Dual Radio Networks: Are two disjoint paths enough?

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***Abstract*—Newer applications for Wireless Sensor Networks, such as for video and audio applications, require higher data rates compared to traditional low data rate sensor network applications. Platforms with two radios were proposed to address these new classes of applications: each radio can send data on different routes to achieve high data rates and energy efficiency. In this work, we show that in heterogeneous dual radio networks the use of two disjoint paths is not enough to achieve maximal throughput. We present the novel disjoint paths with the same parity problem and how our system called Two Path Protocol (TPP) can improve throughput in dual radio networks. Our algorithm maintains energy efficiency and uses all the hardware resources available to improve end-to-end data delivery. We compare our design with FastForward, the state-of-the-art protocol for dual-radio in a real testbed. Experimental results confirm that our approach doubled the throughput getting very close to the maximum theoretical limit value.**

***Index Terms*—Dual Radio, Parity, Disjoint Paths, Wireless Networks.**

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are composed of sensor nodes that have one or more sensors, a microprocessor, and radio transceivers. Sensor nodes can act as both data generators and network relays. WSNs have many applications, such as environmental monitoring, agriculture, health care, and smart buildings. For traditional applications, three key issues have been taken into account in their design: cost, memory usage, and total power consumption.

The design of a WSN depends significantly on the application. The deployment environment, application design principles, hardware, and design constraints can be very different in each [14] scenario. For example, the deployment environment is important to determine the size, deployment schema, and even the network topology. Related to the hardware design of the sensor nodes, there are two key issues that must be taken into account: the cost and energy consumption.

Because WSNs generally consist of a large number of sensor nodes, minimizing the cost of each device is very important so that the total cost of the network is not very high. This restriction makes most of the WSN platforms design use very little processing power and memory. Because a sensor node is usually powered by batteries or batteries, the power consumption must be minimized to extend the network lifetime. To save energy, one should minimize the number of wireless transmissions, since the radio typically consumes more power than the rest of the hardware architecture components.

Minimizing power consumption at the expense of the network's performance is a well-known tradeoff in the design of WSNs. The design of traditional sensor network platforms has favored low power operation at the cost of communication throughput [4]. This makes sense in a context where most applications collect small pieces of data, such as temperature, humidity, or lighting measurements.

Nowadays, applications are also being developed to collect sound and video data, which has a demand for high throughput in the network. While low power consumption is still important in WSN design, throughput has gained importance in these new types of applications. New technologies of energy harvesting have allowed, the designers of the platforms to partly prioritize other factors besides energy consumption. A good option in this direction is to prioritize energy efficiency in transmission, which is the amount of energy used to transmit a certain amount of data. In this way, we can have higher throughput applications that can consume more energy in total, while conserving the energy efficiency of the system, since they can transmit a larger amount of data within a given energy budget.

To increase network throughput and to maintain energy efficiency, WSN platforms were developed with more than one radio. An example is the Opal Mote [4] sensor, shown in Figure 1. It features a Cortex-M3 SAM3U processor MCU from Atmel and two radios, an AT86FR212 that operates in the 900 MHz band with 10 channels, and an AT86RF231 radio that operates in the 2.4 GHz band and has 16 channels. As each radio operates on a different band, it can prevent the interference of one radio with the other. The use of multiple radios allowed simultaneous transmissions among the sensor nodes, which in addition to increasing the throughput in the network also can improve network stability, delivery rate, reduce the cost of transmission and improve power consumption per byte transmitted. Just to illustrate, Opal mote's radios consume 0.669 and 0.659 pJ/bit/m^2 while the TelosB CC2420 consumes 11.89 pJ/bit/m^2 [7]. The energy consumption gains of the platform have already been demonstrated with in-depth studies in [4]. Besides, Yin et al., [15] showed that the ISM band of 900 MHz provides better connectivity than the 2.4 GHz ISM band. Therefore, the use of two radios brings benefits to the quality and connectivity of the links.

