Power-Efficient Algorithm for IEEE 802.11b Multi-Hop Networks

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Abstract—There has been an upsurge of interest in multi-hop infrastructure-based wireless networks in the past recent years. The fundamental reason being that multi-hop communication provides benefits such as coverage extensions, combating of shadowing at high radio frequencies and reduced infrastructure deployment costs. For IEEE 802.11 Wireless Local Area Networks (WLAN) to utilize multi-hop communication efficiently, power consumption or energy consumption need to be effectively minimized. The basic approach to reduce power consumption is to lower the transmit power to the optimum level that still achieves correct reception of a packet. Adopting this minimization approach, this paper presents a power efficient multi-hop communication algorithm for IEEE 802.11. The proposed scheme estimates the number of nodes, transmit power level and the separation distance of nodes based on transmission distance, system throughput, energy consumption and cost, transmitter costs and operation period, and network percentage of use. Simulation results show that our method significantly reduces power consumption as compared to conventional multi-hop communication.

Index Terms—Relays, Power Consumption, IEEE 802.11, Multi-hop Communication.

I. INTRODUCTION

There has been a phenomenal spate of interest in multi-hop communication in recent years. This is indicated by the seed concept in 3GPP, mesh networks in IEEE 802.16, and coverage extensions in HiperLAN/2 through relays [3]. A multi-hop wireless network is one in which a packet may have to traverse multiple consecutive wireless links in order to reach its destination [4]. Over the years multi-hop communication has manifested itself under numerous forms, such as *Packet Radio Networks* developed several decades ago for military applications, and more recently *ad hoc* networks which refer to a collection of hosts communicating over a wireless channel. Multi-hop communication provides benefits such as range extension, combating of shadowing at high frequencies, network partitioning avoidance and reduced infrastructure deployment costs.

The IEEE 802.11 WLANs are becoming increasingly more popular, as they are envisioned as the cornerstone of future wireless broadband communication. The merging of such inhomogeneous technologies may form a network with an increased system capacity and hence improved system performance. The resulting network may use WLAN techniques for peer-to-peer communication or serve as relay networks to extend the range and increase the capacity of future wireless broadband networks, which provides links to the wired Internet [1]. WLANs use traditional LAN technology with a wireless interface, and provide relatively high-speed data communication (up-to 11Mbps for IEEE 802.11b) in small areas such as a building or an office [2]. Even though IEEE 802.11 families of WLAN provide a low cost broadband wireless access, they have a limited range. One way to extend the range of WLANs is to use multi-hop communication. The typical way of implementing multi-hop communication in static networks, is to randomly select node transmit power levels (normally maximum transmit power) that can link the nodes together to cover a specific range (conventional multi-hop system). This mechanism result in higher consumption of transmit power and energy, and a higher probability of interference.

This paper presents an efficient power consumption multi-hop communication algorithm (PMCA) for IEEE 802.11. IEEE 802.11b is chosen for this study due to its popularity and its widespread use in the WLAN infrastructure, thus the conclusions drawn are general as far as 802.11a and 802.11g physical (PHY) layers are concerned. The rest of the paper is organized as follows. In Section II, we show the relationship between relay-based multi-hop communications and transmit power. Section III presents the modeling of the IEEE 802.11 performance metrics, i.e. received signal strength (RSSI), Signal-to-noise ratio (SNR), Bit Error Rate (BER), Throughput and Path loss. The proposed algorithm is presented in Section IV. In Section V we evaluate the performance of the algorithm via simulations. Finally, Section VI concludes the paper.

II. RELAY MULTI-HOP COMMUNICATION

In this section we analyze the relationship between multi-hop communication and transmit power. Our objective is to show that transmit power is significantly reduced by increasing the number of hops from source to destination.

