

# Studies on determination of the optimum distance between the Tmotes for optimum data transfer in a network with WLL capability

N C Santhosh Kumar, N K Kishore

**Abstract**—Using mini modules of Tmotes, it is possible to automate a small personal area network. This idea can be extended to large networks too by implementing multi-hop routing. Linking the various Tmotes using Programming languages like Nesc, Java and having transmitter and receiver sections, a network can be monitored. It is foreseen that, depending on the application, a long range at a low data transfer rate or average throughput may be an acceptable trade-off. To reduce the overall costs involved, an optimum number of Tmotes to be used under various conditions (Indoor/Outdoor) is to be deduced. By analyzing the data rates or throughputs at various locations of Tmotes, it is possible to deduce an optimal number of Tmotes for a specific network. This paper deals with the determination of optimum distances to reduce the cost and increase the reliability of the entire sensor network with Wireless Local Loop (WLL) capability.

**Keywords**— Average throughput, Data rate, Multi-hop routing, Optimum data transfer, Throughput, Tmotes, Wireless Local Loop.

## I. INTRODUCTION

In recent years, wireless communication has experienced phenomenal growth caused by the need for connectivity. A low-rate wireless personal area network (LR-WPAN), is a network designed for low cost, ultra-low-power, short-range wireless communications. The range of transmission can be increased with tradeoffs. It is foreseen that, depending on the application, a long range at a low data transfer rate may be an acceptable trade-off [1]. The TmoteSky is a readily available hardware kit for data acquisition and data transmission. Therefore, it must adhere to certain protocols, failing which the entire monitoring system becomes less reliable. The distribution monitoring system, which is under investigation, is a Wireless Personal Area Network (WPAN). The LR-WPAN protocol is modeled according to IEEE 802.15.4 standard and Zigbee specification [2]. The analysis is carried out to workout suitable distances between the Tmotes for which there is minimum loss in data transfer. The only way to calculate the loss of received packets is by including an acknowledgement byte (ACK) along with the actual data. The result of the analysis invariably includes an error, as the ACK bytes are not programmed with the actual payload data. The investigation is performed on a data packet, where there are no ACK bits programmed. Manual check is not possible for the simple reason,

that it is too time consuming to obtain even a single data point on the Error Vs Distance plot. The wireless industry focuses on communication with higher data throughput, leaving out a set of applications requiring simple wireless connectivity with relaxed throughput and latency requirements[3]. These intended applications require low-complexity wireless links that are low in cost relative to the device cost. In order to reduce the cost of the components and to facilitate production of these devices, the development of standardized protocol solutions are necessary[3]. TaskGroup4 of the IEEE 802.15 Wireless Personal Area Network working group defines a wireless communication standard protocol for LR-WPANs under three categories i.e. data rate, battery drain, and quality of service (QoS). A Wireless Sensor Network (WSN) usually consists of 10s to 1000s of such nodes that communicate through wireless channels for information sharing. On a network, data is divided into pieces and packaged for transmission over the network. Called packets, these pieces all have additional information attached to them. At the minimum, the "label" has the address of its destination on the network and that of the computer sending it. It also has a sequence number so that the packets can be reassembled in proper order. (There are other items included as well, but these will do as the actual data can be obtained from the sequence numbers of the various packets and its corresponding labels. With the help of the destination computer ID, it may be verified whether the payload has reached the exact destination). A WSN consists of low cost nodes which could either have a fixed location or could be randomly deployed to monitor the environment. Sensors usually communicate with each other using a multi hop approach. The flow of data ends at special nodes called base stations (sometimes also referred as sinks). A base station links the sensor network to another network (like a gateway) to disseminate the data sensed for further processing. Base stations have enhanced capabilities over simple sensor nodes as they have to carry out complex data processing; this justifies the fact that base stations should have workstation class processors. Usually, the communication between base stations is initiated over high bandwidth links. Keeping in mind, one of the biggest problems of sensor networks is power consumption, which is greatly affected by the communication between nodes. To solve the issue, intermediate aggregation points are introduced in the network. This reduces the total number of messages exchanged between nodes and saves some energy. Usually, aggregation points are regular nodes that receive data from neighboring nodes, perform some kind

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of processing, and then forward the filtered data to the next hop. As a result of this added information, the data transfer rate associated with any medium refers to the maximum amount of total data transmitted per second, including "address labels." The actual content transmitted is less. In wireless networking, there is even larger additional information than that encountered in cabled connectivity. As a radio is used, a small slice of time is used to switch from transmit to receive mode. Other internal functions required to receive data signals from the bridge and alter them to work over a radio connection consume more slices of time. Since time lost equals data throughput lost, a radio connection generally is not as efficient as a direct-cabled connection. Much of the recent work in ad-hoc routing protocols for wireless networks [4], [5], [6] focuses on coping with mobile nodes, rapidly changing topologies, and scalability. Less attention is paid to finding the efficient way of using the nodes for maximum data rate and minimum loss in data. The contribution of this paper deals with optimizing the performance of the nodes under changing topologies. The routing technique used is the multihop data transmission. Minimizing the hop-count maximizes the distance traveled by each hop, which is likely to minimize signal strength and maximize the loss ratio[7].

