ADAPTIVE TRANSMIT POWER CONTROL BASED ON SIGNAL STRENGTH AND FRAME LOSS MEASUREMENTS FOR WLANS

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ABSTRACT OF THE THESIS

Adaptive Transmit Power Control based on Signal Strength and Frame Loss Measurements for WLANs

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In the past few years, we witnessed a rapid penetration of Wireless Local Area Networks (WLANs) into the home and enterprise. Emerging technology such as the IEEE 802.11n radio, which is getting increasingly affordable, makes delivering multimedia content over wireless networks possible and this would drive the technology further into our daily life. As the number of available wireless channels in the unlicensed spectrum is limited (3 non-overlapping channels in 2.4GHz unlicensed band and up to 24 non-overlapping channels in 5GHz unlicensed band), they have to be shared by multiple WLANs consisting of Access Points (APs) and STAtions (STAs). In a Multi-Dwelling Unit (MDU) WLAN deployment, e.g. in an apartment building or hotel, transmissions in overlapping cells tend to interfere with each other. This will adversely impact the aggregate wireless network throughput and thus the quality of experience for applications such as multimedia streaming. Hence there is a need for automatic and adaptive resource management strategy to ensure a good overall network performance.

In this thesis we propose an adaptive per-link Transmit Power Control (TPC) solution for WLANs. TPC can reduce interference, increase channel reuse, and eventually increase the overall capacity in dense 802.11 wireless networks. However intelligent algorithms are required to adapt transmit power in a practical and distributed way to achieve improvement in performance. It becomes more challenging given different types of interference (cooperative and non-cooperative) in the unlicensed band as well as the hidden node problem. From a detailed study of the previous efforts at power control, we observe that in order to make better decisions on transmit power; an AP needs to actively monitor several factors. Hence we develop a TPC algorithm based on both link margin estimation as well as frame loss rate measurement. Compared to previous solutions that adapt the transmit power based on measurement of a single parameter (either received signal strength or frame loss rate), the proposed power control mechanism can diagnose and take remedial action for hidden nodes and channel access asymmetry problems manifesting as frame losses. It is adaptive to mobility, complementary to any rate control algorithm and can also be incrementally deployed amidst non-cooperative nodes. We have implemented the algorithm as an application running on Atheros chipset-based 802.11n APs, taking practical system-level limitations into account. The proposed solution achieves significant transmit power reduction at the APs (to as low as 60% of the maximum power) for STAs as far as 70ft and over ∼60% increase in total network throughput through interference mitigation.

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Dedication

To my parents, brother and my late grandparents.

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Chapter 1
Introduction

In the past few years, we witnessed a rapid increase in WLAN deployment in school campuses, shopping malls, hotels, airports, apartment buildings and at homes. Emerging technology such as IEEE 802.11n radio [7], which is getting increasingly affordable [1], makes delivering multimedia content over wireless networks possible and this would drive the technology further into our daily life. As the number of available wireless channels is limited (3 non-overlapping channels in 2.4GHz unlicensed spectrum and up to 24 non-overlapping channels in 5GHz unlicensed spectrum) , they have to be used or shared by multiple WLANs consisting of Access Points (APs) and numerous STAtions (STAs). For example, in a Multi-Dwelling Unit (MDU) WLAN deployment like an apartment building or hotel, the transmissions in overlapping cells tend to interfere with each other. This will adversely impact the aggregate wireless network throughput and thus the quality of experience for applications such as multimedia streaming.

Fig.1.1 shows a typical deployment scenario. A satellite IP gateway such as Direct TV and Thomson's MFH3 [2], Gigabit Ethernet backbone and 802.11n APs can be used to distribute High Definition (HD) video to wireless Set Top Boxes (STBs) in a MDU. Unplanned, randomly deployed and closely placed APs and STAs in such a scenario result in heavy inter-cell interfere. Off-the-shelf APs come with default factory setting that end users rarely change. Hence there is a need for automatic and adaptive resource management strategy to ensure a good overall network performance.

1.1 Need for Adaptive Transmit Power Control

A STA associates and communicates only with its nearest AP. By minimizing the transmit power of the AP and its STAs to a level that still ensures successful communication between them, the interference to other transmissions in the vicinity could be minimized by taking

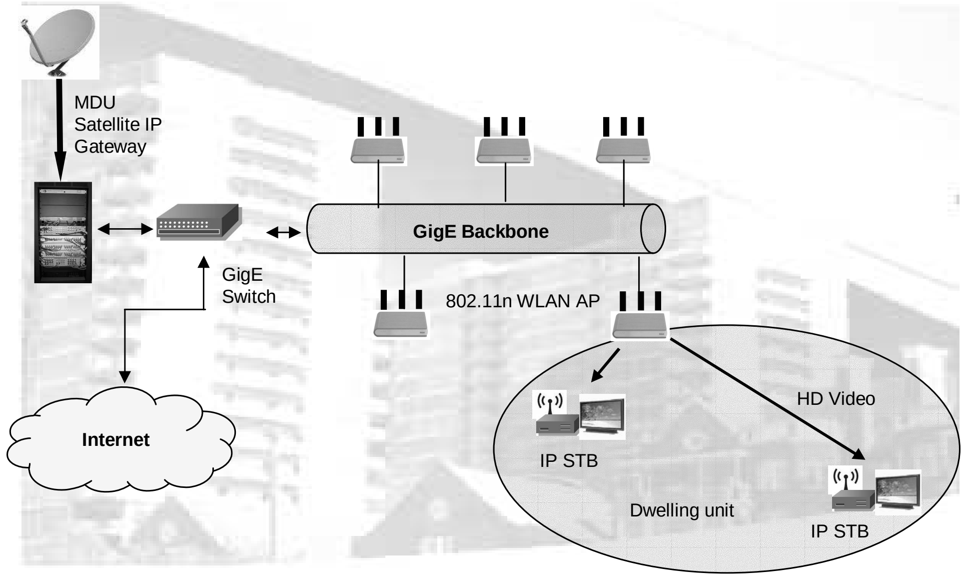

Figure 1.1: Typical Wireless Video Distribution System in a Multi-dwelling Unit

advantage of the attenuation of the transmitted signal power with distance. That is, other APs and its associated STAs at a certain distance can reuse the same channel without interference. This principle allows many AP-STA pairs to communicate at the same time in a given area while using only a limited number of wireless channels.

The lesser the transmit power, the lesser the spatial interval needed to reuse the same channel without interference. This ensures an increase in the overall network capacity in a dense deployment. For example, in cellular networks, smaller cell sizes with lower transmit power leads to the higher overall network capacity. The objective of Transmit Power control (TPC) on a wireless device (AP or STA) is to use minimum transmit power while meeting the requirements for throughput and packet loss rate. TPC helps reduce interference with other devices, improve channel reuse, and eventually increase the overall capacity in wireless networks. Of course, TPC also helps conserve energy and improve battery life of mobile devices.

A transmitter can use lower power to transmit data when the receiver is close to it and still experience good channel conditions. However when the distance between the transmitter and receiver is relatively large and the channel condition is not good, the transmitter needs to use a higher power to transmit data in order to ensure that it is received correctly by the receiver and also to maintain the link throughput. The challenge is how a transmitter determines and adapts (if the channel condition changes) its transmit power to transmit data signal to a receiver dynamically.

1.2 TPC Design Considerations

TPC aims to use the minimum transmit power possible to achieve successful transmission at a target data rate. Since power control is done in a distributed manner certain undesirable side effects are inevitable. The design of an efficient TPC algorithm has to take those effects into account. TPC can exacerbate the classic hidden terminal problem and also introduce channel access asymmetry between two links operating on the same channel. The interaction between two transmitter (Tx)- receiver (Rx) links can be summarized in the Fig.1.2.

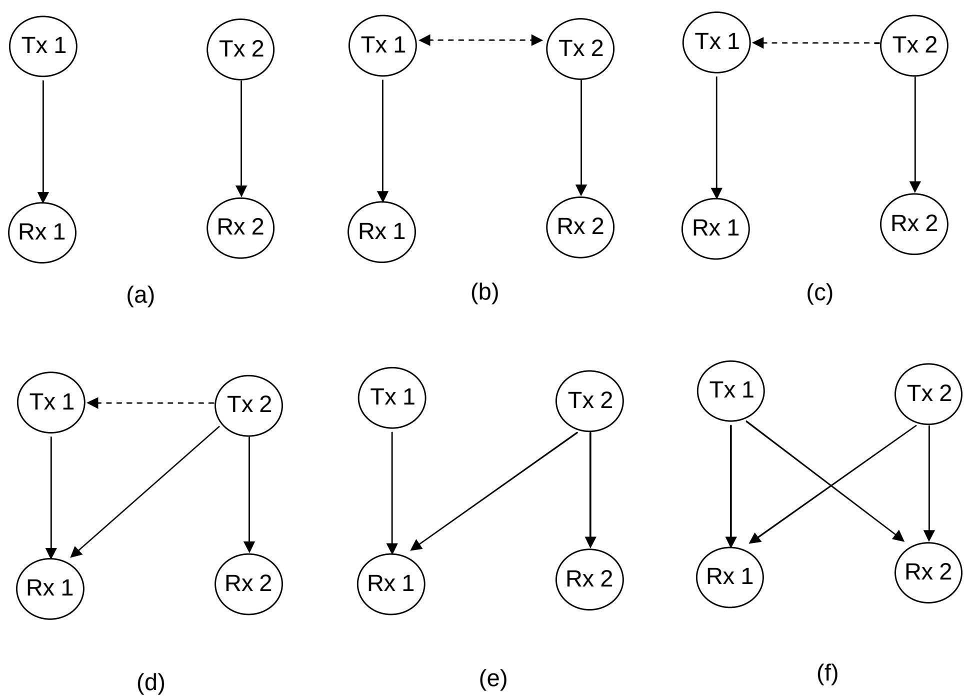

Figure 1.2: Scenarios that result from TPC

A solid arrow ($\rightarrow$) from Tx to Rx indicates that the Rx is in the communication range of Tx. A dashed arrow ($\dashrightarrow$) from Tx_2 to Tx_1 indicates that Tx_1 can carrier sense Tx_2 (i.e., Tx_1 can hear Tx_2's transmissions).

A detailed study of the frequency of occurrence of the six scenarios in unplanned dense deployments has been presented in [16]. When TPC is applied on a link it can result in any of the five scenarios presented in Fig.1.2. Scenario (a) represents the best case where, the application of TPC has resulted complete spatial reuse. Scenario (b) represents no gain as far as spatial reuse is concerned but it is a wise choice to operate in the lowest possible transmit power if the target data rate can be sustained. Scenario (c) represents the exposed node problem that results in channel access asymmetry. $Tx_1 \rightarrow Rx_1$ link is starved since Tx_2 cannot hear Tx_1's transmissions and always perceives a clear channel. Scenario (d) also results in channel access asymmetry but the problem manifests itself in the form of packet losses at Rx_1 due to simultaneous transmissions by Tx_1 and Tx_2. Scenario (e) and (f)represent the classic hidden terminal problem. The transmitters are not in each other's carrier sensing range and hence this problem again manifests itself as packet losses at Rx_1 or both Rx_1 and Rx_2 due to simultaneous transmissions.

1.2.1 Need for Two Triggers

Most TPC solutions presented in literature fail to account for scenarios (c),(d),(e) and (f) (and power control has an increased tendency to result in one of the scenarios) since they rely entirely on only one trigger, either the Signal to Noise Ratio (SNR) deduced from Received Signal Strength Indicator (RSSI) measurements or Frame Loss Rate (FLR). If the power control solution is based on SNR, hidden terminal problem and asymmetric channel access problems cannot be diagnosed and there would be performance degradation due to frame losses. In such cases if the frame losses were monitored, an increase in transmit power to either leverage capture effect or to bring the interfering transmitter within the carrier sensing range would have a desirable effect. Solutions based on frame loss rate measurements alone are non-trivial as the minimum number of samples required to accurately deduce the channel conditions is a critical design choice and also they take a lot of time to converge.

In this thesis we propose an adaptive per-link TPC solution that converges to the minimum transmit power based on RSSI and link margin measurements and also leverages FLR measurements to diagnose and remedy any adverse effects that TPC might have introduced. The need to quickly converge to the minimum power to operate at justifies the choice of RSSI measurements as the primary trigger. The desire to counteract the adverse effects that might have arisen due to power control as detailed earlier justifies the use of FLR as the secondary trigger. Our algorithm as demonstrated in our experimental results clearly identifies and remedies scenarios (d),(e) and (f). Scenario (c) cannot be identified, since exposed terminal problem does not result in packet losses. In [16], Symphony identifies exposed terminal problem through the use of a metric called Expected Transmission Time (ETT). Calculation of ETT and diagnosis of asymmetry in channel access is non-trivial since ETT calculation is complicated by variable packet size, queuing before transmission and packet aggregation in 802.11n.

1.2.2 Interaction with PHY rate control

Calculation of link margin depends on the target data rate for transmissions. We use the maximum data rate that can be supported on a 802.11n device, Modulation and Coding Scheme 15 (MCS15, 130Mbps in 20MHz bandwidth with 2 spatial streams) as our target data rate. The reason being, the airtime will be the smallest to transmit a frame using the highest data rate so that the time that a transmitter interferes with other devices will be minimized. The possible values of target data rate can be selected by the AP or STA in different ways. Our TPC algorithm is complementary to any rate control algorithm since the constant monitoring of FLR ensures that we would negate any adverse effect TPC might have had on rate control.

1.2.3 Granularity of power control

A TPC algorithms shouldn't make unrealistic assumptions about the capabilities of the wireless card and driver. The granularity of power control in terms of magnitude is a critical design choice. Commercially available Atheros 802.11n AR5008 cards [3] allow power settings between a minimum and maximum of 1dBm and 15dBm in steps of 0.5dBm. In our implementation we choose to use any one of 15 different power levels in 1dBm increments between 1dBm and 15dBm. Our TPC solution entirely uses the statistics provided by the Atheros driver for Linux kernel and this makes it readily *deployable even without any modifications to the driver*. In fact, the statistics we use are provided almost by all wireless cards making it easily adaptable to work with any make of wireless cards.

