Multipath Routing for Dual-Radio Wireless Sensor Networks

Nildo dos Santos Ribeiro Júnior,
Advisor: Marcos A. M. Vieira,
Co-advisor: Luiz F. M. Vieira

[1]Departamento de Ciência da Computação
Universidade Federal de Minas Gerais – Belo Horizonte, MG – Brasil

`{nildo,mmvieira,lfvieira}@dcc.ufmg.br`

Abstract. *The design of a Wireless Sensor Network depends significantly on the application. For the traditional applications, such as environmental monitoring, smart buildings or agriculture, the design prioritized reducing the cost, the energy expenditure and memory usage at the expense of not having a higher throughput. Modern applications, such as surveillance or traffic monitoring, usually require using cameras and transmitting video data through the network. For such applications, dual-radio platforms were developed where their design prioritizes achieving higher throughput and conserve the energy efficiency of the network. In this work, we propose a multipath routing algorithm to find two disjoint paths with the same parity between a pair of nodes in the network. The new routing algorithm, combined with a forwarding scheme that alternates the radios throughout the paths, allows all nodes in the paths to use both radios in parallel all the time, doubling the throughput in comparison with a single path routing scheme. We evaluated our algorithm and forwarding scheme in a real world testbed with 100 nodes of the Opal dual-radio platform. Our scheme were able to double the throughput when compared with FastForward, the state-of-the-art protocol for dual-radio platforms, and achieve up to 96% of the theoretical limit.*

1. Introduction

The design of traditional wireless sensor networks (WSNs) has favored low power operation at the cost of communication throughput. Minimizing cost and power consumption is achieved at the expense of the network's performance. This made sense in the context of the beginning of the development of WSNs, where most applications would be to collect small pieces of data, such as temperature or lighting values. Applications are now also being deployed to gather acoustic and visual data, which have a high demand for communication throughput. Transmitting multimedia content through WSNs not only enhances existing sensor network applications, such as tracking, home automation, and environmental monitoring, but also enables several new applications.

Researchers have developed new platforms for WSNs aimed to deliver radio diversity, which can be achieved by having more than one radio in each WSN mote. Such platforms can be used to improve throughput when they are able to operate two radios at the same time. It is also desirable that these radios operate in different frequency band, so they will not interfere with each other while communicating, reducing packet loss due to interference and allowing simultaneous transmissions without interference in the same sensor node. Radio diversity can significantly improve end-to-end delivery rates, network stability and transmission costs at only a small increase in energy cost over a single radio [Kusy et al. 2011].

The ability to simultaneously transmit and receive packets through different radios was exploited in the design of FastForward, a high-throughput transport protocol for dual-radio WSNs [Ekbatanifard et al. 2013]. In FastForward, each forwarder receives packets through one radio and sends them though the other one, as it is shown in Figure 1(a). This scheme allows all the intermediate nodes in the path to be receiving and transmitting packets at the same time, achieving an end-to-end throughput equal to the channel capacity. This result is twice the maximum throughput it is possible to achieve with single-radio platforms, because the radio would have to spend half of its time receiving packets and the other half forwarding them.

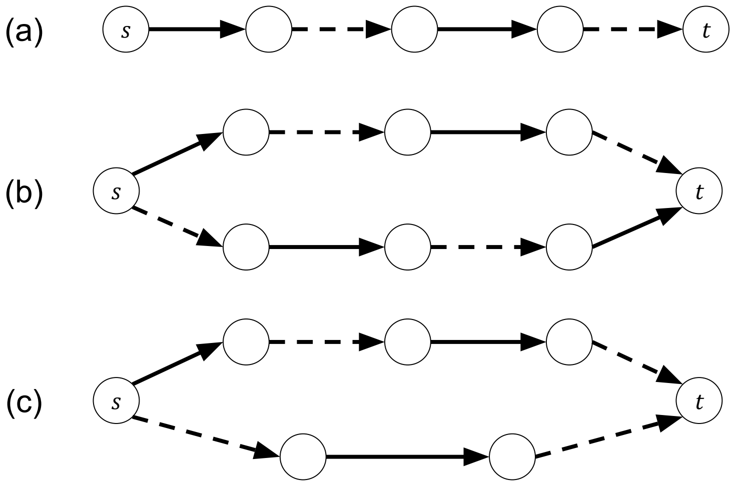


Figure 1. Examples of a forwarding scheme using a single path, two paths with the same parity and two paths with different parities.

