Chapter 1

The Impact of Node Heterogeneity on ZigBee Network Routing

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Based on the IEEE 802.15.4 LR-WPAN standard, the ZigBee standard has been proposed to interconnect simple, low rate, and battery powered wireless devices. The deployment of ZigBee networks is expected to facilitate numerous applications, such as home-appliance networks, home healthcare, medical monitoring, consumer electronics, and environmental sensors. An effective routing scheme in a ZigBee network is particularly important in that it is the key to achieve resource (e.g., bandwidth and energy) efficiency in ZigBee networks. Routing in a ZigBee network is not exactly the same as in a MANET. In particular, while Full Function Devices (FFD) can serve as network coordinators or network routers, Reduced Function Devices (RFD) can only associate and communicate with FFDs in a ZigBee network. Therefore, different from traditional MANET routing algorithms, which only take into account node mobility to figure out a best route to a given destination, node heterogeneity plays an important role in ZigBee network routing. In this chapter, we firstly perform extensive evaluation, using NS-2 simulator, to study the impact of node heterogeneity on ZigBee mesh network routing. The results show that the ZigBee mesh routing algorithm exhibits significant performance difference when the network is highly heterogenous. Then, we study the mesh routing and its support of device mobility with different mobility cases. Under a rich set of preliminary tests, our results indicate that ZigBee device type plays a significant role in determining the routing performance in most mobile scenarios.

1.1. Introduction

With wireless networking technologies permeating into the very fabrics of our working and living environment, simple appliances and numerous traditional wired services can now be wirelessly and efficiently connected. This provides simple yet effective control/monitoring conveniences, while allowing very interesting applications to be developed on top of these wireless gadgets. The ZigBee standard [1], designed to interconnect simple devices that previously have not been networked, is the latest attempt to address this wireless network vision. In the context of a business environment, this wireless movement can facilitate better automated control/management of facilities and assets. Moreover, there are also many applications for home-appliance networks, as well as in the area of home healthcare, medical monitoring, consumer electronics, and environmental sensors.

ZigBee is a network and application layer specification developed by a multi-vendor consortium called the ZigBee Alliance [2]. Backed by 150+ member companies, the ZigBee standard was ratified in late 2004, and was publicly released for non-commercial use in June of 2005. Various ZigBee compliant product prototypes and application scenarios have already been developed by the industry, yet the performance and the supporting facilities of ZigBee networks have not been thoroughly evaluated. In particular, knowledge of how nodal mobility and nodal diversity (i.e nodes of different networking capabilities) affects the workings of the ZigBee routing protocols is of significance.

Routing in a ZigBee enabled network is very similar to the one in a Mobile Adhoc NETwork (MANET). In both cases, maintaining an end-to-end route is challenging since the network topology may change very frequently due to node failures, mobility, and many other factors. Various MANET routing protocols have been proposed in the last few years [3–9]. Among them, Adhoc On-demand Distance Vector Routing (AODV) [3] and Dynamic Source Routing (DSR) [4] are two of the most popularly deployed schemes. These routing algorithms of MANET aim to figure out the best route, even if the network is highly dynamic, toward a given destination at any time by consuming minimal messages/time overhead. Moreover, every participating node in MANET routing is implicitly assumed to be MANET router capable, and assumed to operate with the same set of functionalities.

However, such general yet implicit assumption in MANET routing does not hold in ZigBee networks. In a ZigBee network, each participating node plays the role as either a Full Function Device (FFD) or a Reduced Function Device (RFD), depending on its function capabilities (e.g. amount of memory, computation capability, energy level, and etc). While FFDs can serve as network coordinators or network routers (thus capable of routing), RFDs can only associate and communicate with FFDs (and are not allow to participate in network routing). As a result, traditional MANET routing schemes can't be applied to ZigBee networks. It turns out that node heterogeneities must be taken into account in designing an effective routing scheme for ZigBee networks.

In this chapter, we firstly study the impact of network heterogeneity on ZigBee mesh routing. Particularly, we are interested to find out how different mixture of mobile ZigBee routers and mobile ZigBee end devices influences the performance of ZigBee mesh routing. We present a rich set of simulation results illustrating the effect caused by the diversity in node capabilities. Our results reveal that routing performance does degrade when the network is comprised of an increasing number of ZigBee end devices. Moreover, compared to AODV routing results, we do see significant differences in routing performance when network nodes are not assumed to be equally capable. Additionally, we found that the routing performance is closely tied to the ZigBee node type used.