## II. EXPERIMENTAL DETAILS

The experiment is carried out with a 2 Node network as well as a 3 Node network for analyzing the average throughput of the network. When the distance between the nodes is increased, packet collisions take place and few packets are resent due to dropping of packets. To analyze the performance of the network under increasing number of nodes and varying network congestion levels, an experiment is carried out with the total number of sensor nodes in the network increased upto 7. The coordinating nodes are the TmoteSky modules. The master computer is placed at the receiving end node, where data analysis is necessary. For reasons of simplicity in calculations and analysis, the distance between any 2 nodes in the network which consists of more than 2 Nodes, is taken to be equal. This reduces the complexity involved in the data throughput calculation and analysis at the receiving end node. If the distance between any two nodes is not equal, the average throughput of the data rate between the two sections is to be deduced. In Fig. 1, (if  $d_1 \neq d_2$ ), the data rate between the two sections will be different. The total network traffic will be the average of all the data rates across the different sections. When the number of nodes increase, it becomes increasingly difficult to work out the average of all the data rates. Moreover, the data rates calculated, when the distance is not equal can not be used as a reference for designing a network. Thus, the entire work is carried out with equidistant nodes. Fig. 1 shows the complete block schematic of the experimental network employed in this work. Fig. 2 shows the setup at a height 'H' from the ground plane. The antennas play an important role in data transmission when the motes are in a noisy environment. The location and orientation of the antennas play an important role in lossless data transmission. Initial experiments are performed with the antennas at ground level. Literature indicates that, the antenna

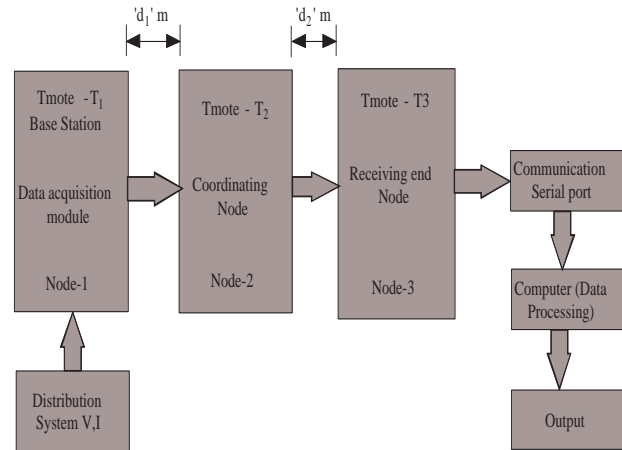


Fig. 1. Block diagram of the experimental setup

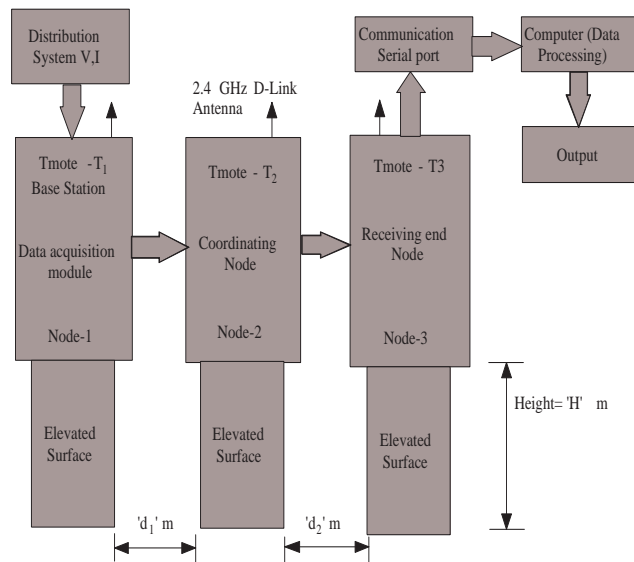


Fig. 2. Scheme depicts 3 node network with motes placed at height 'H'.

performance improves with the distance, when placed above the ground [8]. The aim is to analyse the change in average data throughput values as a function of distance. The data analysis is also carried out for a Multihop network. To realize a Multihop data transmission network, 3 or more nodes are to be used. The experiment is carried out with 3 Nodes. Tmote at Node 1 is responsible for data acquisition from the distribution system. The other function is to transmit the acquired data to Node 2. Multihop data transfer allows the TmoteSky module to transmit the data through a series of hops in the network. The first hop ends at Node 2. Node 2 transmits the data to Node 3.

The TmoteSky module at Node 3 receives the data and transmits the data to the PC to which it is connected. The data transmission takes place by means of a serial communication port. The data to be analysed is obtained by accessing the serial

port to which the TmoteSky module is connected. The idea of placing the Tmote at a height 'H' facilitates a better line of view for the antenna to improve its gain. The gain depends on the S/N (Signal to Noise) ratio, where S is the signal strength and N indicates the magnitude of Noise induced in the signal.

### III. EXPERIMENTAL METHODOLOGY

One of the factors of foremost consideration is free right of way and line of sight, in which the signal to be transmitted does not get any hindrance from the environment[9]. So, it may be said that the experimental verification of results and compliance of standards are subject to a certain degree of error or have a tolerance. Scheme in Fig. 1 and Fig. 2 can be extended to any number of nodes within the specified limits of the Zigbee standard. Zigbee standard [10] specifies the use of a maximum of  $2^{64}$  nodes in the 2.4 GHz range. Once the base Tmote acquires the data, the data is transferred to other Tmotes on the network by means of Handshaking [11], [12]. So, it is necessary to know which Tmote is acting as the base station (which is responsible for starting the handshake operation), and the other Tmotes which are coordinating the base Tmote to make the transferred data available at the user end. The distances between the Tmotes are fixed in such a way that, when the external antenna is not used, the Tmotes internal antenna is sufficient, for it to remain on the network. Once the strength of the antenna is not strong enough to transfer the data, the Tmote goes out of the network and tries to get back into the network by a resynchronization command from the base station. It is very important to know the range of the antenna. If the distance to the base mote is beyond the antenna range, the Tmotes can not get the resynchronization command and they continue to be outside the personal area network. The communication port, to which the Tmote is connected, on the receiving end is accessed and all the data are analyzed to calculate the total number of packets received. The port remains open for sometime and then remains closed for sometime. In the mean time, when it is open, it would have acquired the data sent from the base station. By calculating the exact time the port is open, the data rate at the receiving end can be calculated. Obviously, when the distance increases, the data rate decreases. As, the ADC accumulates the data for 5 seconds and then starts transferring the acquired data one by one in preference of time stamp. So, when a Tmote is out of range from the base station, the base station Tmote looks for another Tmote within the range to send the data. If it can not connect with any of the other Tmotes in the range, then it sends a resynchronization command to the earlier Tmote and begins the transfer, in the mean time the base station may have already acquired samples from the distribution system for the period in which one of the coordinating Tmotes are not in the network. The experiment is first performed using 2 Nodes and then extended to 3 nodes (Indoor and outdoor Multi-hop data transfer). The data reaches the receiving end node in two steps, first step being from the base station (Tmote-1) to Coordinating node (Tmote-2) and from Tmote-2 to the receiving end node (Tmote-3). The objectives are to find the data rate in terms of number of packets, total bytes,