Since the cost of transceivers is decreasing, and the demand for data is increasing, it is expected that dual radio networks will become more common in the next few years. Therefore, it

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is of utmost importance to understand and design mechanisms that fully utilize their resources.

Dual radio networks have been proposed as the solution for many applications, including when using multiple gateways, for reliable emergency signaling, for critical infrastructure, for improving performance in the industrial Internet of Things, for low data rate applications where more content can be transferred in a shorter amount of time resulting in significant overall energy savings, for high throughput application such as video and audio, etc.

To fully exploit heterogeneous dual-band radio networks and achieve their maximal performance, we propose Two Path Protocol (TPP) that finds two disjoint paths of the same parity size. This allows the usage of two radios from all nodes in the paths from the source to the destination, doubling the end-to-end throughput while maintaining energy efficiency.

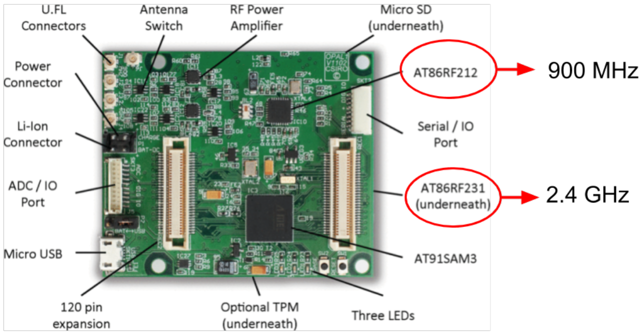


Figure 1: Opal Mote that operates with two heterogeneous radios in different bands.

The main contributions of this article are: (i) the description of the novel problem of finding two disjoint paths of the same parity size that can increase the throughput in dual radio networks that operate in dual-band with heterogeneous radios; (ii) topology results demonstrating the benefits of disjoint path routing with same parity size; (iii) experimental evaluation in a real testbed with more than 100 sensor nodes; (iv) and the results that show, compared to the state-of-the-art FastForward protocol for dual radio networks, we double the throughput. Moreover, we achieve 96% of the maximum theoretical limit.

The article is organized as follows: in Section II we present the related work. In Section III we define the problem. In Section IV, we display results in a real testbed. Finally, Section V presents the conclusion and future works.

II. RELATED WORK

Multiple path systems were studied in mesh networks [1], [9], [11], but they assume that radios are homogeneous, not heterogeneous as in this work, and they do not deal with the restriction of parity. They also do not use two different channel bandwidths. There are many research projects on networking with multiple radios. However, none of them consider the path lengths to have the same parity. The novelty in our work is the use of the same parity path sizes, enabling reception at the receiver at nearly the theoretically optimal rate. This enables the throughput to double compared to FastForward.

Traditional data collection protocols in WSNs do not support a high throughput since they were designed to minimize the energy consumption of the sensor nodes. In the traditional platform with a single radio, several specific protocols have been developed for mass transfer of data, for example, the Flush [6], FlushMF [13], and the PIP (Packets in Pipe) [10] protocols. These protocols establish a route of a single path between a source node and a destination node, disable the radio duty cycle and force optimal packet scheduling from end-to-end on that path.

Burst Forward [2] is a technique that combines high throughput and low power consumption. Sensor nodes, with the exception of the source and destination nodes, use radio duty cycling to keep the radio off and save energy. Burst Forward can achieve high throughput by grouping multiple packets into bursts, using a two-level retransmission scheme and storing data in flash memory. However, since all of these protocols were developed for single radio platforms, they suffer from the fundamental problem of having only one radio: it is not possible to transmit and receive packets at the same time. Thus, the total throughput in the network is limited to up to 50% capacity of the communication channel.

