A Simulation-Based Performance Analysis of Various Multipath Routing Techniques in ZigBee Sensor Networks

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Abstract. Multipath routing is generally known for its highly effective performance in applications involving data streaming. However, to date, only a handful of research studies have looked at the performance of multipath routing in WSN systems. Moreover, according to our knowledge, there has been no earlier study on the use of multipath routing in ZigBee WSNs.

In this paper, three multipath routing techniques (Multipath AODV, Multipath DSR, and Multipath ZDR) are compared to ZigBee's standard AODV single path routing protocol. Simulations are conducted in WSNs of different sizes using the IEEE 802.15.4 / ZigBee stack provided in OPNET, and statistics such as end-to-end delay, packet delivery ratio, and battery consumption are collected. The obtained results indicate that Multipath ZDR achieves the largest packet delivery ratio while also providing the shortest end-to-end delay, but at the cost of greater energy consumption. The standard ZigBee AODV shows inferior performance with respect to most metrics when under a stressed network load; however, being a single-path routing protocol, it naturally consumes less energy than other examined protocols. Multipath AODV and DSR perform considerably poorer than Multipath ZDR with regard to all considered metrics as a result of increased inter-path and intra-path interference.

Keywords: Wireless sensor networks, ZigBee, multipath routing, OPNET simulations.

1 Introduction

Wireless Sensor Networks (WSNs) are best described as ad-hoc, multi-hop networks comprised of small, simple and inexpensive wireless devices – the so-called sensor nodes. The nodes are responsible for sensing an environment and reporting their results to a central processing unit commonly referred to as sink. Due to their small size, sensor nodes are constrained in processing speed, memory, and most importantly, energy. Consequently, the optimization of a WSN's performance in the three given categories is critical for their effective utilization in the real world. Originally developed for military purposes, WSNs have moved into the commercial

J. Zheng et al. (Eds.): ADHOCNETS 2009, LNICST 28, pp. 300–315, 2010.

mainstream through applications such as parking space monitoring, fire protection, and home automation.

One specific area of research in the field of WSNs is *effective data routing* – that is, the end-to-end transfer of data packets, from a source to a destination, along the most appropriate path comprised of multi-hop links. The majority of WSN routing protocols focus on creating a single path between two nodes which wish to communicate with each other, following some well-known paradigms common to wired networks. It is often forgotten, however, that wireless networks (including WSNs) operate in a unique medium – the air – and as a result are subject to different network characteristics, one of which is *connection redundancy*. Namely, a node wishing to communicate in a wireless network must broadcast its signal over an open medium where all surrounding nodes within the transmission range can hear this broadcast. From the physical-layer perspective, this is equivalent to simultaneous transmission of data over multiple one-hop wired connections. This further implies that in wireless networks, multiple multi-hop paths between two nodes can easily be formed and exploited, at no extra costs in terms of overhead traffic or network infrastructure.

Although not much studied in the framework of WSNs, *multipath routing* represents an important concept in the general networking theory. Up to date, the performance and benefits of multipath routing have been the subject of numerous research investigations. Specifically, multipath routing has been shown to improve throughput [HYPERLINK \l "Jen" 1], reduce end-to-end delay 2], increase fault tolerance [HYPERLINK \l "Sun" 3], and ensure security 4], while also mitigating network-wide congestion [HYPERLINK \l "Jen" 1], in a wide range of network scenarios. From the practical point of view, multipath routing is shown to be especially effective in applications involving real-time streaming of data 5].

The IEEE 802.15.4 / ZigBee suite of standards [HYPERLINK \l "Zig09" 6] is recognized as the technology of choice for applications involving WSNs. To our knowledge, there has been no earlier study on the use of multipath routing in WSNs involving ZigBee technology. The goal of our work is to contribute to this largely overlooked research field. Specifically, we are interested in examining the performance of various multipath routing protocols in the context of the ZigBee standard.

The remainder of this paper is organized as follows: Section 2 provides an overview and discussion of several existing multipath routing protocols. The key characteristics of the ZigBee standard are outlined in Section 3. In Section 4, our OPNET-based simulation framework as well as our main simulation results are presented. Section 5 concludes the paper with a summary of the findings and an outline of possible directions for future work.

2 Multipath Routing

In this section, we provide a brief overview of the earlier contributions on the subject of multipath routing in wireless networks. When considering multipath routing in the wireless domain, three key components come into play: 1) the type of multi-path formation strategy, 2) the type of multi-path usage strategy (i.e. strategy for sending of user data along the formed paths), and 3) the overall benefits gained by a multipath routing strategy. In the proceeding sections each of these concepts is explained in more detail.

2.1 Multipath Formation Strategies

In wireless networks, a number of possible criteria can be employed when forming (i.e. selecting) multiple routing paths between two communicating nodes. Following is a listing of the best known multipath formation strategies 4]. The main idea behind each of the enlisted strategies is illustrated in Figure 1.