number of bytes written on Tmote (this is indicative of the number of resynchronization commands the Tmote gets from the base station). The percentage error in packet reception is calculated by the number of packets lost at the receiving end. A data packet consists of many fields like the payload address, payload data, list of headers, source and destination address. The preamble consists of the address of all the fields, the size of the payload and the Cyclic Redundancy Check (CRC) byte for error detection. The size of the preamble is 12 bytes (pre programmed). The exact data which is lost can not be found out, but the number of packets (bytes) lost is found out by the difference in the number of bytes received. The maximum and the average data rate are calculated by opening the communication port for a known period of time. The typical opening and closing time of the port is of the order of 50  $\mu s$ . The combined time of closing and opening of the ports can be neglected in comparison to the test transfer time of 1 min. Multipath and interference effects cause occasional retransmission to avoid errors in the data. A 90% success rate can be used as a conservative estimate for a well-designed system, which means that 10% of the data must be resent. The data transmission rate of a wireless network can be estimated using two factors: the volume of data that must be transmitted and the additional overhead that is required by the given protocol to perform error detection and correction. Data range is the most difficult parameter to estimate simply because of the multipath effects that occur in indoor environments. The antenna used in this case is an Omni directional antenna. By knowing the total number of packets/bytes (pre programmed to be 40 bytes/packet) of data transfer in a known time (1 minute), the data rate can be analyzed. By analyzing the path loss distance, the data range is calculated.

### IV. RESULTS AND DISCUSSION

As there is no comprehensive analytical formula relating average throughput, distance and the payload size, the average throughput values of the Tmotes are experimentally determined, analyzed and discussed with the help of various plots. The exact relation between the Average throughput and the distance is not known. So, the averages of a number of trials are used to arrive at a single data point. The experiment is conducted with number of trials and it is found that, as shown in Fig. 3, the average of 5 trials lead to a percentage error of less than 1%, which is acceptable for any system. Thus, 5 trials are taken for each data point obtained on the plot. The more the number of trials, the more accurate is the relation. Due to the lack of knowledge of the exact relation, it is difficult to calculate the standard deviation of the plot.

#### A. Analysis of throughput: QoS Protocol- Average throughput Vs Distance, 1 min test transfer, without acknowledgement bit, without the external antenna

Nodes are arranged in compliance with the scheme shown in Fig. 1. The data transfer is initiated, and the data is transmitted with the aid of the internal antenna provided in the Tmote. As distance increases, the average throughput falls, because of the build up of congestion in the network. The analog to

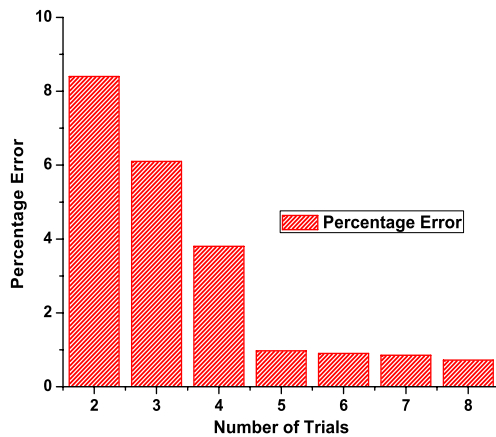


Fig. 3. A bar chart of Percentage error Vs Number of trials

digital converter (ADC) is programmed in such a way as to accumulate all the samples for 2 s, and then transmit all the data as a whole under one single chunk. Fig. 4 shows the comparison of the average throughput values for an outdoor and an indoor network. When distance between any 2 nodes is less, there is a match between the rate at which the source end antenna transmits and the rate at which the receiving end antenna receives. This equilibrium is disturbed as distance increases. As the distance increases, the rate at which the ADC provides data to the source end antenna becomes greater than the rate at which the receiving end antenna receives the data. This is the reason for build up of congestion in the network.

When data packets are transferred indoors, a phenomenon called "multipath" transmission occurs. The transmitted signal bounces off objects in its path, creating multiple copies of the same signal. These signals arrive at the receiver at different points in time and with different phases.

When multiple copies of the transmitted signal arrive at the same time but with different phases, they can partially cancel each other out, thereby reducing the signal. This reduction is independent of over-the-air data rate. Due to multipath effects and greater Signal to noise ratio, more number of nodes are required to transmit the same data over the same distance, with the same average throughput rate as compared to an outdoor network. The maximum indoor range is close to 17 m (40 bytes/s or 1 packet/s), and the same for the outdoor network is close to 30 m (shown in Fig. 4). The increase in the average throughput is attributed to the fact that the outdoor network has lesser Signal to noise ratio than that of an indoor network, allowing the antenna to have fairly constant gain for a maximum distance. It may also be noted that the average throughput values for an outdoor network are higher than the indoor network, as it facilitates clear line of view compared to an indoor network.