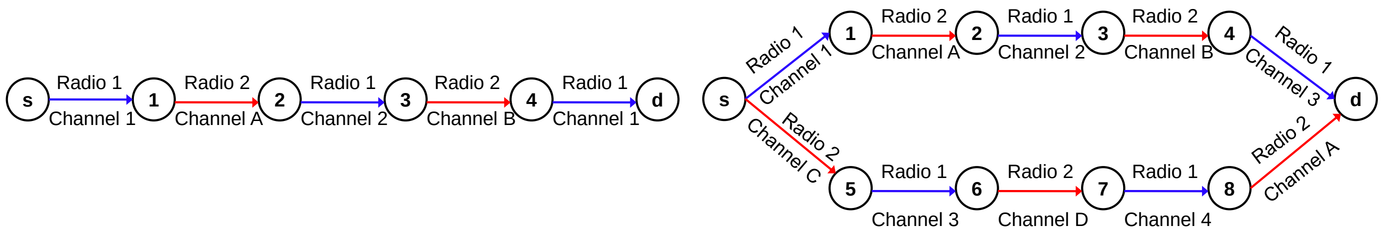
With the development of platforms with two radios, it becomes possible to send and receive packets at the same time. FastForward [3] was developed aiming to take advantage of this new possibility. It was the first bulky data transfer protocol designed for platforms with more than one radio. In FastForward, packets are transmitted from a source node to a destination node through a unique path between them. However, the use of radios over the hops of this path is alternated, with each intermediary node receiving packets over one radio and, simultaneously, transmitting packets on the other radio. Therefore, the theoretical limit for the throughput using this protocol becomes 100% of the capacity of the channel.

In FastForward, the use of two radios in different bands helps to solve the problem of packet interference. Also, it uses the technique used by previous protocols to switch channels between the radios of the same band, which helps even further to reduce the effect of interference between transmissions. Figure 2a shows the scheme of radio and channel allocation used on FastForward. In FastForward, two transmissions being made by the same radio and by the same channel will be at least three hops away from each other.

Note that in FastForward, the intermediate nodes use all the available radio resources because they are always receiving packets in one radio and transmitting in the other. However, the source and destination nodes only use half of the available radio resources. The source node only transmits in one radio, and the destination node receives only in one radio. To take advantage of the two radios also in these nodes, we present an approach in the next section that uses two paths for data transmission.

III. PROBLEM DEFINITION AND SOLUTION

In this section, we present a description of a new bulk multi-hop data transmission protocol for WSNs that uses platforms



(a) Radio and channel allocation scheme used in FastForward.

(b) Scheme of allocation of radios and channels used in the new design.

Figure 2: Two mechanisms for Dual Radio Networks.

with two heterogeneous radios and uses two paths in the network to transmit packets simultaneously. The protocol is designed to work together with other protocols of WSNs, which improve energy use. When an application needs to make a bulk transfer of data, it uses the protocol, which configures the paths to be used and causes these nodes to exit the energy saving mode and remain in the transmission mode until the transfer is completed at high throughput.

The basic principle of the proposed design is to use 100% of the radio resources of the sensor nodes chosen for data transmission. Since the source node has two radios available, and it is responsible for transmitting packets, then it must transmit the packets on the two radios simultaneously, so that the two radios are busy all the time while there are packets to be sent. At the destination node, the two radios must be simultaneously receiving packets. While in the intermediate nodes, one radio must be busy receiving packets while the other is forwarding packets. In addition to switching between radios in each hop, as in older protocols, channel switching is used for radios that transmit in the same frequency band. Four channels are assigned to each band. Figure 2b shows an example of the radios and channels allocation in the two paths used. Note that on all nodes, the two radios are used. In addition, the destination receives two packets at once, one in each radio.

Our protocol uses two paths to transmit data, but because each node has only two radios that can operate simultaneously, these paths must be chosen so that they obey two restrictions. First, they must be disjoint, except for the source node and the destination node. All other nodes must belong exclusively to one path or the other. If an intermediate node is chosen for both paths, it will not be able to simultaneously receive and transmit both flows passing through it, creating a bottleneck that undermines all the gain from our protocol.

