Self-reorganizing Dynamic Formations of Mobile Autonomous Robots for Communication Network Optimization

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1 STAGE OF THE RESEARCH

This doctoral research intends to study a method to autonomously self reorganize a formation of mobile robots to optimize network performance.

Currently, a program has already been developed that allows the robots to retrieve the received signal strength of their neighbours along with positional information of themselves and their neighbours. A routing protocol has also been developed and tested that uses the signal strength. It is intended to improve this protocol with the addition of positional data of each robot. Further studies will be conducted in uncommon environments, such as underground mines, to further its applications.

Control algorithms have been developed and simulated to autonomously reorganize a small formation of car like robots to optimize communication links. These algorithms will also be used to automatically set up communication networks using droppable, non-moving routing nodes. Along with being simulated, experiments will be conducted in physical environments.

2 OUTLINE OF OBJECTIVES

Although a lot of routing protocols for MANETs already exist and have been thoroughly simulated, there has been little actual experimentation in realistic environments and scenarios. Using the signal strength of each connection to establish routing is also a rarity, especially in actual implementations on robots. Relative distance of each robot will also be used to improve route selection.

Expending on studying the use of signal strength for routing in MANETs, the PhD work will also design and implement control algorithms for autonomous topology control of swarms of robots to optimize communication network performance.

Both the routing algorithms and the autonomous control of swarms will be studied in various environments, including indoors, outside, and in underground environments.

The main objectives of this work are:

- Develop a routing protocol based on signal strength.
- Incorporate relative distance information in routing protocol.
- MANET routing protocol experimental studies and comparisons with various route cost calculation equations.
- Develop algorithm for placement of robots and autonomous reorganization of their topology in a swarm towards the goal of optimizing the communication network.
- Simulations of the robot control algorithm automation.
- Experimental studies of automatic placement of robots and their autonomous self reorganization towards the goal of optimizing the MANET‘s performance..

3 RESEARCH PROBLEM

The field of swarm robotics is quickly expending. One on the key issues in controlling a swarm of robots is the communication between the operator and the robots, and between the robots themselves. The communication network used by these swarms is typically called a Mobile Ad-Hoc Network. (MANET).

MANETs generally use the IEEE 802.11 standard for wireless computing. Their dynamic nature required routing protocols to be used as the routes cannot be manually reprogrammed as with fixed and static networks. The use of signal strength of each individual link between the agents in the MANET requires the extraction of this information, the link cost calculation, its propagation throughout the network, and the total route cost calculation. This raises some issues such as the amount of processing power

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required and the amount of network overhead, especially when scaling to very large MANETs.

It is hoped that by using signal strength, along with incorporating relative distance information for cost calculations and studying various cost calculation equations for different environments, the new protocol can improve the MANET performance under various scenarios where other common protocols perform poorly or fail. The main metric that is targeted is the time needed for routing change, therefore reducing the amount of time to establish a new route when a link is broken. Other targeted metrics are reducing latency and increasing bandwidth.

When controlling a swarm of robots, some of the robots are normally autonomous. With only one operator normally, only one robot can be controlled at a time, the others must act autonomously, or remain idle. The issue of controlling the autonomous robots, with the scope of optimizing the MANET, is also a main goal of this research.

4 STATE OF THE ART

Routing based on signal strength has been discussed since the first uses of MANETs, however, most of the common wireless routing protocols do not make use of this information. The proposed routing protocols are rarely implemented and are usually only studied in simulations.

The Signal Strength based Adaptive Routing (SSA) Protocol is described in (Dube et al., 1997). The protocol is a reactive protocol that selects routes based on their continuous link connectivity duration and the average signal strength of the connection. SSA is composed of two separate protocols. The Static Routing Protocol (SRP) is used to retrieve and record the signal strength information in the signal stability table. The second part, the Dynamic Routing Protocol (DRP), maintains the routing table.

