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Mobile Dynamic Tree Routing Protocol (MDTR) in ZigBee /802.15.4 based Wireless Sensor Network

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☐ ABSTRACT ☐

Many wireless sensor network applications like forest fire detection and environment monitoring recommend making benefit from moving humans, vehicles, or animals to enhance network performance. In this research, we had improved our previous protocol (Dynamic Tree Routing DTR) in order to support mobility in a wireless sensor network. First, we had mathematically approximated the speed threshold for mobile sensors, which enables them to successfully associate with nearby coordinators. Second, we test our (MDTR) protocol in a network with mobile sensors sending packets toward network's main coordinator. The simulation results obtained from network Simulator (NS2) showed a good approximation of speed threshold, and good performance of MDTR in term of delay, throughput, and hop-count compared with AODV and MZBR Protocols.

Keywords ZigBee, Hierarchical Tree Routing, Mobile Dynamic Tree Routing, Wireless Sensor Networks, IEEE 802.15.4.

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بروتوكول التوجيه الشجري الديناميكي المتنقل (MDTR) في شبكات الحساسات اللاسلكية المعتمدة على تقنية ZigBee /802.15.4

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☐ ملخّص ☐

العديد من تطبيقات شبكات الحساسات اللاسلكية كتطبيقات حرائق الغابات ومراقبة البيئة تحبذ الاستفادة من حركة الأشخاص أو الأليات أو الحيوانات في الغابة لتحسين أداء الشبكة.

قمنا في هذا البحث بتطوير بروتوكولنا السابق (بروتوكول التوجيه الشجري الديناميكي DTR) ليدعم الحركية في شبكات الحساسات اللاسلكية، وفي هذا الإطار قمنا أولاً بتقريب عملية حساب السرعة الحديه التي تمكن الحساس من الارتباط بنجاح مع المنسقات المجاورة. وقمنا ثانياً باختبار أداء البروتوكول (MDTR) في شبكة حساسات تحتوي على عدد من الحساسات المتحركة التي تقوم بإرسال الحزم باتجاه منسق الشبكة الرئيسي.

بينت نتائج المحاكاة باستخدام محاكي الشبكات الإصدار الثاني NS2، تقريباً جيداً لحساب السرعة الحدية، كذلك أظهرت أداءً جيداً للبروتوكول MDTR من ناحية زمن التأخير ومعدل النقل وعدد القفزات مقارنة بالبروتوكول AODV والبروتوكول MZBR.

الكلمات المفتاحية: ZigBee، التوجيه الهرمي، التوجيه الشجري الديناميكي المتنقل، شبكات الحساسات اللاسلكية، المعيار IEEE 802.15.4.

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Introduction

ZigBee is designed especially for low power and low-cost devices on top of the IEEE802.15.4 standard. It entered into many applications field, like home networking, and wireless sensor networks. Many of these applications make benefit from moving objects in the monitoring area, like people, animals or vehicles in forest fire detection applications. Their routing protocol must be capable to handle node mobility in order to keep good performance because when sensor moves, the path and the link quality to destination frequently changes and the routing protocol must update its view to surrounding environment in order to know the current state of the network. ZigBee mainly uses two kinds of routing protocols, reactive routing like Ad-Hoc On-Demand Distance Vector (AODV) [1], hierarchical routing like ZigBee Tree Routing protocol (ZTR) [2], or a combination of them to accommodate various applications requirement. AODV is reactive routing protocols [3] which use full path routing table and update the routing path only when the source node needs to send a packet and there is no entry in the routing table, or when the path to the destination is changed. Creating and updating the path requires broadcasting rout request command in the network, and waiting to receive the route reply from destination upon best route towards the destination. This kind of protocols consumes less energy than the proactive routing protocols, but it still consume a considerable amount of sensor resources to maintain the full path routing table, especially when the network contains mobile sensors. In another hand, ZTR is a tiny and resource conservation protocol in its nature, because it doesn't use broadcast control packet to build and maintain the routing table, and uses only addressing schema and child-parent relationship to route the packets.

There are many researches about validation and performance comparison of ZigBee /802.15.4 based protocols in fixed networks and less research in mobile networks. In fixed networks we mention IZTR protocol[4], which is an improvement of ZTR protocol, it calculates the hop count between source and destination based on their depth and selects the reduced hop neighbor, avoiding busy link and low energy neighbors. IZTR outperforms the performance of ZTR and Energy efficient Shortcut Tree Routing ESTR; it reduced overall energy consumption in the network and packet latency to be suitable for power line monitoring applications. Another improvement to ZigBee Tree routing is ZBR_M [5], in this protocol the sending sensor asks its neighbor if the destination is in their own descendant. If so, it forwards the packet to that neighbor to reduce hop-count. In mobile networks, the authors in [6] have compared the AODV and DSDV routing protocols based on IEEE802.15.4 under different mobility models. AODV protocol showed higher throughput and less packet loss ratio than DSDV protocol, also in [7], the authors evaluate the AODV protocol on top of IEEE 802.15.4 with variations in traffic load and packet size in different mobility models.

Our routing protocol Mobile Dynamic Tree Routing (MDTR) which is an improvement version of (DTR) protocol [8], which in turn an improvement of modified ZigBee Tree Routing Protocol (MZBR) [9] had adopted many factors to update it's one hop neighbors table, and to qualify the surrounding neighbors and links, in order to make a suitable routing decisions.

1 Research Importance and Goal

The performance of routing protocol may become very bad if the protocol doesn't consider modifications to deal with sensors mobility. So we aim in this research to approximate the boundaries of the mobile sensor speed which enables them to join the network, and the routing protocol to begin its forwarding. We also aim to enhance our routing protocol to be capable of working in a hybrid wireless sensor network of fixed and mobile sensors.

2 Research Method

We mathematically approximated the mobile sensor speed threshold in deferent scenarios, and then we used Network Simulator Version 2 (NS2) to simulate the scenarios and verify the approximated speed threshold values. Also, we used NS2 to test and compare the performance of MDTR, AODV and MZBR protocols in a wireless sensor network having multiple mobile sensors.