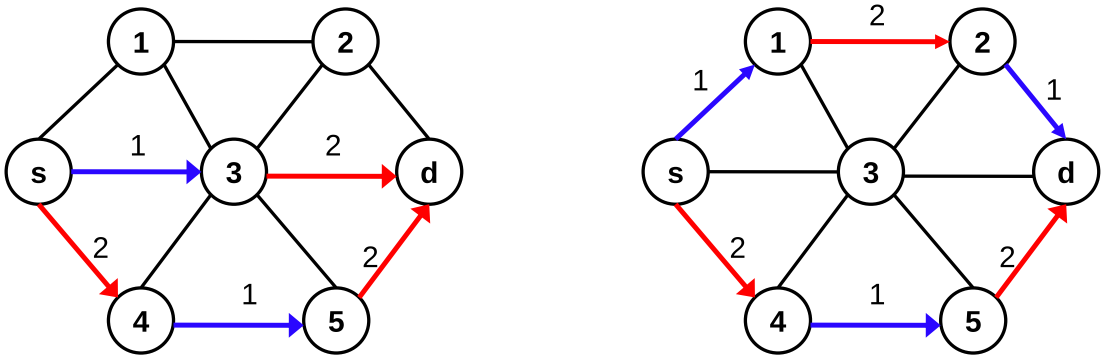
The second constraint is that the two paths must have the same parity in the number of hops. We need two paths with an even number of hops or two paths with an odd number of hops. This is to enable both the radios on the source and destination to operate simultaneously as the source node needs to transmit packets through different radios and the destination node must receive packets also by different radios. Figure 3a illustrates why this restriction exists. In it, we have a network with seven nodes, and we choose two pairs of different disjoint paths between the source node s and the destination d. The paths chosen in (a) have different parity. As the source node needs to send through different radios and intermediate nodes need to toggle the radio on which they send, the destination ends up receiving packets from both paths for the same radio, which will result in collision. The paths chosen in (b) have the same parity. This is why the destination ends up receiving a packet for the two different radios, which can occur at the same time.

Given a graph $G = (V, E)$, the disjoint parity paths problem is to find two simple paths P_1 and P_2, starting at the same source node s and ending in the same destination node t, with all intermediate nodes disjoint, with both paths having the same number of hops parity, i.e., $|P_1| \mod 2 = |P_2| \mod 2$.

A routing algorithm will usually try to find the shortest path between a source and a destination. In our case, the problem is to find the two disjoint paths with the same origin and destination with the lowest cost. If there was no restriction that the paths must have the same parity, this would be a well-known problem in graph theory, that would be easily solved using the algorithm of Suurballe [12]. However, such an algorithm could generate a solution such as the one in Figure 3a, which can not be used with our scenario.

In the source node, the packets to be sent are placed in a queue. Each packet is marked with a sequence number to enable them to be identified and ensure the correct reception at the destination node. Firstly, two packets are removed from the queue, one is sent by one radio and the other sent by the other. The source node queries its routing table to find the next hop of these messages. Even though it is for the same destination, these queries return two different addresses (one for each radio) since each message will be routed through disjoint paths. As soon as one of the radios ends the transmission and the transmission has occurred successfully, another packet is removed from the queue and transmitted over the radio that completed the transmission. The procedure repeats itself until all packets have been transmitted.

In each of the intermediate nodes in the two paths, upon receiving a packet by one of the radios, each intermediate node queries its routing table to determine the address of the next hop, to which it must forward this message. In the intermediate nodes, the routing contains only one forwarding address for each destination, since each intermediate node can be part of only one of the paths between the source node and the destination node. The message is placed in a queue and, whenever the radio transmitter is ready to transmit the next packet, a message is taken out of the queue and sent by that radio. Again, as the time of receiving and sending packets is greater than the processing time, the two radios spend



(a) Example of disjoint paths with different parity in a network. (b) Example of disjoint paths with same parity in a network.

Figure 3: Two disjoint paths: without and with the same parity size. The color and number indicate the radio number.

the majority of the time receiving and transmitting packets simultaneously.