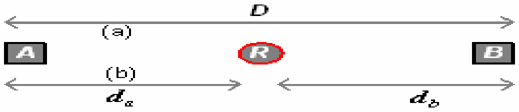

Figure 1: Two hop Multi-hop communication

In Figure 1, node A and B represent the transmitter (Tx) and receiver (Rx) respectively, D denotes transmission distance, and R represent a relay. The link between Tx and Rx in terms of transmit (P_{T_x}) and received (P_{R_x}) power is mathematically expressed as:

$$P_{Rx} = \left(\frac{\lambda}{4\pi D}\right)^2 P_{Tx} = \frac{P_{Tx}}{L_P} \tag{1}$$

where $L_P = \left(\frac{4\pi D}{\lambda}\right)^2$ is the free space path loss between two isotropic antennas.

Modifying equation (1) resolves into

$$P_{Tx} = P_{Rx}\left(\frac{4\pi}{\lambda}\right)^2 D^2 \tag{2}$$

Let $\left(\frac{4\pi}{\lambda}\right)^2 = K$

where K is a constant, $\lambda = c/f$, c is speed of light and f transmission frequency.

This analytical approach clearly illustrate that a single hop indicated by Figure 1(a) is expressed as:

$$P_{Tx} = P_{Rx}KD^2 \tag{3}$$

Two hop communication indicated by Figure 1(b) is mathematically expressed as:

$$P_{TxA} + P_{TxR} = P_{Rx}Kd_a^{\,2} + P_{Rx}Kd_b^{\,2} \tag{4}$$

where $d_a = d_b = \frac{D}{n}$, n being the No of hops

From equation (4), we can now generally define multi-hop communication as:

$$P_{Tx_n} = \left\{ n \cdot P_{Rx}K\left(\frac{D}{n}\right)^2 ; \forall 1 < n < \infty \mid 0 \leq P_{Rx}K\left(\frac{D}{n}\right)^2 < 20\text{dBm} \right\} \tag{5}$$

From (5) we observe that Tx power decays exponentially with an increase in number of hops. The decay is mathematically expressed as:

$$\alpha = e^{-\beta} \tag{6}$$

where α is Tx power and β number of hops

An increase in the number of hops results in increased infrastructure costs. Subsequently, high infrastructure costs results in high overall costs (energy + infrastructure). It is therefore clear that a mechanism that enables the implementation of multi-hop communication systems with optimum power consumption and optimum infrastructure costs is required. This mechanism is discussed in Section IV.

III. NETWORK PERFORMANCE METRICS

Throughput, RSSI, SNR and BER are used in IEEE 802.11b as some of the basic metrics that determines the performance of the network. In this paper we will use these performance metrics to validate the results achieved by our method. The Path loss propagation model will enable us to characterize the channel variations that are encountered in WLAN environment.

A. RSSI and SNR

In wireless communication, SNR is defined as the ratio of Energy per bit E_b to noise power spectral density N_o. In IEEE 802.11b E_b / N_o is modified as in (13), and hence the SNR is expressed as in [5] as:

$$SNR = 10\log\left(\frac{E_c}{N_o}\right) \tag{7}$$

where E_c is the energy per chip

The SNR is defined as in (7) due to a constant chip rate of 11Mchips/s used in IEEE 802.11b. The Direct Sequence Spread Spectrum (DSSS) PHY Layer modulates each transmitted bit with an 11-*bit* Barker code compelling the chip rate to be fixed at 11Mchips/s. This technique decreases noise energy inside the receiver bandwidth, and hence probability of error is also reduced.

The Additive White Gaussian Noise (AWGN) at the receiver (802.11 devices) is expressed as in [6] as:

$$N_o = kTB \tag{8}$$

where k = Boltzmann constant = 1.38 * 10^{-23} J/°K/Hz
T = ambient temperature = 20 °C = 293 °K
B = bandwidth of receiver = 18 MHz

Therefore

$$SNR = \frac{RSSI}{N_o} \tag{9}$$

where *RSSI* is the receiver sensitivity expressed as in (1)

B. Bit Error Probability

The BER (Bit Error Probability) is used as the standard measure of the quality of digital signals in wireless communication systems. It indicates the ratio of the number of bits received in error vs the total number of bits sent. For a given SNR, the bit error probability can be easily attained for the IEEE 802.11b modulation schemes, DBPSK, DQPSK, and CCK [8].