Using the beacons sent by the wireless adapters firmware, the signal strength is simply classified as either strongly or weakly connected. The length of time that the beacons have been continuously received over that link is also stored. When a node attempts to forward a packet, it first searches for a route in the routing table maintained by DRP. If the route does not exist, a route search is initiated. When a route is broken, the node that is attempting to forward the packet will notify the source node, which will then search for another route. If the notification of the broken route is unable to arrive to the source, the source will send a request for a new route after a timeout period.

The route selected will use only strongly connected links when possible. If a route consisting solely of strongly connected links is unavailable, it will search for a route that includes weakly connected links.

The SSA routing protocol is simulated and compared with a simple routing algorithm that chooses the smallest number of hops. It is determined that the SSA routing protocol significantly reduced the number of route reconstructions vs. the simple hop minimizing algorithm. The usefulness of the continuous connectivity lifetime is found to vary greatly depending on the scenario and must be configured properly for each case. It does not seem that this protocol has been implemented outside of a simulation environment.

A mechanism to improve TCP performance in adhoc networks using signal strength is proposed by (Klemm et al., 2005). It is found that the causes of 802.11 link performance degradation can be attributed to congestion of the shared channel medium or to the mobility of the nodes. The paper‘s objectives are to reduce the packet losses due to the mobility of nodes in MANETs.

Suggestions to reduce link failures are made to react to the loss of a link. When a link failure is determined to be due to a node moving out of range, the transmission power of the network adaptor is temporarily increased and a search for a new route is initiated. Care is taken not to include routes of links that have temporarily increased transmission power. By using signal strength information, it is possible to determine when a route is approaching failure and then pro-actively search for a new route. If the route degradation is due to congestion and it is determined that the neighbour is most probably in range from prior signal strength data, the node will persist over a longer period of time to communicate with its neighbour instead of searching for better routes.

A problem is found that signal strength degrades as the networks channel becomes congested. To determine if the links degradation is due to congestion or due to the node moving out of range, the number of packets overheard by the node is counted. If the count is large, then the degradation can be attributed to channel congestion. Care must be taken not to increase transmission power in this case as it can lead to further deterioration of the communication link.

It is determined through simulations using network simulator 2 that under low load, the TCP performance is increased by up to 75%. On a congested network under heavy load, TCP performance is increased by 14-30%. TCP performance is determined from the number of packets lost.

In the above papers, by using simulations, the use of signal strength information in route finding is discovered to be very beneficial. It is however very rare to find any of these proposals implemented and tested on real hardware. Because loss in signal strength and network performance can be due to multiple causes, further improvement in routing can be accomplished by determining its cause.

(Necsulescu and K.Schilling, 2013) investigated the cost calculation and performance evaluation for a signal strength based MANET routing protocol. In this paper, a signal strength based routing protocol is evaluated. The evaluation consists of an experiment where a mobile, car-like robot, is remotely operated down a hallway with multiple network access nodes located in the offices. This results in a dynamic, multi-hop WiFi network. A camera is mounted to the front of the robot providing live video streaming for the operator. The performance of the protocol is then evaluated with respect to video frames received per section for various parameters. Results using BATMAN, OLSR, and BABEL protocols are also provided for comparison.

(Qian et al., 2012) and (Nagatani et al., 2011) presented interesting results regarding the use of signal intensity in controlling robot motion for the case of nuclear radiation source finding. These results were found relevant for the development of the robot control using signal intensity in this paper.

5 METHODOLOGY

5.1 Signal Strength Routing Protocol

The calculation of the cost of a link between two nodes is derived from the free space path loss of radio waves. The path loss can also be denoted as the local average received signal power at the receiver node relative to the transmission power of the transmission node. The equation for path loss (1) is retrieved from (Andersen et al., 1995):

$$L = L(d_0) + 10 * n * \log_{10} \frac{d}{d_0} + X_0 \tag{1}$$

Where: $L =$ path loss in (dB), d is distance in m, $L(d_0)$ is the path loss at a known, close distance $d0$, n is the power law relationship between distance and received power, and X_o is a zero mean Gaussian random variable