The power adjustment is effected by issuing a request to the wireless card through *ioctl* (input/output control) calls provided by the device-driver. The algorithm we have developed has been evaluated only on the AP side for now assuming predominant down

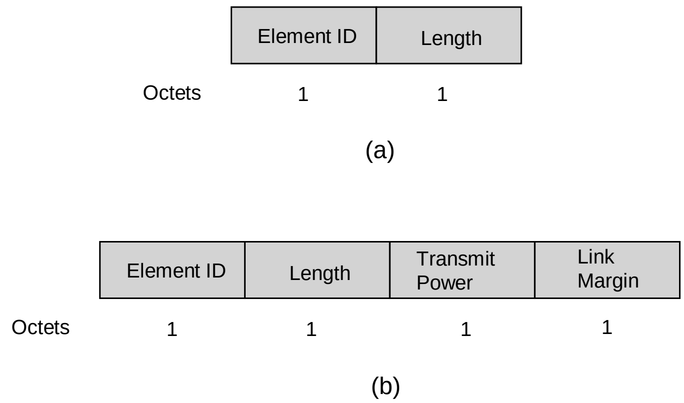

Figure 1.3: (a)TPC Request IE (b)TPC Report IE

link traffic as in a video distribution system shown in Fig.1.1. The framework for STA side TPC is in place and an upgrade to that capability is trivial once there is a provision made available for adjustment of transmit power in the STA mode exactly as in AP mode using a certain *ioctl* call. Currently Atheros AR5008 cards do not provide that capability in STA mode. Other means of power adjustment available on the STA side (for example, *iwconfig athX txpower YdBm*) will either lead to service disruption or change in power setting for all control, management and data frames which is undesirable.

1.2.4 802.11h Measurement Framework

IEEE 802.11h [5] is the amendment added to the IEEE 802.11 standard for spectrum and transmit power management extensions. It provides guidelines for TPC and Dynamic Frequency Selection (DFS) capabilities in IEEE 802.11 devices operating in the 5GHz spectrum (802.11a and 802.11n). We leverage the *TPC Request*, *TPC Report* and *Power constraint* Information Elements (IE) which are part of 802.11h action frames to exchange link quality information (RSSI and/or link margin).

In our solution the AP requests its associated STAs periodically to report their transmit power and downlink link margin information by sending a *802.11h TPC Request*. The *TPC request* is a 802.11h action frame that contains a *TPC request* IE as shown in Fig.1.3(a). After receiving a *TPC request*, the requested STA measures the received power of the transmissions from the AP and sends a *802.11h TPC report* to the AP. The TPC report is again a 802.11h action frame that contains a *TPC report* IE as shown in Fig.1.3(b).

	Element ID	Length	Local Power Constraint
Octets	1	1	1

Figure 1.4: Power Constraint IE

The *TPC Report* element contains transmit power and link margin information sent in response to a *TPC Request* element. The transmit power field (3rd octet) shall be set to the transmit power used to transmit the frame containing the *TPC Report* element. The field is coded as a signed integer in units of decibels relative to 1mW (dBm). The link margin field (4th octet) contains the link margin at the time for the rate at which the frame containing the *TPC Request* element was received. The field is coded as a signed integer in units of dBm. The Link Margin is the received power minus the receiver sensitivity specified for the target data rate. After receiving a *TPC report*, the AP stores the information in its database for the purpose of power adaptation as described later.

The AP calculates the minimum transmit power for its transmission to each of the STAs. It also calculates the transmit power to be used by the each of the STA's for their transmission to the AP based on the link margin (received power of transmissions from the STA measured at the AP minus sensitivity for the target data rate) and transmit power conveyed by the *TPC Report* IE. This estimated transmit power is conveyed to the individual STAs by sending a management frame with the *Power constraint* IE carrying the minimum transmit power as shown in Fig.1.4.

1.3 Our contribution

In this thesis, we describe an adaptive per-link TPC algorithm that will opportunistically reduce the transmission power to reduce interference, improve channel reuse and overall network capacity while meeting the requirements for throughput and packet loss rate. Unlike previous transmit power control solutions our algorithm leverages both the RSSI measurements as well as FLR measurements to precisely deduce the minimum transmit power required for a target data rate. The algorithm also has provisions to tackle the classic hidden terminal problem and asymmetric channel access problem usually exacerbated by power control. The design of the algorithm takes practical system level considerations into account and also does not need any modification to the existing MAC protocol. Our TPC algorithm is currently implemented to support the maximum data rate but is complementary to any rate adaptation algorithm. These attributes makes our solution readily and incrementally deployable. Performance evaluation of the scheme has been done by implementing the TPC algorithm as an application running on Atheros 802.11n APs based on AR5008 chipset. These 802.11n transmitter receiver pairs have 3×3 antenna configuration and can provide up to 130Mbps throughput with 2 spatial streams (third antenna for diversity) while operating in the 20MHz bandwidth. Results show a significant transmit power reduction at the AP (to as low as 60% of the maximum) for STAs as far as 70ft and over ∼60% increase network capacity through interference mitigation. Also performance in the presence of non-cooperative interference and remedial action for channel access asymmetry problems manifesting as frame losses are demonstrated.

1.4 Thesis Organization

The thesis is organized as follows. Chapter 2 introduces related and prior work in the field, their approach, pros and cons. Chapter 3 details the AP side TPC algorithm. Chapter 4 explains the STA side TPC algorithm. Chapter 5 deals with the discussion of experimental results. Chapter 6 concludes and provides suggestions for future work.

Chapter 2

Prior Work

A number of distributed transmit power control algorithms were proposed to reduce interference and increase capacity in 802.11 wireless networks. Most of them adapt the transmit power based on the either the FLR or SNR. If the power control solution is purely based on SNR, hidden terminal problem and asymmetric channel access problems cannot be properly diagnosed and there would be performance degradation due to frame losses unless RTS/CTS is used. However, the use of RTS/CTS eliminates potential interference limited simultaneous transmissions. In such cases if the frame losses were monitored, an increase in transmit power to either leverage capture effect or to bring the interfering transmitter within the carrier sensing range would have a desirable effect. Solutions based on FLR measurements alone are non-trivial as the minimum number of samples required to accurately deduce the channel conditions is a critical design choice and also they take a lot of time to converge. Most solutions have not been implemented and realized in practice to verify effectiveness in real world environment and also make unrealistic assumptions that makes them not incrementally deployable in the presence of non-cooperative nodes.

A lot of work has been done in the area of transmit power control for cellular networks, but the solutions cannot be used for infrastructure WLANs since the fundamental MAC scheme is different. Similarly solutions proposed for ad hoc networks, though discussed here, cannot be directly extended to infrastructure WLANs since the goal of those solutions and the fundamental assumptions vary significantly. Most of the solutions suggested advocate modification to the 802.11 MAC which makes them difficult to either be implemented or incrementally deployed. The TPC solutions discussed in this thesis are all per-link solutions (except for [11] which is a per-cell solution) aimed at either reducing power consumption or interference mitigation and spatial reuse.

2.1 TPC for ad hoc networks

BASIC proposed in [10] is a simple scheme which uses maximum power to transmit RTS/CTS and minimum power to transmit data for reducing power consumption. This results in poor spatial reuse since the whole transmission floor is reserved. PCM [10] was suggested as an improvement to BASIC where maximum power is used for data transmission periodically to mitigate the loss of ACK packets due to collisions at the transmitter. They were primarily aimed at conserving battery life. Both the methods do not promise significant gains in terms of spatial reuse.

In [20], the authors propose SHUSH, a reactive TPC algorithm sensitive to interference as an improvement to PCM and BASIC. SHUSH uses the optimum power for RTS/CTS and data transmissions until there is interference. The interferers are identified and the transmit power required to reach them is calculated and used for RTS/CTS or first data packets to SHUSH them. The algorithm tackles asymmetric channel access problem through two principles: principle of interruption and principle of patience. When an ongoing transmission is interfered, it calculates the transmit power required to SHUSH the receiver and waits till the interferer is done to avoid domino effect (principle of patience). Interrupted transmission has a higher priority to regain access of the channel (principle of interruption). This method requires modification of the MAC to identify interferers and to achieve the interruption principle.

In PCMA [12], the authors aim to create a power control MAC protocol that retains the collision avoidance property. In case of [10] RTS/CTS precludes simultaneous transmissions in the vicinity. But PCMA increases spatial reuse by allowing simultaneous transmissions that does not affect the ongoing ones to occur. Periodic out of band busy tones are used to advertise interference tolerance levels based on which other nodes calculate their transmit power bounds. Modified RTS/CTS is used to convey desired power levels for successful data transfer. If the desired transmit powers are less than the power bound then transmissions can go ahead. This ensures simultaneous transmissions. Problem of hidden terminals doesn't arise since transmissions are power bounded to ensure concurrency. Asymmetric channel access problem however is not solved. The algorithm requires extensive modification of the MAC and hence cannot be incrementally deployed.

In [13], Muqattash and Krunz suggest POWMAC for Mobile Adhoc NETworks (MANETS).

POWMAC allows concurrent transmissions that satisfy interference constraints to occur. Instead of using RTS/CTS to reserve transmission floor, they are used within an access window to exchange maximum tolerable interference limits at each station so that concurrent interference limited transmissions can occur in future. Each device maintains a power constraint list which consists of every other node's address, channel gain, maximum tolerable interference and activity time. This enables interference limited concurrent transmissions to occur thus improving spatial reuse. However, assumptions such as precise measurement of interference and changes to the fundamental MAC make this solution not incrementally deployable.

All the TPC solutions for ad hoc networks that are presented here are purely SNR based techniques and have been evaluated only through simulations. None of the above mentioned algorithms have been implemented in practice to assess performance in real world deployment.

2.2 TPC for WLANs

2.2.1 SNR based TPC techniques

Sheth and Han in [17, 18, 19] detail their implementation of TPC in 802.11b WLAN. They address practical issues such as the layer to implement the TPC solution in, provisions to tackle mobility, etc. The notion of leveraging the 802.11h framework for power control is not entirely new. In [9] Grilo and Nunes proposed a link adaptation and TPC scheme based on 802.11h, 802.11a and 802.11e for goodput maximization.

In [21], the authors highlight the limitations of power control in indoor WLANs. They study the possible granularity of power control in both the magnitude and time dimensions given the practical limitations of radio hardware. They highlight the distribution of RSSI in indoor environments and through measurements show that there are only 2-4 distinct power levels that result in significant RSSI variations. They propose online RSSI, an algorithm to determine the set of useful power levels and argue that it leads to faster convergence.

All the three solutions, since entirely based on SNR cannot diagnose and remedy hidden terminal problem and channel access asymmetry resulting in frame collisions at the receiver.

In [11], Mhatre et al., propose a conservative per-cell power control solution in which all nodes in a cell use the same transmit power and Clear Channel Assessment (CCA) threshold. The algorithm requires precise measurement of total interference at each AP which is unrealistic. The solution is not incrementally deployable as CCA tuning is forbidden in 802.11. Joint tuning of power and CCA ensures that asymmetry in channel access is completely eliminated but there are no provisions to tackle the hidden terminal problem since packet losses are not monitored.

2.2.2 SNR and FLR based TPC techniques

Automatic and adaptive radio resource management strategies have already been investigated in unplanned infrastructure WLAN deployments. Aditya et al., in [8] have studied the impact of AP density on end user experience in detail. They prove that optimal channel selection and TPC can help accommodate more APs in a given area. They also suggest ARF and ERF for rate adaptation and PARF and PERF for power adaptation. ARF and PARF are FLR based methods while ERF and PERF innovate on their previous versions by incorporating SNR feed back to avoid probing to arrive at the appropriate rate or power. The solution has been implemented in actual hardware but lacks provision to react to frame losses due to receiver side interference.

In [15] and [14], the authors propose joint rate adaptation and TPC mechanisms for reducing power consumption. Every transmitter constructs a rate-power table offline with a quadruplet matched against a transmit power-rate combination that ensures more data transfer per unit energy consumption than the traditional approach. The quadruplet consists of the packet length, path loss between the transmitter and receiver, short retry count and long retry count. MiSer [15], assumes knowledge of network configuration (possible sources of interference) and the wireless channel model at the transmitter to construct the table a priori. The authors suggest a pragmatic approach of using 802.11h to deduce the wireless channel conditions at run time. Both the algorithms have not been implemented in practice. Receiver side interference is eliminated by the use of RTS/CTS but it precludes spatial reuse. Also in highly dynamic and mobile environments the algorithm might face severe degradation in performance.

2.2.3 FLR based TPC techniques

Symphony [16], proposed by Kishore et al., is a joint rate and power control solution that aims at opportunistic throughput maximization and reduction in power consumption. It requires loose synchronization between the transmitter and the receiver to periodically switch between a reference phase and operational phase where the reference phase provides the benchmark for the performance after optimization in operational phase. The algorithm is not SNR based and uses packet delivery ratio to estimate link quality and the appropriate data rate for transmission. Once the data rate is deduced it tunes its transmit power to the lowest possible value. Hidden terminal problem is diagnosed by comparing performance with and without RTS/CTS and asymmetry in channel access is found by calculating the Expected Transmission Time (ETT). The problem with the solution however is the choice of mechanisms to diagnose every problem associated with power control. The dilemma that arises whether to increase transmit power or decrease rate does not arise when SNR is also used simultaneously with FLR to make decisions. Also ETT calculation is non-trivial as it is complicated by variable packet size, queuing before transmission and packet aggregation in 802.11n. Symphony deals with system level implementation issues and hardware limitations that only a handful of power control solutions do.