The *frame error probability* is expressed as:

$$P_{frame\_error} = 1 - \left(1 - P_{phy\_error}\right) \cdot \left(1 - P_{MAC\_error}\right) \tag{10}$$

where P_{phy_error} is the physical layer overhead error probability and P_{MAC_error} the MPDU (MAC Protocol Data Unit) error probability.

$$P_{phy\_error} = 1 - \left(1 - P_{bit\_error1}\right)^{24\cdot 8} \tag{11}$$

where P_{bit_error1} is the *bit error probability* when transmitting physical layer overhead.

$$P_{MAC\_error} = 1 - \left(1 - P_{bit\_error2}\right)^{(28+MSDU)\cdot 8} \tag{12}$$

where P_{bit_error2} is the *bit error probability* when transmitting the MPDU.

To express P_{bit_error1} and P_{bit_error2} , E_c / N_o is derived from E_b / N_o using the 11-*bit* Barker spreading sequence. The Barker sequence modifies E_b / N_o to the following equation.

$$\left(\frac{E_b}{N_o}\right)_{DBPSK} = 11 \cdot \frac{E_c}{N_o} = 11 \cdot SNR \tag{13}$$

The P_{bit_error1} and P_{bit_error2} is now derived from (13) for IEEE 802.11b modulation schemes.

For 1 Mbps DBPSK, P_{bit_error1} is expressed as:

$$P_{bit\_error1} = Q\left(\sqrt{11 \cdot SNR}\right) \tag{14}$$

This equation applies to every operational mode since it is also used for physical layer overhead information transmission.

For 2 Mbps DQPSK, P_{bit_error2} is calculated as:

$$P_{bit\_error2} = Q\left(\sqrt{5.5 \cdot SNR}\right) \tag{15}$$

For 5.5 Mbps CCK$_{5.5}$, P_{bit_error2} is calculated as:

$$P_{bit\_error2} = \min\left(1 - (1 - SER)^{0.25}, 0.5\right) \tag{16}$$

where $SER = 14 \cdot Q\left(\sqrt{8 \cdot SNR}\right) + Q\left(\sqrt{16 \cdot SNR}\right)$

For 11 Mbps CCK$_{11}$, P_{bit_error2} is defined as:

$$P_{bit\_error2} = \min\left(1 - (1 - SER)^{1/8}, 0.5\right) \tag{17}$$

where

$$\begin{aligned} SER &= 14 \cdot Q\left(\sqrt{8 \cdot SNR}\right) + Q\left(\sqrt{16 \cdot SNR}\right) \\ &+ 174 \cdot Q\left(\sqrt{8 \cdot SNR}\right) + 16 \cdot Q\left(\sqrt{10 \cdot SNR}\right) + \\ &24 \cdot Q\left(\sqrt{12 \cdot SNR}\right) + Q\left(\sqrt{16 \cdot SNR}\right) \end{aligned}$$

The Q function is defined as the area under the tail of the Gaussian probability density function with zero mean and unit variance. It is expressed as:

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{\frac{t^2}{2}} \, dt \tag{18}$$

C. IEEE 802.11b Throughput Analysis

In this subsection we present an analysis of the IEEE 802.11b throughput using similar approach as in [7] and [8]. Throughput is analyzed under Distributed Coordination Function (DCF) MAC layer scheme illustrated in Figure 2. In this paper we consider the same parameters, assumptions and conditions considered in [7] and [8].

To model the throughput we need to calculate the average time to transmit a single frame which is dependent on

- The time taken to successfully transmit a single frame
- The time taken between two consecutive frame transmissions if there exists a failed frame transmission

As shown in Figure 2, the time taken to successfully transmit a frame is defined as:

$$T_S(i) = DIFS + T_{backoff}(i) + T_{data} + SIFS + T_{ack}\,[\mu s] \tag{19}$$

where i = the number of consecutive unsuccessful transmission.