By letting $X_0 = 0$, d_0 as $4\pi/\lambda$, $L(d_0) = 0 (L \to 0$ as $d \to 0)$, and $n = 2$ for free space as specified by (Andersen et al., 1995), the path loss becomes (2). It is then solved for d in (3), which is shown in Figure 1.

$$L = 20 \log_{10} \left(\frac{4\pi d}{\lambda} \right) \tag{2}$$

$$d = \frac{\lambda}{4\pi} * 10^{\frac{L}{20}} \tag{3}$$

Through experimentation, it was determined that the connection between two nodes becomes unusable around 91-92dB. A cost of 1000 is therefore chosen to represent 91dB, which corresponds to a distance of 314.6m from equation (3), or $d = 314.6$ for $L =$ 91dB. To assign a cost of 1000 for the value of 91dB, (3) is multiplied by the constant a.

$$\text{cost}_{\text{strength}} = a * d \tag{4}$$

where:

$$a = \frac{1000}{L(91)} = \frac{1000}{314.5576} = 2.8334 \tag{5}$$

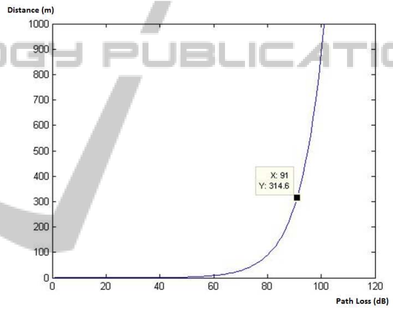

Figure 1: Distance with respect to path loss.

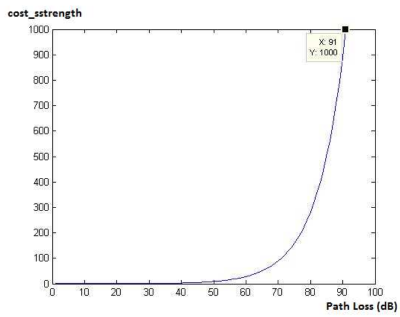

Figure 2: Cost Calculated from Path Loss.

An experiment was conducted to test this protocol and compare its performance against other commonly used wireless routing protocols.

The experiment consists of a mobile node and three fixed nodes. The fixed nodes are identical Lenovo X61t laptops with Intel based WiFi adaptors. The mobile node is a 4 wheeled car like robot which has an on-board x86 PC with an Atheros5000 based WiFi network adaptor. The laptops are running Xubuntu 12.04 and the mobile robot is running

Ubuntu 12.04 Server. An AXIS IP camera is mounted to the front of the mobile robot.

An operator, using a laptop, sits in a corner office. The two other laptops are placed such that the operator and the farthest laptop have no direct connection. The transmission values of the laptop and robot WiFi adaptors were modified as well and automatic power management turned off. The robot is then placed at one end of the corridor and is driven remotely by the operator to the other end. The route changes according to the signal strengths. The initial setup of the experiment is shown in Figure 3.

The signal strength routing protocol performed better than OLSR and BABEL routing protocol and was comparable to the performance of BATMAN in this experiment. A historgram of best performance of the FPS received for the signal strength routing protocol for this experiment is shown in Figure 4.

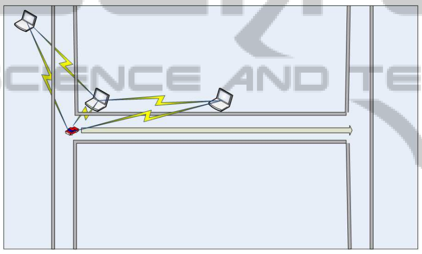

Figure 3: Signal Strenght Routing Protocol Experiment Setup.

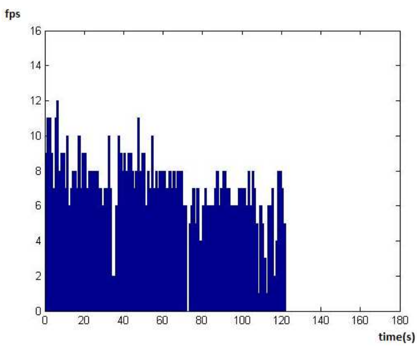

Figure 4: Best Result from Various Parameters of the Signal Strength Routing Protocol.