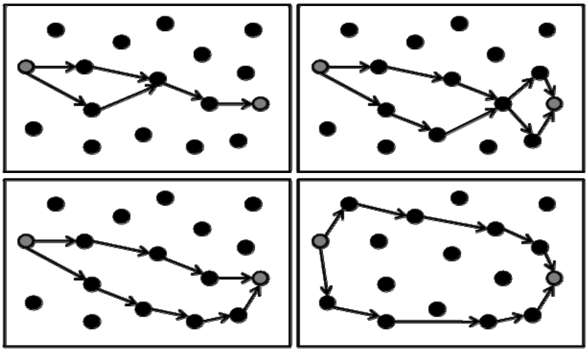


Fig. 1. Various path formation strategies. Top-left: partially-disjoint paths. Top-right: edge-disjoint paths. Bottom-left: node-disjoint paths. Bottom-right: zone-disjoint paths.

- *Partially-disjoint Paths Strategy* allows each of the chosen paths to share one or more nodes with any of the other paths.
- *Edge-disjoint Paths Strategy* precludes each chosen path from sharing any edges with any of the other paths.
- *Node-disjoint Paths Strategy* precludes any two chosen paths from sharing one or more nodes with each other.
- *Zone-disjoint Paths Strategy* requires that each chosen path be unique (the path must not share nodes or edges with other paths) and also must not be within the interference range of other chosen paths, as much as physically possible.

2.2 Multipath Usage Strategies

In a network where multiple routing paths are established between two communicating nodes, there are two possible ways of sending data along the established paths:

- *Consecutive Data Transmission*: With this type of transmission, data is initially sent along a *primary* path, and only in the case that the primary path fails, alternate paths are used.
- *Concurrent Data Transmission*: Under this type of transmission, data is divided and sent along each of the multiple paths at the same time.

2.3 Benefits of Multipath Routing

Some of the commonly recognized benefits of multipath routing include: increased reliability and security, better load and energy balancing, and improved performance with respect to end-to-end delay and throughput. Below, we discuss the enlisted benefits in more details, and give examples of multipath routing protocols that maximize each particular benefit.

In the context of wireless networking, *reliability* is typically defined as the probability that a data packet sent by a node eventually arrives at its intended destination. Several studies have shown that multipath routing protocols, both consecutive and concurrent, are rather effective in increasing the reliability of the underlying wireless network. For example, the consecutive multipath routing protocol AODV-BR [HYPERLINK \l "Lee00" 7] finds multiple paths from a source to a destination and stores them in the nodes' routing tables for later use. As soon as a routing failure on the primary path is detected, the transmission of data is shifted to one of the alternative, previously recorded, paths. SPREAD 4] is an example of an N-path concurrent routing protocol. This protocol takes a piece of information and divides it into *N* data segments – one for each path – using a secret sharing scheme. The protocol guarantees that as long as *T* of the *N* segments are received, the original piece of information can be reconstructed. By introducing path and information redundancy, the protocol is shown to increase the overall reliability of the underlying wireless system. Another benefit of the SPREAD protocol is increased security of data. Namely, in a system that deploys SPREAD, an adversary should be able to identify and eavesdrop on each of the *N* paths and obtain at least *T* data segments in order to reconstruct the original data. This is a very difficult objective, especially in large-scale WSNs.

The benefits of multipath routing in terms of *load balancing* are pretty intuitive: by distributing the traffic over a larger number of paths, multipath routing is likely to achieve a better distribution of energy load across the network compared to single-path routing, ultimately resulting in a longer lifetime of individual network nodes as well as of the entire network. EBMR [HYPERLINK \l "Yun" 8] is an example of a multipath protocol that attempts to maximize the above outlined benefit by creating an energy-weighted, directed sub-graph from the network topology. Subsequently, using a breadth first search algorithm, EBMR finds multiple paths that satisfy the energy requirements for maximizing network lifetime.

With the recent advances in the technology, WSNs comprised of camera- and microphone- equipped sensors are becoming more prevalent. In such networks, the quality of provided service (e.g. low end-to-end delay and high throughput) is often an issue. In the literature on wired networks, there is plenty of evidence proving that multipath routing can achieve substantial improvements in various aspects of QoS performance (see 9] and [HYPERLINK \l "Mur96" 10]). However, only a handful of studies have looked at the QoS related benefits of multipath routing in the wireless domain – one example of such a study is 11]. In this paper, we are set to examine the performance of multipath routing in the context of one particular type of wireless networks – ZigBee-based WSNs. According to our knowledge, our study is the first of its kind to be published in the literature.

2.4 The Challenges of Multipath Routing in the Wireless Domain

Adapting the paradigm of multipath routing into the wireless world is shown to face a few challenges, the most serious ones being caused by the broadcast nature of the underlying communication medium. Namely, concurrent transmission of data through multiple paths in a wireless network creates the problems of intra-path and inter-path interference, both illustrated in Figure 2.