$DIFS$ = Distributed Inter Frame Space period

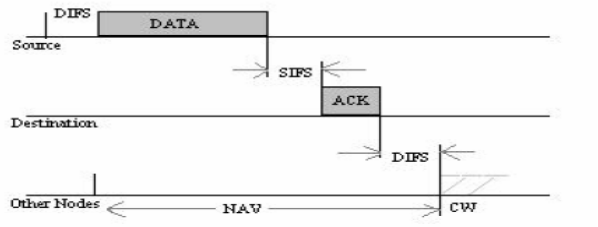

Figure 2: IEEE 802.11 MAC Layer DCF Operation

$SIFS$ = Short Inter Frame Space period

$T_{backoff}\ (i)$ = Backoff Time Interval

T_{data} = Data frame transmission duration

T_{ack} = Acknowledgement frame transmission duration.

T_{data} and T_{ack} are defined as:

$$T_{data} = tPhy_{PLCPpreamble} + tPhy_{PLCPheader} + \left(\frac{(28 + MSDU) * 8}{txr[Mbps]}\right)\mu s \tag{20}$$

$$T_{ack} = tPhy_{PLCPpreamble} + tPhy_{PLCPheader} + \left(\frac{14 \cdot 8}{txr[Mbps]}\right)\mu s \tag{21}$$

where txr = Transmission rate (1,2,5.5 or 11Mbps)

$tPhy_{PLCPpreamble}$ and $tPhy_{PLCPheader}$ = Physical layer overhead information.

MAC Service Data Unit (MSDU) = Information passed from IP layer to MAC layer.

$T_{backoff}\ (i)$ is expressed as:

$$T_{backoff}(i) = \left(\frac{2^i (CW\min + 1) - 1}{2}\right) * SLOT\,[\mu s]\, 0 \le i < 6 \tag{22}$$

Or

$$T_{backoff}\ (i) = \left(\frac{CW\ \max}{2}\right) * SLOT\ [\mu s]\, i \ge 6 \tag{23}$$

Secondly, if the frame transmission fails then the time between two consecutive frame transmissions is defined as:

$$T_f(i) = DIFS + T_{backoff}(i) + T_{data} + (SIFS + T_{ack} + SLOT)\mu s \tag{24}$$

By using (19) and (24) we derive the average transmission time for a single frame as:

$$T_{frame} = T_S(0) + \sum_{i=1}^{+\infty} (1 - p)p^i \left[\sum_{j=0}^{i-1} T_f(j) + T_S(i)\right][\mu s] \tag{25}$$

Throughput is then finally modeled as:

$$Throughput = \left(\frac{MSDU\ \ * 8}{T_{frame}}\right) Mbps \tag{26}$$

D. Channel Modeling

In a wireless environment, the RSSI is largely influenced by transmit power, large-scale path loss and small-scale multi-path fading. Path loss determines the mean RSSI as a function of distance. Multi-path fading is caused by the superposition of multiple in-phase and out-of-phase copies of the original transmitted signal. It causes rapid fluctuations in the RSSI over very short time scales [9]. Since we are dealing with fixed nodes we do not consider multi-path fading in this paper, because there is relatively no movement between the sender and the receiver.

Path loss is a fundamental and very important factor in the design or simulations of wireless systems. It is the link between the transmitter and the receiver. There are several well-established mathematical models for path loss. In this paper we consider the log-distance path loss model expressed as in [10].

$$\overline{PL(dB)} = \overline{PL(d_0)} + 10 \cdot n \cdot \log\left(\frac{d}{d_0}\right) \qquad (27)$$

where d_0 is the close-in reference distance, d the distance between the transmitter and the receiver, and n the path loss exponent defined in [10].