3 Sensor Mobility Consideration in ZigBee /IEE802.15.4 based WSN

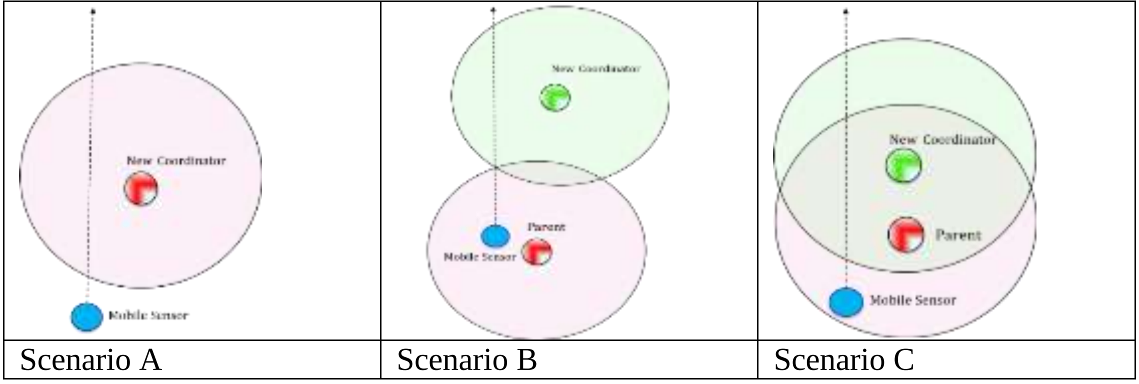
We noticed that moving sensor may fail in association when it moves faster than certain speed called speed threshold $Speed_{thresh}$, this speed depends mainly in Beacon Intervals BI and transmission range R of nearby coordinators. We will try to approximate this speed threshold in ZigBee/IEE802.15.4 beacon enabled WSN considering only time-consuming events. If sensor moves faster than this threshold it may enter new coordinator's Personal Operating Space (POS) and leave it without completing association procedure.

3.1 Mobile Sensor Speed Thresholds in Deferent Scenarios

When sensors want to join the network, it firstly scans available channels for a suitable coordinator to associate with it, and according to ZigBee / IEE802.15.4 standard there are 4 types of channels scan [3]:

- **Energy Detection Scan:** This scan is used by the coordinator to find peak energy in each channel, in order to select a suitable one for starting a new network.
- **Active Scan:** In Active Scan, the coordinator or device sends a *beacon request command* in each channel to locate available coordinators. This scan is used by the coordinator to select a network identifier before starting a new network, or by the device to find available coordinators in its POS for the association.
- **Passive Scan:** Like active scan but no *beacon request command* is required. It used only by devices before association in beacon-enabled mode.
- **Orphan Scan:** This scan is performed when the device loses the synchronization with its parent**.**

Three scenarios were considered according to the relative positions of the mobile sensor and nearby coordinators, also the relative time of beginning channels scan to the time of sending beacons from the coordinators when the mobile sensor enters the coordinator POS in order to approximate the mobile sensor Speed Threshold in each scenario. We suggest three scenarios that represent different situations the mobile sensor may face when moving through wireless sensor network as shown in the figure (1):



Scenario A | Scenario B | Scenario C

Figure (1) Mobile sensor movement scenarios

3.1.1 First Scenario (Scenario A)

In the first scenario, mobile sensor began moving while it was outside coordinator's Personal Operating Space, then it enters during coordinator's POS for a period of time depending on sensor speed, and leaves it as shown in scenario (A) of the figure (1). Here we can notice tow situations depending on the channel used by the coordinator and the currently scanned channel by the mobile sensor when it enters the coordinator's POS.

3.1.1.1 Best Case in Scenario (A)

In this case, the mobile sensor begins scanning the available channels, and then, it enters the coordinator's POS before it finishes the last channel scan, whereas the coordinator is sending beacons in the same last channel at the moment when the mobile sensor enters the coordinator's POS, as we clarified in figure (2).Therefore, the mobile sensor receives the beacon before finishing the last channel scan and began association message exchange directly. The time required for association equals to, the beacon receiving duration, which is too short, the association message exchange, and the time required to send one large packet. The detailed approximate computation of these sub-periods is presented in next paragraph.

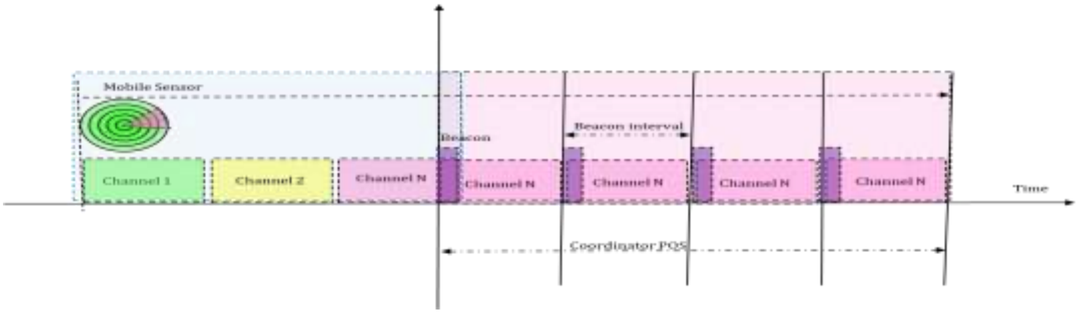


Figure (2) Best Case during Channels Scan in Scenario (A) where $n = BO$

3.1.1.2 Worth Case in Scenario A

The moving sensor begins new scan with first channel a little time equal to beacon period before it enters the coordinator POS, and the coordinator transmits the beacons in the same first channel after the mobile sensor has finished the first channel scan as shown in figure (3). In this case, two consecutive channels scan are required in order to detect the coordinator's beacon.

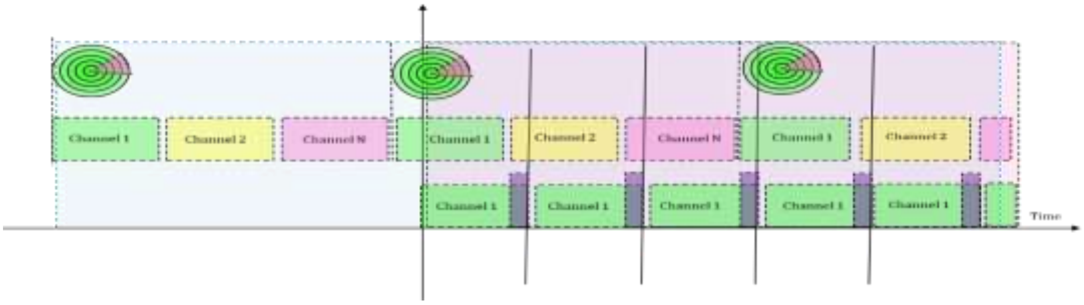


Figure (3) Worth Case during Channels Scan in Scenario (A) where $n = BO$

Scan time on energy detection, active, and passive scan depend on how many channels exist and the time interval between two consecutive beacons ($Beacon\ Interval\ (BI)$) from nearby coordinators, and in order to receive at least one beacon from each nearby coordinators, the sensor must spend equal or larger time than BI in each channel[10].