- *Intra-path interference* is the radio interference among the nodes that belong to one particular, i.e. the same, routing path. Neighbouring nodes on that path are naturally in the communication range of each other, and as such are likely to interfere with each other's transmission. Intra-path interference is particularly severe in cases when the radio ranges of nodes two or more hops away overlap.
- *Inter-path interference* is the radio interference between nodes belonging to different routing paths. This type of interference occurs when two or more paths happen to be in relative proximity of one another, causing the radio ranges of (some of) their nodes to overlap. Hence, when one of such nodes is active and transmitting, the respective nodes on other path(s) must back-off in order to minimize the probability of packet collision.

Both of the above mentioned interference types are shown to result in severe degradation of network performance. Hence, one can expect to see significant QoS-related improvement from the use of multipath routing in the wireless domain only if sufficient care is taken to mitigate the effects of intra-path and inter-path interference.

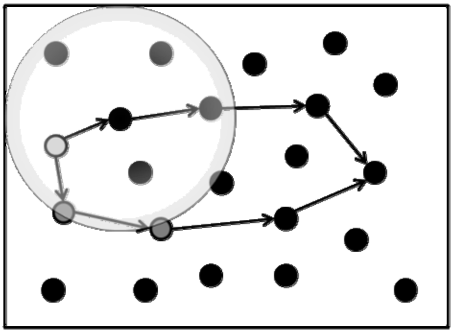


Fig. 2. Nodes affected by intra-path (light gray) and inter-path (dark gray) interference

3 ZigBee Wireless Sensor Networks

ZigBee [HYPERLINK \l "Zig09" 6], generally classified as a low-rate wireless personal area network (LR-WPAN) technology, is one of the most promising and prevalent WSN standards in use today. Built on top of the IEEE 802.15.4 standard, it is designed with low-cost, low-power, low-complexity, flexible routing and network scalability in mind. Popular applications of ZigBee technology in the real world include: advanced metering infrastructure, home/building automation and security, medical monitoring. The following section will provide a brief outline of the ZigBee standard.

3.1 ZigBee Network Topology

The ZigBee standard defines three different types of devices: *end-devices*, characterized as reduced functional devices (RFDs), and *routers* and *coordinators*, characterized as fully functional devices (FFDs).

- *End-devices* are the simplest component of the network and they are only responsible for sensing the environment, packaging the data, and transmitting it to their FFD parent.
- A *router* is responsible for receiving data from its children, or generating its own data, and routing it to its final destination using one of two available routing algorithms. Routers also must maintain parent/child relationships, as well as generate and transport the necessary control messages needed to support network operation and maintenance.
- Finally, the *coordinator* shares the same functionality as a router and is also responsible for initiating the network formation and/or recovery.

The ZigBee standard allows the formation of three types of topologies: star, tree, and mesh.

- The *star topology* is the simplest of the three topologies, consisting of only a single coordinator with a number of end-devices as its children.
- In the case of a *tree topology*, the devices organize themselves into a tree-like structure with the coordinator representing the root of the tree, routers representing the roots of sub-trees, and end-devices representing leaves.
- In a network of *mesh topology* routers and coordinators form multiple links among each other while having end-devices as their children, as illustrated in Figure 3. Link/path redundancy is one of the key characteristics of the mesh topology, and it aims to improve network robustness and the network routing function.

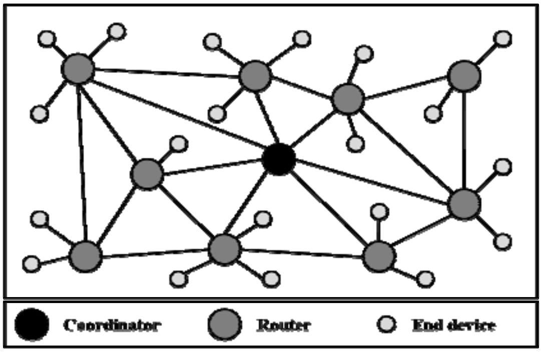


Fig. 3. A ZigBee wireless sensor network operating in mesh mode

3.2 The ZigBee Stack

The ZigBee communication stack is comprised of 4 main layers: the physical (PHY), medium access control (MAC), network (NWK) and application (APL). The bottom two layers (PHY and MAC) are defined in the IEEE 802.15.4 standard while the upper two (NWK and APL) are defined in the ZigBee standard.

The PHY layer supports the 2.45 GHz, 915 MHz, and 868 MHz bands for communications. The 2.45 GHz band has a total of 16 channels, achieving a raw data rate of 250 Kbps, while the 915 MHz band has 10 channels with a raw data rate of 40 Kbps. The 868 MHz band has only one channel and a raw data rate of 20 Kbps.

The MAC layer is responsible for regulating one-hop communication between nodes that happen to be within each other's radio range. This includes: mechanisms aimed to ensure link reliability, CSMA-CA for collision avoidance, and acknowledging of successfully received packets. Device association and disassociation between a child and a parent is also managed at the MAC layer.