IV. POWER EFFICIENT MULTI-HOP ALGORITHM

In this section, we present our proposed algorithm. The motivation for the implementation of the algorithm is to optimize transmit power consumption in IEEE 802.11b multi-hop communication systems. At present, the standard approach is to randomly set transmit power levels (normally maximum levels) that establishes links between the nodes and cover the area of particular interest. The high levels of transmit power result in high power consumption and more interference. Our proposed algorithm is a major solution to this problem. Its principle is to optimize power consumption by estimating the number of nodes, transmit power level and the separation distance of nodes based on transmission distance, system throughput, energy consumption and cost, transmitter costs and operation period, and percentage of network use.

A. Node Characteristics

The design of the algorithm is fundamentally based on the speccification of IEEE 802.11b compliant products currently available on the market. We propose a WLAN Access point (AP) as in [11] for the design of our algorithm. Cisco Aironet 1100 Series AP is a high-speed WirelessLAN device operating in the 2.4GHz spectrum. It incorporates both IEEE 802.11b and IEEE 802.11g into one device.

B. Proposed Algorithm

The basic idea of our power efficient multi-hop algorithm is to establish a threshold point that determines if a multi-hop communication is optimized in terms of power consumption and infrastructure costs. The threshold point is expressed as:

$$P_{C_{ij}} = \left\{ \left(P_i - P_j\right) \cdot D_{ij}(t,p) \cdot E_C \mid P_i \neq P_j \right\} \qquad (28)$$

where $i \in N \mid \forall_i > 1$

$j \in \left(n = N + 1\right)$

$$\mathit{Threshold} = \begin{cases} i - 1 & \mathit{if} \quad P_{C_{ij}} > N_C \\ j - 1 & \mathit{if} \quad P_{C_{ij}} \leq N_C \end{cases} \qquad (29)$$

where $i - 1 \neq \text{Optimized Multihop}$

$j - 1 = \text{Optimized Multihop}$

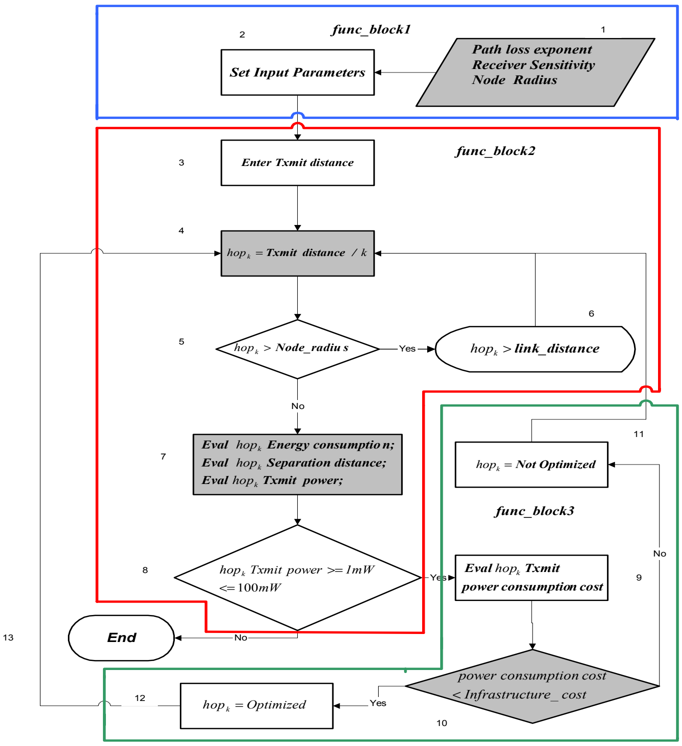

Figure 3: PMCA Algorithm Flow Chart

The power consumption cost calculated as a function of P_i (Node-i Power), P_j (Node-j Power), D_{ij} (Node warranty Percentage of use) and E_C (Node Energy cost) in equation (28), is compared with N_C (infrastructure cost) in (29) by the threshold point to determine if the multi-hop communication is optimized.

