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Designing a Maintenance Free Multi-Channel Wireless Sensor Network Protocol

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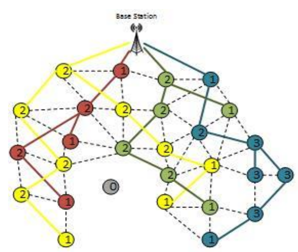
Graphical abstract



Abstract

Wireless sensors are low powered device that is scattered to monitor its surroundings. These energy-constrained devices are usually constructed in a hierarchical structured manner where after sometime some of the nodes may deplete energy resulting disruption of the routing topology in a wireless sensor network. A faulty parent node may cause the reconstruction of the network's routing topology if a maintenance solution is not provided to the protocol. Thus this study focuses on the maintenance free environment for a multi-channel wireless sensor network. A tree-based solution is proposed for the multi-channel protocol and a route diversion is proposed for the maintenance solution. The multi-channel characteristics is used as a tool to determine the route diversion of the children node. A simulation is built to compare the proposed protocol with existing tree-based multi-channel protocol. The result of the proposed protocol shows an improvement to the packet delivery rate by 15%.

Keywords: Wireless sensor network, multi-channel protocol, adaptive routing, tree-based protocol, maintenance-free WSN

Abstrak

Sensor tanpa wayar adalah peranti berkuasa rendah yang bertaburan untuk memantau kawasan sekitarnya. Alat-alat kekang tenaga ini biasanya dibina dengan cara yang berstruktur hierarki di mana selepas beberapa ketika beberapa nod kehabisan tenaga yang menyebabkan gangguan laluan topologi dalam rangkaian sensor tanpa wayar. Nod induk yang rosak atau bermasalah boleh menyebabkan pembinaan semula laluan topologi rangkaian jika penyelesaian penyelenggaraan tidak disediakan kepada protokol. Oleh itu kajian ini memberi tumpuan kepada persekitaran tanpa penyelenggaraan untuk rangkaian sensor tanpa wayar berbilang saluran. Satu penyelesaian yang berasaskan pokok adalah dicadangkan untuk protokol berbilang saluran dan lencongan laluan adalah dicadangkan untuk penyelesaian penyelenggaraan. Ciri-ciri pelbagai saluran digunakan sebagai alat untuk menentukan lencongan laluan nod anak. Simulasi dibina untuk membandingkan protokol yang dicadangkan dengan protokol pelbagai saluran berdasarkan pokok yang sedia ada. Hasil protokol yang dicadangkan menunjukkan peningkatan kepada kadar penghantaran paket sebanyak 15%.

Kata kunci: Rangkaian sensor tanpa wayar, protokol pelbagai laluan, penyesuaian laluan, protokol berasaskan pokok, rangkaian sensor tanpa wayar bebas penyelenggaraan

1.0 INTRODUCTION

In recent years, the wireless communication has advanced and the development of low-cost and low-power sensor nodes has grown tremendously. Typically, sensors are scattered in a rough environment and sometimes densely implemented. These nodes are expected to analyse the complex phenomena over large regions of space for long periods. Sensor nodes have the ability to compute, communicate and coordinate in a small transmission range. Although their capacities are limited, by combining these small sensor in a large number enables them to create a self-organized network called Wireless Sensor Network (WSN).

In a typical wireless sensor network setting, static sensor nodes are often deployed densely with one static sink. Data from surroundings are collected and processed by the sensor nodes and are relayed to the sink in terms of packets. Because of data relaying nature of the sensor nodes, sensor nodes that are closer to the sink consumes more energy and have shorter lifetime as compared to the one farther away. This makes the maintenance important for wireless sensor network. Most of previous protocol does not provide solution for the nodes deplete energy especially in multi-channel wireless sensor network. The cost of reconstruction for the whole network is high. A simple solution or alternative for node depletion is highly desirable.

In multi-channel WSN environment, the challenges is higher than in single channel because the nodes need to be on the same channel in order to communicate with each other. In a multi-channel wireless sensor network, it is important to keep the routing topology because the maintenance cost is higher than the topology of a single channel network. A good maintenance solution should be provided to the protocol. Therefore, a maintenance free solution is desirable and proposed in our research.