The NWK layer is primarily concerned with network discovery and formation, as well as end-to-end packet delivery (i.e. packet routing). As indicated earlier, there are two different types of routing strategies in ZigBee-based networks: tree-routing or mesh-routing. In the case of tree-routing, packets are routed up and then down the underlying network tree based on the locations of the source and its respective destination. Tree routing is known to induce minimum overhead, as ZigBee deploys a deterministic tree-based address assignment scheme and nodes can easily determine if a packet needs to be sent up or down the tree. In the case of mesh-routing, packets are routed using a simplified version of the well-known ad-hoc routing protocol AODV [12]. Mesh-routing is generally more demanding in terms of network overhead and yet more effective in terms of its performance (e.g. packet delay) than tree routing.

Finally, the APL layer resides at the top of the stack. Its main responsibility includes providing end-points of communication for application objects. Application objects are manufacturer implementations of a real world ZigBee network application and are usually defined by a profile which allows for interoperability between various vendors' devices.

4 Simulations

The main goal of our work is to examine the performance of three multipath routing algorithms (Multipath AODV, Multipath DSR, and Multipath ZDR) in ZigBee WSNs and compare them to the performance of the single-path AODV mesh routing

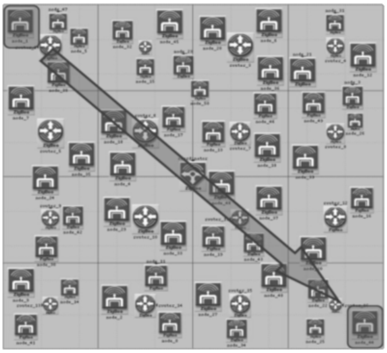


Fig. 4. A ZigBee wireless sensor network configuration in OPNET Modeler

protocol defined in the standard. To accomplish this task, simulations are conducted using *OPNET Modeler* [13]. Figure 4 shows an example of a network setup as used in our study. In each simulated network, one single active (i.e. source) node situated in the top-left corner is considered. The respective destination node is assumed to be located in the bottom-right corner. Data flows diagonally through the network. In Sections 4.1 to 4.3, we provide further comments on each of the implemented algorithms, the network parameters employed in the simulations, and the performance metrics used in the study.

4.1 Implemented Multipath Algorithms

In this section, we provide a brief description of the three prominent multipath algorithms used in our study. Since these algorithms are not implemented as part of the ZigBee standard, we also summarize some of the key issues arising from their implementations.

The first multipath algorithm selected for implementation is Split Multipath Routing (SMR) [3]. SMR is an on-demand multipath routing protocol that is essentially a multiple path extension of the popular DSR protocol. By using two primary paths and storing multiple other discovered paths for later use, SMR is able to recover quickly from broken routes and minimize control message overhead. Similar to DSR, SMR uses source routing and stores its discovered routes as full paths at the source node. Consequently, the source node injects these (full) paths into the respective packet headers. As a result, an intermediate router with a packet to forward must only extract the next hop from the list found in the packet's header. Although this mechanism is simple to implement, it suffers from an increase in transmission overhead since each packet must store the entire path. In addition to this, the protocol also requires increased storage requirements at the source node in order to store multiple full-path lists. The multiple paths discovered by SMR are not guaranteed to be node-disjoint; though, our implementation ensures that the SMR paths actually deployed in simulations are in fact node-disjoint.

The second multipath algorithm used in our study is a multiple path extension of the popular AODV protocol - AOMDV [14]. This protocol finds multiple edge- or node- disjoint paths and uses them consecutively to increase packet delivery while reducing end-to-end delay and traffic overhead. We chose to study this algorithm due to its close ties to ZigBee standard which deploys a watered-down version of the standard AODV protocol. Also, when compared to a multipath DSR, a multipath AODV protocol is likely to benefit from the use of distance vector routing which only requires a router to store the next hop node towards destination, ultimately resulting in less transmission overhead and storage requirements.

The final multipath algorithm included in our study is based on the principal of zone-disjointedness. Interference Minimized Multipath Routing (I2MR) [1] attempts to create maximally zone-disjoint paths that minimize both intra- and inter-path interference in an attempt to increase the overall throughput. The performance of this protocol is interesting to examine in the context of ZigBee-based WSNs because: 1) the single channel nature of the standard, and 2) the fact that the interference range of a wireless sensor is typically up to twice its communication range. With I2MR, 3 zone-disjoint paths are used concurrently to send data from a source to a destination. In our implementation, only 2 concurrent paths are used to provide consistency with the other analyzed protocols. In the remainder of this paper, we refer to 'our' version of I2MR as Multipath Zone Disjoint Routing (Multipath ZDR).

Since none of the three selected multipath routing algorithms were originally designed for the ZigBee stack, some modifications had to be made to the OPNET's ZigBee Modeler to have these protocols successfully ported. As mentioned in Section 3.2, the NWK layer is responsible for forming the network and routing data across multiple hops. Thus, the majority of introduced modifications were made at this (NWK) layer. Also, the modifications were implemented (only) on routers and coordinators, as these are the only routing-capable nodes in the standard.