Moreover, we study the mesh routing and its support of device mobility with different mobility cases. Without a doubt, mobility support is important to the proper function of many envisioned ZigBee applications. Since mobility is anticipated and unavoidable, adequate mobility support is important in ensuring ubiquitous connection to/from the mobile devices. Our simulation results reveal that existing ZigBee provisions for mobility is inadequate, and mobility problem was not thoroughly considered by the standard. Furthermore, we found that the current recovery mechanisms are not reliable, or responsive enough in all mobility cases. The situation worsens when there are multiple instances of mobility in the ZigBee network, yet routing performance in ZigBee network is closely tied to the ZigBee node types used.

The rest of this chapter is organized as follows. In section 1.2, we give a brief overview of IEEE 802.15.4 and the ZigBee mesh routing specifications. Section 1.3 presents simulation results, illustrating the behavior of ZigBee mesh routing under different level of nodal diversity both in the moderately and highly mobile ZigBee network. Then, in section 1.4, we show simulation results which study the mobility support of ZigBee mesh routing in several mobility scenarios as well as under different mobility speed. Finally, section 1.5 summarizes the impact of nodal diversity in ZigBee mesh network, the mobility support of mesh routing, and concludes the chapter.

1.2. Overview

1.2.1. *IEEE 802.15.4*

Based on the PHY and MAC layers specified by IEEE 802.15.4 WPAN standard [10], the ZigBee specification establishes the framework for the Network and Application layers. The protocol stack of ZigBee networks is detailed in Fig. 1.1. Specifically, at the MAC layer, IEEE 802.15.4 controls access to the radio channel using Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) or the optional slotted CSMA/CA mechanism, as respectively utilize by the beaconless and beaconed modes. At the PHY layer, IEEE 802.15.4 defines a total of 27 channels: 16 channels at a maximum rate of 250 kbps in the ISM 2.4 - 2.4835 GHz band, 10 channels at 40 kbps in the ISM 902 - 928 MHz band, and one channel at 20 kbps in the 868.0 - 868.6 MHz band. Table 1.1 summarizes the high level characteristics of the IEEE 802.15.4 standard.

Two device types are specified within the IEEE 802.15.4 framework: full function device (FFD) and reduced function device (RFD). An FFD generally has more responsibilities in that they must maintain routing tables, participate in route discovery and repair, maintain beaconing framework, and handle node joins. Moreover, an FFD has the capability of communicating with any other devices within its transmission range. On the other hand, an RFD simply maintains the minimum

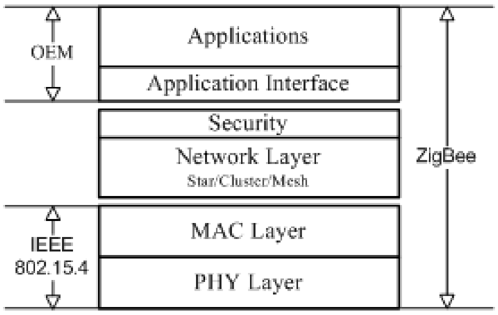


Fig. 1.1. ZigBee protocol stack in relation to IEEE 802.15.4 standard

Table 1.1. Characteristics of IEEE 802.15.4 Standard

Frequency Band	868-868.6 MHz	1 channel; 20 kbps
	902-928 MHz	10 channels; 40 kbps
	2.4-2.4835 GHz	16 channels; 250 kbps
Channel Access	Slotted/Unslotted CSMA-CA	
Range	10 to 30 meters	
Addressing	Short 16-bit or IEEE 64-bit	

amount of knowledge to stay on the network, and it does not participate in routing. RFDs can only associate and communicate with FFDs. FFDs and RFDs can be interconnected to form star or peer-to-peer networks.

1.2.2. *ZigBee Mesh Routing*

Based on IEEE 802.15.4, the ZigBee Alliance specifies the standards for the network layer and the application layer. More specifically, the ZigBee network layer defines how the network formation is performed and how the network address is assigned to each participating ZigBee node. Note that the assigned network address is the *only* address that is used for routing and data transmission in ZigBee networks. Three device types are defined in ZigBee: ZigBee coordinator, ZigBee routers, and ZigBee end devices. An RFD can only be a ZigBee end device; whereas an FFD can be either a ZigBee coordinator or ZigBee router. The ZigBee coordinator is responsible for starting a new network. ZigBee coordinator and routers are “routing capable”, while the ZigBee end devices can’t participate in routing and have to rely on their corresponding ZigBee parent routers for that functionality.

Every node in a ZigBee network has two addresses, namely a 16-bit short network address and a 64-bit IEEE extended address. The 16-bit network address is assigned to each node dynamically by its parent coordinator/router upon joining the network. This address is the only address that is used for routing and data transmission. It is analogous to the IP addresses that we use on the Internet; whereas the extended address is similar to the MAC address, which is a unique identification of each device and is mostly fixed at the time the device is manufactured.