$$BI = 2^{BO} * aBaseSuperframeDuration$$

$$channel_{Scan_{duration}} = \left(2^{n} + 1\right) * aBaseSuperframeDuration \ (1)$$

Where:

- $aBaseSuperframeDuration$: is the minimum value of super frame in beacon enabled mode and it equals to 15.36 MS in 2.4 GHZ band.
- BO: Is the Beacon Order, which take a value between 0 and 14 in beacon-enabled mode.
- $channel\_Scan_{duration}$: is time required to scan each channel.
- n : is the Scan Duration parameter, its value is equal or larger than beacon order ($n >= BO$);

The overall scan duration (t_{scan}) will be equal to ($N * Scan_{Duration}$ where N is the number of available channels [11]

$t_{scan} = N\left(2^{n} + 1\right) * aBaseSuperframeDuration$ (2)

The time required for scanning channels and complete association messages exchange

$t_{scan+asso} = t_{scan} + t_{assosiate\_MSG}$ (3)

Here the time required to associate with a new parent is equal to

$t_{assosiate\_MSG} = t_{Asso_{req}} + t_{ack} + t_{macResponseWaitTime} + t_{data_{req}} + t_{ack} + t_{Data_{rep}} + t_{ack} + t_{Asso_{res}} + t_{ack}$ (4)

The association message exchange is shown in figure (4)

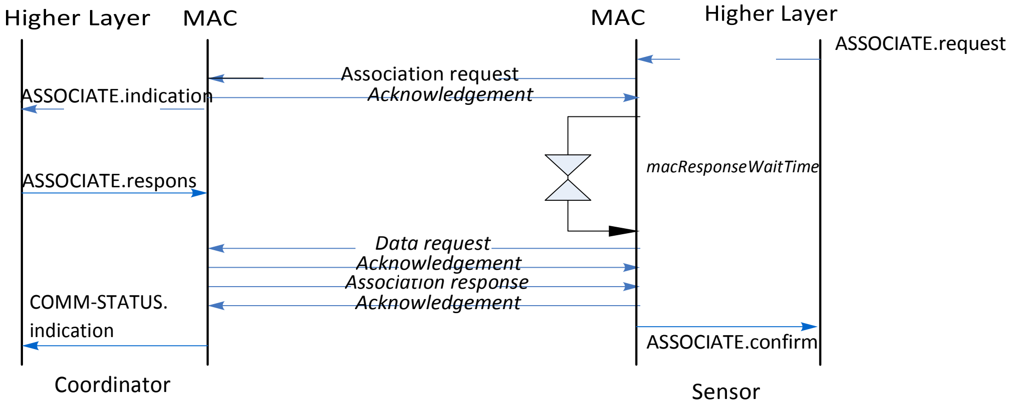


Figure (4) association message exchange in ZigBee /IEEE802.15.4 based WSN *[12]*

In the previous figure, the most time-consuming event in association message exchange is $t_{macResponsewaitTime}$, where $macResponseWaitTime$ is the maximum time, in multiples of $aBaseSuperframeDuration$ the device should wait for response after sending a request [13].

$t_{macResponsewaitTime} = 32 \times aBaseSuperframeDuration$ (5)

The frames, which are exchanged during association, belong to mac command frames which general structure is shown in figure (5)

2 Octets	1	4 to 20	0 to 14	1	variable	2
Frame control	sequence number	Address Fields	auxiliary Security header	Command Type	Command payload	Frame check sequence
MAC Header				MAC Payload		MAC Footer

Figure (5) MAC Command Frame Structure *[13]*

The addressing fields size in mac header is variable with max size of 20 bytes [10], and the security field is optional with max size of 14 byte, the mac command payload n varies according to command type defined in command identifier field, and finally the physical layer adds 6 bytes to the total size of MAC layer. The following table shows the command payload according to the command type.

Table (1) MAC Command Frames Payload

Mac Command Frame	Command Payload (Bytes)
the association request	2
association response	4
Data request	1
Orphan notification	1
Coordinator realignment	9

Here we can ignore the time of sending and receiving acknowledgment and mac command packets when comparing by scan duration or $t_{macResponsewaitTime}$, because their duration is in term of micro seconds to few milliseconds and the time deference gets larger when beacon interval increases [14].

$$t_{assosiate\_MSG} = 32 \times aBaseSuperframeDuration \quad (6)$$

Finally, we will compute the time required to send one large packet. From [15] the time required to send one packet in IEE802.15.4 based WSN over the 2.4GH band is equal to

$$t_{Send_{pkt}} = t_{BO} + t_{frame} + t_{ta} + t_{ack} + t_{ifs} \quad (7)$$

Where: t_{BO} : Back-off period = $1.1245\,ms$. t_{ta}: Turnaround time =192 µs. t_{ack} : Transmission time for an ACK. t_{ifs}: Inter Frame Spacing time, its max value is equal to 640 µs. t_{frame}: Frame transmission time.

$$t_{frame} = \frac{8*(frame_{byload}+frame_{headers})}{B} \quad (8)$$

B: is bit rate and it equal to 250kbps in 2.4 GHz band. The time for sending one bit is 1/250000 = 4 µs [13].

In IEEE802.15.4 standard, max frame payload size is 81 bytes or 102 bytes depending on the protocols used in the upper layer, and the maximum frame size with all headers is equal to133 bytes with a maximum of 127 bytes in mac layer and 6 bytes in the physical layer. Acknowledgment don't have payload or high layer headers, it only includes mac header and footer (5 bytes) and physical header (6 bytes), so the time duration to send acknowledgment frame is equal to $t_{ack} = 8 * 11 * 4 = 352$ µs , the total duration to send the maximum size packet $t\_frame = 133 * 8 * 4 = 4.256\,ms$, and the total duration to send a packet and receive an acknowledgment from parent

$$t_{Send_{pkt}} = 1.1245 + 4.256 + 0.192 + 0.352 + 0.64 = 6.5645\,ms$$

Also, it takes little duration when compared with channels scan, so we can ignore it. Thus, the overall time of channel scan and association in worst case is equal to

$$\mathrm{t}_{\mathrm{total(A)}} = \mathrm{t}_{\mathrm{(scan+asso)(A)}} = 2 * t_{scan} + t_{assosiate\_MSG}$$

$$t_{total(A)} = \left(2N\left(2^n + 1\right) + 32\right) * aBaseSuperframeDuration \quad (9)$$

If we consider that the sensor moves through the diameter of coordinators POS (2R), Then the speed of sensor mustn't be larger than the following value.

$$Speed_{thresh(A)} = \frac{2R}{t_{total(A)}} \quad (10)$$

But in most cases sensor doesn't move through new coordinator diameter, we suppose that sensor moves at least (R) meters through coordinator POS, as shown in scenario (A) figure (1).

$$Speed_{thresh(A)} = \frac{R}{\mathrm{t}_{\mathrm{total(A)}}}$$

$$Speed_{thresh(A)} = \frac{R}{\left(2N\left(2^n + 1\right)+32\right)*aBaseSuperframeDuration} \quad (11)$$

3.1.2 Second Scenario (Scenario B)

In the second scenario, the sensor is associated with the specific coordinator and it moves outside its coordinator POS to enter another coordinator POS at the same time it leaves the POS of the first one as shown in scenario (B) figure (1).

