, Artech House, 1996.
[8] O. Maye, J. Schaeffner and M. Maaser. An optical indoor positioning system for the mass market. In *Proceedings of the 3rd Workshop on Positioning Navigation and Communication (WPNC'06)*, Hannover, Germany, 2006.
[9] M. Köhler, S.N. Patel, J.W. Summet, E.P. Stuntebeck and G.D. Abowd. TrackSense: Infrastructure free precise indoor positioning using projected patterns. In A. LaMarca, M. Langheinrich and K.N. Truong, *Pervasive Computing*, Lecture Notes in Computer Science, Vol. 4480, pp. 334–350, Springer, 2007.
[10] Y. Fukuju, M. Minami, H. Morikawa and T. Aoyama. DOLPHIN: An Autonomous Indoor Positioning System in Ubiquitous Computing Environment. In *Proceedings IEEE Workshop on Software Technologies for Future Embedded Systems*, 2003.
[11] J. Collin, O. Mezentsev and G. Lachapelle. Indoor positioning system using accelerometry and high accuracy heading sensors. In *Proceedings of GPS*, 2003.
[12] W. Figel, N. Shephred and W. Trammell. Vehicule location by a signal attenuation cellular system. *IEEE Transactions on Vehicular Technology*, VT-18:105–110, 1969.
[13] M. Hata and T. Nagatsu. Mobile location using signal strength measurements in a cellular system. *IEEE Transactions on Vehicular Technology*, VT-29:221–225, 1991.
[14] V.N. Padmanabhan. User location and tracking in an in-building radio network. Technical Report, MSR-TR-99-12.
[15] E. Elnahraway, X. Li and R.P. Martin, The limits of localization using RSS. In *Proceedings of the 2nd International Conference on Embedded Networked Sensor Systems*, Baltimore, MD, USA, pp. 283–284, 2004.
[16] W.C. Jakes, *Microwave Mobile Communications*, IEEE Press, 1994.
[17] J. Parsons. *The Mobile Radio Propagation Channel*, Halsted Press, 1992.

[18] D. Akbarov, S. Kim, Y. Park and H. Gyuyoung. An improved TDOA positioning method using pattern matching for CDMA networks. In *Proceedings Mobility Conference*, pp. 268–273, 2007.

[19] F. Winkler, E. Fischer, E. Grass and P. Langendorfer. An indoor localization system based on DTDOA for different wireless LAN systems. In *Proceedings of the 3rd Workshop on Positioning Navigation and Communication (WPNC'06)*, Hannover, Germany, 2006.

[20] Y. Zhao, B. Le and J. Reed. Infrastructure support – The radio environment MAP. In B. Fette (Ed.), *Cognitive Radio Technology*, 2nd edn., Elsevier, 2009.

[21] A. Sofasi-Jazi, S.M. Riad, A. Muqaibel and A. Bayram. Report on through the wall propagation and material characterization. Time Domain and RF Measurement Laboratory, Bradley Department of Electrical Engineering, Virginia Polytechnic Institute and State University Blacksburg, USA, pp. 62–70, 2002.

[22] J. Zhang, M. Nakhkash and Y. Huang. In-situ characterisation of building materials. In *Proceedings IEEE 11th International Conference on Antennas and Propagation*, pp. 269–274, 2001.

[23] Y. Huang and M. Nakhkash. Characterization of layered dielectric medium using reflection coefficient. *IEE Electronic Letters*, 34(12):1207–1208, 1998.

[24] L.F. Chen, C.K. Ong, C.P. Neo, V.V. Varadan and V.K. Varadan. *Microwave Electronics, Measurement and Materials Characterization*, John Wiley & Sons 2004.

[25] R. Hoppe, G. Wolfe and F.M. Landstorfer. Measurement of building penetration loss and propagation models for radio transmission into buildings. In *Proceedings IEEE International Conference on Vehicular Technology*, pp. 2298–2302, 1999.

[26] D. Zrno, D. Šimunić and M. Roboz. Indoor propagation prediction software and WLAN measurements at 2.4 GHz. *Proceedings of Softcom*, CD, 2004.

[27] M.W.M.G. Dissanayake, P. Newman and H.F Durrant-Whyte. A solution to the simultaneous localization and map building problem. *IEEE Transactions on Robotics and Automation*, 17(3):229–241, 2001.

[28] J.A. Castellanos, J.M.M. Montiel, J. Neira and J.D. Tardos. Sensor influence in the performance of simultaneous mobile robot localization and map building. In O. Khatib and J.K. Salisbury (Eds.), *Experimental Robotics IV*, pp. 287–296, Springer-Verlag, 2000.

[29] M.W.M.G. Dissanayake, P. Newman, H.F. Durrant-Whyte, S. Clark and M. Csorba. An experimental and theoretical investigation into simultaneous localisation and map building. In O. Khatib and J.K. Salisbury (Eds.), *Experimental Robotics IV*, pp. 265–274, Springer-Verlag, 2000.

[30] E.M. Royer and C.-K. Toh. A review of current routing protocols for ad-hoc mobile wireless networks. *IEEE Personal Communications*, 6(2):46–55, April 1999.

[31] M. Mauve, J. Widmer and H. Hartenstein. A survey on position-based routing in mobile ad-hoc networks. *IEEE Network*, 15(6):30–39, November/December 2001.

[32] Zh. Huang and Ch.-Ch. Shen. A comparison study of omnidirectional and directional MAC protocols for ad-hoc networks. In *IEEE Globecom 2002*, 17–21 November, pp. 57–61, 2002.