The PMCA algorithm consists of three functional blocks as depicted in Figure 3. In *func_block1,* the channel conditions are established through the path loss. The receiver sensitivity and node radius are set for a single hop link in accordance with the maximum transmit power. Then, in *func_block2,* the algorithm determines the number of hops, transmit power levels and node radius for a specific transmission range based on the single hop link parameter settings (*func_block1).* In *func_block3,* the algorithm determines the power consumption cost based on equation (28) and utilizes the *threshold* in equation (29) to determine optimized and un-optimized number of hops.

V. PERFORMANCE EVALUATION

In this Section we evaluate the performance of the power efficient multi-hop algorithm using computer simulations. All simulation tests were run in Matlab [12]

A. Simulation Scenario

For our simulation, we create a scenario composed of infrastructure-based architecture with fixed AP for our multi-hop communication. As shown in Figure 4, 20 AP are deployed in a 1200m x 1200m flat area. The distance

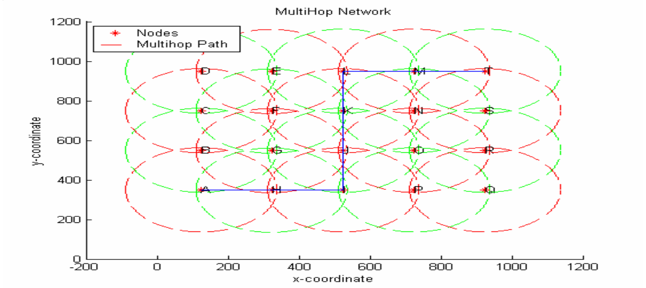

Figure 4: Conventional Multi-Hop Communication

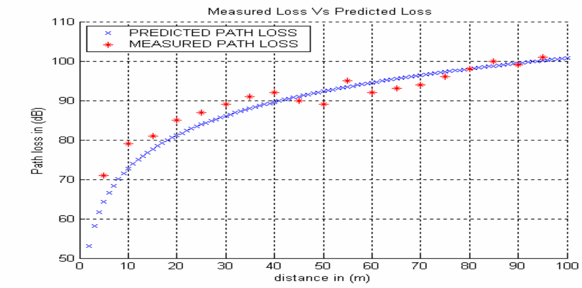

Figure 5: Comparison of Measured Path loss and Theoretical Path loss

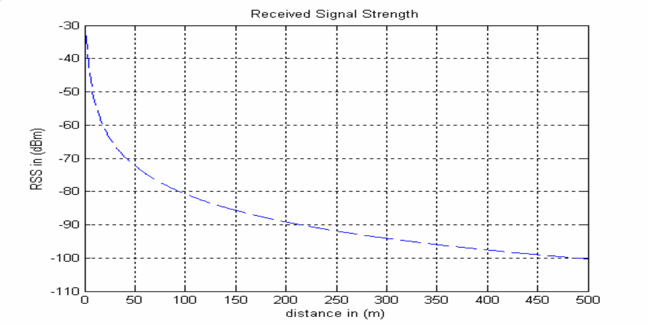

Figure 6: Simulated IEEE 802.11b RSS vs Distance

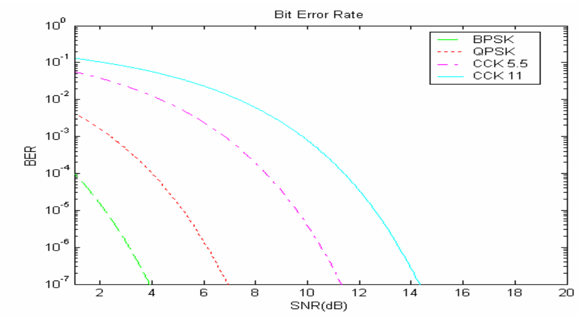

Figure 7: Throughput as a function of distance and MSDU length

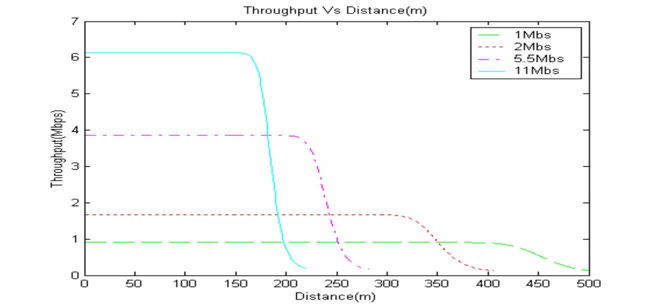

Figure 8: Simulated IEEE 802.11b Throughput vs Distance

between any two nodes for the scenario shown in Figure 4 is 200m.The transmit power of each node is set at a maximum of 100mW as specified in [11]. For simplicity, the path indicated by Figure 4 (A to T) is simulated. The pathconsistsof 8 nodes covering a transmission range of 1400 m. The nodes are operating under the DCF MAC layer scheme. This scenario represents the conventional multi-hop system.

B. Simulation Results

This subsection provides results for the power efficient multi-hop algorithm based on the previously discussed simulation scenario.

1. Propagation Model

In order to validate the use of the log-distance model in our study, we conducted some practical measurements and compared them with the theoretical analysis of the model. The measurements were performed using off-the-shelf IEEE 802.11b hardware, the Linksys WUSB54G wireless USB adapter and a PDA. The measurements were taken around the soccer field at Tshwane University of Technology, for distances varying from 1m to 100m. The experimental data and theoretical analysis results are shown in Figure 5.