The problem with FastForward's scheme is that the source and the destination nodes, despite having two radios available on them, they only use one radio each, since it uses only one path. The idea bringing the main contribution of this dissertation is to fully utilize all the available radios, even those in the source and destination nodes, to achieve the maximum theoretical throughput using dual-radio platforms. In order to accomplish this goal, we calculate and use two disjoint paths, where each intermediate node will receive packets through one radio and retransmit them through the other one, just as the previous scheme, but the source node will be using both radios for transmissions and the destination node will be using both for receiving packets, as shown in Figure 1(b).

Using two disjoint paths to transmit packets potentially doubles the throughput compared with the single path scheme, theoretically achieving twice the channel capacity. However, it adds a new constraint to the routing problem. The two paths must have lengths of the same parity. If this is not the case, there will be a bottleneck in the network, where the destination node would be receiving packets coming from two different paths through the same radio, and the result would be a maximum throughput equal to the one we would achieve using a single path. This situation is illustrated in Figure 1(c).

The parity restriction defines a new graph problem of finding two vertex disjoint simple paths between a source and a destination with lengths of the same parity. The problem arises from the practical application in dual-radio WSNs described here, and did not have a solution in the literature. In this dissertation, we discuss the nature of this problem for directed and undirected graphs, present a practical solution and evaluate the gains in throughput in the network in a physical testbed with dual-radio platforms.

The main contributions of this dissertation are:

- The introduction of a new graph problem of finding two vertex disjoint simple paths with lengths of the same parity. We show that the decision version of the problem in undirected graphs is polynomial, but we proof the same problem in directed graphs to be NP-complete.
- An optimal centralized routing solution for the minimization version of the problem in directed graphs, modeled as integer linear programming.
- The design and implementation of a distributed heuristic solution for the minimization problem in directed graphs.
- Experiments with simulations evaluating different models for real world dual-radio wireless sensor networks.
- Experiments with the proposed multipath routing scheme in a real world testbed with 100 dual-radio nodes, showing that it is possible to achieve a throughput of up to 96% of the theoretical limit.

2. Related Work

Various multipath routing algorithms for WSNs in the literature aim to solve different problems, but none of them find two paths with the same parity. Some algorithms consider the problem of finding exactly two disjoint paths in a network [Ishida et al. 1995, Ogier and Shacham 1989, Lee and Reddy 2010, Griffin and Korkmaz 2011]. Others are designed to find k disjoint paths between a source and a destination node, with a general k. Some of these are centralized algorithms [Khuller and Schieber 1991, Iwama et al. 1997, Chen et al. 2004, Srinivas and Modiano 2003, Bhandari 1997, Suurballe 1974, Hashiguchi et al. 2011], and others are distributed [Ganesan et al. 2001, Li and Wu 2005, Baek et al. 2007, Sidhu et al. 1991, Fang et al. 2009, Omar et al. 2011, Kumar and Varma 2010]. These last distributed algorithms are efficient, but do not try to minimize the length of the routing paths.

The routing algorithm that comes closer to solve our problem is OFDP [Zhang et al. 2016]. It is a distributed algorithm for finding k disjoint paths with minimum length in WSNs. Unlike other decentralized algorithms, OFDP does not fix the paths it finds. Instead, it marks the nodes as occupied and consider the edges to be only backwards and with negative weights. Then, in each iteration it searches for augmenting paths in the network. OFDP finds k disjoint paths between a source and a destination with minimum total length in the k^{th} round, if they exist. However, none of the algorithms cited consider the problem of finding disjoint paths with the same parity. We developed the first algorithm to solve this problem.