2.2.4 TPC for controller based WLANs

In enterprise class controller based WLAN architectures some solutions for adaptive power control and channel selection have been successfully implemented. Such solutions cannot be adopted directly to unplanned and randomly deployed WLANs such as the ones addressed by our work since they are centralized solutions. The central controller makes optimum resource management decisions on the fly with reliable information from its APs. Aruba's Adaptive Radio Management (ARM) [4] is one such product that ensures adaptive channel and power assignment, airtime fairness and load balancing among others through a controller based centralized solution.

The adaptive per-link TPC algorithm presented in this thesis addresses most of the drawbacks pointed out in the previous techniques. The algorithm cognitively adjusts the transmit power based on active monitoring of two parameters including SNR (RSSI measurements) at the receiver and the FLR at the transmitter. Both the parameters can pick up variations due to mobility and this makes the algorithm reactive to node mobility. In addition the algorithm also addresses remedies for common problems aggravated by the use of TPC such as hidden terminal problem and asymmetric channel access problem manifesting as frame losses at the receiver. Pure exposed node problem is not addressed in this solution. Our TPC algorithm is easily implementable as it does not require modifications to the driver or the fundamental 802.11 MAC and is also incrementally deployable with provisions to perform independently in the presence of non-cooperative interference. As mentioned in Section 1.2.4 the algorithm makes use of the measurement framework provided by 802.11h for TPC to determine the link quality. Our solution is complementary to any rate adaptation algorithm which doesn't lay any restrictions on its deployment. The algorithm has been implemented and evaluated on Atheros AR5008 chipset based APs.

Chapter 3
AP Side TPC Algorithm

3.1 Transmit power estimation based on signal strength measurements

To determine the transmit power, an AP requests each of its associated clients (STAs) to measure its received signal strength and to report the received signal strength or its estimated link margin as well as the STA's current transmit power. The AP unicasts or multicasts *TPC Request* message to each of its associated STAs periodically (every T_m seconds, set to 100ms in our implementation). In addition, once a new STA is associated, the AP issues new TPC request to it. Fig.3.1 shows the AP TPC measurement operation. The requested STA will measure the received signal power, estimate the link margin for the down link, and report the received signal strength or the estimated link margin and its transmit power to the AP by sending a *TPC Report* message. Here the down link is the transmission link from the AP to the STA, and the uplink is the transmission link from the STA to the AP. The link margin estimation is described below.

Based on the received signal strength or link margin measurement reported by the STAs, the AP determines its desired down link transmit power to each of them. The transmit power will meet the throughput and FLR requirements while generating the least interference to other devices in the neighborhood.

The TPC algorithm is to control the transmit power as low as possible while maintaining a target data rate R_t and a target FLR. In our implementation of the algorithm, the target data rate is set to be the highest data rate, MCS15 supported by the 802.11n transmitter and receiver. The reason being the airtime will be the smallest to transmit a frame using the highest data rate so that the time that a transmitter interferes with other devices will be minimized. The target FLR can be set to be the same value to determine the receiver sensitivity for the target data rate (<10% as specified in IEEE 802.11n standard), or a value small enough to ensure the quality of service. The possible the values of target data rate

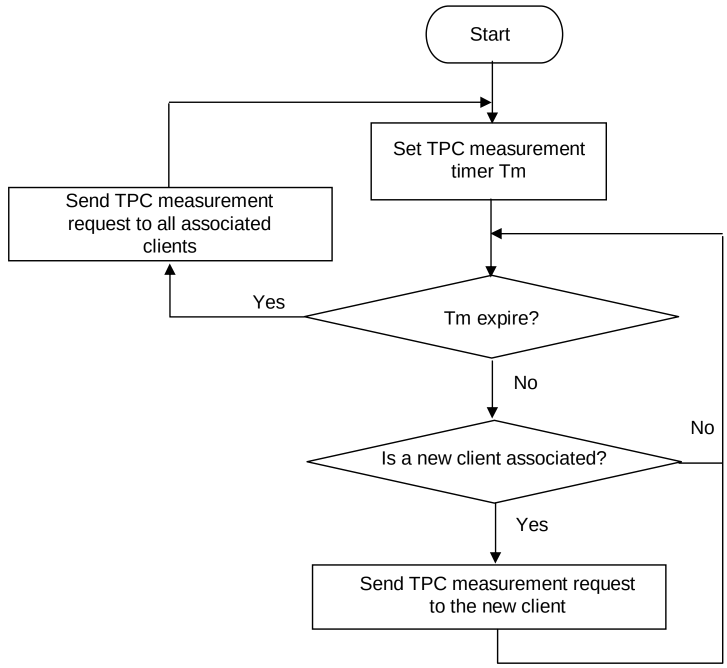

Figure 3.1: AP TPC measurement operation

can be selected by the AP or STA in different ways. The target data rate can be determined by the AP and notified to the STA. One method to notify the station about the targeted data rate is to include the target data rate value in a control message such as the *TPC request*. Another method is to transmit the *TPC request* at the target data rate. If the target data rate is the rate at which the *TPC request* is sent then the receiver sensitivity value that corresponds to the data rate has to be used in the following calculations.

For a client k, to guarantee the target data rate, the targeted received power P_{rk} is equal to

$$targetP_{rk} = S_{tk} + D \tag{3.1}$$

where S_{tk} is the receiver sensitivity for the target data rate and D is the margin to be above the receiver sensitivity. S_{tk} for MCS 15 rate is -61dBm in 802.11n devices. D is a design tuning parameter. Note that the unit in the above equation and the following equations unless specified otherwise is dBm.

If the path loss is L_k, the targeted transmit power is

$$targetP_{tk} = L_k + S_{tk} + D = I_k + D \tag{3.2}$$

where I_k is defined as $I_k = L_k + S_{tk}$

The link margin $M_k(j)$ in the *TPC report* for the j_{th} measurement is

$$M_k(j) = P_{rk}(j) - S_{tk} \tag{3.3}$$

Note that $P_{rk}(j)$ is the j_{th} sample of the received power measured at the receiver. The j_{th} sample of I_k is then

$$I_k(j) = L_k(j) + S_{tk} = P_{tk}(j) - P_{rk}(j) + S_{tk} = P_{tk}(j) - M_k(j) \tag{3.4}$$

where $P_{tk}(j)$ is the actual transmit power of the j_{th} *TPC request*.

We use a linear estimation method to calculate I_k,

$$aveI_k(j) = \alpha \times aveI_k(j-1) + (1-\alpha) \times I_k(j) \tag{3.5}$$

$$\Delta I_k(j) = |I_k(j) - aveI_k(j)| \tag{3.6}$$

$$varI_k(j) = \beta \times varI_k(j-1) + (1-\beta) \times \Delta I_k(j) \tag{3.7}$$

where $aveI_k(j)$ is the smoothed link quality (path loss plus receiver sensitivity) after the j_{th} measurement, i.e. the estimator of the average. $varI_k(j)$ is the smoothed mean deviation of link quality. $\Delta I_k(j) = |I_k(j) - aveI_k(j)|$ is the difference between the j_{th} measured value just obtained and the current estimation of the average. Both $aveI_k(j)$ and $varI_k(j)$ are used to calculate the estimated value of I_k . The estimated value of I_k is equal to

$$\tilde{I}_k(j) = aveI_k(j) + q \times varI_k(j) \tag{3.8}$$

where α, β and q are design tuning parameters. The value of α and β are chosen to be 0.8 so that random fluctuations in RSSI if any is smoothed out. The value of q is chosen to be 2 so that the system is sensitive to mobility which manifests as variation in path loss.

The new desired transmit power for client k is equal to

$$P_{RSSI_k} = \tilde{P}_{tk} = \tilde{I}_k + D \tag{3.9}$$

When the AP transmit data frames to client k, it uses the transmit power equal to P_{RSSI_k} or $\tilde{P}_{tk}$. That is, the transmit power is controlled on a per-STA or per-destination address or per-wireless link basis. Different transmit power values are used for different STAs or destination addresses. The power setting deduced using the above mentioned procedure is applied only if the difference between the newly calculated value and the currently used

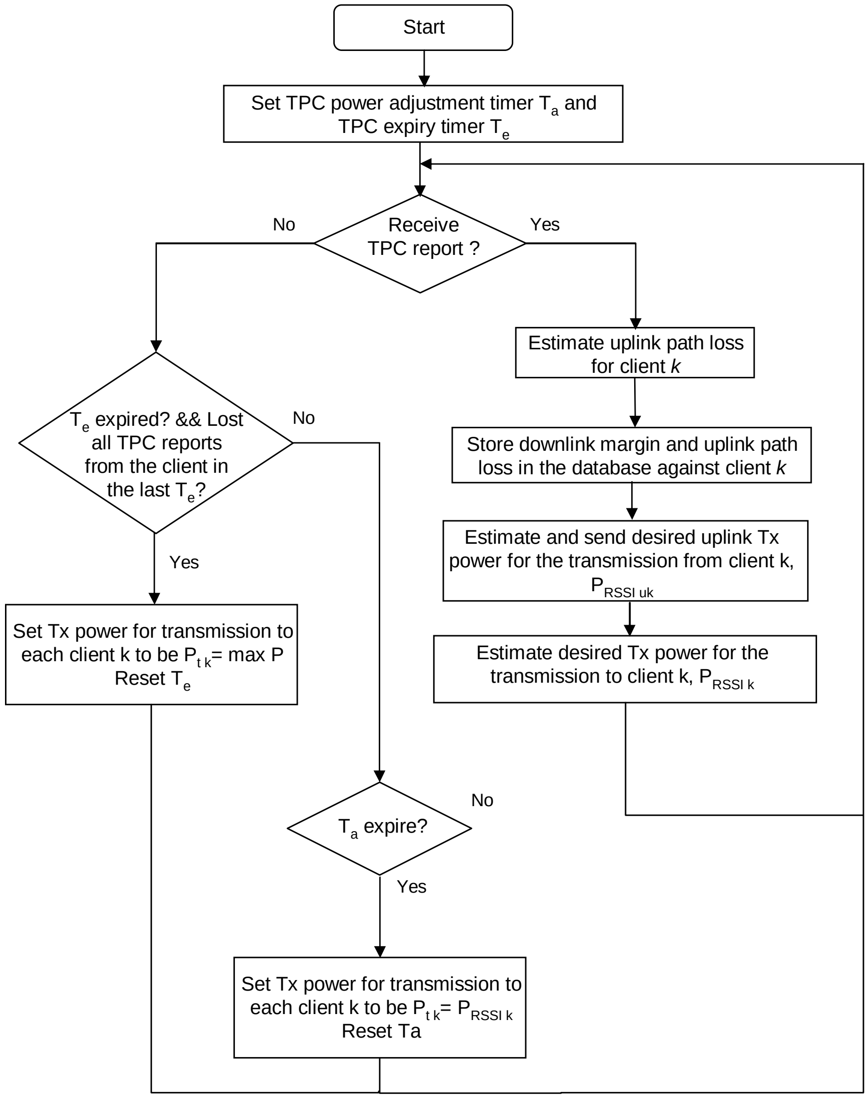

Figure 3.2: AP side TPC operation based on RSSI measurement reports from the STA only

value is grater than or equal to 2dBm. As already pointed out in [21] in Section 2.2.1 the number of distinct power levels that result in a significant change in RSSI is very less. Symphony [16] operates at a 3dBm granularity. We just choose 2dBm to provide a finer granularity to our power control algorithm. Fig.3.2 shows the TPC operation on the AP side based on RSSI measurement reports form the STA only.

In an alternative version of the algorithm, the AP does not change its transmit power per STA (since many wireless cards do not have that capability). The AP determines its transmit power based on the STA experiencing the worst link conditions. It selects a transmit power value to ensure that the received signal strength at its worst STA is high enough for that STA to successfully decode the received frames that are transmitted at the target data rate. If multiple STAs are associated with an AP, the AP's transmit power is

$$\tilde{P}_t = max_k(\tilde{P}_{tk}) \tag{3.10}$$

When an AP boots up, its initial power is the maximum supported power, that is,

$$P_t(0) = maxP \tag{3.11}$$

When a new STA powers up and associates with the AP again, the AP uses the maximum supported transmit power for this STA as its initial value.

$$P_{tk}(0) = maxP \tag{3.12}$$

Furthermore, when a new STA associates to the AP, the AP issues a TPC request for this new client after its association process.

3.2 Power adjustment based on Frame Loss Rate trigger

To react to sudden deterioration of link quality or loss of link, for example, as a client moves away or frame losses caused by receiver side interference, the AP also monitors the loss rate of the frames that it transmitted and adjusts the transmit power based on the *Frame Loss Rate (FLR).*

In our implemented version of the algorithm, the AP periodically determines the frame loss rate (FLR) for its down link transmissions to all of its associated clients. If the FLR during a time interval (say x seconds) is greater than a threshold FT, i.e. $FLR \geq FT$, the AP increases its transmit power to each of its associated client by a value P_d. If the current AP transmit power for the transmission from the AP to client k is P_{tk}, the new transmit power for the AP transmission to client k is the smaller value of $P_{tk} + P_d$ and the maximum transmit power supported by AP, $maxP$, i.e. the new transmit power is

$$P_{FLR_k} = P_{tk} = min\{P_{tk} + P_d, maxP\} \tag{3.13}$$

Since the change to the transmit power at the AP is made to account for sudden deterioration of the link quality, the AP continues to monitor the FLR periodically and adjusts the transmit power at the AP as mentioned above until the FLR is below the threshold

Parameter	**Notation**	**Value**
Maximum AP transmit power	$maxP$	15dBm
Minimum AP transmit power	$minP$	1dBm
Target data rate	R_t	130Mbps
Receiver sensitivity for R_t	S_{tk}	-61dBm
Margin above sensitivity	D	0dBm
Power adjustment step	P_d	2dBm
TPC request timer	T_m	100ms
TPC power adjustment timer	T_a	1000ms
TPC expiry timer	T_e	5000ms
FLR threshold	FT	7%
FLR Up timer	x	2000ms
FLR Down timer	y	5000ms

Table 3.1: Parameter values used in our implementation

FT, i.e. $FLR < FT$. If the FLR is lesser than FT for a particular time interval (say y seconds), the AP decreases its transmit power to each of its associated client by the value P_d and the new transmit power for AP transmission to client k is the maximum of $P_{tk} - Pd$ and the minimum transmit power supported by AP, $minP$, i.e. the new transmit power

$$P_{FLR_k} = P_{tk} = max\{P_{tk} - P_d, minP\} \tag{3.14}$$

The AP continues to monitor FLR. Fig.3.3 shows a flowchart of the procedure of the AP transmit power control (TPC) operation based on RSSI measurement reports from the STAs and frame loss rate measurements.