There are two addressing schemes (of the 16-bit short network address) allowed in ZigBee mesh networks, namely the static address allocation scheme and the tree address allocation scheme. Both schemes work in similar fashion. In both schemes, the parent nodes assign an address "block" to their child router, which is in turn allocated to their respective decedents. The ZigBee coordinator/router is responsible to maintain the amount of free address spaces left, the address block size, and the address to be assigned next.

Two routing schemes are available in ZigBee networks, namely mesh routing and tree routing. The mesh routing scheme is similar to the Adhoc On Demand Vector (AODV) routing algorithm [3], while the tree routing scheme resembles the cluster tree routing algorithm as described in [11]. In this chapter, we will only focus on mesh routing in ZigBee mesh networks. In ZigBee mesh routing, route requests ($RREQ$) are broadcasted on-demand when data is to be transmitted to a destination of an unknown path. Routes are constructed based on the route replies ($RRPL$ from intermediate nodes and destination node), and a route error ($RERR$) message is transmitted to the user when a path can't be found. The route repair mechanism repairs invalid routes when a previous route can not be found. Since only coordinators/routers (FFDs) can actively participate in mesh routing, the end devices (RFDs) have to rely exclusively on their parent nodes to perform mesh routing on their behalves.

The performance of AODV algorithm has been extensively studied (e.g., [12–14] and etc). Yet, previous evaluation studies are mostly IEEE 802.11 centric and would consider all participating nodes routing capable nodes. However, under the innate properties of IEEE 802.15.4 and ZigBee networks (i.e., the addressing structure and service assumptions), the performance bound of ZigBee mesh routing (which is AODV-like) is thus expected to be different than the ones from previous AODV studies. More specifically, when a node "associates" with a new parent node (when the node attaches to a new parent node in range), a new 16-bit network address will be inherited by the child node, and the routing protocol has to react accordingly in order to keep the routing table updated. Moreover, the fact that the ZigBee mesh routing accommodates different device types (device with unequal routing capacities) distinguishes itself from traditional AODV networks. We will examine the impact of node mobility and heterogeneity in ZigBee mesh networks in the next section, and to the best of our knowledge, this issue has not yet been considered in the literature.

1.3. Evaluation I: Impact of Nodal Diversity on ZigBee Routing

This section presents extensive simulation results that illustrate the impact of nodal diversity on the properties of ZigBee mesh routing and the original AODV routing. In particular, we will compare how the nodal composition of a network affects the workings of ZigBee mesh routing. AODV routing performance is used for baseline comparison on how a typical homogenous network would perform as oppose to a heterogenous network environment. We use the NS-2 simulator with Samsung's IEEE 802.15.4 extension [15], and wrote our own ZigBee mesh routing schemes according to the ZigBee standard. We will compare the delivery ratio of various ZigBee network configurations, focusing on the impact caused by various node types.

The simulation is set to closely mimic the settings of a household/factory deployment. Nodes are initially aligned in an equally spaced grid before a selected percentage of nodes become mobile. Nodes move within the set topology according to the random waypoint model developed and described in [16], and all results are averaged across 50 independent trials of the same configuration. We make use of the static addressing scheme described in section 1.2 for mesh routing. The percentage of ZigBee end devices to ZigBee router varies, while the mobile nodes are randomly chosen. Other standard ZigBee network settings apply, and general parameters used is summarized in Table 1.2.

Table 1.2. General Simulation Parameters

Network Size	45m x 45m
Number of Nodes	36 nodes
Transmission Range	10 meters
Network Setup Time	30 seconds
Simulation Duration	300 seconds
Number of Concurrent Data Flows	2
Transmission Rate	10 packets/sec
Mobility Model	Random Waypoint
Traffic Type, Packet Size	CBR, 127bytes
$nwkMaxDepth(L_m)$	5
$nwkMaxChildren(C_m)$	10
$nwkMaxRouter(R_m)$	10

The parameters $nwkMaxDepth$, $nwkMaxChildren$ and $nwkMaxRouter$ are network values defined by the ZigBee standard, and are set at install time. $nwkMacDepth$ denotes the maximum depth of the network from the coordinator, $nwkMaxChildren$ is the maximum number of children allowed at each router, and $nwkMaxRouter$ specified the the maximum number of routers a parent may have as children. Since ZigBee networks were intended to operate at low data rates, our simulation uses CBR flows of 10Kbps. We use packet delivery ratio as our performance evaluation matrices. Packet delivery ratio is averaged over the number of flows in the network to reflect the mean per-flow delivery ratio.