In the destination node, the two radios are used to receive packets. The packets sent on the first path will be received by the first radio and the packets sent on the second path will be received by the second radio. The packets may arrive in a different order from which they were sent, for several reasons: one path may be longer than the other, or one path may have fewer losses than the other. Each packet, being received by the destination node is signaled to the application, along with its sequence number, but on a first-come, first-served basis. It is up to the application to merge the received packets back into the correct sequence, according to its need.

Our design attempts to deliver the largest number of packets with a better effort policy. It trusts packets provided by the link layer and retransmits packets which have not received acknowledgment. If a packet still can not be retransmitted, it is lost, and the application is responsible for retransmitting or not, according to its need. It is also possible to configure the protocol to disable the sending and receiving of acknowledgment packets from the link layer, to enable an even higher throughput at the cost of lower reliability.

For our approach to work successfully, it is not enough to use any two disjoint paths between the source node and the destination node. The need to alternate radios imposes restrictions that need to be considered for everything to work. That's why the problem of finding paths on a network that are compatible with the design needs to consider the same length parity.

Wireless transmission conflict is another challenge. One transmission can interfere with nearby simultaneous transmissions. We do consider the transmission conflict. We solved it by assigning different channels for each conflicting link. Observe in Figure 2b the channel allocation. No nearby link uses the same channel. Our results were performed in the real world, which inherently suffers interference.

It is interesting to observe that even in the case of a long path, the throughput increases because the communication capacity improves since there are two parallel flows.

One should note that the disparity between the two paths can not be easily overcome, say by having a buffer of a single packet. A buffer could be used to introduce a self-loop edge at each node. However, buffering will not solve the problem. It will just multiplex over time. If there is no parity, the radio that receives the packet has to be the same as the one that transmits to the other hop, but the radio is already being used by the previous hop on the next timeslot. Therefore, the parity constraint is necessary to maximize throughput, energy efficiency, and resource utilization.

IV. RESULTS

Figure 3b shows the solution for the network topology of Figure 3a. There are two disjoint paths with the same parity size in the network. Each link uses a different channel than its neighbors, decreasing interference. Every node uses both of its radios, including the source and the destination.

We implemented Two Path Protocol (TPP) using TinyOS 2.1.2 for the Opal platform [5]. This platform has two 802.15.4 radio transceivers operating in different bands: 900 MHz and 2.4 GHz. The two radios share the same SPI bus, which creates a bottleneck for data transfer between the radios and the microcontroller. However, data transfer on the bus is much faster than data transmission over the radio. On the Opal platform, sending an SPI packet to the transmission buffer takes less than 10 % of the time it takes to transmit the packet over the radio [3]. As the design seeks to keep the radios always busy, the two radios will be operating most of the time simultaneously.

We conducted experiments on a real-world large-scale wireless sensor network testbed Twonet [8] that contains 100 Opal sensor nodes which have two radios each. The experiments evaluated the throughput achieved during the data transfer from the source node to the destination. We compare our results with the FastForward results.

The experiments were performed to evaluate the throughput and packet reception rate achieved by TPP. Several rounds of experiments were performed, and each round consisted of the following steps: topology collection, determination of origin and destination nodes, determination of routes, and measurements. The source node and the destination node of each experiment were chosen according to the distance between them. We define the distance from the source node to the destination as the average number of hops of the two paths .

The two radios were configured to transmit using the O-QPSK modulation at 250 kbps and with a transmission power of 3 dBm. In the first experiments, we enabled the MAC layer functionality to verify channel occupation and perform random backoffs. These functions were then disabled to compare the results with FastForward results. We also performed the experiments with and without acknowledgement packets to analyze the compromise between throughput and packet reception rate in both cases.

In each experiment, 1000 packets are sent from the source node. Each packet has a payload of 100 bytes, but the number of bytes actually transmitted by the radio for each packet was 127, because of the additional cost of multiple packet headers, which includes the protocol header and link-layer headers. We use throughput and the packet reception rate metrics to understand the results. We define 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 packet reception rate 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.