As a precautionary mechanism to avoid repetitive switching between two power levels one with $FLR < FT$ and the other with $FLR \geq FT$ (in the continued presence of interference or client movement), lower probabilities are assigned for transition from a higher power level to a lower power level. FT, P_d, x and y are the design tuning parameters. In our implementation, frame loss rate threshold FT is set to 10% (as specified in IEEE 802.11n), transmit power adjustment P_d is set to 2dBm and time thresholds x and y are set to 2 and 5 seconds respectively. The choice of the value for P_d is exactly the same as the choice for power setting threshold as described in Section 3.1. Table.3.1 lists the parameter values used in our implementation of the proposed adaptive TPC algorithm.

Alternatively, the AP can perform the FLR measurement for its transmission to each of its associated clients individually, i.e., the AP maintains the information of per-link frame loss rate (capability not present in the Atheros AR5008 cards). Specifically, the

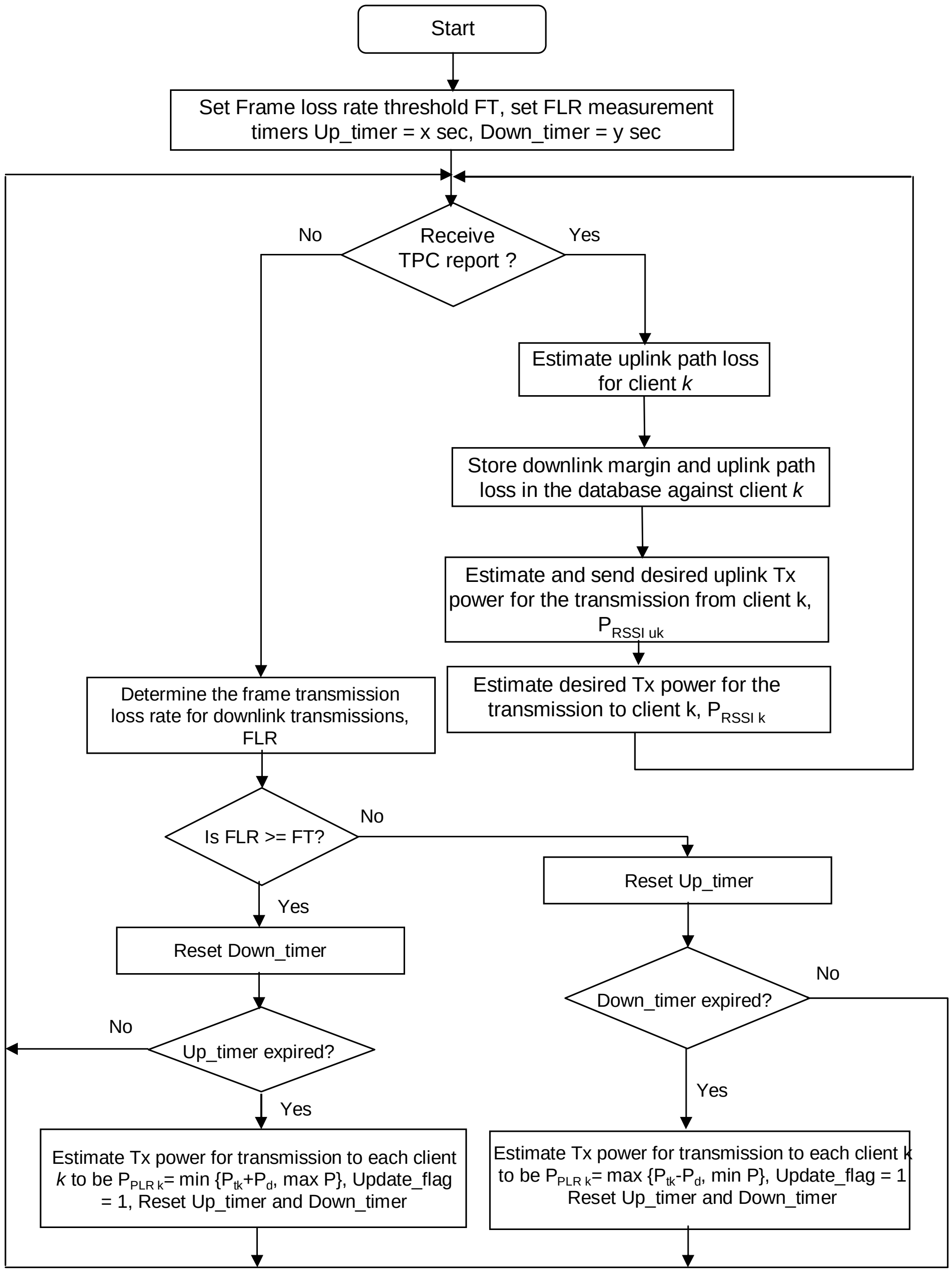

Figure 3.3: AP side TPC operation based on RSSI measurement reports from the STA and the frame loss trigger

AP maintains a window of transmission status for N_{kt} frames that were most recently transmitted to its associated client k $(k = 1, 2,)$. If for client k, the $FLR_k = N_{ke}/N_{kt} \geq FT$, the AP adjust its transmit power for its transmission to client k as specified in (3.13), where N_{ke} is the number of lost or retransmitted frames out of the last N_{kt} frames transmitted to client k by the AP.

Since the change to the transmit power at the AP is made to account for sudden deterioration of the link quality, the AP continues to monitor the FLR_k periodically and adjusts the transmit power at the AP as mentioned above until the frame loss rate is below the threshold FT, i.e. $FLR_k < FT$. If the FLR_k is lesser than FT the AP decreases its transmit power to client k as specified in (3.14) and continues to monitor FLR_k. The entire operation is shown in Fig.3.4

As a precautionary mechanism to avoid repetitive switching between two power levels one with $FLR_k < FT$ and the other with $FLR_k \geq FT$ (in the continuous presence of interference or client movement), lower probabilities are assigned for transition from a higher power level to a lower power level. N_{kt}, N_{ke}, FT and P_d are all design tuning parameters.

3.3 Two modes of operation

The algorithm supports two modes of operation at the AP. In $Mode_1$, the AP chooses to operate at the transmit power determined by the measurement reports (RSSI measurement) obtained from each of its individual client only, that is

$$Mode_1\_P_{tk} = \tilde{P}_{tk} \tag{3.15}$$

where $\tilde{P}_{tk}$ is measured in (3.9). If the link quality suddenly deteriorates and measurement reports from a client k are lost for a particular time interval (expiry timer, T_e), the AP uses the maximum transmit power, $maxP$ for transmission to that client as shown in Fig.3.2. The TPC power adjustment timer, T_a is set to 1 second and expiry timer, T_e is set to 5 seconds in our implementation.

In $Mode_2$, the AP periodically monitors the FLR and uses the greater of transmission powers determined by the measurement reports from each of its clients and the power calculated as a result of FLR measurement as shown in Fig.3.5, that is,

$$Mode_2\_P_{tk} = max\{P_{RSSI_k}, P_{FLR_k}\} \tag{3.16}$$

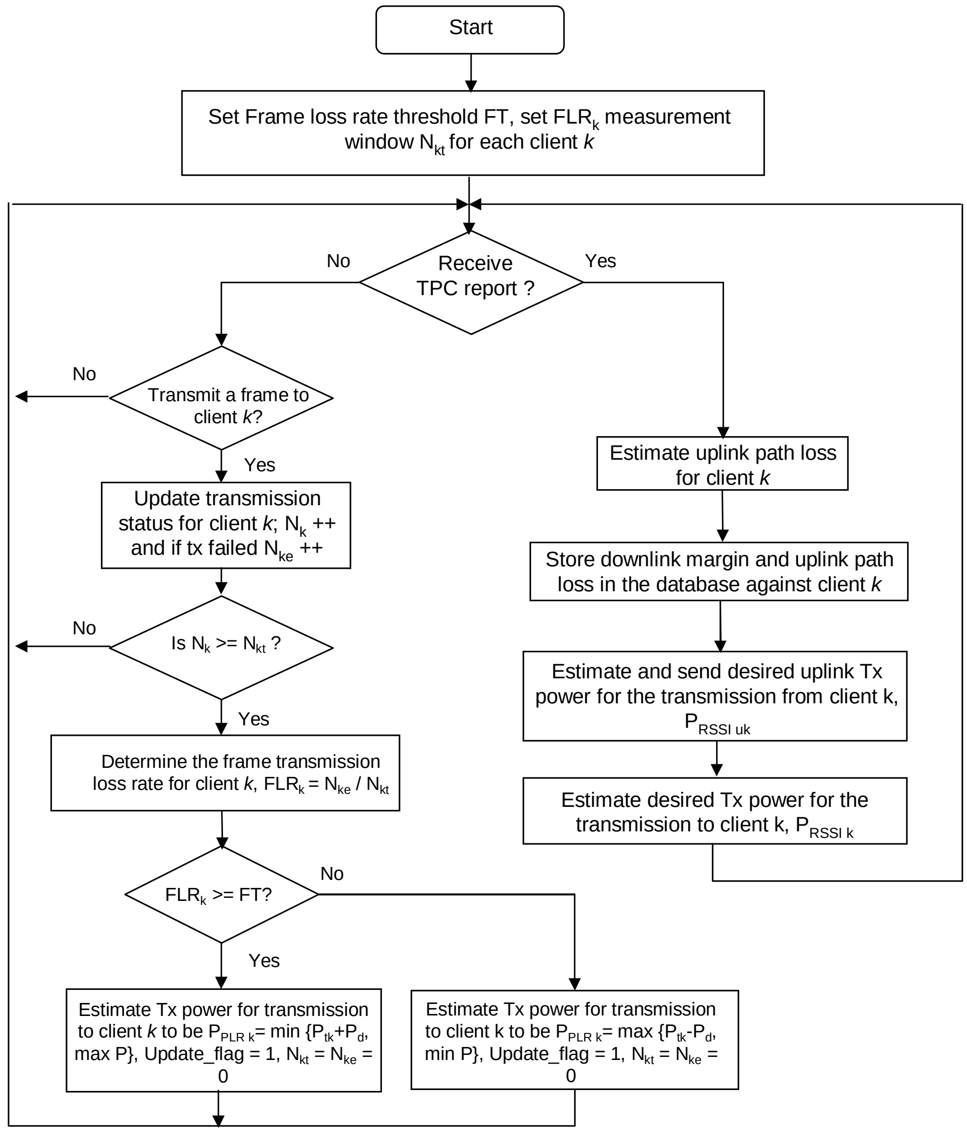

Figure 3.4: AP side TPC operation based on RSSI measurement reports from the STA and the frame loss trigger where the AP maintains the transmission status of a window of packets

where $\tilde{P}_{tk}$ is determined by (3.9) and P_{tk} is determined by (3.13) and (3.14).

The AP may use one of the modes to determine the transmit power. Alternatively the AP may operate in the two modes with time-sharing fashion. That is, the AP switches to $Mode_2$ after it operates in $Mode_1$ for a time period $T1$ or it receives a $Mode_1$ to $Mode_2$ switch message from a neighboring AP. when an AP switches from $Mode_1$ to $Mode_2$, it may send/broadcast a mode switching message to indicate its mode change from $Mode_1$ to

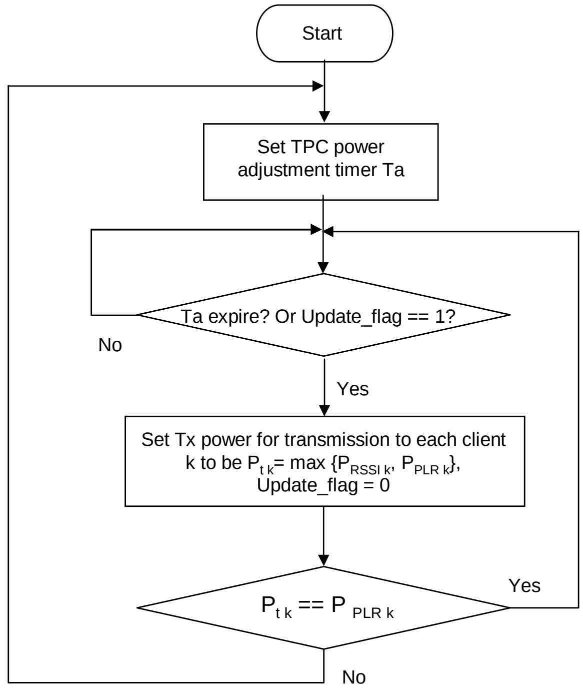

Figure 3.5: Choice of transmit power on the AP when operating in $Mode_2$

$Mode_2$. Similarly, the AP switches to $Mode_1$ after it operates in $Mode_2$ for a time period $T2$ or receives a $Mode_2$ to $Mode_1$ switch message from a neighboring AP. Furthermore it may send/broadcast a mode switching message to indicate its mode change from $Mode_2$ to $Mode_1$.