In the construction of multi-channel WSN, the channel assignment (CA) can be done in various ways. In a static channel assignment scheme, channels are assigned to each node at the beginning of the network construction. The energy set up cost for the static channel assignment is low and the channel assignment is often done centralized. In semi-dynamic channel assignment, the nodes may change its channels due to certain requirements. The semi-dynamic channel assignment schemes offer more flexibility but the channel assignment is not done very frequently. However, in dynamic channel assignment, the cost of topology reconstruction is less, though the construction cost is high. To fully exploit the distributed properties in wireless sensor network, the impact of a centralized and distributed channel assignment scheme is discussed in section 2.

For a static tree-based channel assignment, node depletion on the parent node would cost lost connectivity to the children node. In multi-channel WSN, an example of channel-based trees is proposed in [1]. A distributed WSN requires proper time synchronization. Most of the existing distributed protocol requires scheduling or a dedicated control channel in order to communicate. The distributed control system in need of time synchronization error that cannot be negligible [10, 11]. Improper channel synchronization may cause sender and receiver to be on different channel thus resulting in the deafness problem. It is crucial to ensure nodes to be in the same channel in order to communicate.

In this paper, a channel trees is proposed using a concept of channel hopping to connect the lost tree branch to other channel's tree branch and makes it maintenance free. The constructed channel trees is useful for data relaying especially in many-to-one communication which is a common application of WSN. The proposed protocol is then compared to existing multi-channel trees network in terms of the packet delivery rate. For performance evaluation, extensive simulation experiments has been carried out and the simulation results indicate that the proposed maintenance free approach outperforms the existing multi-channel protocol in terms of data delivery rate.

In the state of the art multi-channel wireless sensor network, the construction of the multi-channel architecture is done either by centralized or distributed. These approaches are discussed scrupulously in this chapter.

The basic primitive function for a sensor nodes is to gather information from its surrounding through its sensor, make some computation locally and transmit the desired data to a base station where all the information is gathered. A general objective of wireless sensor networks is to relay messages from sensor nodes to the base station(s).

Most of the previous works on the wireless sensor network focus on prolonging the network lifetime, providing the network connectivity among sensing related devices and guaranteeing the network coverage.

By using multi-channel, the problem of interference can be reduced. However, using multi-channel it is costly to setup the network. Most of existing study on multi-channel approaches include two separate phase of operation such as the channel assignment and medium access. In single channel, the medium access takes place directly. Therefore, the channel assignment procedure requires communication and time at network initialization. If the channel assignment is combined with other initialization activity, such as topology construction, the overhead could be reduced.

Typically, multi-channel protocols consist of three major channel assignment schemes, namely static channel assignment, semi-dynamic or dynamic. A static channel assignment scheme assigns channel at the beginning of the network implementation, while a dynamic channel assignment assigns channels dynamically according to the current changing requirement.

Wu *et al.* presented in [1], that it is not suitable to use a distributed channel assignment, or described as node based in the paper, such as proposed in [3, 6, 7], because the cost of the construction of dynamic channel assignment is high. Therefore, they proposed a static channel assignment for a real application. In the state of the art, most channel selection process are executed at the beginning of the system deployment and remained unchanged. This is called the static channel assignment. Like Wu *et al.,* [8] also suggested a tree-based relaying network in WSNs. However, they does not provide solutions for multi-channel WSNs.

For a centralized system as presented in [1], it assigns a static channel assignment and indirectly assigns its routing topology. The notion of the TMCP protocol is to partition the whole network into multiple subtrees all rooted at the base station and allocate different channels to each subtree, and then forward each flow only along its corresponding subtree.

It is a static channel assignment where no real time information gathered and it is not changing according to the current requirement of the network. Some of developed protocol uses traffic information to assign frequencies such as in [12]. This is quite important where traffic patterns may change significantly during runtime and some nodes or segments of the network may have more traffic than others.

A good channel assignment method should have the flexibility to effectively alleviate radio interference among concurrent transmissions and reduce packet congestion within a single channel. It is the key performance factor for multi-channel communication. In a centralized system [1, 2], a control node needs to make decision for far away nodes and stores a lot of information about far away nodes. A centralized system involves high communication cost for the network construction.