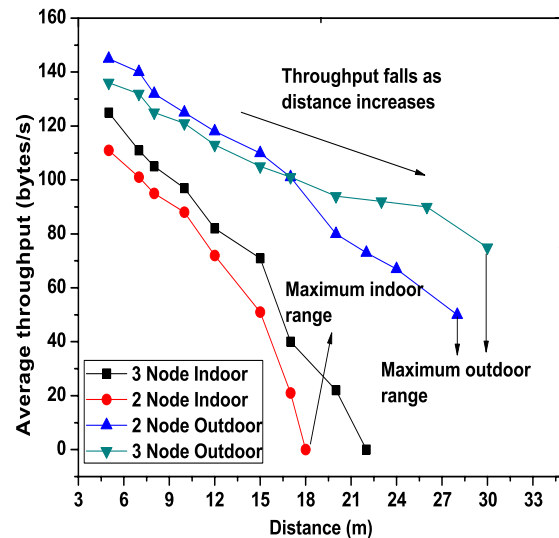


Fig. 4. Comparison of average throughput for a 2 node and a 3 Node (Indoor, Outdoor network)

*B. Average throughput Vs Distance, 1 min test transfer, without acknowledgement and with the 2.4 GHz, 50  $\Omega$ , Omni directional antenna, 7 dbi gain(external antenna).*

There are two possible conditions for data transfer, one is with the antenna and the other way is to execute data transfer without the antenna. For both the cases, the optimum range should be known for better reliability. The cost of the antennas is high, so one can not afford an extra antenna without justifying its purpose. So, the major task is to arrive at the maximum range for the above 2 cases. Reduction in number of nodes indirectly contributes to the reduction in cost. Antennas are preferred to reduce the number of nodes in a sensor network. A D-Link (ANT24-0700, 2.4 GHz Omni-Directional 7dBi Antenna is taken [13]). The 2.4 GHz antenna is preferred over others, as it radiates power uniformly in one plane, and the gain of 7dBi is just suitable for optimum data rate for indoor as well as outdoor applications, as the distance between the nodes in the former generally does not exceed a few 10's of meters and the same for the latter does not exceed a few 100 meters. The antenna under consideration provides satisfactory gain for both indoor and outdoor applications. The detailed specification is appended in the Appendix. Higher the frequency, Antennas affect communication networks nearby. To use an antenna which is operative in the Super High Frequency (SHF) band, license is essential as it interacts with other signals in the nearby frequency bands. The frequency of the 2.4 GHz D-Link antenna is below the frequency for which license is required [14]. A reduction of 1 node in the network indirectly contributes to lesser data traffic, and prompt delivery of data packets due to its relatively higher gain compared to the internal Tmote antenna gain, thereby increasing the average data throughput. The experiment is carried out as mentioned

in the previous section. Fig. 5 shows the relation between the average throughput and the distance for a 2 node and a 3 node network.

Although, from Fig. 4 and Fig. 5, it is evident that, once the distance becomes equal or increases beyond the maximum range (Indoor as well as Outdoor), the average throughput falls at a higher rate. The network traffic is an attributing factor for the drop in the number of bytes received. As the numbers of nodes grow higher, the network traffic increases. So acquisition and transmission of the first few samples are at a higher rate.

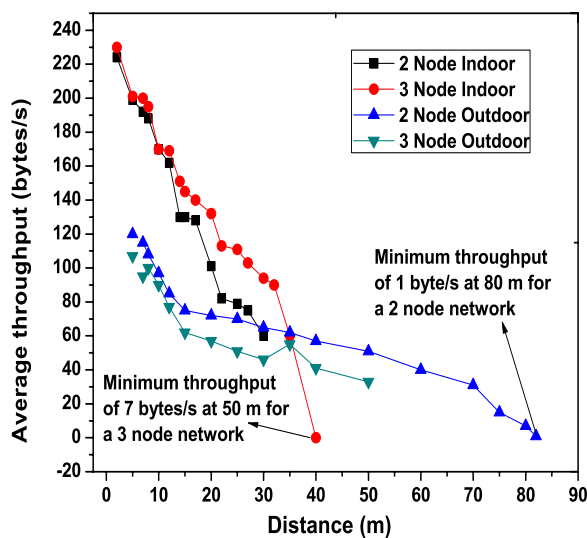


Fig. 5. Comparison of average throughput for a 2 node and a 3 Node (Indoor, Outdoor) network, with the aid of antenna)

With the inclusion of antenna, the indoor average throughput almost doubles and the range of the Tmote increases drastically outdoors. With the antenna, the data transfer is possible for a maximum distance of 70-80 m (outdoor) for a 2 node network and 50 m (distance between any 2 motes) for a 3 node network. Fig. 6 shows the effect of height of antenna above the ground plane on average throughput with distance. The detailed discussions regarding the possible reasons for the increase in average throughput is provided in section (F).

*C. Change in Average throughput Vs Distance, 1 min test transfer, without acknowledgement bit and without the 2.4 GHz, 50  $\Omega$ , Omni directional, 7 dBi gain antenna.*

The average drop in data throughput can be an important measure to arrive at the optimum distance between the Tmotes. If the fall in data rate is large between any two points on the graph between average throughput Vs Distance, it is an indication of the Tmotes incapability to transmit data. Fig. 7 shows the graph plotted on the basis of the observations made for the change in average throughput for varying distances. The maximum fall in average data rate for a 2 Node indoor