1.3.1. *Varying Heterogeneity in Moderately Mobile ZigBee Network*

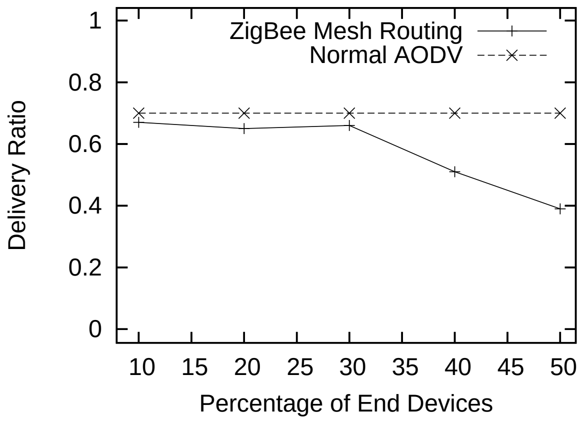
This subsection studies the routing performance of ZigBee mesh routing scheme when there are varying amount of ZigBee end devices in the network, focusing on the scenario when only 20% of the network are mobile nodes. AODV routing results are also graphed as a basis for performance comparison although AODV is run on an all router topology (since AODV requires routing capability from all nodes), and does not change to the percentage of ZigBee end devices in the network. 20% of the network nodes are randomly chosen as mobile nodes, all moving at a speed of 1m/s using the random waypoint model. Two general mobility cases were simulated, focusing on the responses of different node types. In the first scenario, we keep the receiver stationary while setting senders to be mobile. In the second scenario, the sender remains stationary while the receiver is mobile. We repeat the same simulations with two node types, ZigBee router and ZigBee end devices. Source and destination are randomly chosen, but all networking settings remain the same for all simulations. We vary the percentage of ZigBee end devices from 0% to 50% in order to observe the response of ZigBee mesh routing to increasing percentages of ZigBee end devices.

Because end devices do not participate in ZigBee mesh routing, when the total number of devices is fixed, increasing the percentage of end devices effectively decreases the number, and hence density, of ZigBee mesh routing capable devices in the network. This forces all devices to have fewer choices in potential end-to-end paths, and thus may end up using paths at lower qualities and/or more susceptible to path breakages. Reflected in Figs 1.2 and 1.3, all curves of the delivery ratio in ZigBee mesh routing share the same trend of going lower as the percentage of end devices grows. However, the AODV performs relatively well under assumption that all nodes are router capable.

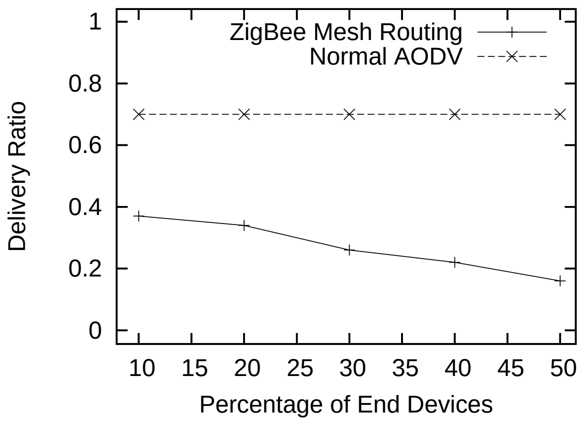
Compared with the cases where a ZigBee end device acts as an end host of the path (either sender or receiver), having a router as the end host tends to show a better performance. This is obvious since the router directly participates in the ZigBee mesh routing, while an end device must always associate itself with a router and changes its own address every time it switches to a new router. When a path is broken, the router can usually re-establish the path faster. Note that the delivery ratio in the case where an end device acts as the receiver is particularly low. This is due to the fact that when the end-to-end path becomes broken, the receiver suffers the aforementioned overhead of router reassociation and address acquiring, as in other cases. In the meantime, the sender has to rediscover the receiver, now with a new address, using application layer recovery mechanisms, further degrading the performance. As expected, AODV assumes all devices as routing capable, therefore changing the percentage of end devices has no impact on the data delivery ratio in both sender and receiver cases.