When sensor moves in network apart from its parent, it will take some time to decide that it had lost the synchronization with it, the decision of losing synchronization is taken by sensor if the number of lost consequence beacons reach the values specified in parameter *aMaxLostBeacons*.

$$t_{lose} = aMaxlostBeacons * (2^{BO} + 1) * aBaseSuperframeDuration \ (12)$$

Then sensor either enter orphan status to re-align with its parent or begin directly a new association procedure to associate with another one. In orphan status, sensor begins an orphan scan, it sends an *orphan notification command* in each channel and wait a time specified with *macResponseWaitTime* parameter for response. If it receives the *coordinator realignment command* from parent, it updates it's association parameters and terminates the orphan scan, else it wait for all channels scan to begin a new association procedure. Orphan Scan takes a long time, and usually, when the node moves in the network and loses synchronization with its parent, the orphan scan will return no result [16] because the sensor usually becomes outside parent POS.

$$t_{orphan} = N * \ macResponseWaitTime + t_{orphan_{MSG}} \ (13)$$

Also, we will ignore the time of sending orphan command messages.

$$t_{orphan} = N * \ 32 \ \times \ aBaseSuperframeDuration \ (14)$$

When all channels are scanned and no *realignment MAC command frames* had been received from a parent, the device performs new passive scan spending same duration defined in equations (2, 6).

Finally, in an ideal situation, and when no other sensors compete to associate, the overall spent time for the sensor from losing the connection with its old parent until the re-association with a new parent is equal to the sum of the previous durations.

$$t_{total(B)} = t_{lose} + t_{orphan} + t_{scan} + t_{assosiate\_MSG}$$

$$t_{total(B)} = \big((aMaxlostBeacons * (2^{BO} + 1)) + N * \ 32 + (N * (2^{n} \ + \ 1) + 32)\big) * aBaseSuperframeDuration$$

$$t_{total(B)} = \Big(\big(aMaxlostBeacons * (2^{BO} + 1)\big) + N * \big(2^{n} \ + \ 33\big) + 32\Big) * aBaseSuperframeDuration \ (15)$$

To determine the Speed Threshold in this scenario we consider the mobile node moves through a distance d within coordinator POS, this distance is equal at least to the coordinator transmitting range (R).

$$Speed_{thresh(B)} = \frac{R}{\Big(\big(aMaxlostBeacons * (2^{BO}+1)\big) + N * \big(2^{n} + 33\big) + 32\Big) * aBaseSuperframeDuration}$$

(16)

We must notice that if there are many sensors that try to associate in short period of time or the mobile sensor sends high load traffic, then many collisions may occur and the mobile sensor may re-initiate the association procedure, which in turn reduces the speed threshold.

3.1.3 Third Scenario (Scenario C)

Third scenario is similar to the second scenario except that the two coordinators have parent-child relationship, so the distance between them is less than transition range, and the mobile node spent less distance within parent node POS as shown in Scenario (C) figure (1), if we assume the distance is not less than (R/2) then

$$\frac{Speed_{thresh(C)}= Speed_{thresh(B)}}{2} \quad (17)$$

4 Mobile Dynamic Tree Routing Protocol (MDTR)

In order to support mobility, sensors must update its one-hop neighbor table, removing some neighbors and adding new ones. To do that we had updated Dynamic Tree Routing Protocol to include these parameters: Neighbor's Relative Status (NRS), Time Out Period (Δt), and Link Reliability (R).

4.1 Neighbor's Relative Status (NRS)

We propose a variable called NRS to evaluate the relative status of neighbors to mobile sensor. It's default value is equal to zero, and when neighbor Link Quality Indicator LQI, which express the strength or quality of received signal [8] is above a certain threshold LQI_{thresh} , and its values is larger than its previous recorded one by at least ΔLQI, this mean that sensor is becoming closer to neighbor, then NRS = 1, NRS becomes (-1) when the quality falls ΔLQI below its previous value. Finally, sensors use NRS value to decide which nearby coordinator may be suitable as next hop.

4.2 Time Out Period (Δt)

We keep making benefit from overhearing packets which we were previously used in DTR, but we adjust the suitable Time Out Period Δt between sending the packet and receiving the overhear one from the next hop neighbor, according to mobile sensor speed and Beacon Order BO. Also when the sensor didn't hear any activity from its next hop neighbor during this period, it considers the link to this neighbor is unavailable or the neighbor is exhausted or the mobile sensor become outside the neighbor Personal Operating Space. In this case, the mobile sensor stops sending more packets to this neighbor until it sense new activity from it.

The max value accepted for Time Out Period is equal to the longest time the mobile sensor still inside neighbor POS, and it equal to the distance the mobile sensor still in the coverage area of its neighbor (d) to the mobile sensor Speed Threshold that in turn depends on Beacon Order.

$$\Delta t = \frac{d}{Speed_{\ threshold}} \quad (18)$$

4.3 Link Reliability in MDTR ($R_{(i,j)}$)

We consider the reliability of link between any two sensors is depend on the number of sent packets via next hop neighbor to the number of their received overhear packets from that neighbor. This consideration is derived from the main equation of link reliability, which equals to the number of successfully delivered packets to the number of sent packets [17].we used the following formula

$$R_{(i,j)} = \left(\sum_{n=1}^{N} Sn_{(i,j)} \,/\, \sum_{n=1}^{N} On_{(j,i)}\right)^{-1} \quad (19)$$

Where:

N : The max packet id of all sent packets from sensor i.

$Sn_{(i,j)}$: = 1 if the packet with id equal to n has sent from the sensor i to the sensor j, else $Sn_{(i,j)}$ = 0.