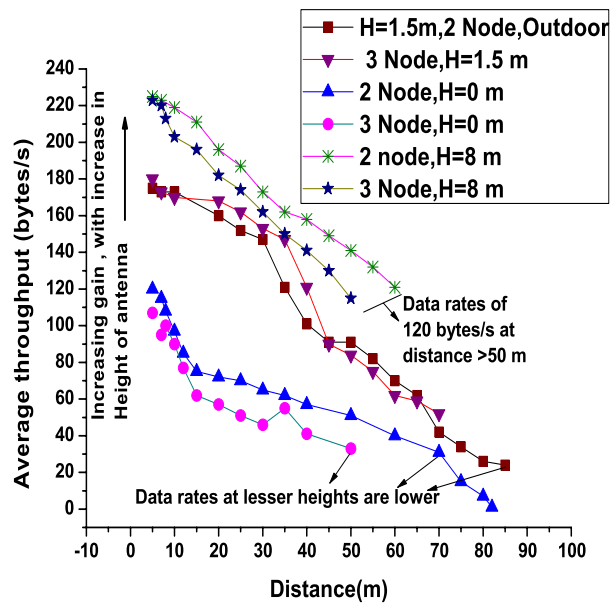


Fig. 6. Effect of height of antenna above the ground plane

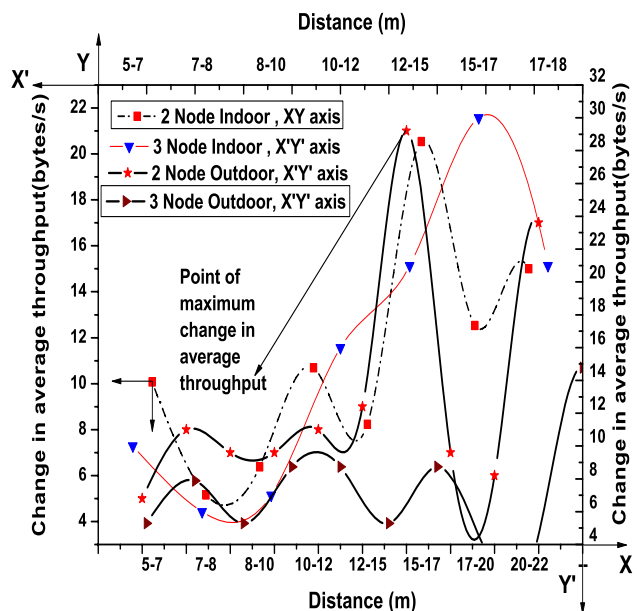


Fig. 7. Change in average throughput as a function of varying distances (without external antenna)

network is between 12-15 m. This is evident from Fig. 7. If the distance is increased beyond this threshold value, it may be a contributing factor for the Tmotes failure to receive data any further. Moreover, if the distance is increased beyond the point of the maximum change in average throughput, the Tmotes performance drastically reduces. The outdoor range is close to 17-20 m for a 2-node network. This is the point of the maximum change in average data throughput.

**D. Change in Average throughput Vs Distance, 1 min test transfer, without acknowledgement bit and with the 2.4 GHz, 50  $\Omega$ , Omni directional, 7 dBi gain antenna**

Maximum change in data throughput occurs at a point when the Tmote is just about to lose its synchronism with the sensor network. When the Tmote is out of range from the antenna, the resynchronization signal is transmitted from the base station to bring it back in synchronism with the network. Effect of number of resynchronizations on node failure is discussed in section (E). For the 2-node outdoor network under investigation, the maximum change in average throughput is at a distances in the range of 12-14 m. Fig. 8 and Fig. 9 shows the relation between the distance (Indoor as well as Outdoor) and average throughputs. Practically, after

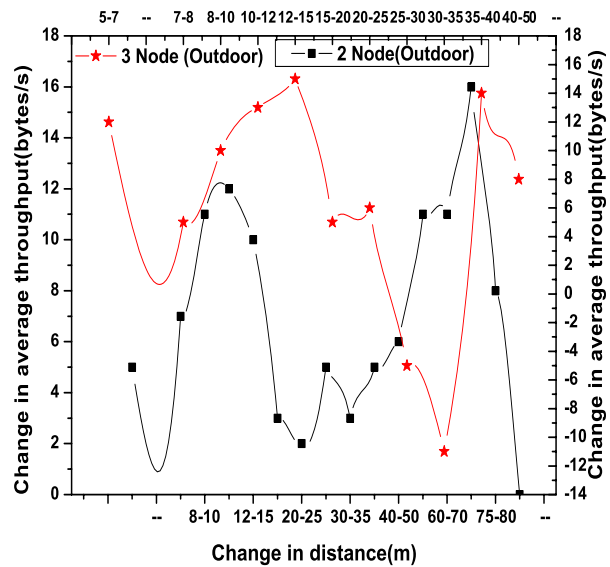


Fig. 9. Change in average throughput as a function of varying outdoor distances (with the external antenna)

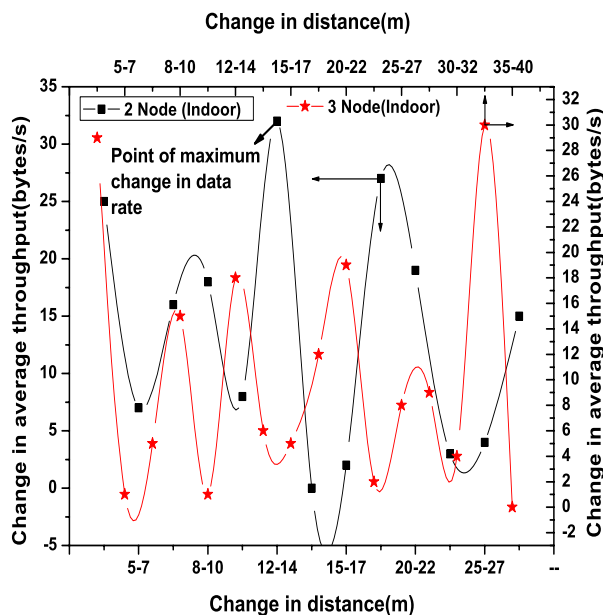


Fig. 8. Change in average throughput as a function of varying indoor distances (with the external antenna)

the point of maximum change in data throughput, the Tmote is more vulnerable for failure in data collection. But, the Tmote continues to perform well until it reaches 25-30 m. The increase in performance of the Tmote may be due to some other factors like the environmental conditions, which include presence of good reflecting objects which may aid the performance of the antenna.

**E. Probability of a Node failure due to increase in resynchronizations at increasing distances. With external antenna (3 min test transfer, or 30 resynchronizations whichever is earlier)**

Failure of a node is defined as the inability of a node to acquire data at the same rate as that transmitted by base mote. If the distances between the Tmotes are high, obviously the Tmote acquires data at a slower rate compared to the transmission rate at the base station. The experiment is carried out initiating a 3 minute test transfer. When the Tmote is out of range, it loses its synchronism with the network. So, the base station sends a resynchronization command to bring back the Tmote into the network and to continue the data transfer process. For example, the Tmote fails to receive data if the coordinating node fails, due to the reason that all the data must pass through the coordinating node on the first hop before reaching the receiving end node. At greater distances the number of resynchronization signals from the base station Tmote increases. Once the Tmote loses synchronism with the network, the base station Tmote requires 5 s to bring back the Tmote into the network. By this time, the congestion in the network increases due to the continuous sampling done at the source end. The number of resynchronization signals, the coordinating mote acquires at the end of a 3 minute test transfer gives the measure of the probability of the nodes failure. If the time of test transfer is more, it improves the accuracy of predicting the probability of failure. Fig. 10 shows the probability of resynchronization of a node as the distance between the Tmotes is increased.