Future experimentation using different cost functions as well as more complex scenarios are planned.

5.2 Addition of Distance to Routing Protocol

The absolute distance of each robot is determined by using odometry. This is achieved by using the onboard gyroscope and encoders. The absolute distance is then kept track of by each robot through dead reckoning, and then broadcast throughout the MANET.

After calculating the relative distance the route score is calculated using path loss equation stated in (Andersen et al., 1995). Similar to the determination of the cost function due to signal strength, the cost function uses the same derivation for cost, however, the right hand side of the Equation is inverted. This is shown in (6).

$$\mathrm{cost_{dist}} = 270\log_{10}\frac{4\pi \mathrm{d_{relative}}}{\lambda} \qquad (6)$$

Only preliminary testing of this protocol has been finished. Further work to combine this information along with signal strength into the routing protocol is still needed. Future experiments are planned to test the new cost calculation method along with trying various cost calculation equations.

5.3 Automation of Swarm Agents with a Dynamic Topology to Optimize Communication Network

Swarms of robots often have un-predictable formations due to their dynamic nature. When a swarm moves or expends to a new area, the topology changes. Due to these topology changes, the distances between the various swarm agents also change, their neighbours change, and therefore, the routes will also change. In this section of the doctoral work, we look at optimizing the topology of the swarm to improve network communication performance. This is accomplished by developing control algorithms for the autonomous robots such that they place themselves in such a way as to optimize the network.

As a first step to accomplishing this, we develop a control algorithm and a Matlab simulation of a simple case with two mobile robots and one operator. The operator will operate one of the robots down a hallway, while the other robot is autonomous and places itself in such a way as to maintain a good connection with the operated robot.

5.3.1 Control Algorithm Formulation

An intermediate robot is assumed to be autonomous with a controller that searches for locations that most efficiently relay the signal from a fixed station to the tele-operated robot to increase operational range and network performance. In contrast to the case of traditional robot control where a desired position is defined, in this case such a position has to be found by the robot while moving (Qian et al., 2012) and (Nagatani et al., 2011).

In actual applications signal intensity at a relay robot is obtained from measurement on board (Andersen et al., 1995) and (Klemm et al., 2005). For simulations signal intensity has to be calculated assuming known relative distance d of the source with regard to the relay robot.

The signal intensity $I(d)$ in dB, at a distance d from the signal source with intensity $I(0)$, is subject to a logarithmic loss $20\log[\frac{2\pi}{\lambda}d]$. The radio engineer formula that is based on the Friis transmission equation (Gaertner and Nuallain, 2012) and (Necsulescu and K.Schilling, 2013), is

$$\begin{aligned} I(d) &= I(0) - L(d) \\ &= I(0) \\ &= I(0) - 20\log\left[\frac{2\pi}{\lambda}d\right](\cos\theta - j\sin\theta) \end{aligned} \tag{7}$$

It is assumed that the position vectors of the intermediate robot, located at (x_r, y_r) with regard to the tele-operated robot d1 , located at (X,Y), and with regards to the fixed base, d_2 are known at all times (See Figure 5).

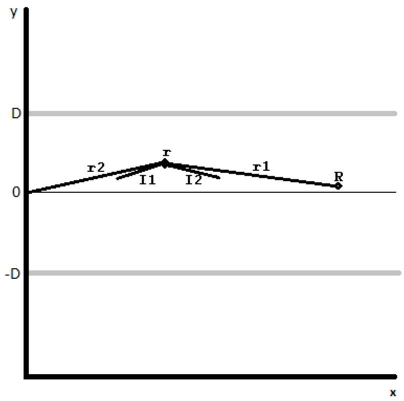

Figure 5: Schematic of Hallway Experiment.

$$d_1 = d_1(\cos\theta_1 = j\sin\theta_1) \tag{8}$$

$$d_2 = d_2(\cos\theta_2 = j\sin\theta_2) \tag{9}$$

Intermediate robot control should drive the robot toward where the signal intensity vectors, I_1 and $I2$ are:

$$I_1 = I_1(\cos\theta_1 = j\sin\theta_1) \tag{10}$$

$$I_2 = I_2(\cos\theta_2 = j\sin\theta_2) \tag{11}$$

I_1 and I_2 are along the vectors d_1 and d_2. While the signal strength I_1 and I_2 are sensed on board, the angles are determined from the relative position vectors d_1 and d_2.