On the other hand, a distributed system [3, 6, 7] is able to compute only local part of a problem solution only. A well develop distributed system can function correctly from global perspective even if some of the nodes are crashing. However, dynamic channel assignment may need scheduling or synchronization in order for it to work accordingly. In multi-channel wireless sensor network, nodes need to be on the same channel in order to have a successful communication.

Based on the observations discussed in this section, we note that a channel assignment that takes place in a multi-channel indirectly gives the routing options to the nodes. Using this observation, we note that the semi dynamic channel assignment offers a more flexible routing options for the channel assignment than a fixed routing such as presented in [1].

With uneven traffic distribution, frequency assignment schemes of static protocols may fail to provide good performance due to unfair channel load distribution.

Considering the complexity of the channel assignment in dynamic channel assignment multi-channel WSN that requires proper scheduling and synchronization, it is concluded that a semi-dynamic channel assignment offers a simpler solution and able to maintain the connectivity on the multi-channel network.

In [4, 9], existing intelligent routing for multi-channel has been discussed. In this paper the idea of combined routing which also integrate intelligent routing is proposed. We proposed on the semi-dynamic channel assignment strategies for multi-channel WSN for the connectivity-oriented deployment and the lifetime-oriented deployment. The channel assignment is solved while concerning the network lifetime and the connectivity ensuring route diversion for faulty nodes.

The proposed multi-channel WSN protocol composes of a three-phase placement solution in which the first two phase focuses on building a multi-channel network forest to provide the basic connectivity to the whole sensor network, and the third phase focuses on forest maintenance, which will be further discussed in the next section.

2.0 METHODOLOGY

In this section, the model framework is explained in the subsection 2.1, while the implementation of the framework is discussed thoroughly in the next subsection 2.2.

2.1 Model Framework

The proposed model focuses on single radio multi-channel wireless sensor network where this paper addresses the usage of multiple channels efficiently. The proposed algorithm consists of channel tree-construction and the channel-tree maintenance. The tree construction is only done once for the setup of the network tree structure; while the tree maintenance is done purposely to maintain the connectivity of the network and therefore the process is repeated until all nodes depletes its energy. This subsection will also describe the channel assignment process and data forwarding process that is to be implemented in the network construction and maintenance phase.

2.1.1 Channel Assignment

The proposed channel assignment scheme are done semi-dynamic. Figure 1 describes the proposed channel assignment schemes. In the tree construction process, the channel assignment are done centralized. The best channel is chosen for each node, and each node is stays on the chosen channel until there is topological changes in the network. When this happens, the node undergo the tree maintenance period, where the adaptive channel assignment takes place in a distributed manner. In this setting, the node will use the information it already has during the tree construction to make a decision for itself for the choosing best channel it should use in order to stay connected to the network.

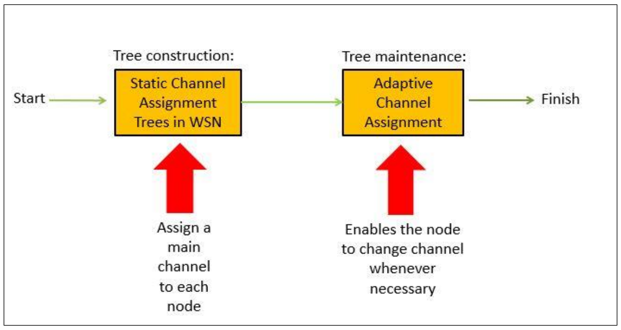


Figure 1 The Channel Assignment Scheme in Tree Construction and Tree Maintenance

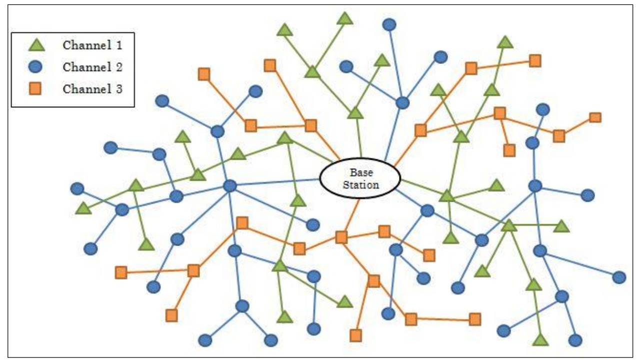


Figure 2 Multiple Channel Network Forest Structure

The tree construction and tree maintenance procedure is further described in the next subsection.