Also, none of the above protocols were designed for dual-radio platforms. Fast-Forward [Ekbatanifard et al. 2013], is the only protocol in the literature to explore the advantages of using dual-radio platforms in order to maximize throughput in a WSN. FastForward transmits packets from a source node to a destination through a single path. The radio used to transmit the packets along the path are alternated in each hop. It assumes that one radio does not interfere with the other, which already helps to solve the problem of intra-path interference. Furthermore, it uses multiple fixed channels for each radio in each hop, reducing even more the effect of interference and eliminating the overhead of switching channels along the way.

To evaluate our protocol in the real world, we used the Opal mote [Jurdak et al. 2011]. Opal includes two onboard 802.15.4 radios operating in the 900 MHz and 2.4 GHz bands to provide radio diversity. The authors present experiments that evaluate Opal's throughput, range and energy consumption, comparing their results with single-radio platforms. They showed that Opal increases throughput by a factor of 3.7 when compared with platforms with just one radio with the same data rate. To compare the energy efficiency between the platforms, they introduced a new metric, called spatial energy cost, which measures the energy to transfer one bit of information in a unit area. One advantage of using the Opal mote is the existence of a large-scale sensor network testbed for public access. Twonet [Li et al. 2013] is a testbed that has 100 Opal nodes and located at the University of Houston, in the USA. Although testbeds generally are limited to a few tens or hundreds of nodes and a fixed network topology, they provide means to realistic, moderate-scale evaluation of sensor network algorithms.

3. Theoretical Contributions

In this dissertation we present the *parity disjoint paths problem*: finding two disjoint paths with the same parity between given source and destination nodes. We studied this new problem for four different network models: directed and undirected graphs, and directed and undirected multigraphs. We also considered the decision version: determining just if such paths exist, and the optimization version: finding the shortest pair of paths.

We prove that the decision version of the problem is NP-complete for directed graphs, by reducing the *even path in digraphs problem* [LaPaugh and Papadimitriou 1984] to it. With this result, we also conclude that the optimization version of the problem is also NP-complete for directed graphs. We also prove that the decision version is polynomial for undirected graphs. However, the optimization version remains an open problem in undirected graphs.

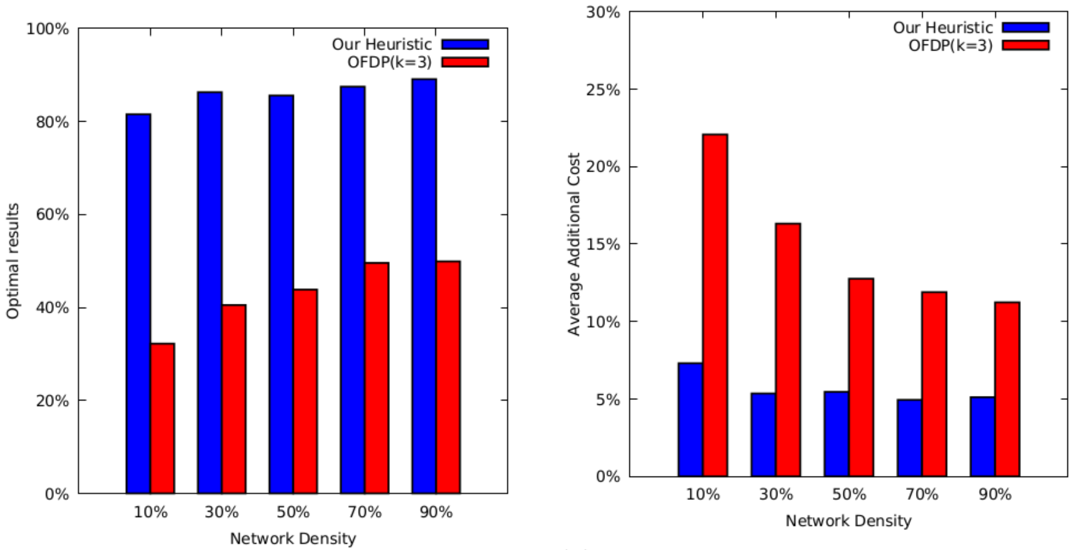
We present a centralized solution with a integer linear programming model to find the solution for the optimization problem in the most general case. We also present a distributed heuristic algorithm, which works by finding a shortest path of a certain parity, and then trying to find an augmenting path of the same parity of the one that was found before. We evaluate the performance of our algorithms with simulations and experiments in the real world.