We show figures that show the performance ofTPP and comparison to the performance of the FastForward implementation. Figure 4 shows the result from the experiments that were done with the channel occupancy check (CCA) enabled. The figure on the left shows the throughput and the figure on the right shows the packet reception rate. We can observe that the TPP achieved higher throughput than FastForward while matching the packet reception rates. On average, the two-way protocol achieved a 60% improvement in throughput in this scenario. The packet reception rate of the new design was similar to FastForward, achieving a 100% packet reception rate in some cases due to the use of acknowledgment packets and retransmissions.

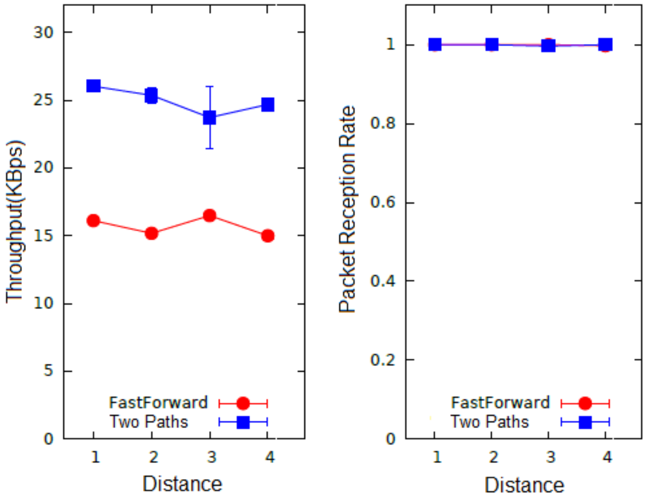


Figure 4: Performance with CCA enabled and with message acknowledgment.

Figure 5 shows the performance of the mechanisms when we disable the CCA in the MAC layer of the radios. In practice, it is not recommended to disable this function because the communication medium may be used by several different networks and one can interfere with the other. The test was performed to evaluate the maximum transmission potential of the protocols. Acknowledgment packets are also used in this scenario. We can observe that in the first cases, a 50 kBps throughput was obtained with our new approach, while the FastForward reaches a maximum of 25 kBps, resulting in a 100% improvement, exactly the maximum limit that could be achieved. Thus TPP achieves higher throughput than FastForward. The packet reception rate of TPP was also always greater than or equal to FastForward, achieving a 100% packet reception rate due to the use of acknowledgment packets and retransmissions.

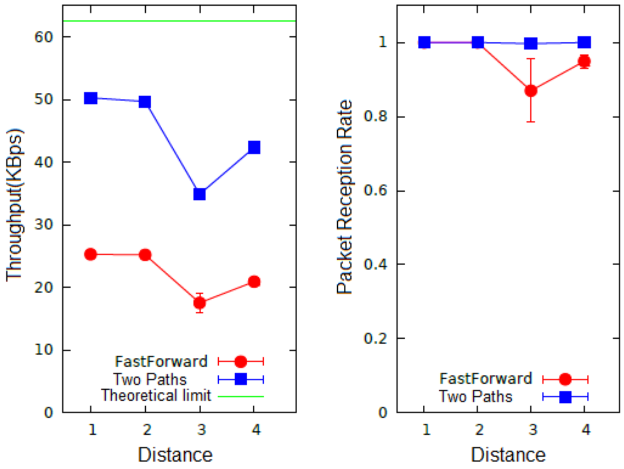


Figure 5: Performance with disabled CCA and with acknowledgment message.

Figure 6 represents a scenario where both the clear channel assessment(CCA) and the acknowledgment messages were disabled. In this scenario, we obtained the maximum throughput of 60 kBps in where the distance was less than or equal to 4 hops. This value is close to the maximum theoretical throughput limit when using two radios. The maximum transmission rate, considering an ideal case, using only one radio is 250 kbps or 31.25 kBps. Then the theoretical limit for two radios is doubled, or 62.5 kBps. Therefore, the achieved rate is 96% of the theoretical maximum throughput and in a real-world testbed. In addition, this value is double the value obtained with the FastForward, indicating the maximum use of the two radios in all the hops of the path. Again, TPP, within the experimental error, always achieved equal or greater packet reception rate compared to FastForward.