1.3.2. *Varying Heterogeneity in Highly Mobile ZigBee Network*

Following the same methodology, we now study the performance of ZigBee mesh routing when more devices are mobile. Specifically, we increase the percentage of mobile nodes from 20% to 50%, all moving at 1m/s under the random waypoint



(a) ZigBee router acting as sender



(b) ZigBee end device acting as sender

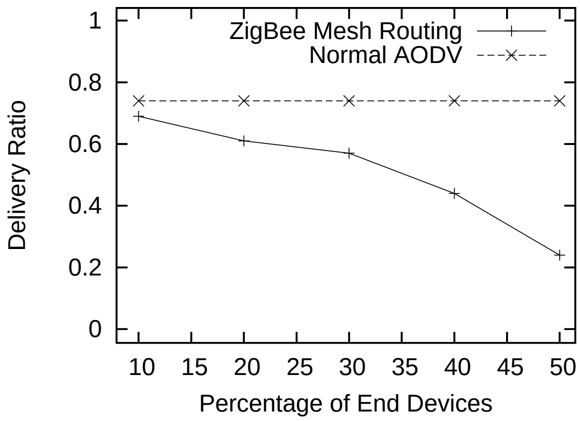
Fig. 1.2. Packet delivery ratio for network with 20% mobile nodes, ZigBee router and end device acting as mobile sender, sending to a stationary destination.

model. All other settings remain the same.

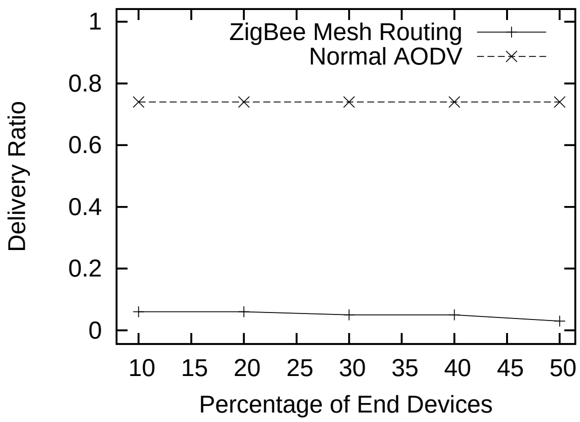
Similar to Figs 1.2 and 1.3, Figs 1.4 and 1.5 show that as the percentage of end devices increases, the number of routing capable devices in ZigBee mesh routing decreases, so does the delivery ratio. Moreover, a larger percentage of mobile devices tends to increase the chance of path breakages, so the absolute delivery ratios are lower, seen in both AODV and ZigBee mesh routing mechanisms.

1.4. Evaluation II: Mobility Support in ZigBee Mesh Routing

In this section, we discussed the ZigBee mesh routing scheme and its support for device mobility. For all of our simulations, the network used in our simulation



(a)ZigBee router as receiver



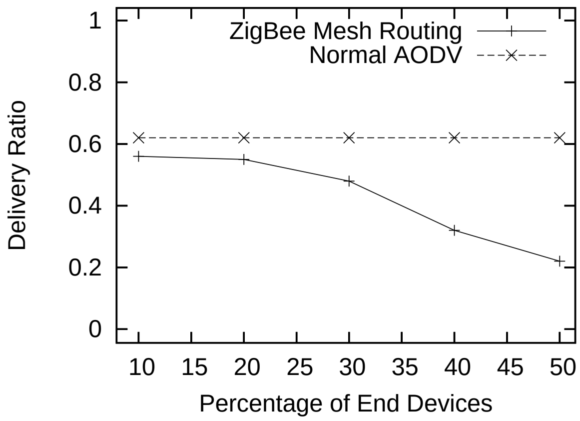
(b)ZigBee end device as receiver

Fig. 1.3. Packet delivery ratio for network with 20% mobile nodes, ZigBee router and end device acting as mobile receiver, receiving from a stationary sender.

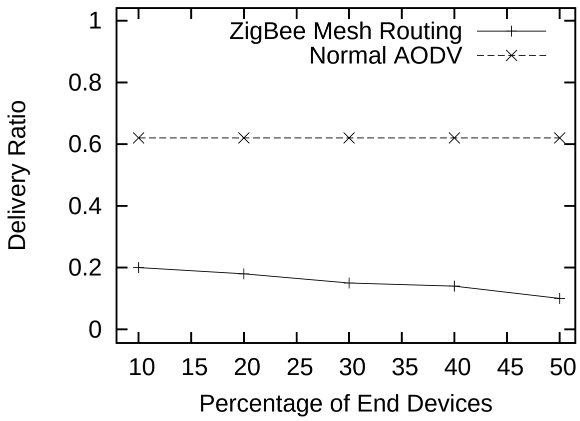
consists of 70% routers and 30% end devices, which are all randomly chosen. All networking settings and general simulation parameters are the same as described in section 1.3 and Table 1.2. Here, we also use packet delivery ratio and relative routing overhead as our performance evaluation matrices. Packet delivery ratio is averaged over the number of flows in the network to reflect the mean per-flow delivery ratio. On the other hand, routing overhead is denoted by a normalized value of the total overhead of the network with respect to the traffic in the network.