4. Experimental Results

In the dissertation, we present various experiments to evaluate the modeling of the network as directed and undirected graphs and multigraphs, showing that a directed multigraph is a better representation for dual-radio networks. Here we will present the main results regarding the routing algorithm itself in comparison with what exists is available out there and the throughput achieved in the real world experiments.

There isn't in the literature other work solving the minimum parity disjoint paths problem, so there is no proper baseline to compare our heuristic with. We decided to compare our heuristic to another simple heuristic using an existing distributed algorithm to solve the minimum k disjoint paths problem, OFDP [Zhang et al. 2016]. To find two paths with the same parity with OFDP, we run it setting $k = 3$. The algorithm will find three disjoint paths in the network with the minimum total weight, therefore, it is guaranteed that at least two of them will have the same parity. Then we choose the pair of paths with same parity and smallest total weight. We chose this algorithm to compare our results because it is a way to use an existing distributed algorithm to find paths with the same parity.

We generated five random instances of a network topology, each one with different densities, increasing the number of edges in the graph from 10% to 90% at equal steps of 20%. In Figure 2(a) we can see the comparison of our heuristic with OFDP($k = 3$) in number of optimal solutions found. Our solution found over 80% of optimal solutions for every tested network density, slightly increasing as the density increases. In Figure 2(b) we show the average additional cost from the non-optimal solutions. Our heuristic's greatest additional cost was about 7% of the optimal in less dense networks. The smallest average additional cost with OFDP($k = 3$) was 11% in more dense networks, but reaching up to 22% at 10% density.



(a) Percentage of optimal results

(b) Average additional cost in non-optimal results

Figure 2. Comparing the results for our algorithm and OFDP($k = 3$) in random network topologies with different densities

Now we present one of the practical experiments in the real-world testbed to evaluate the throughput and data yield using two paths calculated with our algorithm and compare it with with the state-of-the-art protocol for high-throughput in dual-radio WSNs, FastForward, which uses only one path. We configured the two radios to transmit us-

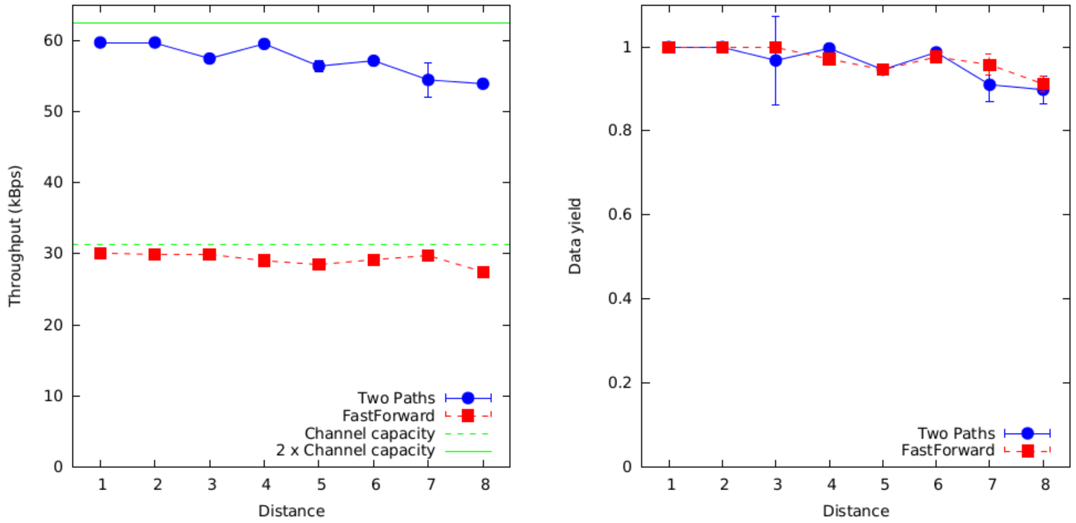


Figure 3. Comparing the performance of our protocol in the real world with FastForward's

ing the O-QPSK modulation at 250 kbps and with transmission power of 3 dBm. In the experiments shown here, we disabled, in the MAC layer, the Clear Channel Assessment (CCA) and the random back-offs in order to compare with FastForward results, which did the same.