$On_{(j,i)}$: = 1 if overhear packet with id equal to n had sent from sensor j and has received correctly in sensor i, else $On_{(j,i)}$ = 0.

We also had updated the total Quality Factor $Quality_f$ to include the link reliability.

$$Quality_f = (\lambda_{er} * \frac{Neighbour_{energy}}{Max_{energy}} + \lambda_{qr} * \frac{Link_{LQI}}{Max_{LQI}}) * R \quad (20)$$

Where:

$\lambda_{er} + \lambda_{qr} = 1$. λ_{er} :Energy Factor. λ_{qr} :Link Quality factor.

4.4 MDTR Protocol Flow Diagram

The combination of NRS, Δt and Link Reliability give the mobile sensor a good mechanism to qualify the neighbors and links during mobile sensor movement, and help our dynamic tree routing protocol in tacking good routing decisions. The following figure represents the flow diagram of packet movement from the time of receiving to the time of forwarding, when using Mobile Dynamic Tree Routing Protocol.

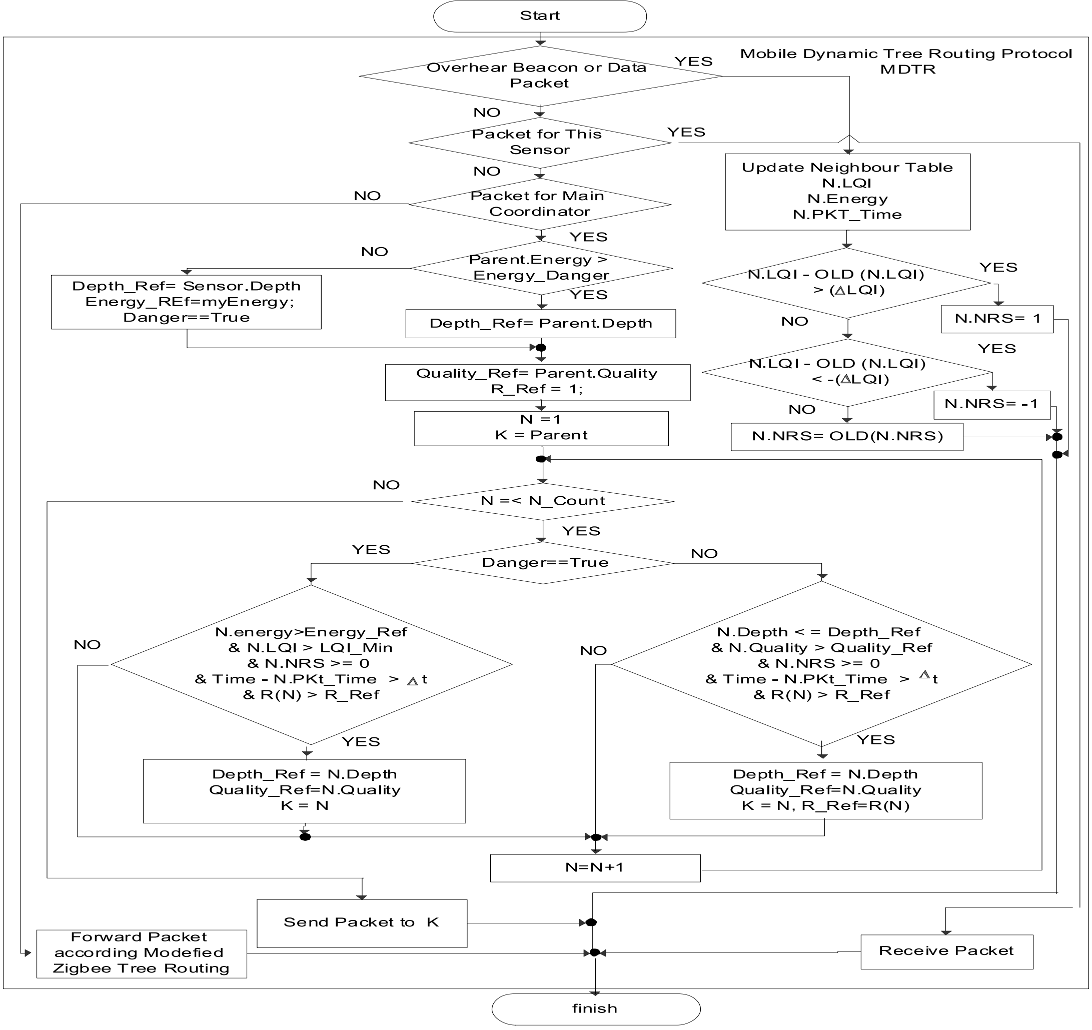


Figure (6) Flow Diagram of MDTR routing protocol in multi to one traffic pattern

5 Performance Evaluation

Network Simulator Version 2 with IEEE 802.15.4 module are used for comparing DTR with MZBR and AODV routing protocols.

5.1 Simulation Parameters and Performance Metrics

The network works in beacon-enabled mode, all sensors are Full Functional Devices FFD except mobile sensors is Reduced Functional Device RFD, they capable only in sensing and sending packets, each FFD sensor in the network sends beacon every 979.2 ms, the network was organized so that sending sensor to have enough neighbors in different depth to forward packets to. For simulations, we used the parameters defined in the table (2). The parameters were chosen so that all sensors capable to join the network. In addition, the sensors position and transmission range were chosen considering that network monitors an important events. For our protocol-specific parameters, we used a larger value for Link

Quality Factor LQI factor because when the sensor is moving, the neighbor link quality is more important than its remaining energy.

Table (2) General Simulation Parameters

Simulation parameters	Value	Simulation parameters	Value
Number of FFD	60	Maximum Children MC	6
Number of mobile RFD	6	Maximum Depth Lm	7
Network Size	120*120 m^2	Energy factor	0.25
PHY/MAC protocol	IEEE 802.15.4	LQI factor	0.75
Link model	Tow ray ground	Energy Danger	0.39 % Initial energy
Routing protocol	MZBR/AODV/DTR	Time Deference Δt	1 Sec
Simulation time	300 -500 s	Packet interval	1 Sec
Association duration	0–80 s	LQI_min	150
Transmission duration	80– 400 s	Initial Energy	10 Joule
Transmission Range	20 m	RxPower	35.28e-3 Watt
Packet type	CBR	TxPower	31.32e-3 Watt
Packet size	100 bytes	IdlePower	712e-6 Watt
Δt	10 Sec	Sensors Speed	0.5 m/s

Performance Metrics like hop count, end-to-end delay, packet delivery ratio PDR, and network lifetime are used to evaluate and compare DTR, MZBR, AODV Protocols.