1.4.1. *Scenarios with varying percentage of mobile nodes*

This subsection studies the performance when there are varying amount of mobile nodes in the network. Mobile nodes move at a speed of 1m/s randomly. Like



(a) ZigBee router acting as sender

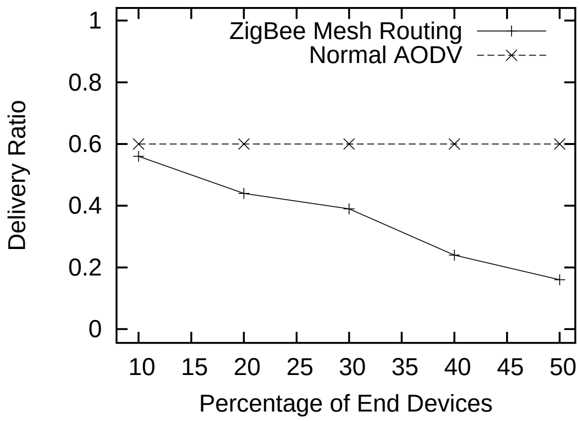


(b) ZigBee end device acting as sender

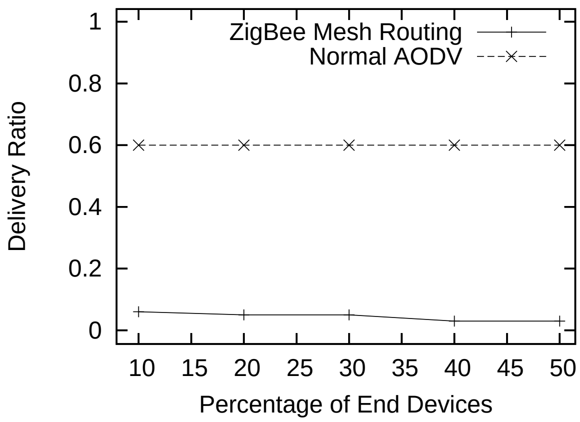
Fig. 1.4. Packet delivery ratio for network with 50% mobile nodes, ZigBee router and end device acting as mobile sender, sending to a stationary destination.

the previous simulations, two general mobility cases were simulated. In the first scenario, we keep the receiver stationary while setting senders to be mobile. In the second scenario, the sender remains stationary while the receiver is mobile. We repeat the same simulations with two node types, i.e., ZigBee routers and end devices. Source and destination are randomly chosen, but all networking settings remain the same for all simulations. We vary the percentage of mobile nodes from 0 to 50% to observe the response of mobile nodes in the network.

From the results depicted in Fig. 1.6(a), it is clear that the device type plays a critical role in determining the delivery ratio for mobile senders. ZigBee routers can typically transmit out more data, while ZigBee devices can only send out half of the amount compare to the routers. Furthermore, the ZigBee end devices are more



(a)ZigBee router as receiver

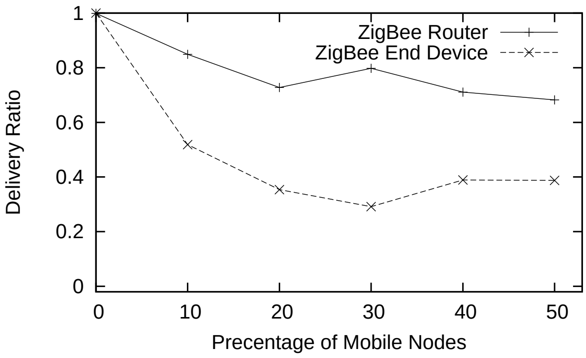


(b)ZigBee end device as receiver

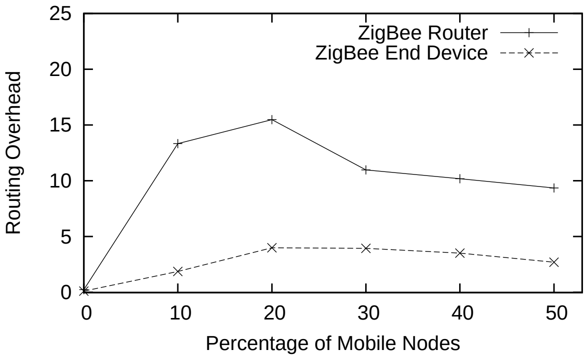
Fig. 1.5. Packet delivery ratio for network with 50% mobile nodes, ZigBee router and end device acting as mobile receiver, receiving from a stationary sender.

heavily influenced by the percentage of mobile nodes in the network compare to the ZigBee router. This is due to the fact the ZigBee end devices need to associate with a new parent when it moves, the extra association time actually degrades the packet delivery ratio. On the other hand, from Fig. 1.6(b), we see that ZigBee routers actually incurs more routing overhead compare to the end devices. The additional routing overhead is from route repair messages that routers send/receive to repair the route.