2.1.2 Channel Tree Construction

The tree construction is done in two parts namely, neighbour classification and the channel initialization. Both of these are done in a centralized manner. The channel tree construction mechanism is initiated by a Base Station for the purpose of data delivery from sensor nodes to the Base Station. The proposed protocol adapts the tree-based approach by pre-determining the best channel to connect to. The operation of the tree construction consists of two mechanism; the Neighbour Classification Phase and the Channel Initialization Phase. Figure 2 describes the conceptual channel trees that forms a network forest using 3 channels. The structure is started to be given in the channel initialization phase. Using the information gathered from this phase, a channel is given in the channel initialization phase. After the channel tree has been constructed, the tree structure will undergo a maintenance period and this is done on the Adaptive Channel Assignment Phase.

2.1.3 Data Forwarding

After the tree construction is done, each sensor node has a channel, and it belongs to the channel tree that is the shortest path route for data forwarding to the Base Station. Now, the data can start to be collected from the surrounding and data can start to be forwarded to the Base Station. A node with packets forwards data messages to its parent that has been previously determined in the second phase. During data forwarding, some of the transmission may fail because of various reasons. A common reason for failure is collision or because of the parent node has deplete its energy. A failure can be detected from the missing acknowledgement messages from the intended receiver. The proposed protocol offers an alternative route to recover the high failure rate in intended receiver. The process of recovering failure nodes is by changing the channels, making a new branch into the neighbouring channel trees, so the connectivity of the network is maintained throughout the implementation. The process is described in the next section.

2.1.4 Channel Tree Maintenance

A tree maintenance is proposed and the whole network reconstruction is avoided by changing the parent of nodes with high failure rate. The tree structure is maintained by making each nodes keep the information on its parent and child during the neighbour classification phase. When a packet is in queue, each nodes sends a message to its neighbouring nodes. When a child node does not receive an acknowledgement message from its parent for a given time interval, it recognizes the failure of its parent, due to energy depletion for example, and sends updates failure rate in itself.

It keeps on updating the failure rate. If a child receives no data for some time interval, it assumes that its parent is no longer active to serve and find a channel with less failure rate for itself.

Due to changing requirements in the network, the channel assignments can be renewed by following the success and failure rates of the packet transfer. If the effective transmission range of a node is r and one BS is placed at the centre of a rectangular field.

2.2 Proposed Algorithm

In this subsection the implementation of the tree construction and the tree maintenance is discussed extensively. The tree construction consists of two phases, namely the neighbour classification phase and the channel initialization phase. The network maintenance phase consist of one phase namely the adaptive channel assignment phase.

2.2.1 Tree Construction: The Neighbour Classification Phase

In order to build a network forest consist of few channel trees such as shown in Figure 2, the whole network undergoes the neighbour classification phase. This phase is initiated by the base station, which is denoted as the root r, followed by next level nodes, which are the nodes that are one hop away from the base station. The process is repeated until the highest level of the network. This phase consists of two processes: getting number of hops for each node v, and classifying neighbours into set of children $Children_v$ and set of parents $Parent_v$. In the model network, a message flooding is done level by level. Starting from the base station, the base station will send a message to the nodes that is within its range. These nodes, say, node v, has an attribute which is the minimum number of hops to the Base Station. Since it has direct connection to the Base Station, the number of hops is said to be 1. After that, these node will send a message to its neighbours, informing its number of hops. The nodes receiving it are included in the set of children of node v, $Children_v$, and since it do not have a direct connection with the Base Station, the minimum number of hops it needs to send a message is the $hops_{Children_v} = hops_v + 1$. Then, the process is repeated until the maximum height of the tree. Figure 3 shows the minimum number of hop in a sample network.