The number of resynchronizations a node is subjected to has a direct impact on the throughput at that node. Thus, more number of resynchronization commands implies less throughput, and as a result the congestion builds up and eventually a



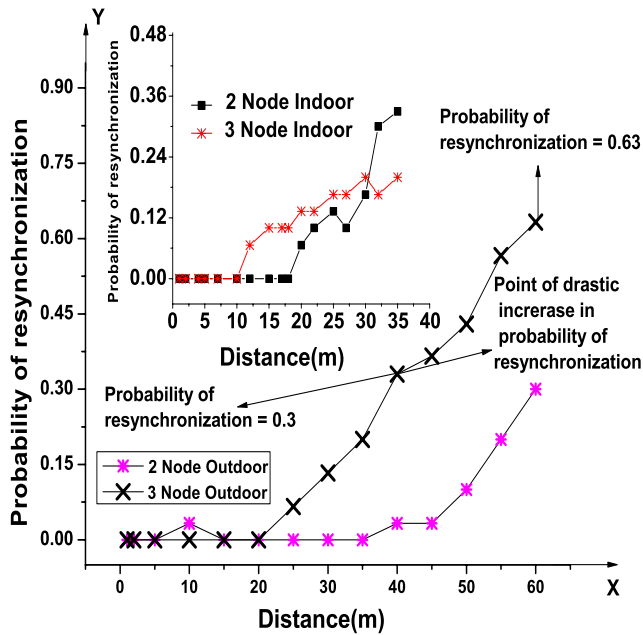


Fig. 10. Probability of resynchronization Vs distance-Outdoor. (Inset) Probability of resynchronization Vs distance-Indoor

node failure. The plot in Fig. 10 shows the probability of a nodes failure to accept data when it is subjected to too many resynchronization signals from the base station. It is clearly observed that the probability of a Tmotes failure is more in indoor networks, than outdoor for the same distances. Even for the same distances the rate of build up of congestion in an indoor network is higher. This is due to the obstructions present in the indoor network, which oppose the signal from reaching the destination. Moreover, the indoor networks do not provide clear line of view. At distances close to 60 m (3-node, outdoor), the probability of resynchronization is 0.63. It is observed that at distances in the range of 40-50 m, the probability of resynchronization is 0.3. The next section discusses the effect of change in antenna height from the ground surface. It reveals a very good result, that with greater heights the data throughput increases and the corresponding congestion in the network at larger ranges also is reduced.

#### F. Effect of height of antenna from the ground level

The installation of the antenna is crucial to its operation. The choice of location and in particular its height can determine its performance to a large extent. It is generally found that higher it is, the greater the cost of installation. A tall mast and a long feeder may be necessary. Long feeder may also reduce the effectiveness of any gain achieved in increasing the height. However, significant levels of gain can be achieved by mounting antennas as high as reasonably possible. For optimum performance the antenna should be mounted above any local objects so that they do not screen it. A rule of thumb of 12 m is a very good general guide, as this tends to take the antenna above signal variations caused (at higher frequencies). However, the height to which the antenna can be raised is

determined to some extent by its size. Larger antennas for lower frequencies are not so easy to raise to great heights. With the ANT24-0700 D-Link Omni directional antenna under investigation, the gain of the antenna increases two fold at heights of 8 m which is clear of the local objects (shown in Fig. 6). This is evident by the increase in the average data throughput at 8 m. This is achieved neglecting the multi path losses in the antenna. The effect of multi path losses becomes prominent when the antenna is placed close to the earth plane. When the antenna is moved into the atmosphere, the degrees of multipath effect losses are reduced. The average throughput increases with height as a result of the clear line of view and reduction in multi path effects. The average throughput values in the case of H=8 m is the highest and the average throughput in the case of H=0 m is the lowest.

#### G. Effect of number of resynchronizations on the network traffic

One of the main reasons for the increase in the network congestion is due to the mismatch between the sampling time and speed of transfer. If the sampling time is too fast, and the speed of transfer is relatively slow, the ADC buffer gets filled up and it affects the data acquisition. Until the buffer is cleared, the ADC can not start collecting samples. As a result of which, congestion starts to creep in the network. As the number of resynchronization signals from the base station to the coordinating Tmote increases, the time for which the coordinating Tmote remains in the network decreases as the Tmote can not acquire data, once the resynchronization signal is received. The duration for which the resynchronization signal is sent is approximately 5 s. Therefore, for 5 s, the Tmote stops receiving the data, and in the mean time, the base station Tmote keeps acquiring the data from the transmission line. In this way, the network congestion increases. It increases linearly and the rate at which it increases depends on the number of nodes. Greater the number of nodes, lower is the load on any one of the Tmotes and the lesser is the congestion due to the resynchronizations

#### H. Percentage error as a function of distance and average throughput

This experiment is carried out by taking a reference value for the total pay load received by the receiving end node. An upper limit of 18k bytes is assumed to be collected at the end of a 3 min test transfer time. The value of 18k is arrived keeping in mind the maximum data that a Tmote module can transfer at the maximum possible average data rate (from Fig. 4 for a 3 Node outdoor network, with a 7 db a 2.4 GHz antenna). The received bytes are manually verified. The percentage error is calculated using (1)

$$\frac{(\text{Theoretical value} - \text{Experimental value})}{\text{Theoretical value}} \times 100 \quad (1)$$

Theoretical Value being the Actual/Known/ True Value.

Fig. 11 shows a 3D projection plot of the relation between the average throughput and the distance, with the associated error. It can be clearly seen from Fig. 11, that the percentage

error increases with increase in distance and the fall in data rate is substantial at greater distances. It can be seen from the projections on the axes, that the error is NIL upto a total threshold distance of 40 m ( $d_1=20$  m,  $d_2=20$  m). The fall in data rate further increases the percentage error.