The AP updates or resets its timer $T2$ if it receives a $Mode_1$ to $Mode_2$ switch message from an neighboring AP if it is already operating in $Mode_2$. Similarly, the AP updates or resets its timer $T1$ if it receives a $Mode_2$ to $Mode_1$ switch message from an neighboring AP if it is already operating in $Mode_1$. The duration of the timers $T1$ and $T2$ is a design choice and ideally $T1$ has to be smaller if the WLAN has non-cooperative WLANs (that do not use TPC) around it. Currently, this idea could not be demonstrated since our algorithm is implemented in the application layer. Broadcast switch messages from one cell cannot be understood by devices in the other cells since the switch message would be a broadcast IP packet.

The following are the reasons why the two operating modes need to be used in a time-sharing manner. Fig.3.6 shows the flowchart of AP transmit power control procedure operating in $Mode_1$ and $Mode_2$ in a time sharing fashion.

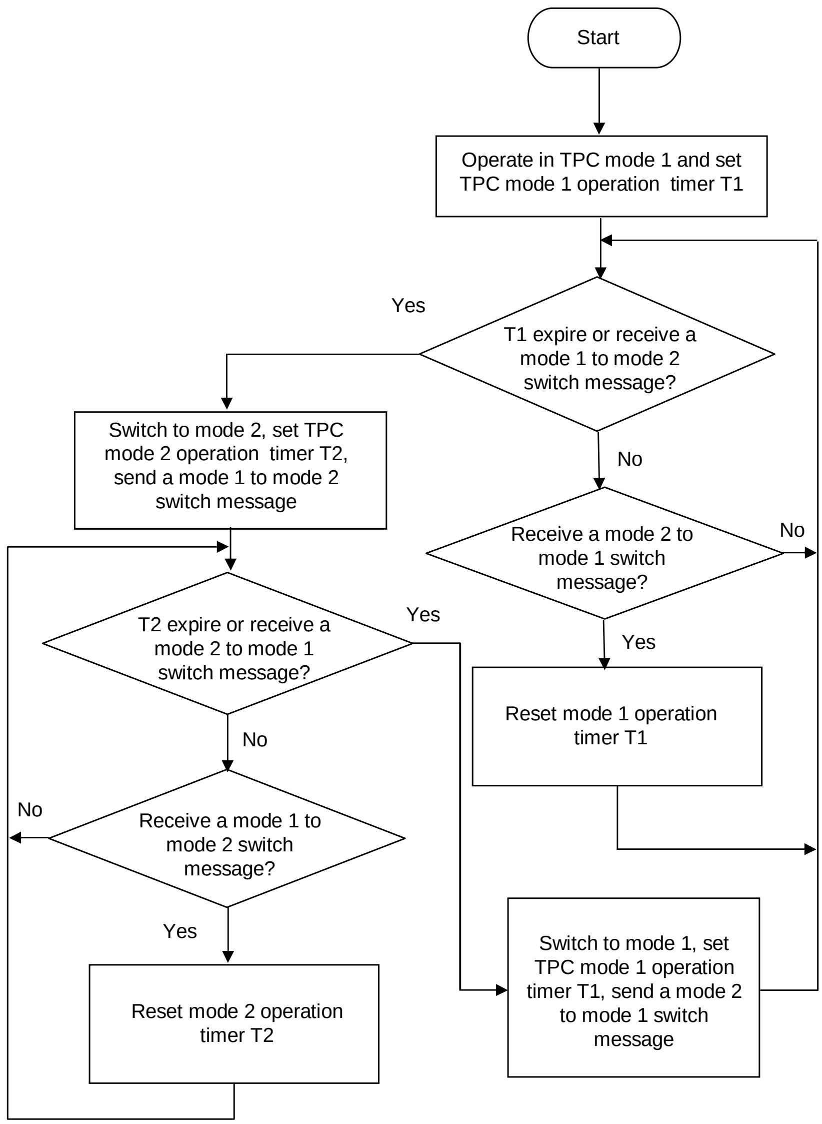

Figure 3.6: AP TPC operating in $Mode_1$ and $Mode_2$ in a time sharing fashion

Scenario 1 (Need for $Mode_1$ to $Mode_2$ transition):

Let us consider the scenario depicted in Fig.1.2(d). Tx_1 operates in $Mode_1$ TPC and uses a low transmit power based only on link quality measurement reports. But Tx_2 does not perform power control and always uses high power. Tx_2 is referred to as the *non-cooperative interferer*. Tx_2 interferes with Tx_1 transmissions, but Tx_1 does not interfere with Tx_1's transmissions, which results in an asymmetric channel access condition. By switching to $Mode_2$, Tx_1 will increase its transmit power if its FLR is high due to collisions at Rx_1 because of simultaneous transmissions by Tx_1 and Tx_2. In $Mode_2$, Tx_1 will increase its transmit power to counteract the frame losses that it suffers.

Scenario 2 (Need for $Mode_2$ to $Mode_1$ transition):

Consider two transmitter (Tx) - receiver (Rx) pairs ($Tx_1 \rightarrow Rx_1$ and $Tx_2 \rightarrow Rx_2$) in scenario depicted in Fig.1.2(a). Both the pairs operate in $Mode_2$ TPC, use reduced transmission power and hence do not interfere with each other. If Tx_2 increases its transmission power to react to sudden movement of Rx_2, it causes the transmission power of Tx_1 to go up because of frame or packet losses at Rx_1 due to interference from Tx_2. Now even if Rx_2 gets back to its previous state the two pairs start interfering with each other resulting in packet losses at the receivers because the transmitters use higher transmit powers as shown in scenario Fig.1.2(f). The transmitters are still out of the carrier sensing range of each other. The transmission powers of Tx_1 and Tx_2 will not decrease due to continued interference to each other at the receiver end. By switching to $Mode_1$ synchronously, the two transmitters will decrease their transmit powers based on only on RSSI reports and hence do not interfere each other anymore. Also, later on when the transmitters switch to $Mode_2$ from $Mode_1$, they do not interfere with each other anymore, the packet loss rate is low and they will not increase the transmission powers.

If Tx_1 broadcasts a mode switch frame, even though Tx_2 is not in the communication range of Tx_1, Rx_2 hears the message and forwards it to its AP, Tx_2. Such an arrangement is possible as there is a provision for the STA to report its beacon receptions to its AP in 802.11k [6].

Chapter 4
STA Side TPC

4.1 Transmit power estimation based on signal strength measurements

The AP also calculates the transmit power of its associated clients or STAs. The target data rate and the target packet loss rate for uplink may be different from the down link data rate. In our implementation, we use the highest supported data rate as the target uplink data rate (MCS15, 130Mbps in 20MHz bandwidth with 2 spatial streams), and the target packet loss rate is set to be the same value used to determine the receiver sensitivity for the target data rate (<10% as specified in IEEE 802.11n standard), or a value small enough to ensure the quality of service.

When a client receives a *TPC Request* it will measure the received signal power, estimate the link margin for the down link, and report the received signal strength and/or the estimated link margin and it's transmit power to the AP by sending a *TPC report* message as shown in Fig.4.1

Based on the RSSI or link margin measurement reported by the stations, the AP determines the client's uplink transmit power. Note that the quality of uplink and down link may not be symmetric. For a client k, to guarantee the target data rate without significant packet loss, the target received power P_{urk} at the AP is equal to,

$$targetP_{urk} = S_{utk} + U \tag{4.1}$$

Where S_{utk} is the AP receiving sensitivity for the target data rate (-61dBm for MCS 15 in 802.11n) and U is the uplink margin to be over the receiver sensitivity. U is a design tuning parameter.

If the path loss for the uplink is L_{uk}, the targeted client transmit power is then,

$$targetP_{utk} = L_{uk} + S_{utk} + U \tag{4.2}$$

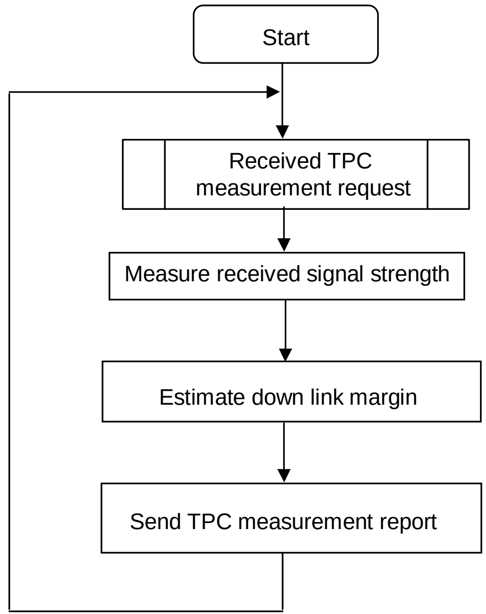

Figure 4.1: STA TPC measurement operation

The AP can estimate the path loss L_{uk} based on the actual client transmit power P_{utk} in the *TPC report* and the actual received power P_{urk} at the AP.

$$L_{uk} = P_{utk} - P_{urk} \tag{4.3}$$

Once again, we use a linear estimation method to calculate the uplink path loss L_{uk}.

$$aveL_{uk}(j) = \sigma \times aveL_{uk}(j-1) + (1-\sigma) \times L_{uk}(j) \tag{4.4}$$

$$\Delta L_{uk}(j) = |L_{uk}(j) - aveL_{uk}(j)| \tag{4.5}$$

$$varL_{uk}(j) = \omega \times varL_{uk}(j-1) + (1-\omega) \times \Delta L_{uk}(j) \tag{4.6}$$

The estimated value of L_{uk} for the j_{th} sample is equal to,

$$\tilde{L}_{uk}(j) = aveL_{uk}(j) + c \times varL_{uk}(j) \tag{4.7}$$

where σ, ω, and c are the design tuning parameters. The value of σ and ω is 0.8 to avoid unnecessary reaction to random fluctuations in RSSI if any and the value of c is 2 to capture the variation in path loss due to mobility.

The new uplink transmit power is equal to,

$$P_{RSSI_{uk}} = \tilde{P}_{utk} = \tilde{L}_{uk} + S_{utk} + U \tag{4.8}$$

The AP can instruct the client to use the new transmit power by sending the message through the *Power constraint* IE to the STA.

In an alternative embodiment, the AP may want all the STAs to use the same transmit power for uplink. The AP then determines the uplink transmit power based on the client experiencing the worst link conditions. If multiple clients are associated with an AP, the uplink transmit power is,

$$\tilde{P}_{ut} = max_k P_{utk} \tag{4.9}$$

When a STA boots up, its initial power can be the maximum supported power by it $P_{u-supported}$. Alternatively, it can be the maximum allowed transmit power specified in the AP management frames (*Power constraint* IE) $P_{u-allowed}$, or the minimum of the maximum supported power and the maximum allowed transmit power, i.e.,

$$P_{ut}(0) = min\{P_{u-supported}, P_{u-allowed}\} \tag{4.10}$$

The new STA will use this maximum power for association and transmission until it successfully receives an instruction to change its transmitting power. When a new STA associates to the AP, the AP issues a *TPC request* for this new client after its association process. After receiving the *TPC report* from this client, the AP determines and adapts the uplink and down link transmit power. The updated uplink transmit power is sent to the client using a management frame (*Power constraint* IE) to instruct the client to use the new transmit power value for uplink transmission.

4.2 Power adjustment based on Frame Loss Rate trigger

To react to sudden deterioration of link quality or loss of link, for example, as a client moves away or frame losses caused by receiver side interference at the AP, the client also monitors its frame loss rate and adjusts the transmit power based on the frame loss rate. In our implementation, a client periodically determines its frame loss rate (FLR_c) for its uplink transmissions to its associated AP. If the FLR_c during a time interval (say x seconds) is greater than a threshold FT_c, $FLR_c \geq FT_c$, the client adjusts its uplink transmit power. If the current uplink transmit power for client k is P_{utk}, the new transmit power for the client k's uplink transmission to the AP is the smaller one of $P_{utk} + P_{ud}$ and the maximum uplink power supported by client, $maxP_{uk}$, i.e. new transmit power is,

$$P_{FLR_{uk}} = P_{utk} = min\{P_{utk} + P_{ud}, maxP_{uk}\} \tag{4.11}$$

Since the change to the transmit power at the client is made to account for sudden deterioration of the link quality, the client continues to monitor the FLR_c periodically and adjusts its transmit power as mentioned above until the frame loss rate is below the threshold FT_c, i.e. $FLR_c < FT_c$. If the FLR_c is lesser than FT_c for a particular time interval (say y seconds), the client decreases its uplink transmit power by the value P_{ud} and the new transmit power for uplink transmission at client k is the maximum of $P_{utk} - P_{ud}$ and the minimum transmit power supported by client, $minP_{uk}$, i.e. new transmit power is,

$$P_{FLR_{uk}} = P_{utk} = max\{P_{utk} - P_{ud}, minP_{uk}\} \tag{4.12}$$

The client continues to monitor FLR_c. As a precautionary mechanism to avoid repetitive switching between two power levels one with $FLR_c < FT_c$ and the other with $FLR_c \geq FT_c$ (in the continued presence of interference or client movement), lower probabilities are assigned for transition from a higher power level to a lower power level. FT_c, P_{ud}, x and y are design tuning parameters. FT_c, P_{ud}, x and y are set to the same values as their AP side TPC counterpart for the exact same reasons. Fig.4.2 shows a flowchart of client transmit power control procedure in accordance with the scheme explained above.

Alternatively, the client k can maintain a window of transmission status for N_{ukt} frames that were most recently transmitted to its associated AP. If the uplink frame loss rate for client k, $FLR_{c_k} = N_{uke}/N_{ukt} \geq FT_c$, the client k adjust its uplink transmit power as specified in (4.11), where N_{uke} is the number of lost or retransmitted frames out of the last N_{ukt} frames transmitted from client k to the AP.