The controller of the intermediate robot has to find the position of the robot where the difference $I_1 - I_2$ becomes insignificant, where:

$$\begin{aligned} & I_1 - I_2 = \\ & (I_1(0) - 20\log\left[\frac{2\pi}{\lambda}d_1\right](\cos\theta_1 - j\sin\theta_1) \\ & -(I_2(0) - 20\log\left[\frac{2\pi}{\lambda}d_1\right](\cos\theta_2 - j\sin\theta_2) \end{aligned} \tag{12}$$

for

$$d_1 = \sqrt{(X - x_r)^2 + (Y - y_r)^2} \tag{13}$$

$$d_2 = \sqrt{x_r^2 + y_r^2} \tag{14}$$

Signal loss vectors are given by:

$$L_1(d_1) = 20\log\left[\frac{2\pi}{\lambda}|d_1|\right](\cos\theta_1 - j\sin\theta_1) \tag{15}$$

$$L_2(d_2) = 20\log\left[\frac{2\pi}{\lambda}|d_2|\right](\cos\theta_2 - j\sin\theta_2) \tag{16}$$

A second goal of the intermediate robot is to avoid collisions during motion. Here, collision avoidance will be presented for the case that the robots move in a corridor of width 2D, assumed for convenience along x-axis (See Figure 5).

The distance of the intermediate robot with regard to the upper wall at $y = D$ is $D - y_r$ and with regard to the lower wall at $y = -D$ is $D + y_r$ (See Figure 5). Velocity command to avoids collisions with these walls is given by:

$$\frac{-1}{D - y_r + \varepsilon} + \frac{1}{D + y_r - \varepsilon} \tag{17}$$

where ε, of a very small value, is included to avoid singularities. These functions give zero velocity command when $y_r = 0$ and $1/\varepsilon$, a very large value, when:

$$y_r = D \text{ or } y_r = -D \tag{18}$$

The velocity command vector for the intermediate robot results as

$$\begin{aligned} & v_d = \\ & \quad -K\{[I_1(0) - L_1(d_1)](\cos\theta_1 + j\sin\theta_1) \\ & \quad -[I_2 - L_2(d_2)](\cos\theta_2 + j\sin\theta_2\} \\ & \quad + jK_B\left[\frac{-1}{D - y_r + \varepsilon} + \frac{1}{D + y_r - \varepsilon}\right] \end{aligned} \tag{19}$$

or, after separating real and imaginary part:

$$v_d = -K\{[I_1(0)-L_1(d_1)]\cos\theta_1 - [I_2 - L_2(d_2)](\cos\theta_2\} + j\{[I_1(0)-L_1(d_1)]\sin[I_2(0)-L_2(d_2)]\sin\theta_2\} + jK_B\left[\frac{-1}{D-y_r+\varepsilon}+\frac{1}{D+y_r-\varepsilon}\right] \quad (20)$$

K and K_B are gains to be determined at the controller design stage.

In actual applications, I_1 and I_2 are obtained from on-board signal intensity measurement, while the relative distances $D-y_r$ of the relay robot with regard to the upper wall and with regard to the lower wall $D+y_r$ are obtained from on board proximity sensors.

Denoting:

$$v_d = A + jB \quad (21)$$

Results in:

$$v_d = \sqrt{A^2+B^2} \quad (22)$$

$$\theta d = \tan^{-1}\left(\frac{B}{A}\right) \quad (23)$$

After each iteration the new position of the intermediate robot is calculated as:

$$x_r(t+\Delta t) = x_r(t) + v_d \Delta t \cos\theta_d \quad (24)$$

$$y_r(t+\Delta t) = y_r(t) + v_d \Delta t \cos\theta_d \quad (25)$$

The results of the simulation showed that the equations work and appear to be suitable for use in controlling a robot.