5.2 Simulation Scenarios

The Network Simulator Version 2 NS2[18] was used for simulation. First, we had simulated the mobile sensor speed threshold according to scenarios (A, B) in order to verify the approximated values. Second, we had tested the operation of MDTR protocol in a wireless sensor network with one mobile sensor, then in a network with many mobile sensors moving in different paths, and we had compared its performance with AODV and MZBR routing protocols.

5.2.1 Simulate Scenario (A) Speed Threshold

In NS2 the available channels equal to 3, the scan duration is equal to beacon order $(n = bo)$ for main coordinator, and $(n = bo + 1)$ for other devices, and if we work in 2.4GHZ frequency band with 250kbps bitrate, with Beacon Order $BO = 6$, and the transmission range of all sensors R is equal to 20 meter then

$$aBaseSuperFrameDuration = 15.36\,ms$$

$$BI = aBaseSuperFrameDuration \times 2^{BO} = 15.3 * 2^{BO} = 15.3 * 2^{6} = 979.2\,ms$$

From equation (11):

$$Speed_{thresh(A)} = \frac{20}{\left(2*3*2^{6+1}+2*3+32\right)*15.36)} = 1.6218\frac{m}{s}\ (21)$$

$$Speed_{thresh(A)} = 5.838\ KM/H\ (22)$$

In Simulation we put the coordinator in the middle of simulation area, the mobile sensor initial position is (X=32.8, Y=11.6). We varied the initial vertical position (Y) of mobile sensor in order to make mobile sensor enter the coordinator POS in deferent times. Simulation results of scenario (A) are shown in the following figure (7).

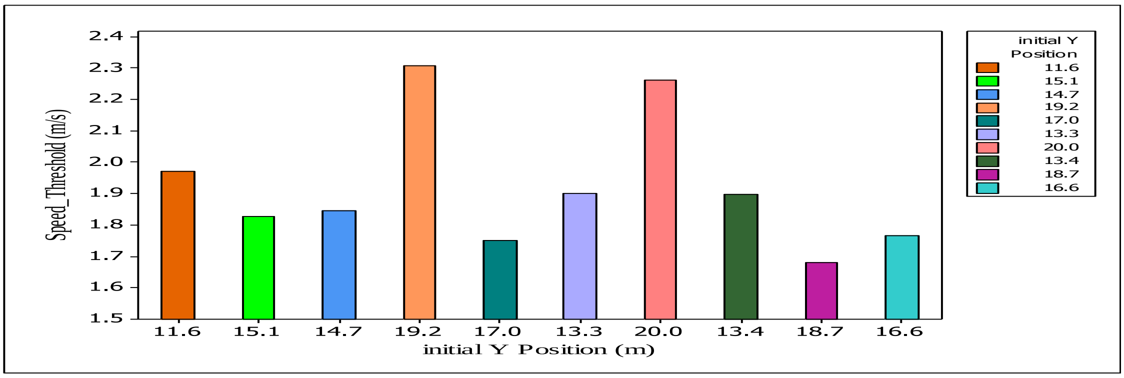


Figure (7) Scenario (A) Speed Threshold Simulation

We notice from the Previous figure (7) the difference in speed thresholds is large, it depends on the time the mobile sensor entered the coordinator POS according to its initial position. The range spread from best case when the sensor receives the beacon directly in its last channel scan upon entering the coordinator POS, to the worst case when the coordinator sends beacon in the first channel a little time before the mobile sensors enter it POS, where the mobile sensor must repeat the scan to detect the next beacon. From all these speed thresholds obtained from simulation tests, we care only about minimum speed threshold, which enables the mobile sensor to successfully join the network, regardless whatever the initial position, or the time it enters the coordinator POS. From figure (7) we notice this speed is very close to the approximated speed threshold calculated in equation (11) which equal to 1.6218 m/s.

5.2.2 Simulate Scenario (b)

In NS2 the max number of lost beacons *aMaxlostBeacons* = 4, and the mobile sensor spend a time equals to $((2^{\mathrm{BO}} + 1) * \mathrm{aBaseSuperframeDuration})$ to decide it has lost one beacon if we take the same configuration presented in scenario (A) then from equation (16)

$$Speed_{thresh(B)} = \frac{\mathrm{R}}{\left((\mathrm{aMaxlostBeacons}*(2^{\mathrm{BO}}+1))+\mathrm{N}*(2^{\mathrm{n}}+33)+32\right)*\mathrm{aBaseSuperframeDuration}}$$

$$= \frac{20}{(4*(2^6+1)+3*2^7+3*33+32)*0.01536} = 1.6801\ m/s = 6.04\,\frac{Km}{H}$$

If we consider that sensors are held by human or animal, then in normal walk model, sensors can join the network during movement when using the previous configuration. The simulation result of scenario (B) is shown in the following figure (8).

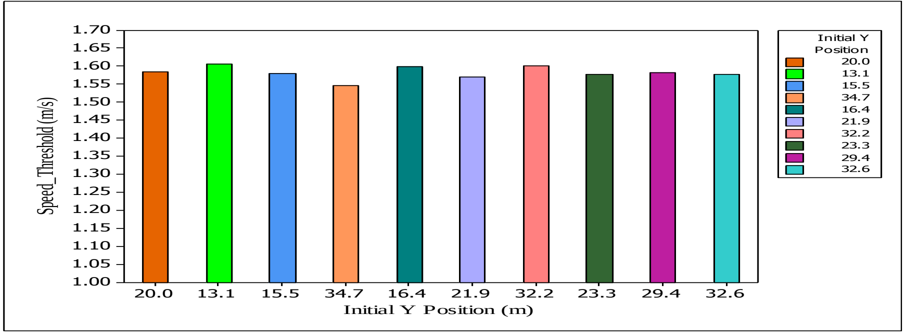


Figure (8) Scenario (b) Speed Threshold Simulation

We notice that the variance in Speed Threshold is less than scenario (A), and it depends on the time when the sensor received the last beacon from its parent before it enters the new coordinator POS, so the difference in Speed Threshold will not exceed the time required to lose one beacon which is about (1 Sec) when beacon order is equal to 6. Also, we notice that the approximated speed threshold is close to simulated speed threshold but it is a little higher than simulated value.

5.3 Basic Mobility Test for MDTR Protocol

In this test, sensor 71 sends Constant Bit Rate traffic to main coordinator "Sensor 0" while moving to a location near sensor 24. We set the initial energy sensor to 10 joules, and the simulation time to 250 sec. The following figures (9,10,11) show routing paths used by each protocol during sensor 71 movement, the shared paths are drawn with one arrow in these figures.