4.2 Parameters

In our study, square-shaped WSNs of three different sizes are considered: 500x500 [m^2], 750x750 [m^2], and 1000x1000 [m^2]. Table 1 outlines the exact configuration of each of the three networks. In all WSNs, the coordinator is placed in the middle of the respective square-shaped area, with routers evenly spaced every 250 meters apart from each other in a grid fashion (see Figure 4). End-devices are randomly placed throughout the network field. All nodes are assumed to be stationary.

Table 1. The three types of networks simulated

Properties	**Network Types**		
Network Size	**Small**	**Medium**	**Large**
Dimensions	500 x 500 m	750 x 750 m	1000 x 1000 m
Area	250,000 m^2	562,000 m^2	1,000,000 m^2
Sensors	17	36	67
Coordinators	1	1	1
Routers	4	8	16
End Devices	12	27	50
Node Mobility	None	None	None
Node Density	~6.8 x 10^{-5} nodes/m^2	~6.75 x 10^{-5} nodes/m^2	~6.7 x 10^{-5} nodes/m^2

Under each of the four studied protocols, five different data rates are simulated: 10, 15, 20, 25, and 30 [packets per second], with each packet comprising 1024 bits of data. For multipath protocols, the number of discovered routes is limited to two. Data is sent concurrently along these paths. Routers and coordinators are configured with a 5 mW transmission power while end devices transmit at 1 mW. In each particular configuration (one particular network size with one particular routing algorithm and under one particular packet rate), results are averaged over 10 randomly seeded runs. The duration of each simulation run is set to 1200 seconds. A summary of the mentioned simulation parameters is provided in Table 2.

Table 2. The parameters set for simulation

Parameter	Value
Duration	1200 seconds or 20 minutes
Packet Rates	10, 15, 20, 25, 30 packets per second
Routing Protocols	ZigBee AODV, Multipath AODV, Multipath DSR, Multipath ZDR
Packet Size	1024 bits
Max Number of Paths	Maximum of 2 paths found and used
Node Type	MICAz Mote from Crossbow Technology
Number of Seeds	10 seeds per configuration
Transmission Power	5 mW for Routers and Coordinators 1 mW for End Devices
Transmission Range (LOS)	~250 m for Routers and Coordinators ~150 m for End Devices
Battery Power	Two 1.5 V 'AA' batteries – 2300 mAh
Simulations	200 per network type – a total of 600

4.3 Metrics

The metrics used in our study include:

- *Packet Delivery Ratio* is defined as the ratio between the number of packets sent by the source node versus the number of packets received by the final destination. Packet delivery ratio is generally used as a measure of network reliability as well as an indicator of severe traffic congestion in the network.
- *End-to-end Delay* is defined as the time taken to *successfully* send a packet from the source to the destination. In contrast to packet delivery ratio, this metric serves as a fine-scale indicator of a varying degree of traffic congestion in the network.
- *Global Battery Consumption* is defined as the total amount of energy consumed *globally* in the network, by all of its comprising elements. Energy consumption is an especially important performance metric in the analysis of WSNs given the battery-powered nature of their nodes.
- *Average Battery Consumption per Node* is defined as the average amount of energy consumed per each individual node involved in forwarding of data. This metric is useful for exemplifying how well a routing protocol distributes energy requirements throughout the network.

4.4 Results

In this section, the results and key observations of our OPNET-based simulation study are presented.

One of the key observations arising from our study is that ZigBee AODV generally finds the (single) shortest hop-distance path between the source and the destination, while Multipath AODV and DSR add a second path – usually only one hop longer than the shortest path. Multipath ZDR attempts to find two maximally disjoint paths separated as often as possible, by at least two hops. Figure 5 illustrates the types of paths chosen by each of the studied algorithms.

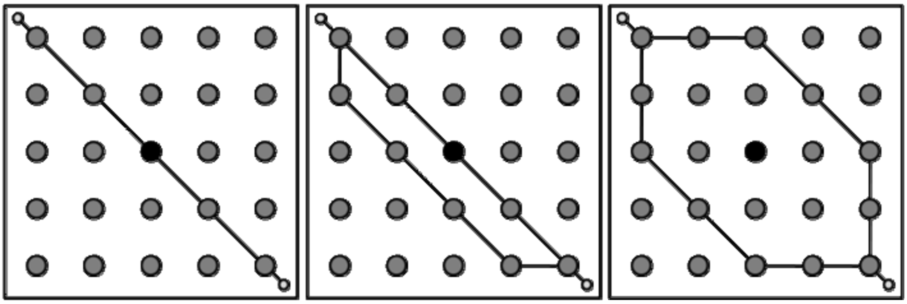


Fig. 5. The paths formed by ZigBee AODV, Multipath AODV/DSR, and Multipath ZDR respectively