In Figure 6, the x position of both the tele-operated and relay robot are plotted with respect to time. It is shown that the relay robot places itself at the point where the signal intensities are equal.

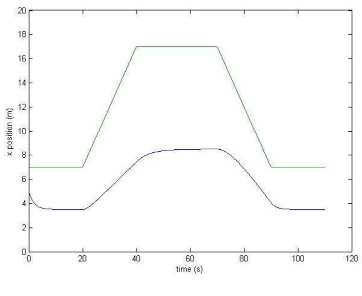

Figure 6: X-position of tele-operated robot and relay robot with respect to time.

In Figure 7, the magnitude of the velocity of the relay robot is shown. The maximum speed it reaches is 0.8m/s which is reasonable for robotus in an indoor environment.

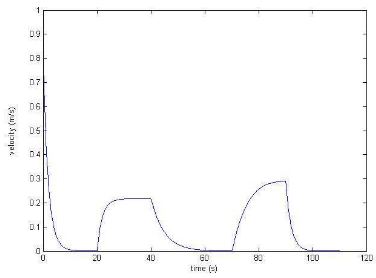

Figure 7: Absolute value of velocity with respect to time.

Future work is planed to do the simulation in an experiment in the hallway used for the signal strength routing experiment. Further work is also planned to expend the method for more complicated scenarios and to simulate those scenarios.

6 EXPECTED OUTCOME

At the end of the PhD work, it is hoped that the following is accomplished:

- A new routing protocol, customizable to use signal strength and/or distance, adaptable to the environment, and with different possible route cost functions is completed. It is hoped that it can improve performance and a variety of different environments and scenarios.
- Methods to automate swarm agents for communication network optimization are developed and simulated. It is hoped to also use these methods in actual deployments and realistic scenarios with dynamic topologies.
- To develop methods to setup wireless communication networks autonomous by using static routing nodes that are dropped by an autonomous robot. The placement of these nodes will be optimized through various techniques, including the use of 3D mapping. The above developed routing protocols will also be tested on these networks.
- Further expansion of the different technologies to be used in uncommon environments, such as underground mines, with harsh conditions. This includes high humidity, poor lighting, and large levels of airborne particles.

REFERENCES

Andersen, J., Rappaport, T., and Yoshida, S. (1995). Propagation measurements and models for wireless communications channels. *Communications Magazine, IEEE*, 33(1):42–49.

Dube, R., Rais, C. D., yeh Wang, K., and Tripathi, S. K. (1997). Signal stability based adaptive routing (ssa) for ad-hoc mobile networks. *IEEE Personal Communications*, 4:36–45.

Gaertner, G. and Nuallain, E. O. (2012). *Link Quality Prediction in Mobile Ad-Hoc Networks*, pages 61–94. In-Tech.

Klemm, F., Ye, Z., Krishnamurthy, S. V., and Tripathi, S. K. (2005). Improving tcp performance in ad hoc networks using signal strength based link management. *Ad Hoc Netw.*, 3(2):175–191.

Nagatani, K., S., K., Okada, Y., Tadokoro, S., Nishimura, T., Yoshida, T., Koyanagi, E., and Hada, Y. (2011). Redesign of rescue mobile robot quince. In *Safety, Security, and Rescue Robotics (SSRR), 2011 IEEE International Symposium on*, pages 13–18.

Necsulescu, P. and K.Schilling (2013). Signal strength based manet routing protocol: Cost calculation and performance evaluation. In *Proceedings of the 3rd IFAC Symposium on Telematics Applications (TA2013)*, Seoul, South Korea.

Qian, K., Song, A., Bao, J., and Zhang, H. (2012). Small teleoperated robot for nuclear radiation and chemical leak detection. *International Journal of Advanced Robotic Systems*, pages 1–9.