As the destination of data streams, all ZigBee receivers encounters some performance degradation (in terms of data delivery ratio) when it is mobile as illustrated in Fig. 1.7(a). Mobile receiver would clearly benefit if it is a ZigBee router. The reason is that ZigBee routers are route capable and the route repair mechanism in



(a) packet delivery ratio



(b) relative routing overhead compared to the actual data throughput

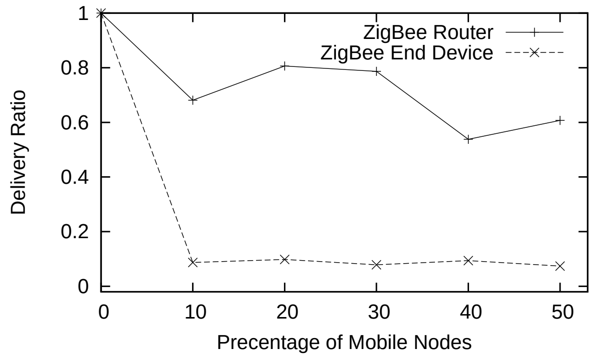
Fig. 1.6. ZigBee router or ZigBee end device as mobile sender, data to stationary destination.

mesh routing can repair some of the mobility induced damages in a timely manner. Results also confirm the intuition that mesh routing consumes more overhead when there are more mobile nodes in the network as shown in Fig. 1.7(b).

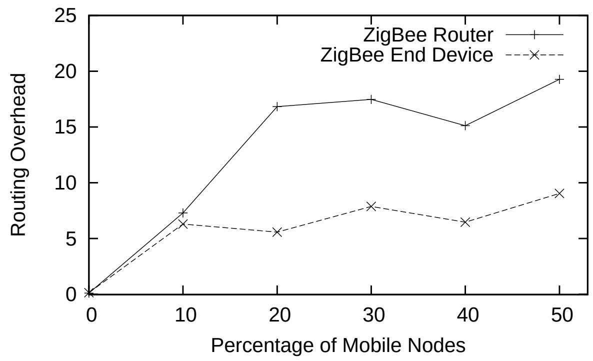
1.4.2. *Scenarios with mobile nodes of varying speed*

Following the same methodology in the previous subsection, this subsection studies the routing performance when the mobile nodes in the network are moving at varying speeds. The ZigBee network in question consist of 70% routers and 30% end devices, and 20% of the nodes in the network are selected randomly as mobile nodes. Specifically, we evaluate for packet delivery ratio when the nodes are moving from 1m/s to 5m/s in 1m/s increments.

Fig. 1.8(a) clearly show that the device type plays a critical role in determining the delivery ratio in mesh routing. ZigBee routers can typically transmit out more data, while ZigBee devices can only send out half of the amount compare to the routers. On the other hand, from Fig. 1.8(b), we see that ZigBee routers actually



(a) packet delivery ratio

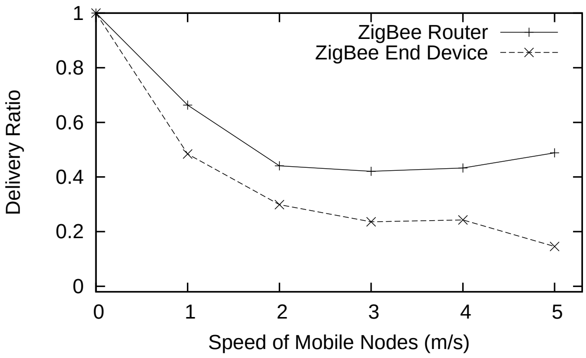


(b) relative routing overhead compared to the actual data throughput

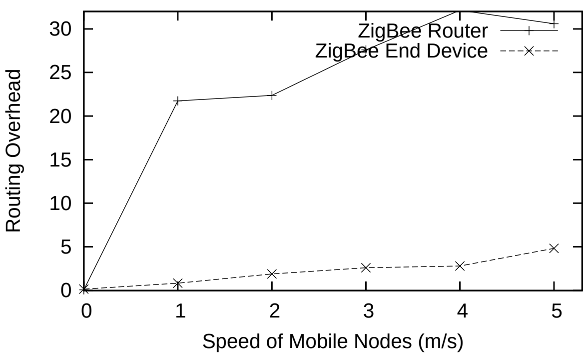
Fig. 1.7. ZigBee router or ZigBee end device as mobile receiver, data from stationary source.

incurs more routing overhead compare to the end devices. The additional routing overhead is from the various route repair messages that routers send/receive to repair the route. We also see that as node speed increases, the delivery ratio decreases.