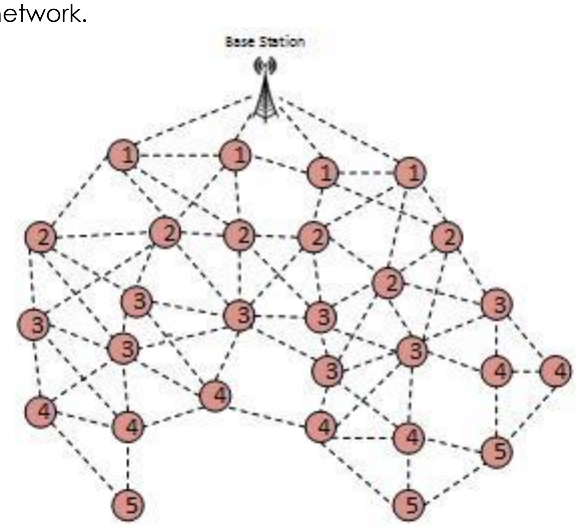


Figure 3 The Minimum Number of Hops

At the current phase, all nodes use one default channel as a control channel to ease the channel assignments. In a flat network, w is defined as a neighbour of a node v if these nodes are interconnected with each other based on physical proximities, that is, the nodes are in the communication range with each other. The algorithm for the first phase is described step by step as follows:

Step 1: The root sends a message to the nodes that are in the first level.

Step 2: When a node receives the message, it records its number of hops as 1, and adds the root as its parent.

Step 3: The node then sends notification messages about its id and the number of hops to its neighbouring node(s) in the next level.

Step 4: When the neighbouring nodes receives the message, the sender ID is added to its list of $Parent_v$, and set the number of hops where the $hops_{Children_v} = hops_v + 1$. .

Step 5: Then, the node sends an Ack message to the sender and the sender add it into the list $Children_v$.

Step 6: Each node set its number of neighbour as the number of its intra-channel interference

Step 7: The process is repeated until it reaches the highest level of the network.

After the implementation of this phase, the flat network has yet to have a multi-channel tree structure. This phase functions as a preparation of information needed in the channel assignment phase. The intra-channel interference is calculated in this phase. Since all nodes are using single channel, each node uses the number of neighbours as the intra-channel interference. The classification of neighbours in this phase is to be used in the third phase in determining the data relaying path. In this phase, each node v in the network transmits one message and receives W_v messages, where $|w_v|$ is the degree of the node v in the tree.

2.2.2 Tree Construction: The Channel Initialization Phase

After the implementation of the first phase, the second phase of the algorithm is initiated. In this phase, the channel assignment is done centralized, according to the number or intra interference inf_v that has been set up in the first phase.

Starting from root r or the base station, a network forest consists of k channel trees, is built in this phase where the root is the control station for the second phase as it decides the channel assignments for each node.

Each channel tree T_{ch} is the shortest path routing tree from the root to every node and each channel tree T_{ch} starts from the root r.

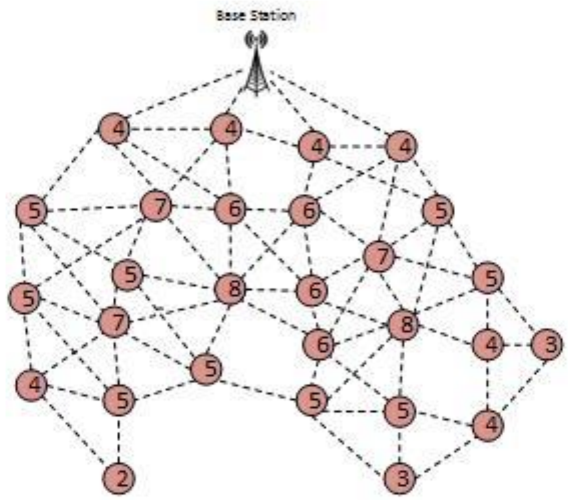
In Figure 4 (a), all the nodes are using the same channel. The use of multiple channel reduces the intra channel interference as shown in Figure 4(b). The step by step channel assignment in the tree construction period is describes below:

Step 1: Starting from $level = 1$ and channel ch = 2, the Base Station assigns a channel to each node by adding u into the channel tree T_{ch} for certain condition.

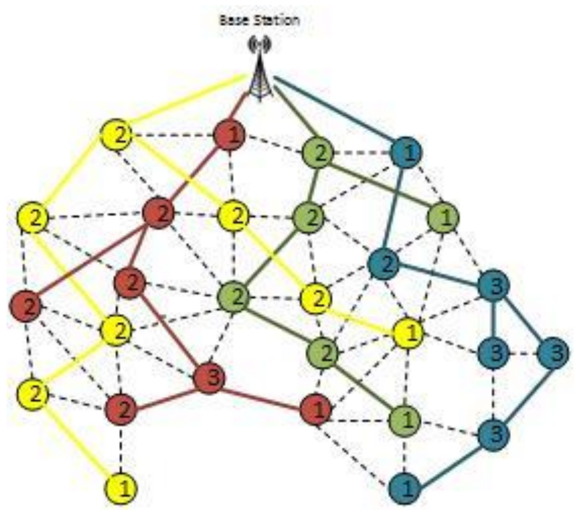
Step 2: Node u is added to the channel tree T_{ch} such that by adding u makes the least interference to channel tree T_{ch}, and u is assigned channel ch such that it does not exceed the maximum intra-interference.