[33] G. Martin. An evaluation of ad-hoc routing protocols for wireless sensor networks. Master's Thesis, University of Newcastle upon Tyne, May 2004.

[34] A. Vasan and U. Shankar. An empirical characterization of instantaneous throughput in 802.11b WLANs, Technical Report CS-TR-4389, UMIACS-TR-2002-69, Department of Computer Science and UMIACS, University of Maryland College Park, 2002.

[35] F. Cali, M. Conti and E. Gregori. IEEE 802.11wireless LAN: Capacity analysis and protocol enhancement. In *Proceedings of INFOCOM*, 1998.

[36] S. Basagni et al. A distance routing effect algorithm for mobility (DREAM). In *Proceedings of 4th Annual ACM/IEEE International Conference on Mobile Computing and Networking, MOBICOM'98*, Dallas, TX, pp. 76–84, 1998.

[37] J. Jeong, H. Kim, S. Lee and J. Shin. An analysis of hidden node problem in IEEE 802.11 multihop networks. In *NCM 2010*, pp. 282–285, 2010.

Biographies

Damir Zrno received his dipl.ing. degree in electrical engineering from the University of Zagreb, Croatia in 2002, and his joint Ph.D degree from both University of Zagreb, Croatia and Aalborg University, Denmark in 2010. Since 2002, he has worked at Faculty of Electrical Engineering and Computing in Zagreb, Croatia as a research assistant on several projects in the area of radio communications including network planning, SAR measurements, radio propagation modeling, radio localization, cognitive network simulation and optimization.

Dina Šimunić is a full professor at University of Zagreb, Faculty of Electrical Engineering and Computing in Zagreb, Croatia. She graduated in 1995 from University of Technology in Graz, Austria. In 1997 she was a visiting professor in Wandel & Goltermann Research Laboratory in Germany, as well as in Motorola Inc., Florida Corporate Electromagnetics Laboratory, USA, where she worked on measurement techniques, later on applied in IEEE Standard. In 2003 she was a collaborator of USA FDA on scientific project of medical interference. Dr. Šimunić is a IEEE Senior Member, and acts as a reviewer of *IEEE Transactions on Microwave Theory and Techniques*, *IEEE Transactions on Biomedical Engineering and Bioelectromagnetics*, the journal *JOSE* and as a reviewer of many papers contributed to various scientific conferences (e.g., *IEEE on Electromagnetic Compatibility*). She was a reviewer of Belgian and Dutch Government scientific projects, of the EU FP pprograms, as well as of COST-ICT and COST-TDP actions. She acted as a main organizer of the data base in World Health Organization, for the service of International EMF Project from 2000 to 2009. From 1997 to 2000 she acted as a vice-chair of COST 244: "Biomedical Effects of Electromagnetic Fields". From 2001 to 2004 she served as vice chair of the Croatian Council of Telecommunications. In 2006 she was elected the first time, and in 2010 re-confirmed as vice-chair of COST Domain Committee on Information and Communication Technologies (ICT). She is one of the proposers as well as a member of COST Transdomain Committee. She is the organizer of many workshops, symposia and round tables, as well as of special sessions (e.g., on telemedicine and on intelligent transport systems during Wireless Vitae, Aalborg, Denmark in 2009). She has held numerous invited lectures, among others at ETH Zürich, Switzerland in 1996 and US Air Force, Brooks, USA in 1997). She is author or co-author of approximately 100 publications in various journals and books, as well as her student text for wireless communications, entitled *Microwave Communications Basics*. She has contributed to the book *Towards Green ICT*, published in 2010. She is also editor-in-chief of the *Journal of Green Engineering*. Her research work comprises electromagnetic fields dosimetry, wireless communications theory and its various applications (e.g., in intelligent transport systems, body area networks, crisis management, security, green communications). She serves as Chair of the "Standards in Telecommunications" at the Croatian Standardization Institute.

Ramjee Prasad (R) is a distinguished educator and researcher in the field of wireless information and multimedia communications. Since June 1999, Professor Prasad has been with Aalborg University (Denmark), where currently he is Director of Center for Teleinfrastruktur (CTIF, www.ctif.aau.dk), and holds the chair of wireless information and multimedia communications. He is coordinator of European Commission Sixth Framework Integrated Project MAGNET (My personal Adaptive Global NET) Beyond. He was involved in the European ACTS project FRAMES (Future Radio Wideband Multiple Access Systems) as a Delft University of Technology (the Netherlands) project leader. He is a project leader of several international, industrially funded projects. He has published over 500 technical papers, contributed to several books, and has authored, coauthored, and edited over 30 books. He has supervised over 50 PhDs and 15 PhDs are at the moment working with him. He has served as a member of the advisory and program committees of several IEEE international conferences. In addition, Professor Prasad is the coordinating editor and editor-in-chief of the Springer International Journal on *Wireless Personal Communications* and a member of the editorial board of other international journals. Professor Prasad is also the founding chairman of the European Center of Excellence in Telecommunications, known as HERMES, and now he is the Honorary Chair. He has received several international awards; the latest being the "Telenor Nordic 2005 Research Prize". He is a fellow of IET, a fellow of IETE, a senior member of IEEE, a member of The Netherlands Electronics and Radio Society (NERG), and a member of IDA (Engineering Society in Denmark). Professor Prasad is advisor to several multinational companies. In November 2010, Ramjee Prasad received knighthood from the Queen of Denmark, the title conferred on him is Riddere af Dannebrog.