Since the change to the transmit power at the client is made to account for sudden deterioration of the link quality, the client continues to monitor the FLR_{c_k} periodically and adjusts its transmit power as mentioned above until the frame loss rate is below the threshold FT_c, i.e. $FLR_{c_k} < FT_c$. If the FLR_{c_k} is lesser than FT_c, the client decreases its uplink transmit power as specified in (4.12) and continues to monitor FLR_{c_k}. As a precautionary mechanism to avoid repetitive switching between two power levels one with $FLR_{c_k} < FT_c$ and the other with $FLR_{c_k} \geq FT_c$ (in the continued presence of interference or client movement), lower probabilities are assigned for transition from a higher power level to a lower power level. FT_c, N_{uke}, N_{ukt} and P_{ud} are the design tuning parameters.

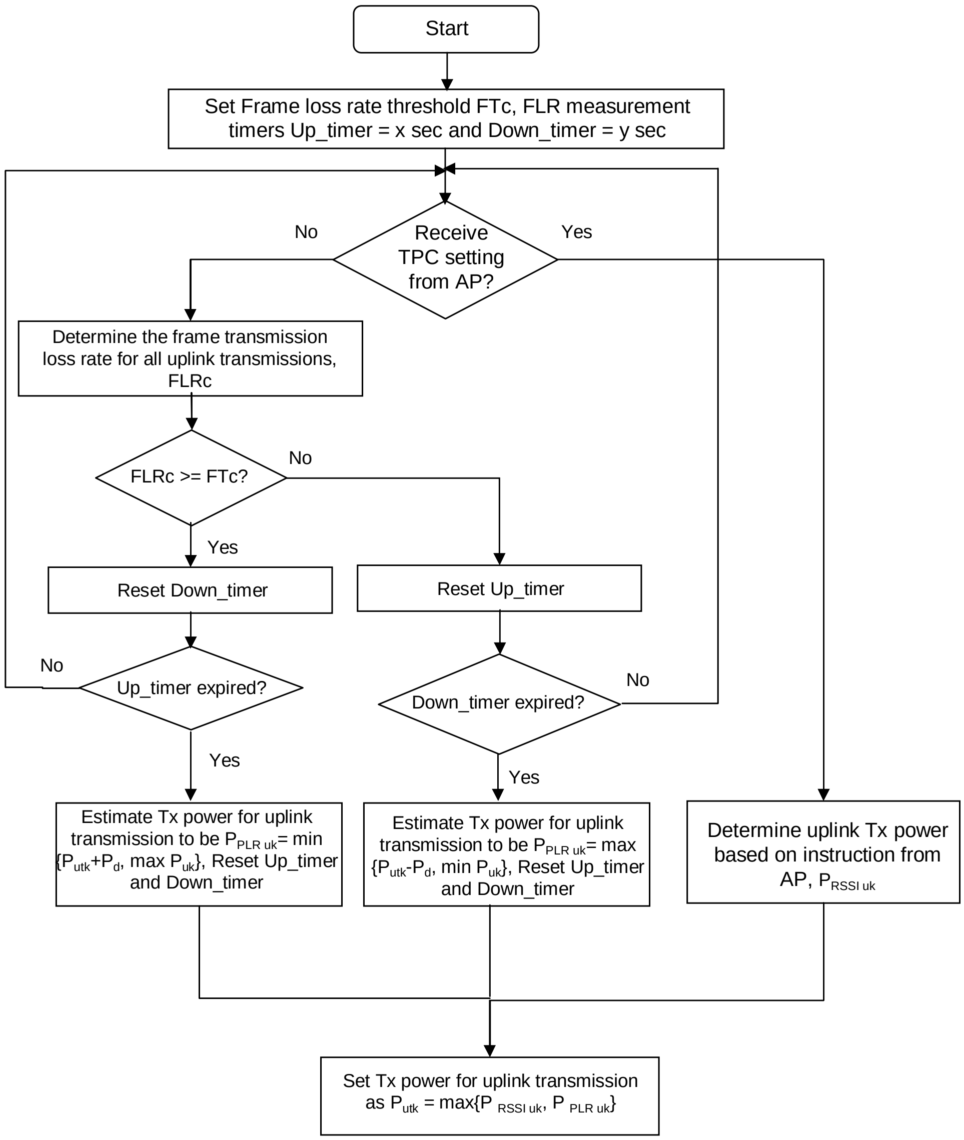

Figure 4.2: STA side TPC operation based on RSSI measurement and frame loss rate trigger

Fig.4.3 shows a flowchart of client transmit power control procedure when the client maintains a window of uplink transmission status as explained.

4.3 Two modes of operation

Similar to the AP, the client can support two modes of operation. In the first mode ($Mode_1$)the client chooses to operate at the transmit power determined for it by the AP

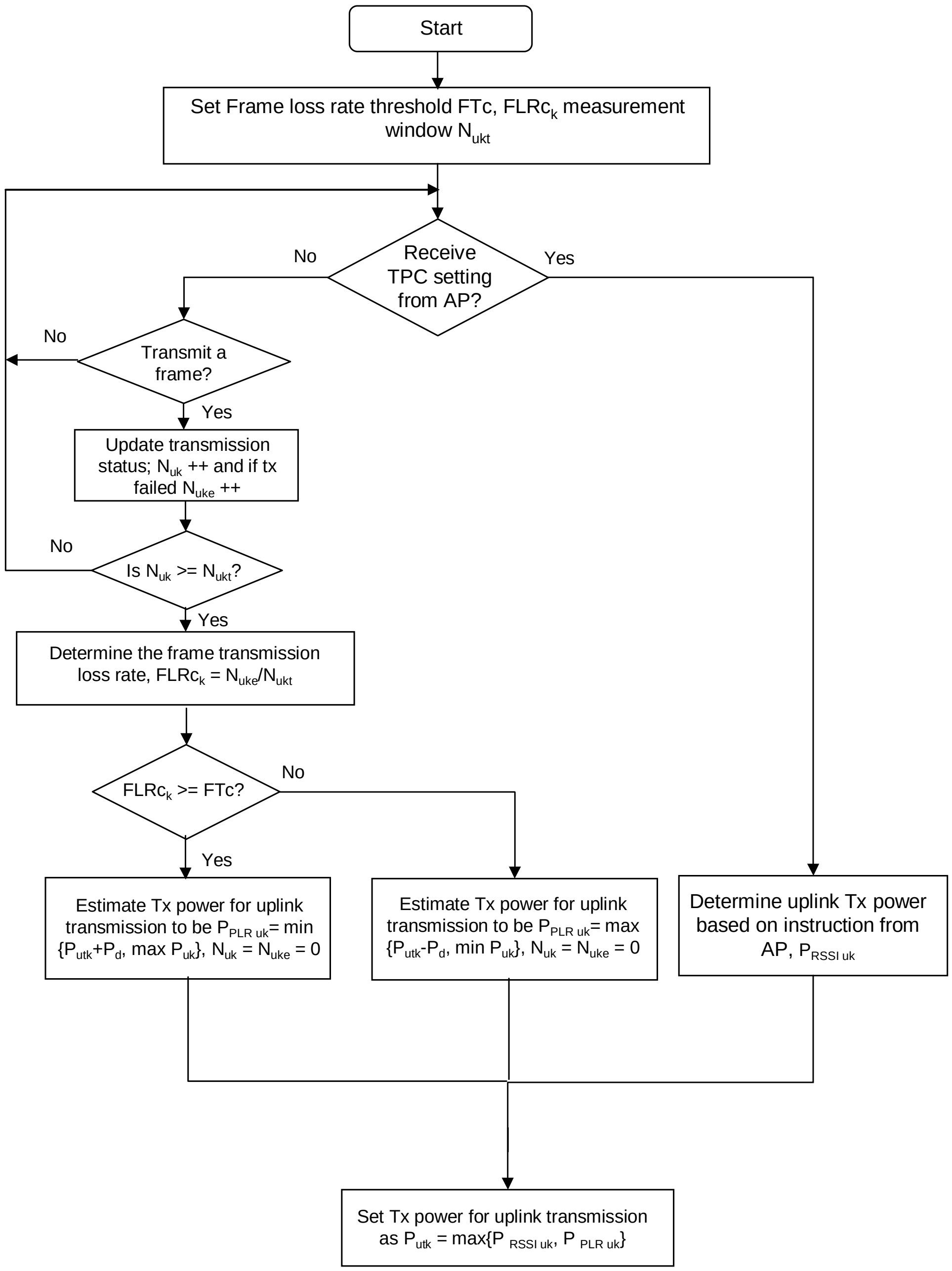

Figure 4.3: STA side TPC operation based on RSSI measurement and the frame loss trigger where the STA maintains the transmission status of a window of packets

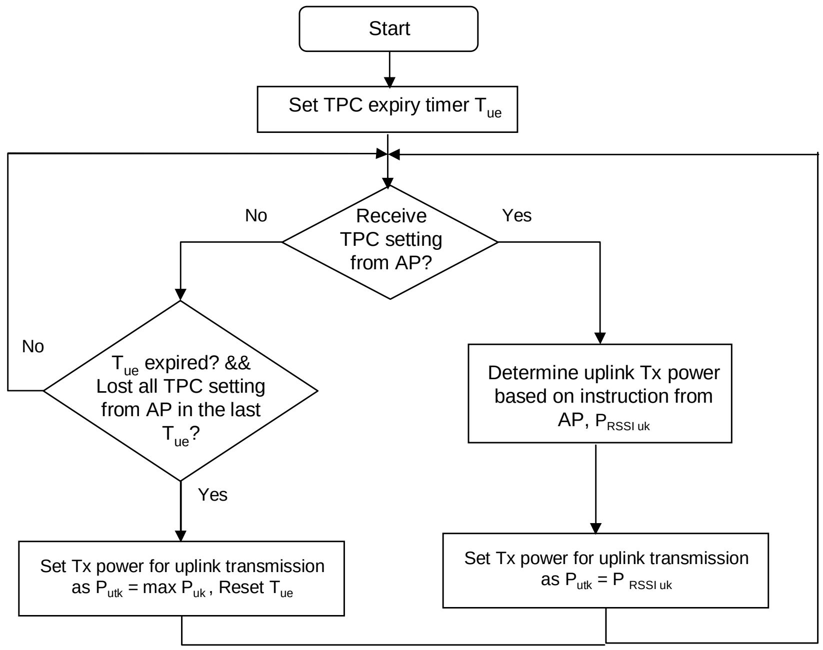

Figure 4.4: STA TPC $Mode1$ operation

that is based on received signal strength measurement only, i.e.,

$$Mode_1\_P_{utk} = \tilde{P}_{utk} \tag{4.13}$$

where $\tilde{P}_{utk}$ is the transmit power that the AP determines for the station k to use according to the received signal strength measurements as shown in (4.8) and (4.9). In $Mode_1$, if the down link quality suddenly deteriorates and the messages containing the power setting decision from the AP are lost for a particular time interval (set to 5 seconds similar to expiry timer, T_e in AP side TPC), the client uses the maximum transmit power, $maxP_{uk}$ for its uplink transmission. Fig.4.4 shows the flowchart of client transmit power control procedure operating in $Mode1$.

In the second mode ($Mode_2$) the client periodically monitors the FLR_c for all its uplink transmissions and uses the maximum of transmission powers determined by the power setting decision by the AP and the power calculated as a result of FLR_c measurement for its uplink transmissions, i.e.,

$$Mode_2\_P_{utk} = max\{\tilde{P}_{utk}, P_{utk}\} \tag{4.14}$$

where $\tilde{P}_{utk}$ is determined by (4.8) or (4.9) and P_{utk} is determined by (4.11) and (4.12).

The client may use one of the modes to determine the transmit power. Alternatively the client may operate in the two modes in a time-sharing fashion. That is, the client switches to $Mode_2$ after it operates in $Mode_1$ for a time period $T1$ or it receives a $Mode_1$ to $Mode_2$ switch message from the AP. Similarly, it switches to $Mode_1$ after it operates in $Mode_2$ for a time period $T2$ or receives a $Mode_2$ to $Mode_1$ switch message from the AP. If the client receives a $Mode_1$ to $Mode_2$ switch message from the AP and it is already operating in $Mode_2$, it reset its timer $T2$. Similarly, if the client receives a $Mode_2$ to $Mode_1$ switch message from the AP and it is already operating in $Mode_1$, it reset its timer $T1$. Similar to the AP, timer $T1$ is set to a low value compared to $T2$. Fig.3.6 shows the flowchart of client transmit power control procedure operating in $Mode1$ and $Mode2$ in a time sharing fashion.

Chapter 5
Results and Discussion

This chapter presents the results of experiments conducted to verify the functionality and performance gains of the proposed TPC algorithm.

5.1 Implementation and setup

As mentioned earlier, performance evaluation of the TPC scheme has been done by implementing the TPC algorithm as an application running on Atheros 802.11n evaluation boards based on AR5008 chipset [3]. These 802.11n AP-STA pairs have 3×3 (omnidirectional) antenna configuration and can provide up to 130Mbps throughput with 2 spatial streams (third antenna for diversity) while operating in the 20MHz bandwidth at the maximum supported modulation and coding scheme, MCS15 (64-QAM and a coding rate of 5/6). The evaluation boards each have a 200MHz MIPS processor and a flash memory system running Embedded Linux. The wireless card on the board can be configured as an AP or STA using a configuration file.

Iperf v2.2.0 (pthreads) and Iperf v1.7.0 (Win32 threads) were used in the host machines (connected to the APs and STAs using 100Mbps Ethernet) to measure the throughput for backlogged UDP traffic. The host machines were two Dell Latitude (D630) laptops (with Intel Code 2 Duo), 2 Dell Latitude (D610) laptop (with Intel Pentium M) and 2 HP Pavilion laptops (with Intel Centrino). The hosts are running either Ubuntu v7.1, v8.4 or Windows XP Operating Systems on them. The Iperf server (traffic sink) is always run on the host connected to the STA and the Iperf client (traffic source) is run on the host connected to the AP unless specified otherwise. In other words the traffic is always down link. STA side TPC could not be demonstrated due to lack of software support for per-packet power control on the STA. Default packet size in Iperf (1470 bytes) was used in all the tests. The duration of each experiment was 900 seconds (15 minutes) and the offered load was 94Mbps unless specified otherwise. The reason for choice of offered load is because of the limitation placed by the evaluation boards that use 100Mbps Ethernet LAN and WAN ports, even though the wireless card is capable of data rates of up to 270Mbps when operating in the 40MHz bandwidth (2 spatial streams at MCS15 PHY data rate).