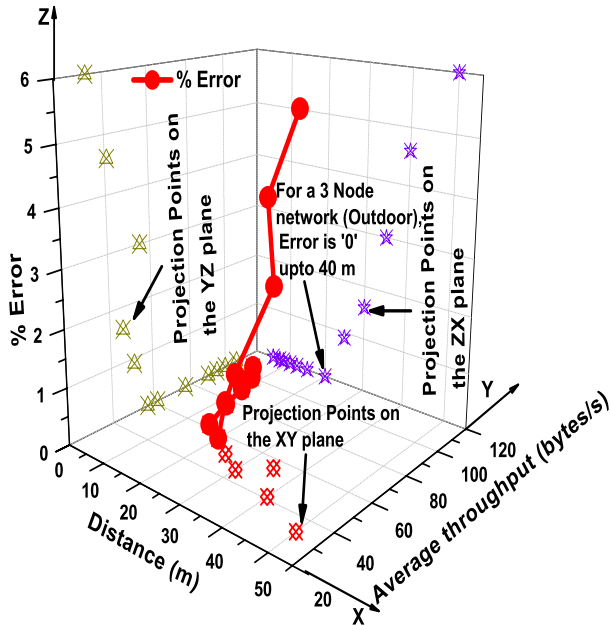


Fig. 11. A 3D projection plot of percentage error as a function of distance and average throughput

#### I. Effect of increase in the number of TmoteSky nodes

Wireless connectivity between any two nodes depends on the distance between them. When large numbers of nodes are present in a network, it increases the range of wireless connectivity. But, it increases the network traffic, forcing the receiving end Tmote to obtain samples at a lesser speed and indirectly build in congestion. To counter this effect, the knowledge of the increase in data traffic when the number of nodes increase, should be known.

*Network congestion* is the situation in which an increase in data transmissions results in a proportionately smaller increase, or even a reduction, in *throughput*. *Throughput* is the amount of data that passes through the network per unit time, such as the number of *packets per second (pps)*. Congestion results from applications sending more data than the network devices can accommodate, thus causing the *buffers* on such devices to fill up and possibly overflow.

When the network traffic increases, 3 things happen simultaneously. First, the queuing delay of the data packets increases. Second, there may be packet losses. Finally, in the congested state, the traffic is dominated by retransmission, so that the effective data rate decreases. Fig. 12 shows the plot between the increase in network traffic and the error, when the number of nodes are increased from 2 to 7. It is evidently clear from the plot in Fig. 12 that the network traffic increases, further

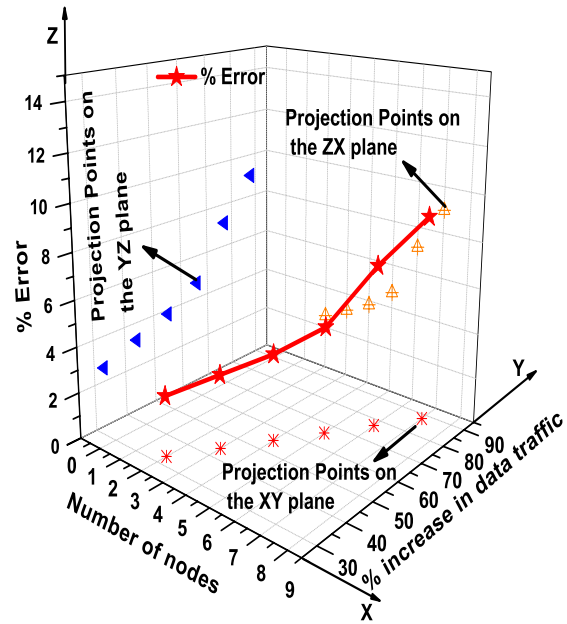


Fig. 12. A 3D projection plot of the increase in network traffic and error as a function of increase in number of nodes

allowing a reduction in average throughput values. Network congestion increases to the extent of 66% when the number of nodes is doubled. The 66% increase in the congestion, is followed by an increase in delivery time and error in packet reception. From Fig. 12, it is clear that, the relation between the increase in percentage of data traffic and the increase in the percentage error is approximately linear. So, a 66% increase in data traffic due to doubling of node can result in an error close to 66% (if multi path losses are included). All the 3 factors invariably affect each other when anyone is affected. So, the increase in number of nodes can improve the range of the wireless transmission by the same amount as the reduction in its average throughput. This is shown in Fig. 13.

#### J. Path loss in the 7 dbi antenna, Signal to noise ratio(SNR) analysis

Radio frequency (RF) signals of a given carrier frequency, such as 2.4 GHz (as it is in this case), lose power as they propagate, called path loss, this is similar to the way a sound becomes softer when it is farther from the source. Path loss in decibels (dB) increases with the square of the distance and is relatively easy to estimate when the path is unobstructed. Traditionally, the increase in SNR is affected by using the narrowest possible receiving-system bandwidth consistent with the data speed desired. However, there are other methods. In some cases, Quadrature Spread spectrum technique can improve system performance. The SNR ratio can be increased by providing the source with a higher level of signal output power if necessary. In wireless systems, it is always important to optimize the performance of the transmitting and receiving antennas. Fig. 14 illustrates the impact of SNR on path loss. It can be noted that, each time distance doubles, path loss