2. Simulation Parameter Settings

This section provides simulation parameter settings for the IEEE 802.11b, conventional multi-hop system and the PMCA based multi-hop system performance evaluation. For the IEEE 802.11b, we utilize the performance metric's models described in Section III. The complete set of simulation parameters and their initial values are shown in table 1.

Table 1: Simulation Parameters

Description	Units	Range of values
Node radius	m	200
Transmission distance	m	1400
Carrier frequency	GHz	2.4
Channel Bandwidth	MHz	22
Transmit Power	mW	100
Transmit antenna gain	_	1
Receive antenna gain	_	1
Close-in reference distance	m	0.26
Path loss exponent	_	2.80
MSDU length	Bytes	700
SLOT	µs	20
SIFS	µs	10
DIFS	µs	50
PLCP preamble	µs	144
PLCP header	µs	48
Minimum contention window size	_	31
Maximum contention window size	_	1023
Warranty	years	1
Energy cost	c/kWh	46.23
Active period	%	100
AP Cost	R	1000
Hours per day	H	12

3. IEEE 802.11b Performance evaluation

In this section we evaluate the performance of the IEEE 802.11b under the channel conditions represented by the path loss exponent shown in table 1. In Figure 6, it is shown that a receiver sensitivity of approximately –88 dBm is required for a node radius of 200m, -91 dBm for 250m, -96 dBm for 350m and -98 dBm for 400m. The required SNR for a specific BER, given the modulation scheme (BPSK, QPSK and CCK) is shown in Figure 7. It is also shown in

Figure 7 how the transmission rate is influenced by the SNR for a specific BER. A maximum SNR of 14 dB is required to transmit data at 11Mbps when the BER is at a minimum of 10^{-7}. Data is transmitted at 1Mbps when the SNR is reduced to a minimum of 4 dB for the same BER. In Figure 8, throughput as a function of distance is shown. Maximum distances of approximately 200 m for 11 Mbps, 250 m for 5.5 Mbps, 350 m for 2 Mbps and 400 m for 1 Mbps are achieved.

4. Proposed Algorithm Result

In this section we compare the conventional multi-hop system and PMCA based multi-hop system in terms of performance. The conventional multi-hop system is set in accordance with the IEEE 802.11b performance metrics values specified at 200m for the 11 Mbps transmission.