Figure (9) MZTR mobile sensors test

Figure (10) AODV mobile sensors test

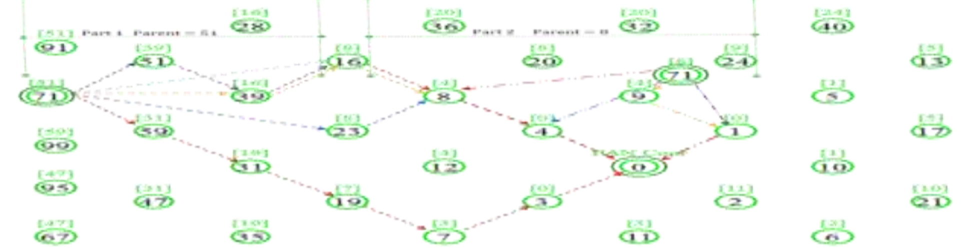


Figure (11) MDTR mobile sensors test

The following table shows general performance metrics of mobile test

Table (3) General performance metrics

Protocol	Routing Paths	Hop Count	Dropped packets	PDR %	e2e_delay (sec)	Jitter (sec)
MDTR	9	2.8935	18	90.00%	0.032177	0.0057
AODV	5	3.1111	30	83.33%	0.072020	0.0463
MZBR	2	3.5957	45	75.00%	0.044470	0.0198

We notice that MDTR used the maximum available paths toward main coordinator "Sensor 0", and kept hop-count less than other protocols, this reflected in good packet delivery ratio and a good end to end delay as shown in the table (3). MZBR used only 2 paths, it still using the first default hierarchical tree path (71,51,39,16,8,4,0) even the sensor 71 moved away from its parent, until it totally lost the connection with it, whereas MDTR sent packets to sensors 59,39,16,32 during this period when the sensor became closer to them and their quality became larger than sensor 71 parent quality. When sensor 71 lost the connection with its parent, and before deciding that it had actually lost the connection, MZBR Still forwarding packets to parent resulting in many dropped packets, while MDTR can detect that its parent is in abnormal state, and try to find any available neighbor to forward packets to it, saving many packets from dropping. AODV also could find other suitable paths while moving by triggering path search procedure before transition, but this brings more delay to packets, after sensor decides that it had lost the connection with parent, it begins orphan scan, then passive scan, during this periods sensor couldn’t sent or accept any data packets, until it re-associate with other parent. When sensor 71 complete association with new parent "sensor 8", it also still using the same second hierarchical tree path (71,8,4,0) when using MZBR until the end of simulation, Whereas AODV and MDTR could find other paths as mentioned before.

5.4 Sensor Mobility Test

Network size is 120*120m^2, and the main coordinator is in the middle of the network. The network consists of Full Functional Devices (Coordinator, Sub-Coordinators) which periodically send beacons, these sensors form the network backbone, and the network contains the Reduced Functional Devices (Mobile Sensors) which send Constant Bit Rate traffic with 100 bytes payload at a rate of 1 packet/second to the network main coordinator. We had configured the mobile sensors to move through the network in different paths towards and away from the main coordinator, in order to test the routing protocols action when the mobile sensor depth becomes higher or lower its parent depth. The paths from its initial positions to the final positions are shown in figure (12) with dashed lines. The network parameters Cm, Rm, LM are chosen to successfully build the network and to make sub-coordinators capable of accepting mobile sensors when they entering their POS while moving. When the network formation ends, the sensors join the network in multi-hop fashion with child-parent relationship similar to scenario (C) in figure (1), so the speed of mobile sensor speed were chosen tacking into consideration the approximated speed threshold defined in equation (17), which equal to the half of the speed threshold calculated in scenario (B) equation (16). The speed threshold in this case when using same other configuration is equal to

$$Speed_{threshold(C)} = \frac{1.6801}{2} = 0.84005\ m/s \quad (23)$$

The following figure (12) shows the Wireless Sensor network topology.

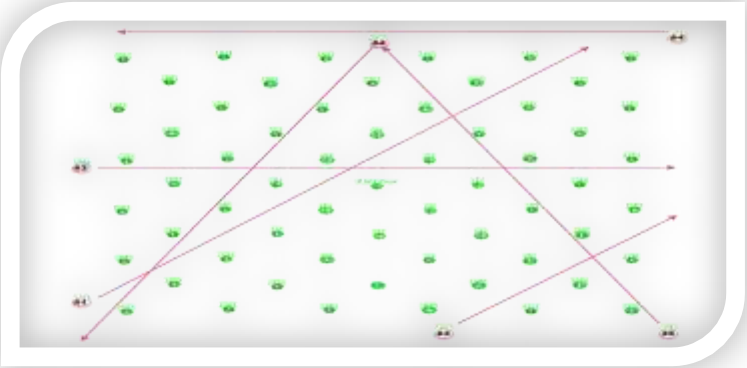


Figure (11) Wireless Sensor Network Topology

We notice that sensor (29) couldn't join the network because it couldn't locate any good quality beacon from nearby coordinators, but this not affects the operation of the network nor the routing protocols, cause every spot in the network is covered with more than one coordinator. So the lower depth nearby coordinators had found other parent to associate. The following figure (13) shows the simulation results.

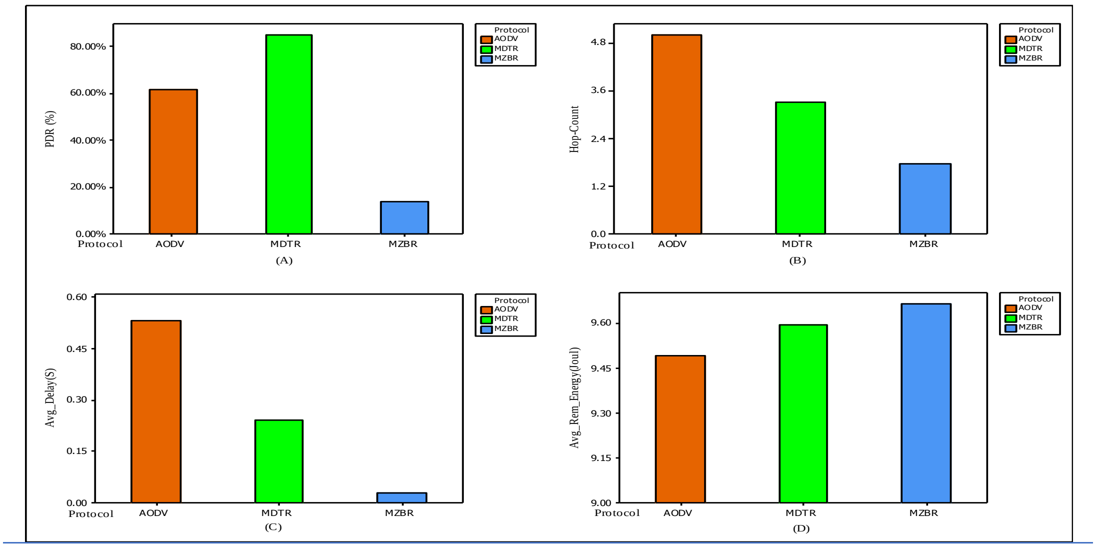


Figure (12) Performance Metrics of Routing Protocols (Packet delivery ratio (A), hop count (B), end-to-end delay (C), and average remaining energy (D))