Since, it is expected that 5GHz will be the favored spectrum for use of 802.11n (more number of non-overlapping channels compared to 2.4GHz spectrum) the tests were conducted on 5GHz channels. Before each test, a sniffer (such as Network Stumbler) was used to make sure that there was no other device operating on the same or adjacent channels. The tests were conducted in Thomson Corporate Research, Princeton Lab.

The default maximum power used by the AP is 15dBm. The target data rate used in our implementation is 130Mbps even though the automatic rate control algorithm provided by the card manufacturer is allowed to function.

5.2 Reduction in Transmit Power

The first experiment was designed to show the reduction in transmit power achieved by the use of the proposed adaptive TPC algorithm. The performance of TPC is studied by varying the distance between the AP and STA. Fig.5.1 shows the floor plan with the positions of the AP and the STAs. The positions of the STAs have been chosen so as to study the effect of distance and obstacles (walls, cubicles, etc.) on the link quality measurements and TPC performance. The experiment was conducted on channel 56.

The distances between the AP and the client at positions a, b, c, d and e are approximately 20ft, 26ft, 30ft, 41ft and 70ft respectively. Although the experiments were conducted in an office environment, the insights obtained from the experiments on the performance of TPC should be general.

Fig.5.2 shows the result of this experiment. The Y-axis on the left represents the throughput and the Y-axis on the right represents the transmit power used for each STA. The X-axis in not linear. The default maximum power used by the AP is not shown in the graph. The throughput achieved with the TPC is very close to that using the maximum power. However with TPC, the transmit power used is much less than the maximum power. That is, the transmitter does not need high transmit power to achieve high throughput when a receiver is close to a transmitter with a good channel. The TPC mechanism cognitively

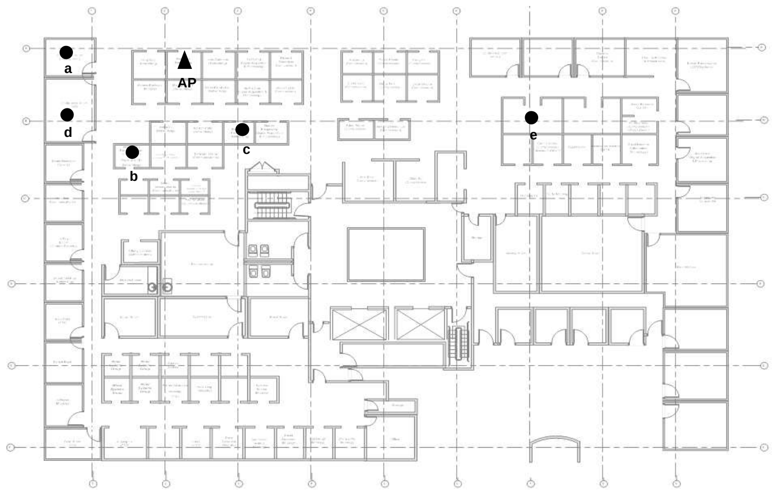

Figure 5.1: AP and STA positions on Thomson CR floor plan for verifying TPC power reduction functionality

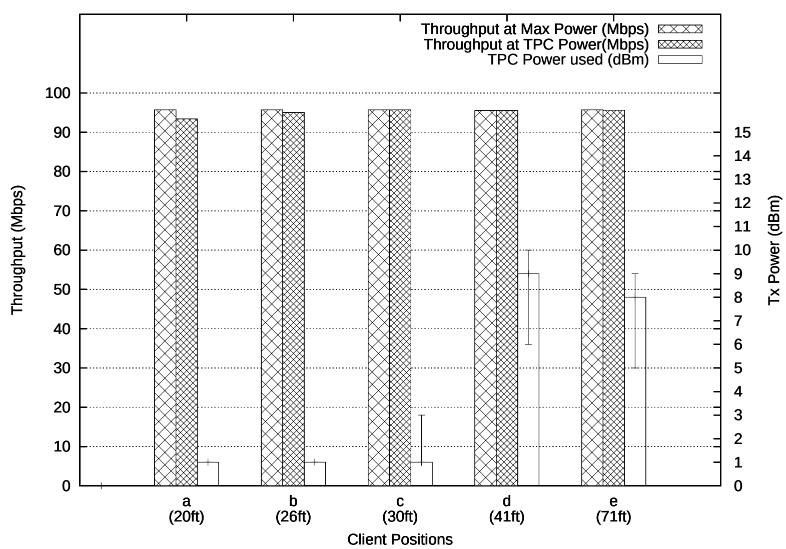

Figure 5.2: Power reduction achieved by TPC

adjusts the transmit power based on the active monitoring of wireless link environment so that the interference to other APs is minimized without compromising the throughout.

The transmit power at the AP for STAs separated by larger distances or walls is relatively higher than the transmit power at the AP for closer STAs. This is because the decision to use a particular value of transmit power is made based on the perceived link quality (RSSI) as reported by the STA. Results show a significant transmit power reduction (to as low as 60% of the maximum) for STAs as far as 70ft (LOS) hence reducing the amount of interference caused. Here the statistical mode of the transmit power values used by the TPC algorithm is shown with the error bars depicting the maximum and minimum values. The Y-axis on the left represents the throughput in Mbps and the Y-axis on the right represents the transmit power estimated and used by the TPC algorithm. Since we use the maximum rate as the target rate there is no power adaptation for STAs separated by a distance greater than the one, where the RSSI is not sufficient to ensure maximum data rate. If the result of the rate adaptation algorithm is used for setting the target data rate then, power adaptation for STAs separated by large distances can also be achieved.

5.2.1 Per Station Power Control

The TPC algorithm proposed here adapts the transmit power on a per-client/per-link basis. The capability could not be shown in the first experiment because of the unavailability of large number of Atheros evaluation boards. This experiment was designed to demonstrate per station power control capability of the TPC mechanism with one AP and three STAs, where each STA experiences different channel conditions (good, fair and bad). The transmitter connected to the AP sends three UDP streams simultaneously, one for each receiver. This experiment was conducted on channel 40. Fig.5.3 shows the location of the AP and STAs. STA1 is located 26ft from the AP, STA2 is located 52ft from the AP with 1 wall in between, and STA3 is located 80ft from the AP.

Three UDP streams, 15Mbps each is transferred simultaneously to the three STAs to emulate three high-data rate video streams. The performance at maximum power is used as the baseline to assess the performance at TPC power. The TPC transmit power used for the individual STAs and RSSI at each STA are measured and compared against similar numbers obtained in the default maximum power case. The tests show that TPC does not adversely affect the quality of data transfer achieved at maximum power. The following figure (Fig.5.4) shows the transmit powers used by the AP for the different STAs and the RSSI measured with and without TPC. STA1, STA2 and STA3 correspond to STAs experiencing a good link, a fair link and a bad link respectively. The Y-axis on the left represents the RSSI (actual received power in dBm - noise floor in dBm) measured in dBm and the Y-axis on the right represents the transmit power used (in dBm) with and without TPC. The noise floor measured during the experiment was -100dBm.

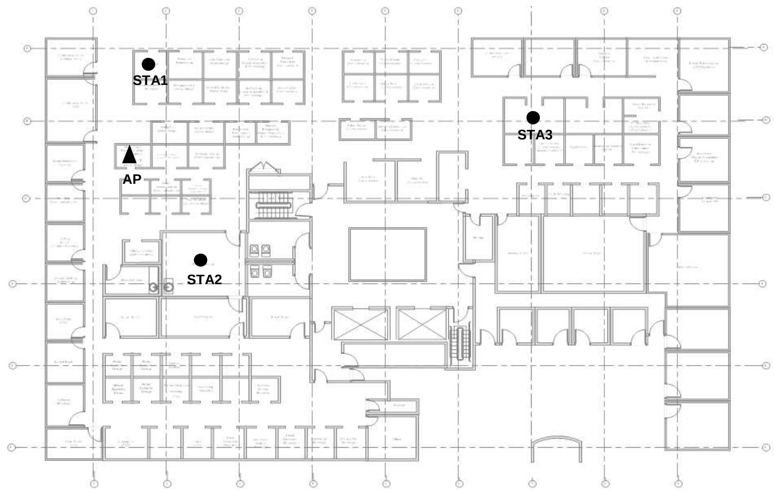

Figure 5.3: AP and STA positions on Thomson CR floor plan for verifying per-link TPC

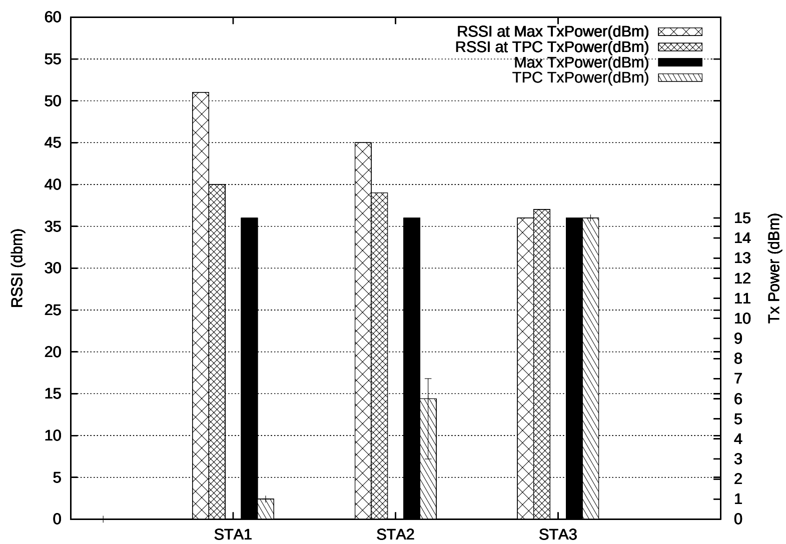

Figure 5.4: Per-STA capability of TPC demonstrated with one AP and three STAs

We see that, the AP continues to use maximum power for STA2 as it already experiences a bad channel. Reducing the transmit power would have adversely impacted the throughput and packet loss rate performance of that link as well as the others. For the clients experiencing good and fair channel conditions the TPC mechanism at the AP appropriately reduces the transmit power based on the feedback (RSSI) from the STAs.

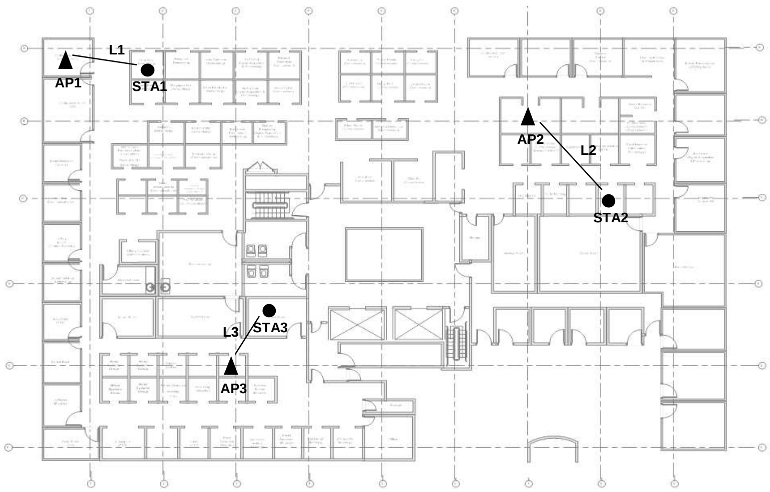

Figure 5.5: AP and STA positions on Thomson CR floor plan for verifying increased spatial reuse using TPC

5.3 Increase in Spatial Reuse

This experiment demonstrates increased spatial reuse by showing that the TPC lowers transmit power for closer STAs and hence mitigates co-channel interference with neighboring APs. The result is a significant increase in total network throughput. Links L1, L2 and L3 are depicted in the Fig.5.5. First we study the interaction between L1 and L3 with and without TPC and then we do the same with links L2 and L3 i.e., a pair of links is involved in an experiment at any given time. Channel 40 is used for experimentation. Maximum possible load is pumped over each link simultaneously. The performance at maximum power is used as the baseline to assess the performance with TPC mechanism. The TPC transmit powers used over each link, the UDP throughput over each link and the aggregated network throughput were measured.

The aggregate UDP throughput for the two link pairs L1L3 and L2L3 at maximum transmit power and TPC transmit power are shown in Fig.5.6. It clearly illustrates the spatial reuse achieved by interference mitigation when using the TPC mechanism. Both link pairs show a ∼60% increase in aggregated throughput when operating at the power determined with TPC mechanism that is calculated by the APs based on link quality reports from the corresponding STAs. Due to the limitation of 100 Mbps Ethernet interface on the 802.11n board the actual throughput gain achieved due to transmit power reduction could

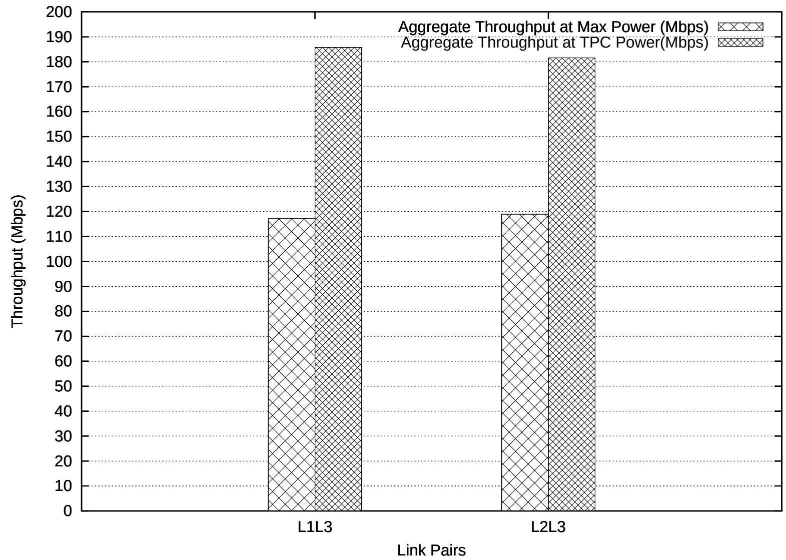

Figure 5.6: Demonstration of spatial reuse by using adaptive TPC

not be measured.