As the previous results, Fig. 1.9(a) also shows that the device type plays a critical role in determining the delivery ratio in mesh routing. In addition, ZigBee receivers tend to encounters more severe performance degradation when it is traveling at higher speeds. As depicted in Fig. 1.9(a), ZigBee router as the mobile receiver exhibited more resiliency against high node speeds, even though it consumes more overhead than ZigBee end device as the mobile receiver as illustrated in Fig. 1.9(b). ZigBee router typically suffers less packet losses under mobile scenarios. This behavior is closely related the fact that ZigBee routers are routing capable, while the ZigBee end devices are not.



(a) packet delivery ratio



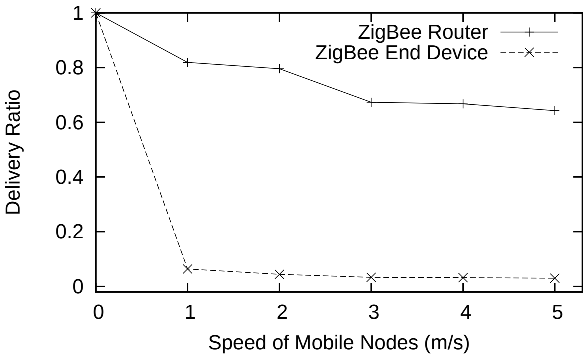
(b) relative routing overhead compared to the actual data throughput

Fig. 1.8. ZigBee router or ZigBee end device as mobile sender, data to stationary destination.

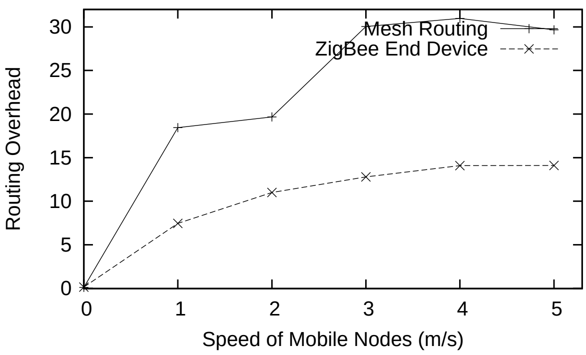
1.5. Conclusions

Routing in a ZigBee network is not exactly the same as in a MANET. In particular, while Full Function Devices (FFD) can serve as network coordinators or network routers, Reduced Function Devices (RFD) can only associate and communicate with FFDs in a ZigBee network. Therefore, different from traditional MANET routing algorithms, which only take into account node mobility to figure out a best route to a given destination, node heterogeneity plays an important role in ZigBee network routing.

In this chapter, we firstly study the impact of network heterogeneity on ZigBee mesh routing. Particularly, we are interested to find out how different mixtures of mobile ZigBee routers and mobile ZigBee end devices influence the performance of ZigBee mesh routing. We performed extensive evaluation using NS-2 simulator, with our own ZigBee implementation. The results indicate that the ZigBee mesh routing algorithm exhibits significant performance difference when the network is highly heterogenous. Routing performance in ZigBee network does degrade when



(a) packet delivery ratio



(b) relative routing overhead compared to the actual data throughput

Fig. 1.9. ZigBee router or ZigBee end device as mobile receiver, data from stationary source.

the network comprises of an increasing number of ZigBee end devices. Moreover, the delivery ratio worsens when there are more instances of mobility in the network (in highly mobile scenarios). Furthermore, comparing to AODV routing results, we do see significant difference in routing performance when network nodes are not assumed to be equally capable. We also reveal that the ZigBee end devices tend to perform worse than ZigBee routers in both sending and receiving packets, since the end devices incur much overhead in associating with new parents when there is network mobility. On the other hand, ZigBee routers typically suffer less packet loss when there are intensive amounts of mobility in the ZigBee network, yet the additional service overhead of ZigBee (such as association with children devices) still degrades the performance of ZigBee routers in almost all scenarios.

In addition, we study the mesh routing and its support of device mobility with different mobility cases. Our evaluation results indicate that ZigBee end devices experiences detrimental packet losses in almost all mobility scenarios. This situation worsens under multiple instances of mobility, and when mobile nodes travel at higher speeds. Yet, ZigBee router typically suffers less packet losses under mobile scenarios.

This behavior is closely related the fact that ZigBee router are routing capable, while the ZigBee end devices are not. We also realized that the current recovery mechanism is inadequate in accommodating multiple instance or rapid mobility. Additional design work should be proposed to resolve the various problems pointed out in this chpater.

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