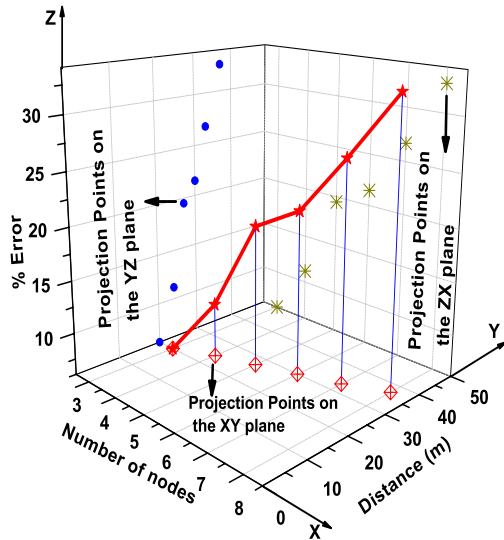


Fig. 13. Effect of increase in number of nodes and distance

increases 6 dB (this applies only to the 2.4-GHz band). The following plot obtained confirms the path loss of almost 6 dB over doubling the distance. To determine whether two radios can hear each other over a given range, one should consider two other variables: transmit power and receive sensitivity. Transmit power is simply how "loud" the signal is. Transmit power is expressed in dB and is usually a positive number. Often, transmit power is expressed in dB relative to a milliwatt (dBm). Fig. 15 shows a 3D projection plot of the SNR and the relative error of reception and the path loss distance. It may be noted that, the projections of points on the XY-YZ plane is more concentrated than the XY plane. Thus, it is clear that lesser the density of the points on the planes, the more is the path loss, because, the density of the locus of points is an indirect measure of the distance upto which the wireless transmitter has control upon. The data points marked by arrow mark in Fig. 16 are a less dense locus of points when the TmoteSky is slowly taken out of range. It can also be seen from the 2D plane plot in Fig. 14 that, the strength of the signal has almost reduced 6 dB, when the distance is doubled from 30 m to 60 m.

## V. CONCLUSION

In the present work, efforts are made to study the topologies of the WLL network and arrive at the optimum distance between the Tmotes for optimum data transfer. Some of the results obtained indicate that, in general, placing an amateur antenna system higher in the air enhances communication capabilities and also reduces chances for electromagnetic interference with neighbors. It can be concluded that as number of nodes increase, the network traffic increases and the nodes become less reliable. So, a compromise between the number of bytes of payload data and the average throughput has to be achieved. With another multipath effect, called Inter Symbol Interference (ISI), other copies of the signal may arrive slightly

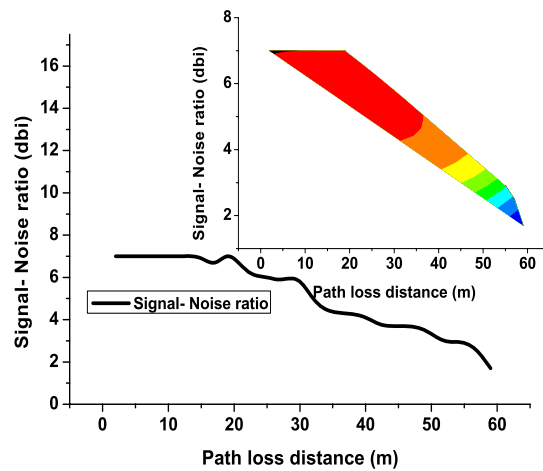


Fig. 14. Reduction in signal strength at the receiving end. (Inset) locus of all points of SNR Vs distance on a 2D plane

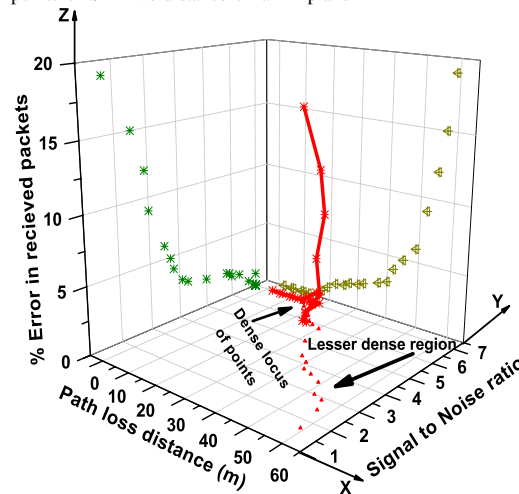


Fig. 15. A 3D projection plot of the impact of SNR on path loss distance and percentage error

later in time, interfering with a subsequent data bit(s) rather than the original data bit. This is an unwanted phenomenon as the previous signal has similar effect as noise, thus making the communication less reliable. The gain and the range of the antenna are also reduced. The results shown can be taken as a reference for detailed analysis and can be used to arrive at the optimum number of nodes and the data traffic each node is capable of handling.

## APPENDIX

## A. TMOTE SCHEMATIC [15]

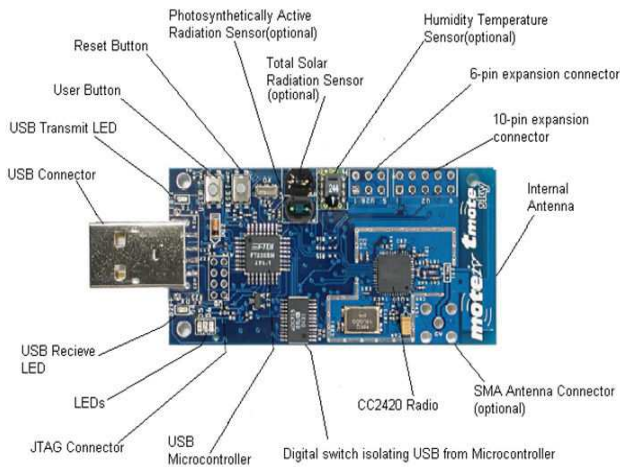


Fig. 16. A schematic of the TmoteSky module

## B. D-Link ANT 24-0700 [13]

**Specifications:** Frequency Range: 2.4GHz-2.5GHz. Gain: 7dBi. Voltage Standing Wave Ratio (VSWR):1.92:1 Max. Polarization: Linear, Vertical. Half Power Beam Width (HPBW): Horizontal: 360 degrees. Vertical: 24 degrees. Impedance: 50 Ohms Nominal. Connector: Reverse SMA. RP-SMA to TNC Adapter. Cable: 1.5m RG-178 50 Ohms. Operating Temperature: -40F to 149oF (-20oC to +65oC). Storage Temperature: -22oF to 167oF (-30oC to +75oC).

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