Step 3: Node u then informs its neighbours about its current channel to be used in the third phase.

Step 4: Once all of the nodes in this level are assigned with a channel, the process is repeated in the next level. The nodes at the next level choose one of the channels that are being used by its set of parents to ensure connectivity, and one parent that is using the same channel as the node is elected to be its main parent.



(a) Before channel assignment



(b) After channel assignment

Figure 4 The intra channel interferences reduces after the channel assignment using multiple channel trees

2.2.3 Tree Maintenance: The Adaptive Channel Assignment Phase

After the second phase, a dynamic routing is achieved by the channel hopping mechanism. Here, the proposed protocol suggests the concept of channel borrowing and channel reuse as it allows the network to respond to the requirement quickly. In this phase, each node is an autonomous node where decision for channel allocation is done locally.

Step 1: A node forwards the packet to its parent.
Step 2: If the packet is received by the parent, node waits for next task in next round.
Step 3: Otherwise, failure rate in each node is updated.
Step 4: Repeat Step 1 to Step 3 until failure rate reaches a threshold.
Step 5: The node changes its channel.
Step 6: Eventually, the solution of the best channel of each node converges, and the node keeps using the same channel, until another occurrence of node failure or congested channel.

Failure rate increases each time a node fails its transmission. The rate increases each time the node fails to deliver the message, until it reach a threshold level. Using this method, the tree maintenance process ensures the connectivity other the children nodes by letting the nodes to gets nodes to get attached to another channel trees when the parents depletes its energy using the rules mentioned above.

Figure 5 shows a sample network condition when a node depletes its energy. The network is the same network in Figure 4, except that the node shaded in grey has leave the network where previously, it has two children. Using the rules as stated above, the children simply choses other parents and get attached to other the channel trees. Using locally made decision, the global network is maintained.

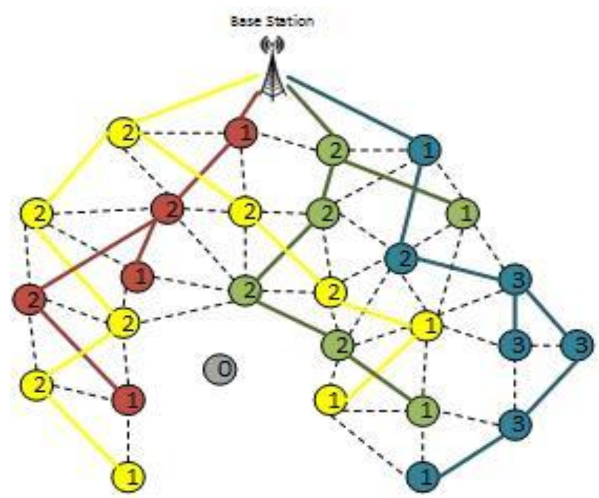


Figure 5 The Tree Maintenance

When the channel decision is done locally, the autonomous nodes would be able to divert its path whenever a channel is busy, to balance the network load, or to permanently divert the path to other candidate parent.

This could ensure a clean end-to-end data transfer. Since each node now can make a decision within itself, the coordination among nodes is achieved without central authorization, scheduling or completely sharing information. Figure 6 shows the flowchart of the adaptive channel assignment phase.