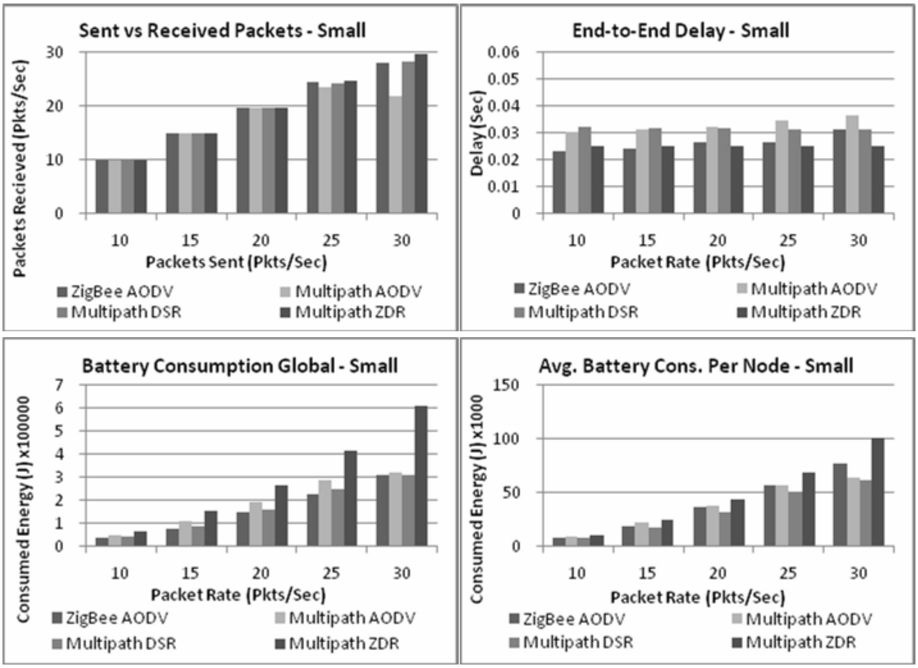
4.4.1 Small ZigBee Network

The performances of the four studied protocols in the network of small size – covering 500x500 [m^2] and comprising 17 nodes – are depicted in Figures 6 to 9.

Specifically, the packet delivery ratio obtained with each of the four protocols, and under five different packet rates, is shown in Figure 6. According to this figure, when the inter-arrival rate is in the range of 10 to 25 pkts/sec all protocols are able to handle the traffic quite well, delivering almost all of the packets to the final destination. However, once the inter-arrival rate reaches 30 pkts/sec, only Multipath ZDR succeeds in delivering all the packets, while Multipath AODV delivers only 75% of the packets. The superior performance of Multipath ZDR can be explained by the fact that: 1) this protocol exploits two concurrent paths while ZigBee AODV exploits only one, and 2) the two paths of Multipath ZDR are far less correlated in terms of inter-path interference than the paths of Multipath AODV and Multipath DSR.

With respect to end-to-end packet delay (Figure 7), Multipath AODV and DSR show persistently inferior performance compared to the other two protocols. As in the case of packet loss, this can be explained by the fact that Multipath AODV and DSR chose paths with large inter-path interference. It is interesting to note that Multipath ZDR employs longer (multi)paths compared to those of Multipath AODV and DSR, but still manages to produce a shorter end-to-end delay. Such results, once again, underline the potential severity of path interference, as also observed in [5].

Figure 8 displays the global battery consumption of each studied protocol under different packet rates. Here, in contrast to what was observed in Figures 6 and 7, Multipath ZDR emerges as the worst performing protocol, while the performances of the other protocols appear relatively close to each other. The inferiority of Multipath ZDR, from the perspective of overall energy consumption, can be explained by the following: in an attempt to minimize the inter-path interference, Multipath ZDR tends to deploy paths that are further away from each other and, thus, generally longer than the paths of the other three protocols (see Figure 5). By engaging longer paths and, consequently, a larger number of nodes, Multipath ZDR naturally ends up consuming more of the network's energy relative to the other protocols.



Figs. 6, 7, 8, 9. Sent vs. received packets, end-to-end delay, global battery consumption, and average per node battery consumption in a small sized network

4.4.2 Medium ZigBee Network

The performances of the four studied protocols in the network of medium size – covering 750x750 [m^2] and comprising 36 nodes – are depicted in Figures 10 to 13.

With respect to packet loss (Figure 10), the performances of all four protocols degrade. This is especially evident under higher packet rates (20 to 30 pkts/sec). Specifically, at the packet sending rate of 30 pkts/sec, the packet receiving rate of all protocols remains below 20 pkts/sec. The observed degradation is directly related to the increase in the average length of the deployed path(s)[1].

Namely, as the length of deployed path(s) increases so does the average transit time of packets sent along such path(s). This, coupled with an increasing packet rate, implies that a larger number of packets will now be in transit in the network at any instance of time, ultimately resulting in a higher probability of packet collisions and, ultimately, larger packet loss.

The end-to-end packet delays observed in the medium size network (Figure 11) are generally larger than those of the small size network (Figure 7). This, again, is a natural consequence of the larger network size and respectively longer routing paths.