The interaction between the link pairs can be understood by referring to Fig.1.2, which lays out the scenarios arising out of the use of TPC. Clearly the relationship between the link pairs has transformed from scenario (b) to (a).

As an extension another test was conducted with 2 pairs to find the relation between aggregated throughput and the distance between the two APs. One AP-STA pair is permanently located at P0 as shown in the Fig.5.7 and the other pair is placed at increasing distances from the first pair to find out the aggregated throughput with and without TPC. The distances between the APs used in this experiment are as follows; P1=56ft (LOS), P2=97ft (LOS), P3=109ft (LOS), P4=86ft (3walls) and P5=97ft (4walls).

109ft was the maximum linear distance of separation between the two pairs in our research facility. Hence obstacles are used between AP-STA pairs already separated by a large distance for demonstrating spatial reuse. The distance between an AP and its associated STA at each location was restricted to 10ft to ensure that the interaction between the two links is always represented by scenario (b) before TPC and scenario (a) after TPC, as depicted in Fig.1.2. As shown in Fig.5.8, the difference in aggregate throughput increases sharply beyond a certain point.

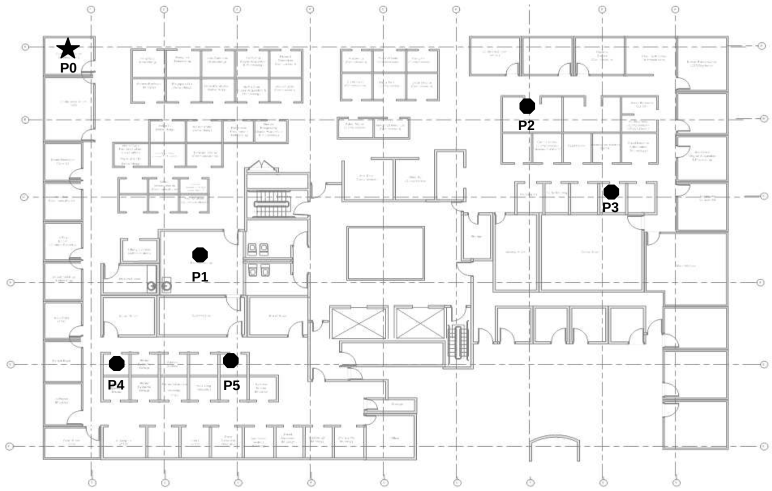

Figure 5.7: AP and STA positions on Thomson CR floor plan to show distance vs aggregated throughput with and without TPC

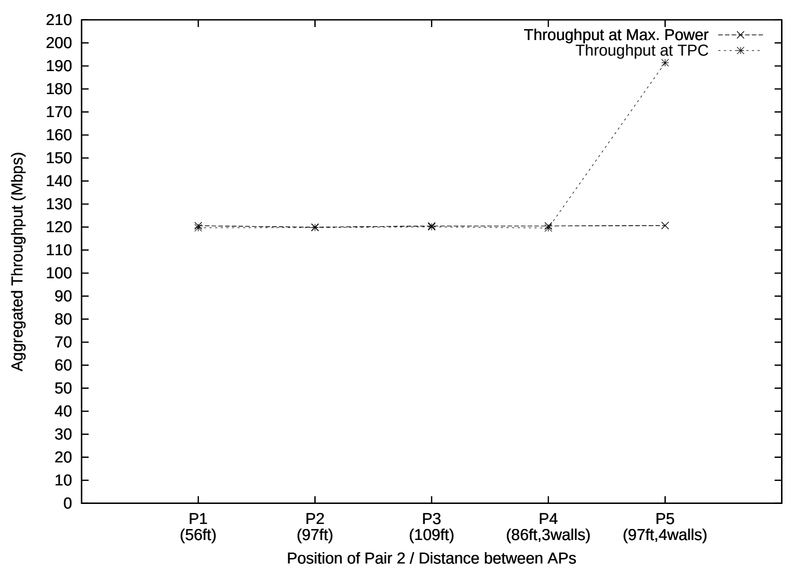

Figure 5.8: Distance vs aggregated throughput with and without TPC

5.4 Use of FLR Trigger

This experiment demonstrates that the TPC mechanism, in addition to its signal strength reports uses FLR to calculate the transmit power for a particular station. As shown in Fig.5.9, the link L1 is the link between AP1 and STA1. Link L2 is the link between AP2 and STA2. Link L2 is the source of non-cooperative interference and always operates at

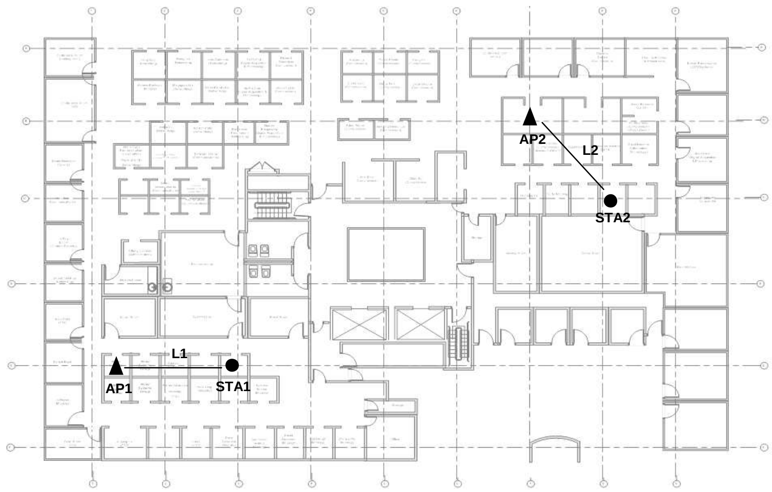

Figure 5.9: AP and STA positions on Thomson CR floor plan for demonstrating use of FLR trigger in TPC

maximum power. We observe the effect of FLR trigger on TPC mechanism on link L1 throughout the entire duration of the experiment. The TPC transmit power used over link L1 and the UDP throughput over each link were measured. The experiment was conducted on channel 56.

Fig.5.10 shows that when link L1 operates in $Mode_1$ TPC it results in an asymmetry in the link. The transmissions from AP1 is not heard by AP2. Hence AP2 always perceives a clear channel and accesses the channel assuming that it is not shared by any other APs. This problem manifests itself as frame losses due to collisions at STA1. When operating in$Mode_2$ the asymmetry in the link is removed. As the FLR increases beyond the frame loss threshold (FT set to 7% in our experiment) on link L1 the transmit power at the corresponding AP is increased incrementally till $FLR < FT$. In this case, the transmit power on the AP1 is increased till AP2 is able to realize that the channel is being shared or the frames are properly received without errors at the receiver STA1 due to capture effect. Note that maximum power is almost always not needed to achieve either of this.

The transmit power variation during the course of the experiment is shown in Fig.5.11. Even though the maximum power used while operating in $Mode_2$ TPC is shown as 15dBm in Fig.5.10 by the error bars, for majority of the time the transmit power fluctuates close to 9dBm.

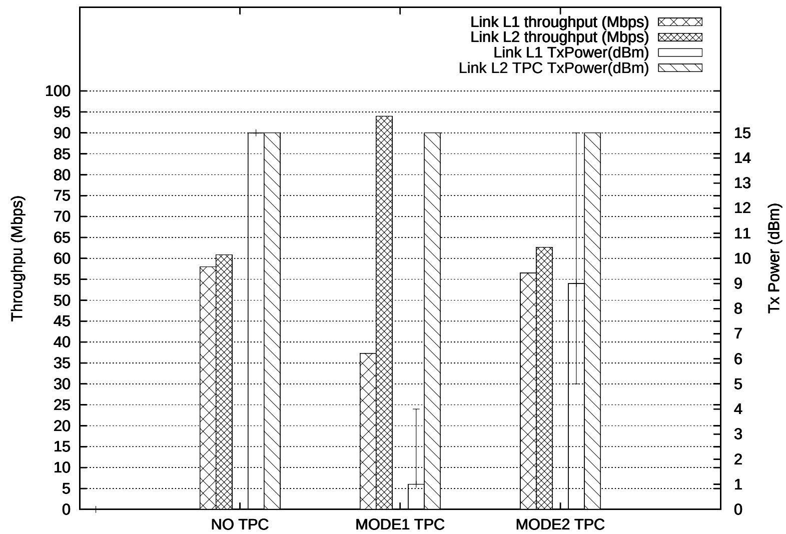

Figure 5.10: Advantage of using of FLR trigger in TPC (Mode2 TPC)

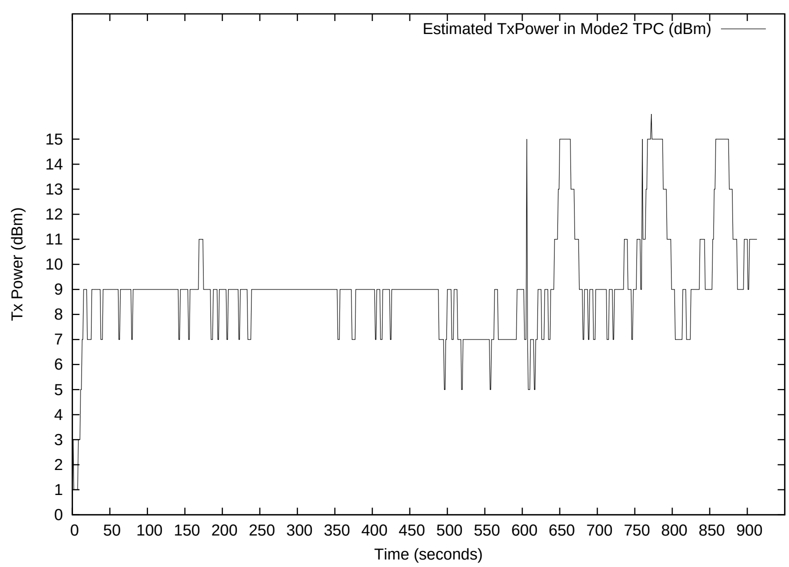

Figure 5.11: Transmit power of Link L2 based on FLR trigger in TPC (Mode2 TPC)

This experiment also demonstrates the performance of our TPC algorithm in the presence of non-cooperative interference and remedial action for frame losses at the receiver. The interaction between the links can be understood by referring to Fig.1.2. The relationship between the links L1 and L2 has transformed from scenario (d) to (b).

Chapter 6

Conclusion

Power control in wireless networks is a well researched topic. Yet, most of the solutions proposed earlier either (1) require changes to the MAC making them not incrementally deployable, or (2) make unrealistic assumptions and ignore limitations placed by the wireless card and device driver rendering them not implementable in practice, or (3) fail to address the hidden node and channel access asymmetry problems (manifesting as frame losses) that are exacerbated by TPC, while retaining the performance gains. In this thesis we propose an adaptive per-link transmit power control solution for WLANs based on both link margin estimation using 802.11h and FLR measurement which addresses all the above mentioned problems. The algorithm has been implemented as an application running on Atheros AR5008 chipset based 802.11n APs (evaluation boards from Atheros). The proposed solution achieves significant power reduction at the APs (to as low as 60% of the maximum) for STAs as far as 70ft and over ∼60% increase network capacity through interference mitigation. The power control mechanism also diagnoses and takes remedial action for hidden nodes and channel access asymmetry problems manifesting as frame losses by measuring the FLR. The claims are substantiated through experimental results.

6.1 Suggestions for Future Work

Even though the current implementation achieves the goals that were initially laid out, there is still a lot of scope for improvement. Presently, the adaptive TPC mechanism is implemented as an application and the 802.11h functionality is emulated by generating and exchanging IP packets. If the algorithm were to be implemented as a loadable kernel module for the driver, then the 802.11h action frames and management frames can be generated and made use of. The STA side TPC can currently be effected only through an *ioctl* call that in turn achieves what the following command does *"iwconfig athX power YdBm"*. Provision for per-packet power control on the STA is required to successfully implement the solution on the STA.

The AP maintains and makes available certain statistics (frames sent, frames lost, frames retried, etc.) for all the down link transmissions. This results in making power adjustments at the AP for all data transmission when frame losses occur due to receiver side interference at one of the STAs. Per-link statistics at the AP would help in tracking down the troubled node and power adjustments can be made for transmissions to that STA alone.

The exposed node problem as depicted in Fig.1.2(c) cannot be solved by our TPC solution. Such a scenario can lead to asymmetric channel access problem that does not manifest as frame losses since the receiver Rx_1 is out of the communication range of Tx_1. Even though Expected Transmission Time (ETT) of frames is a good metric to diagnose the problem, its calculation is non-trivial with frame aggregation, queuing and variable frame sizes. An efficient mechanism to accurately estimate ETT is worth exploring.

Currently the algorithm uses the maximum PHY rate as the target rate for power adjustment with the aim of minimizing frame airtime and hence the duration of interference. Another approach is to have an efficient link adaptation strategy can accurately estimate the target rate and provide it as an input to our power control mechanism. Comparison between such a strategy and ours could provide valuable insights.

Large scale experiments to assess performance in dense deployments could not be carried out due to unavailability of a large number of evaluation boards and a proper field test setting. Even though provisions to adapt to mobility are in place they could not be evaluated since the evaluation boards were not battery run.

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