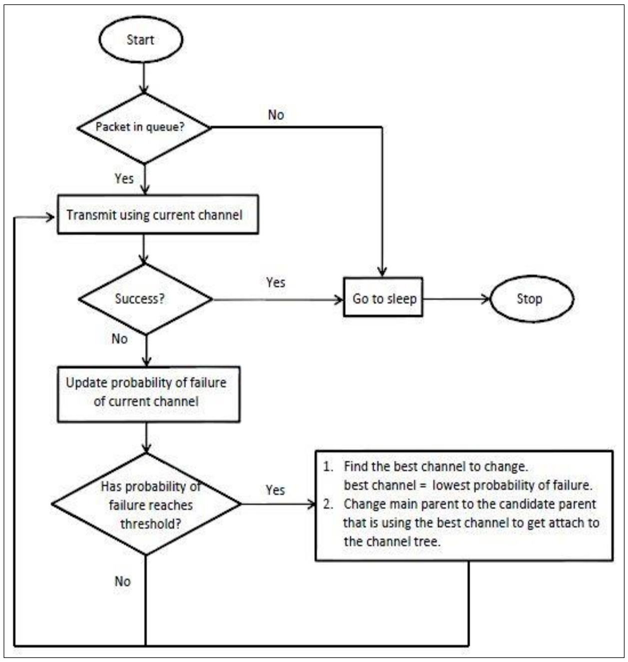


Figure 6 Adaptive Channel Assignment Phase

3.0 RESULTS AND DISCUSSION

Simulation experiments has been set up to evaluate the performance of the proposed approaches. The simulation is described in this section. An object-oriented programming is used to develop the simulation using JAVA to simulate a realistic communication. An assumption is made in this model where a node is assumed to be able to received message whenever it is in the transmission range of the sending nodes. We used a simplistic interference models, which is fixed ranges for communication and interference. For the analysis on wireless sensor network simulation, a simple interference models are used in which only take interference signals from nodes in a particular range into account. In conducting this experiment, the radio model used is the CC2420 radio transmission, power consumption model as in [5].

In order to simulate the data transmission, time is discretized into a number of iteration *rounds*. In each round, a reliable data transmission in each round is assumed. Each node can tune it transceiver into sending, receiving or idle. In the network, the proposed method adopt the tree-topology where a parent node may have a several children nodes, and because of its half-duplex properties, only one node could send or receive message at a time.

In other words, in each *round*, only one node can send or receive message. In the data transmission process, each node can only either be in their sending or receiving mode because of it is considered to have only one radio. The transmission from the sender to the receiver is assumed to be successful according to a certain rules:

Case 1: If a destination node t has depleted its energy or it is in offline mode, the data transmission has failed.

Case 2: If the receiver is in idle mode, the destination node will change the status to receiving. In this case, data transfer is considered to be successful.

Case 3: If the destination node t is in either sending or receiving mode from other sender node, the collision is assumed to happen and data transmission is failed.

After each *round*, the node is assumed to be idle if there is currently no packet that it is currently holding. In the same *round*, it is ready to receive a packet if the node is idle. Nodes that are having a packet will forward the packet to its parents. If a node has depleted the energy while it still holds some packets, the packets is considered lost.

3.1 Experiment 1: Network Priority

In this experiment, 250 nodes are scattered randomly on the field. The base station is set to be the middle of the field. In the simulation, after the tree has been set up, after the channel trees has been constructed, packets are generated at each node, and the packet is relayed to the parents. The nodes which still has the packet will relay it to their parents until it reaches the Base Station. The performance of the proposed protocol is evaluated by comparing the end-to-end packet delivery ratio (PDR) that is the ratio of the number of packets successfully received by the Base Station to the total number of generated packets.

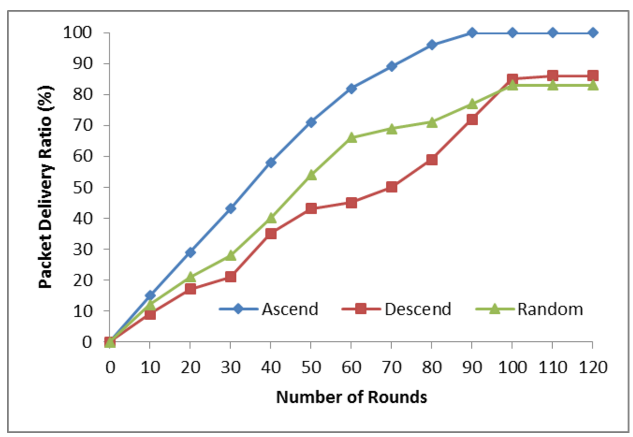


Figure 7 Comparison on the packet delivery ratio of ascending, descending and random ID priority

Each node is given an ID, where the ID is given by the Base Station based on the physical distance to the Base Station. The one that is closer to the Base Station is assigned a lower ID and vice versa. In this experiment, the ID priority is investigated whether it affects the packet delivery ratio. For example, in ascending order id priority, nodes with lower id is given the higher priority to send message.