A final issue to study is the energy cost of communication. With a larger throughput, the total spent energy is expected to be higher. However, the energy spent per transmitted byte becomes smaller. According to [5], the Opal draws an average of 49 mA of current if the two radios are operating simultaneously. As TPP reached a throughput of 60 kBps, we have spent 2.7 mJ/kB of energy. While with the maximum throughput reached by FastForward, 30 kBps, we would have spent 5.4 mJ/kB of energy. Therefore, overall, compared to FastForward, TPP consumes half of the energy per byte transmitted on

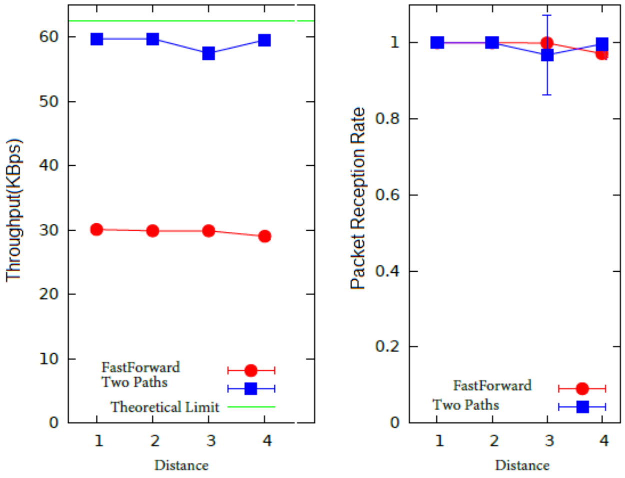


Figure 6: Performance with CCA disable and no acknowledgment message.

each node in the network in the average case, however, the number of relay nodes required for this new design is doubled. But since the source and destination nodes are always the same, our design will have better total energy efficiency than FastForward. Therefore, TPP is a suitable protocol to use in the emerging sensor network applications that require high throughput and energy efficiency.

V. CONCLUSION

We presented Two Path Protocol (TPP) a novel solution to double the throughput in wireless networks. This is achieved by using two radios and routing via two disjoint paths with the same parity length. Interference is avoided by using different channel assignments for each conflict link. Furthermore, the techniques we described here can work in conjunction with other techniques that can be used for avoiding or managing interference thus making it useful in environments with heavy interference that require multi-pronged solutions. We showed that, in dual radio networks with heterogeneous radios, two disjoint paths are not enough to improve data delivery, the path length parity must also be considered.

Generally using nodes with multiple radios, coupled with software that can use the multiple radios simultaneously, can increase the network datarate in many data intensive WSN applications. As a case study, this work demonstrated the challenge of using two radios simultaneously. If not done carefully, the performance can potentially be worse than using a single radio. This work then shows a solution the engineers can use to effectively utilize the dual-radio platforms to obtain almost the optimal data rates. Specifically, we presented here a novel solution to double the throughput in wireless networks. This is achieved by using two radios and routing via two disjoint paths with the same parity length.

Experiments performed in a real environment in the physical world show that the throughput reaches a rate of up to 60 kBps, which represents 96% of the maximum theoretical limit of 62.5 kBps, when we used two radios 802.15.4 using O-QPSK modulation at 250 kbps in parallel, without clear channel assessment. The packet reception rate was also always greater than or equal to FastForward, achieving a 100% packet reception rate in most cases.

As future work, we plan to develop a decentralized routing scheme for two paths. The problem of finding two disjoint paths with the same parity can also be investigated from a theory perspective, probably necessitating good heuristics or approximate solutions. Also, future work includes algorithms for enabling multiple source nodes to send data to their respective destinations at the same time. We plan to integrate it to a bulk data collect protocol ([6], [13], [10]) and to include mechanisms that minimize co-channel interference between paths.

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