From previous figure (13A) we notice that MDTR outperforms AODV and MZBR routing protocols in Packet Delivery Ratio (PDR), because our protocol becomes adaptive to changes in links and neighbors by using $(NRS, \Delta T, R)$ where (NRS) helps mobile sensor to avoid walking away neighbors, and (ΔT) helps to discard non-active neighbors, and (R) helps sensor to select a most reliable neighbor. Moreover when using MDTR the mobile sensor still capable of forwarding packets to other sensor when the link to its parent goes too bad in quality. The combination of previous factors reduced the number of lost packets, which in turn reflected in better packet delivery ratio. We also notice from figures (13B) and (13C) that MDTR outperforms AODV in average Hop-Count, and average packet's end-to-end delay, because it gives more importance to neighbor depth, and it always selects the nearest neighbor to main coordinator when available, while AODV may frequently select the best full path to the main coordinator which maybe not the shortest path. In spite of reactive routing protocols like AODV don't update the routing table until needed, the mobility if sensor causes many changes to the routing path which consume a considerable amount of mobile sensor resources as shown in figure (13D), and make more overhead in the network. Also if the paths change becomes larger due the increase of mobile sensor speed the AODV may become in-adaptive to that changes. MZBR Protocol offers worth Performance in term of Packet Delivery Ratio because when using this protocol the mobile sensor still sending packets to its parent although it moves away from it towards main coordinator which result in many packets drop. Good results in other performance metrics like hop-count and delay returned to the fact that only received packets will enter in calculating these metrics. For remaining energy, we can mention that MZBR like other ZigBee Hierarchal Tree routing protocol is energy-conserved protocol in nature, but the extra level of conservation as shown in figure (13D) is because dropped packets saved the energy of all forwarding sensors toward main coordinator.

5.5 Mobile Sensors Speed Test

We changed the speed of mobile sensors from a speed lower than speed threshold to a speed higher than the speed threshold, the following figure (14) shows packet delivery ratio according to mobile sensors speed.

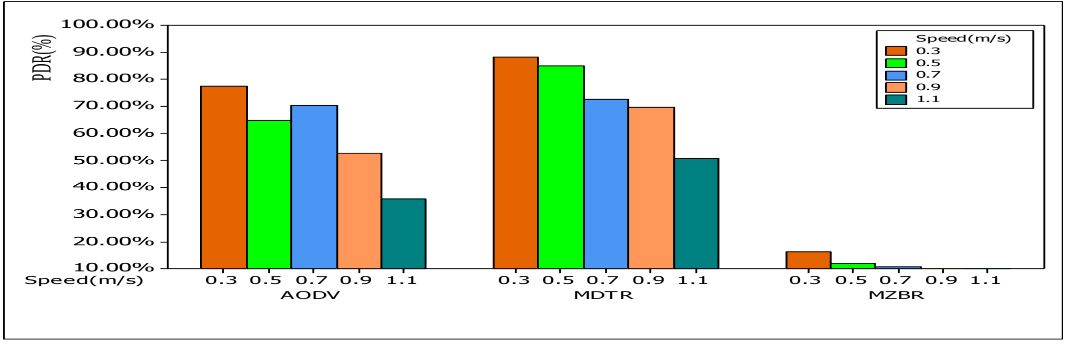


Figure (13) Percentage Packet Delivery Ratio according mobile sensors speed

We notice that packet delivery ratio decreases when sensor speed increases because when sensor speed increases the changes in link quality also increase and tracking these changes becomes more complex. When the mobile sensors speed becomes higher than speed threshold, the mobile sensor may unable to associate with nearby coordinators, instead it may associate with many-hop away sensors, and when the speed still increasing, the mobile sensor becomes incapable of associating with any coordinator in the network while moving. This happens partly when the speed equal to 0.9, and fully when speed equal to 1.1 m/s where packets received by the main coordinator is coming only from packets sent from initial and final positions of mobile sensors. We also notice that MDTR outperforms other protocols in packet delivery ratio in all speeds test, and the MZBR protocol performs badly in mobility.

6 Discussion and Challenges

Here we can highlight some points:

- When the application requires using mobile sensors which are hold by animals like forest fire detection application, then we can use the speed threshold equations to determine which animals we can use if the transmission range and beacon interval is fixed, or we can choose transmission range and beacon interval to obtain certain speed threshold in order to enable specific animal to join the network while moving.
- The association procedure consumes a large time during sensor movement, especially when we use multiple channels or when the beacon interval gets larger. Reducing this time, will help to increase the speed threshold and enable faster sensor to join the network, also this will improve the overall performance of all ZigBee hierarchical tree protocols, also improving parent selection criteria during association plays the main role in construction default hierarchical tree routing path, which affects the performance of ZigBee Tree Routing based protocols.
- When mobile sensor moves apart its parent and began to lose parent beacons, there is a chance of finding another coordinator during this period when using our protocol, while in modified ZigBee tree routing protocol sensor still forwarding packets to its unreachable parent until deciding that it has lost the connection and began the search for another one.

7 Conclusion

Sensor mobility leads to frequent changes in wireless links and frequent association attempts with new coordinators, however since association consumes a large period of time, and the mobile sensor may be unable to re-association with the network after it loses the association with a parent if it moves faster a certain speed called speed threshold. We approximate this speed mathematically and verify it by simulation. We also improved our routing protocol MDTR to be immune to the neighbors and links changes during mobile sensor movement, and to be capable of forwarding the packet to suitable next hop neighbor. The simulation results showed a good approximation of speed threshold and good performance of our protocol in term of delay, throughput and hop count compared with AODV and Modified ZigBee Routing Protocols.

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