In each experiment, the source node sends 1000 packets. Each packet has 127 bytes, where the payload has 100 data bytes. We define the throughput as the total number of bytes received by the destination node per second, including those not related to the payload in the packet. We define the data yield as the number of unique packets received by the destination node divided by the total number of packets sent by the source node. The experiments were repeated 10 times for each instance, and the values presented are the mean and standard deviation of the results obtained. The results are shown in Figure 3. The green dashed line represents the maximum transmission rate using only one radio: 250 kbps, or 31.25 kBps. The continuous green line represents the theoretical throughput limit when using two radios, which is twice of the previous value: 62.5 kBps.

In this experiment we obtained the maximum throughput of 60 kBps, which is close to the maximum theoretical throughput limit when using two radios. Therefore, the value obtained is 96% of ideal theoretical maximum flow and it was obtained in a real environment. In addition, this value is twice the value achieved with FastForward, indicating the maximum use of the two radios in intermediate nodes. This experiment is important because it shows that our solution could reach 96% of ideal theoretical maximum flow in practice.

About energy consumption, with a larger throughput, it is expected the total energy expenditure to increase. But the energy consumption per transmitted byte becomes smaller. According to [Jurdak et al. 2011], the Opal consumes an average of 49 mA of current if both radios are operating simultaneously. As our protocol reached a flow rate of 60 kBps, we have an energy expenditure of 0.82 mA/kB. While with the maximum flow reached by FastForward of 30 kBps, we would have an energy expenditure of 1.64 mA/kB. Thus, our protocol consumes less energy per byte transmitted on each node. Because the number of nodes using two paths does not double, since the source and destination nodes are always the same, our protocol will have a greater overall energy efficiency than FastForward.

5. Publications

Partial results of this dissertation was already published in the The Brazilian Symposium on Computer Networks and Distributed Systems in 2017 (SBRC 2017), in a paper titled *"Maximizando a Vazão Através de Multiplos Caminhos em Plataformas com Dois Rádios"*. Now we have submitted the full contributions of this dissertation to journals. To IEEE Communications Magazine (Qualis A1) we submitted the new problem description, theoretical contributions and throughput experiments, and to the ACM Transactions on Sensor Networks (Qualis B1) we submitted the distributed algorithm, simulations and experiments, and we are waiting for the reviews from both journals.

References

Baek, J. W., Nam, Y. J., and Seo, D.-W. (2007). An energy-efficient k-disjoint-path routing algorithm for reliable wireless sensor networks. In *IFIP International Workshop on Software Technolgies for Embedded and Ubiquitous Systems*, pages 399–408. Springer.

Bhandari, R. (1997). Optimal physical diversity algorithms and survivable networks. In *Computers and Communications, 1997. Proceedings., Second IEEE Symposium on*, pages 433–441. IEEE.

Chen, Y.-q., Guo, X.-f., Zeng, Q.-k., and CHEN, G.-h. (2004). Amr: a multipath routing algorithm based on maximum flow in ad-hoc networks. *Acta Electronica Sinica*, 32(8):1297–1301.

Ekbatanifard, G., Sommer, P., Kusy, B., Iyer, V., and Langendoen, K. (2013). Fastforward: High-throughput dual-radio streaming. In *Mobile Ad-Hoc and Sensor Systems (MASS), 2013 IEEE 10th International Conference on*, pages 209–213. IEEE.

Fang, X., Shi, S., and Li, J. (2009). A disjoint multi-path routing algorithm in wireless sensor network. *Journal of Computer Research and Development*, 46(12):2053–2061.

Ganesan, D., Govindan, R., Shenker, S., and Estrin, D. (2001). Highly-resilient, energy-efficient multipath routing in wireless sensor networks. *ACM SIGMOBILE Mobile Computing and Communications Review*, 5(4):11–25.