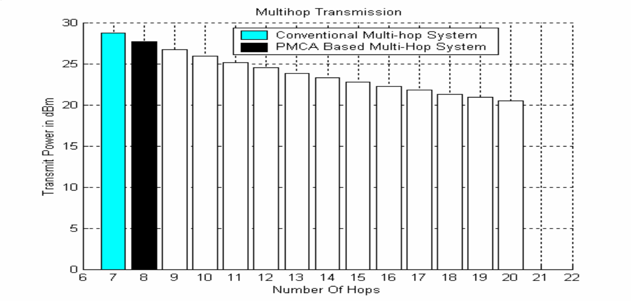

Figure 9: Transmit Power Comparison of the PMCA based System and Conventional System

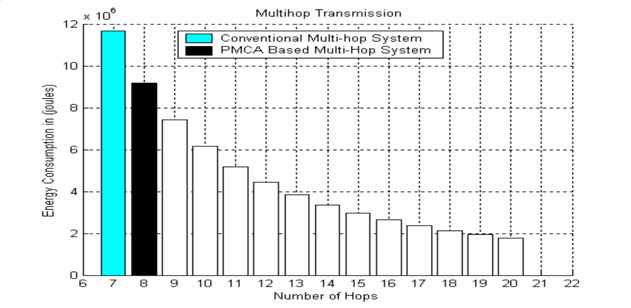

Figure 10: Energy Consumption Comparison of the PMCA based System and Conventional System

It is shown by Figure 9 that, the conventional system covers a transmission range of 1400 m using 8 nodes with each node having a transmit power of 105mW (28.69 dBm for all nodes) and covering a radius of 200m. It is also indicated that the PMCA based system covers the same range using 9 nodes with each node having a transmit power of 73 mW (27.65 dBm for all nodes) covering a radius of 175 m. The results shown in Figure 10 indicate that, energy consumption is significantly reduced when transmit power is reduced. This conclusion is substantiated by [13], whose practical experiments revealed that energy consumption is significantly reduced when transmit power is reduced. Figure 11 also indicates that the PMCA based system is optimized in terms overall cost (energy + infrastructure). In the PMCA based system, 21% of energy consumption and 14% of overall cost is saved.

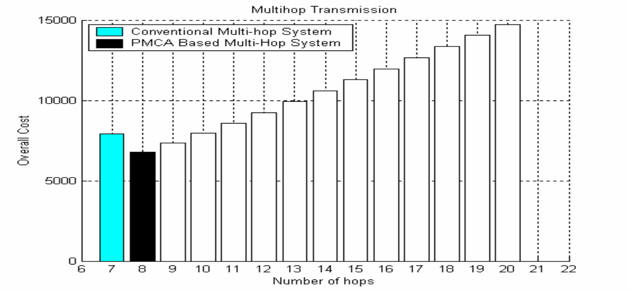

Figure 11: Cost Comparison of PMCA based System vs Conventional system

VI. CONCLUSION AND FUTURE WORK

In this paper, we presented an algorithm that ensures implementation of IEEE 802.11b multi-hop networks with less transmit power consumption. It is also shown that energy consumption is substantially optimized when transmit power is significantly reduced. The algorithm showed that if the network is implemented with the correct number of nodes with appropriate power levels, a substantial amount of energy is saved (21 % in this case). The reduction of algorithm delivers a significant framework for transmit power consumption optimization of IEEE 802.11b multi-hop communication. Furthermore, it serves as a network planning tool that can be utilized when extending the range of WLANs, since to the best our knowledge, tools like ATOL used for GSM, do not exist for IEEE 802.11 networks. WLAN's are ideated as providers of permeate and user seamless communication in future wireless broadband technologies, hence it is of utmost importance that we optimize the performance of these networks.

Future work will asses delay and routing issues associated with this study, as we did not take them into consideration, but are aware of their implications. Practical tests will also be conducted at the Meroka Institue in CSIR to validate our results.

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