This experiment has been repeated in the same network coordinate with different ID priorities. As shown in Figure 7, the ascending ID order achieves packet delivery rate of 100%. By giving different type of priorities to the sending nodes, it is proven that the ascending order performs better than descending ID and random ID priority.

To analyse this results, we must note that the closer nodes are given lower ID. An ascending order priority means the closer ID nodes are given priority to do any tasks than the one farther away nodes. This is because lower ID nodes may be the parent node. When parents node given the priority to forward the packet, the parents are in the lower number of hops, so data losses due to energy depletion is less likely to happen. On the contrary, when children node are given the priority to communicate, the parents node needs to wait until all packets are collected packets from the children node before passes all the packets one by one to the next level node. From this results, it is concluded that using ascending ID order gives better PDR than the lower id. Therefore, in the next experiment, ascending ID priority order is used to compare the result with similar work. The neighbouring nodes with hop count less than that in the message forwards the message to the neighbouring nodes.

From the experiments, it is shown that the ID priority in selecting the winner node to send message has given some impact in the overall network performance. This gives the basis of our data relaying scheme and the results is generated based on this scheme.

3.2 Experiment 2: Comparison of the Proposed Protocol with Existing Tree-based Protocol

Using the same network such as in Experiment 1, the performance of the proposed protocol is compared to previous developed protocol [1]. In this experiment, an ascending ID priority is used to generate the result to compare the proposed protocol with the existing tree-based protocol proposed in [1]. It can be seen in Figure 8 that the proposed protocol reaches 100% packet delivery rate and while PMIT protocol reaches 85%. Since the proposed protocol offers the maintenance solution, it can avoid the packet lost because the route has been diverted to other channel trees. 15% of the packets lost in the transitional node(s) that has depleted its energy. The energy waste factor that has been considered in this experiment is including the idle listening and energy lost during sending messages retries in each round during the operation phase.

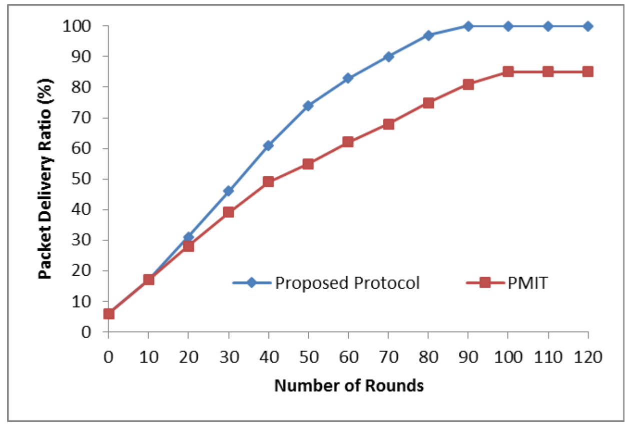


Figure 8 Comparison of the proposed protocol with PMIT in terms of PDR

Implementation of the idea of this proposed protocol has shown an improvement of previous protocol where it offers more flexibility and fault tolerance form the one in [1]. It is to be noted that the network density has much effect on the network, on the channel tree topology and thus it effects the overall network performance. In future, a suitable number of channels and children node is to be further investigated.

By using the proposed protocol, the dedicated control channel can be fully eliminated and there is no need to do scheduling after the third phase implementation. Therefore, it can avoid time synchronization error as used in previous distributed protocols. It also uses less channel resource and could significantly increase PDR compare to a scheme with a fixed channel assignment in a high traffic rate. The exact advantage depends mainly on other variations used in the network.

4.0 CONCLUSIONS

In previous sections the proposed algorithm for maintenance free tree-based multi-channel wireless sensor network has been presented. The conclusion that can be drawn from this research is that the development process of the channel assignment is an effective way to build a maintenance free environment to address node failure.

In this paper the performance of the proposed protocol is compared with existing literature in terms of packet delivery ratio. In the next experiment the end-to-end delay and the network lifetime will be further investigated.

Acknowledgement

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