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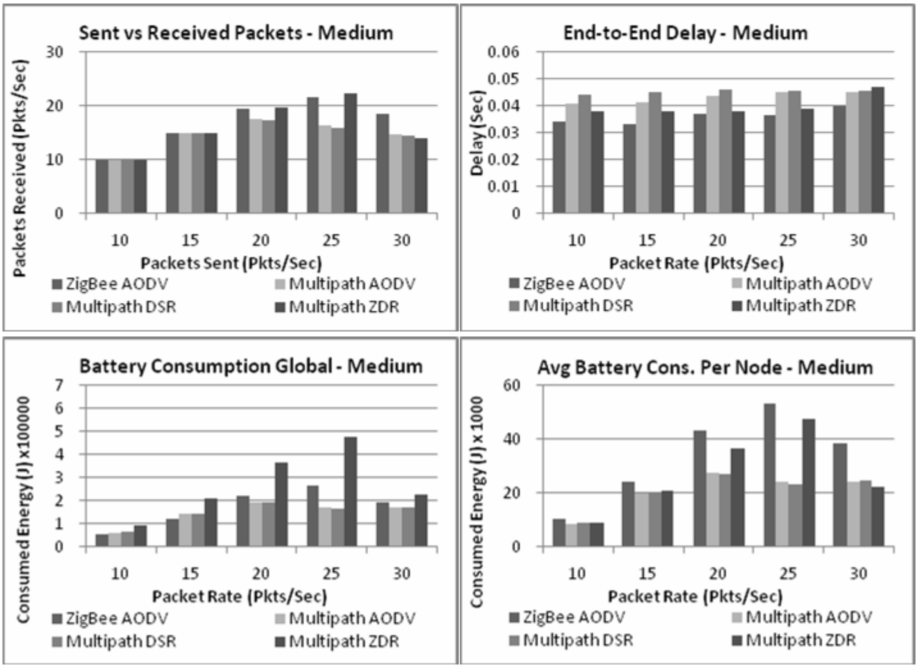
[1] In all simulation runs, the sending and receiving nodes are situated in the upper-left and lower-right corners of the network, respectively, as shown in Figure 3. Hence, the hop distance between the two nodes increases as the network size increases.



Figs. 10, 11, 12, 13. Sent vs. received packets, end-to-end delay, global battery consumption, and average per node battery consumption in a medium sized network

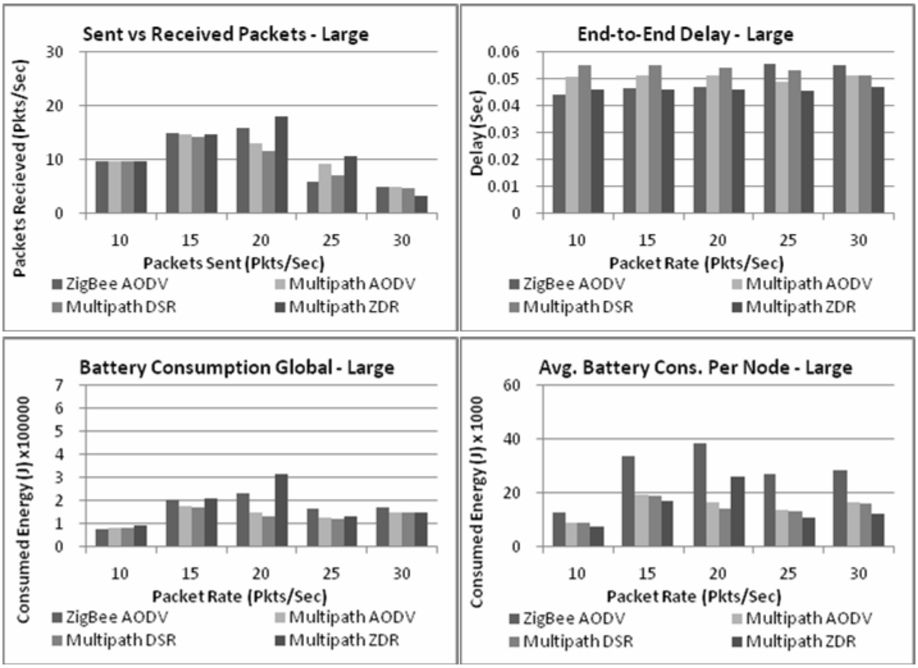
Among the four studied protocols and for packet rates between 10 and 25 pkts/sec, Multipath AODV and DSR result in longer packet delays relative to ZigBee AODV and Multipath ZDR – similar to what was observed in the case of the small sized network.

The global battery consumption under the four observed protocols in the network of medium size is shown in Figure 12. Once again, for all packet rates, Multipath ZDR is the largest consumer of energy due to a larger number of nodes involved in routing, compared to other protocols. It should also be emphasised that although in Figure 12 Multipath AODV and DSR appear to consume considerably less energy than Multipath ZDR (especially at the rate of 25 pkts/sec), these results are, in fact, partially influenced by the poor ability of Multipath AODV and DSR to successfully deliver packets to the final destination.

In the medium sized network, all of the multipath protocols consume less energy per node due to better distribution of traffic (i.e. routing-related load) across the network – see Figure13. From the practical point of view, this implies that the multipath protocols are less likely to result in premature node and/or network failure.