Griffin, M. and Korkmaz, T. (2011). Distributed verification of global multiple disjoint paths in mobile wireless networks. In *Wireless Communications and Mobile Computing Conference (IWCMC), 2011 7th International*, pages 666–670. IEEE.

Hashiguchi, T., Tajima, K., Takita, Y., and Naito, T. (2011). Node-disjoint paths search in wdm networks with asymmetric nodes. In *Optical Network Design and Modeling (ONDM), 2011 15th International Conference on*, pages 1–6. IEEE.

Ishida, K., Kakuda, Y., and Kikuno, T. (1995). A routing protocol for finding two node-disjoint paths in computer networks. In *Network Protocols, 1995. Proceedings., 1995 International Conference on*, pages 340–347. IEEE.

Iwama, K., Iwamoto, C., and Ohsawaa, T. (1997). A faster parallel algorithm for k-connectivity. *Information processing letters*, 61(5):265–269.

Jurdak, R., Klues, K., Kusy, B., Richter, C., Langendoen, K., and Brünig, M. (2011). Opal: A multiradio platform for high throughput wireless sensor networks. *Embedded Systems Letters, IEEE*, 3(4):121–124.

Khuller, S. and Schieber, B. (1991). Efficient parallel algorithms for testing k and finding disjoint s-t paths in graphs. *SIAM Journal on Computing*, 20(2):352–375.

Kumar, A. and Varma, S. (2010). Geographic node-disjoint path routing for wireless sensor networks. *IEEE Sensors Journal*, 10(6):1138–1139.

Kusy, B., Richter, C., Hu, W., Afanasyev, M., Jurdak, R., Brünig, M., Abbott, D., Huynh, C., and Ostry, D. (2011). Radio diversity for reliable communication in wsns. In *Information Processing in Sensor Networks (IPSN), 2011 10th International Conference on*, pages 270–281. IEEE.

LaPaugh, A. S. and Papadimitriou, C. H. (1984). The even-path problem for graphs and digraphs. *Networks*, 14(4):507–513.

Lee, Y. O. and Reddy, A. N. (2010). Disjoint multi-path routing and failure recovery. In *Communications (ICC), 2010 IEEE International Conference on*, pages 1–6. IEEE.

Li, Q., Han, D., Gnawali, O., Sommer, P., and Kusy, B. (2013). Twonet: Large-scale wireless sensor network testbed with dual-radio nodes. In *Proceedings of the 11th ACM Conference on Embedded Networked Sensor Systems*, page 89. ACM.

Li, S. and Wu, Z. (2005). Node-disjoint parallel multi-path routing in wireless sensor networks. In *Embedded Software and Systems, 2005. Second International Conference on*, pages 6–pp. IEEE.

Ogier, R. and Shacham, N. (1989). A distributed algorithm for finding shortest pairs of disjoint paths. In *INFOCOM'89. Proceedings of the Eighth Annual Joint Conference of the IEEE Computer and Communications Societies. Technology: Emerging or Converging, IEEE*, pages 173–182. IEEE.

Omar, S., Zoulikha, M., and Cousin, B. (2011). Energy efficiency in ad hoc wireless networks with node-disjoint path routing. In *Systems, Signal Processing and their Applications (WOSSPA), 2011 7th International Workshop on*, pages 127–130. IEEE.

Sidhu, D., Nair, R., and Abdallah, S. (1991). Finding disjoint paths in networks. In *ACM SIGCOMM Computer Communication Review*, volume 21, pages 43–51. ACM.

Srinivas, A. and Modiano, E. (2003). Minimum energy disjoint path routing in wireless ad-hoc networks. In *Proceedings of the 9th annual international conference on Mobile computing and networking*, pages 122–133. ACM.

Suurballe, J. (1974). Disjoint paths in a network. *Networks*, 4(2):125–145.

Zhang, K., Han, Q., Yin, G., and Pan, H. (2016). Ofdp: a distributed algorithm for finding disjoint paths with minimum total length in wireless sensor networks. *Journal of Combinatorial Optimization*, 31(4):1623–1641.