4.4.3 Large ZigBee Network

Figures 14 to 17 depict the performances of the four studied protocols in the network of large size – covering 1000x1000 [m^2] and comprising 67 nodes.



Figs. 14, 15, 16, 17. Sent vs. received packets, end-to-end delay, global battery consumption, and average per node battery consumption in a large sized network

From Figure 14 it is obvious that the performances of studied protocols continue to deteriorate as path lengths between the source and its respective destination increase. Here, already at the rate of 15 pkts/sec, a noticeable loss of packets can be observed. At the rate of 30 pkts/sec, all protocols struggle significantly, and are able to deliver only 15% of the packets to the final destination.

With respect to packet delay (Figure 15), the earlier observed trend also continues. In particular, due to the larger network size, the length of the deployed path(s) also increases, implying longer end-to-end delays under all four protocols. Relative to each other, at the rates of 10 to 20 pkts/sec, Multipath ZDR and ZigBee AODV perform slightly better than Multipath AODV and DSR. However, at 25 pkts/sec, ZigBee AODV begins to underperform other (multipath) protocols because of its poor ability to handle high traffic loads. It is interesting to observe that overall, as the packet rate increases, there appears to be only a slight increase in end-to-end delay across all protocols. This is a somewhat misleading notion, as the large end-to-end delay experienced by the dropped packets cannot be recorded, and consequently is omitted from the presented results.

The average battery consumption per node trend continues in the large network as well (Figure 27). The Multipath protocols fully exploit the two paths available by sending (only) one half of the packets down each path. This, ultimately results in decreased energy consumption per node in comparison to that under the single-path ZigBee AODV protocol, as depicted in Figure 17.

4.5 Per-Hop Packet Loss

The preceding discussion has shown that, under high packet rates, the performances of all examined protocols get seriously affected by packet loss. In order to gain a better understanding of this phenomenon, we have looked at the spatial (per-hop) distribution of packet loss along the deployed paths. A sample of our collected results is presented in Figure 18 (a), and it shows the number of received packets at each node/router along two deployed paths. The respective network topology and two deployed paths are outlined in Figure 18 (b) with sending and receiving nodes annotated with *end device 1* and *end device 44*, respectively. The first of the two deployed paths involves end device nodes 1 and 44, and intermediate routers 1, 6, 11, and 16. The second path involves end device nodes 1 and 44, and intermediate routers 1, 5, 10, 15, and 16.

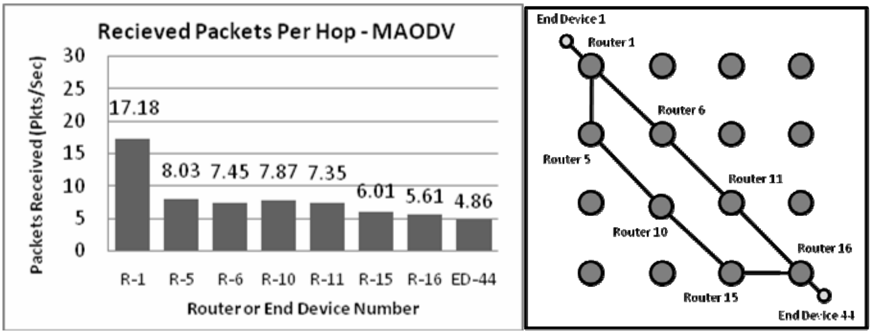


Fig. 18. (a) Received packets per-hop for Multipath AODV with a rate of 30 pkts/sec. (b) Two deployed paths of Multipath AODV.

Based on Figure 18 (a), it is evident that at the rate of 30 pkts/sec, nearly one half of the sent packets get lost right at the first hop – during the transmission from the child (sending end device 1) to the parent (router 1)[2]. Such a drastic packet loss in the first hop is a result of intra-path interference. Namely, under high packet rate, and due to the physical proximity of the child and the parent, every other packet transmitted by the child ends up colliding with one of the packets sent by the parent or by the parent's one hop neighbours (which also have the ability to interfere with the child's transmission). This ultimately leads to a reduction of the packet rate to a lower level which is, subsequently, much better managed at other downstream hops.

5 Conclusion and Future Work

In this paper, we have presented the results of our simulation-based study on the performance of three different multipath routing protocols in ZigBee-based WSNs. The performances of the three protocols are also compared to the performance of the

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[2] Note that the traffic after router 1 gets divided between the two deployed paths. Hence, a considerably lower number of packets gets received at the other routers.

ZigBee standard (single-path) AODV routing protocol. The results clearly indicate that, under high data rates, all examined protocols become significantly impaired by intra- and/or inter- path interference. Out of the four examined protocols, Multipath ZDR generally provides the best performance (largest throughput and smallest packet delay), thanks to its ability to offset the detrimental effects of inter-path interference through the utilization of zone-disjoint paths. Unfortunately, the benefits of Multipath ZDR come at the price of large energy consumption, especially compared to that of single-path ZigBee AODV.

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