Advanced Power Control Techniques for Interference Mitigation in Dense 802.11 Networks

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Abstract— **In this paper we propose an enhanced Transmit Power Control (TPC) scheme and a new fractional Carrier Sense Multiple Access with Collision Avoidance (F-CSMA/CA) scheme for use in a dense 802.11 network. The new schemes improve the energy normalized Media Access Control Goodput performance in networks with overlapping Basic Service Sets (OBSSs) by mitigating the interference effect using TPC and reducing interference generated during neighboring BSS-edge transmission using inter-cell coordination. The scheme works seamlessly with a CSMA/CA multiple access technique, and is suitable for evolution of future WLAN systems such as IEEE 802.11ah [4], and High Efficiency WiFi (HEW) [5]. Numerical results demonstrate an increase in the normalized goodput of up to 80% in downlink transmission and 100% in uplink transmission over existing schemes.**

Index Terms—
Transmit Power Control (TPC), Overlapping Basic Service Sets, (OBSS), Wireless Local Area Network (WLAN), Interference Mitigation, Dense Networks

I. INTRODUCTION

Fueled by the availability of new wireless devices and applications, total network traffic has been projected to grow to about 100 exabytes/month by 2015, with 46% of this traffic being transmitted on wireless local area networks (WLANs) [4]. To support this traffic, 802.11WiFi networks are increasingly being deployed in dense environments which consist of multiple Basic Service Sets (BSSs), and Access Points (APs), serving client WLAN stations (STAs). Recent examples of dense network deployment scenarios include use cases identified for 802.11ah which operates in sub-1 GHz [5], and emerging use cases for further development of the 802.11ac specification which operates in the 2.4 and 5 GHz bands, hereafter referred to as High Efficiency WLAN (HEW) [6].

802.11ah supports macro coverage due to larger coverage ranges afforded by the use of the sub-1 GHz band which makes dense deployments of APs and Stations (STAs) more likely [5]. Key use cases of interest include that of WiFi as an outdoor extended range hotspot, and outdoor WiFi, for support of cellular traffic offloading in which the STAs are nomadic with up to 50 STAs supported by a single BSS. This use case entails moderately high data rates, and bursty traffic. Similarly, the need for small cells, and associated dense networks in the 5 and 2.4 GHz bands has been identified as a

use case in the 802.11 study group for High Efficiency WiFi (HEW) [6].

A high density deployment may result in an overlap of adjacent BSSs. When available, adjacent APs in overlapping BSS's (OBSS's) may choose different frequency bands of operation, but in some cases this may not be possible. When multiple OBSS's use the same frequency bands, interference may become a problem especially for STAs on the edge of coverage. The increased interference results in a reduction in the network throughput as seen at the MAC layer, or the MAC goodput [7], and an increase in energy expenditure. Hence, techniques to mitigate the effect of this interference on both the MAC goodput, and energy efficiency of the network, are necessary. The effect of transmission in OBSSs is illustrated in *Figure 1* in which AP1 and AP2 independently transmit data to STAs in their BSSs simultaneously. As shown in the figure, the transmission from AP1 to {STA1, BSS1} (shown in brown) may fail due to the transmission from AP2 to {STA3, BSS2} (shown in patterned blue).
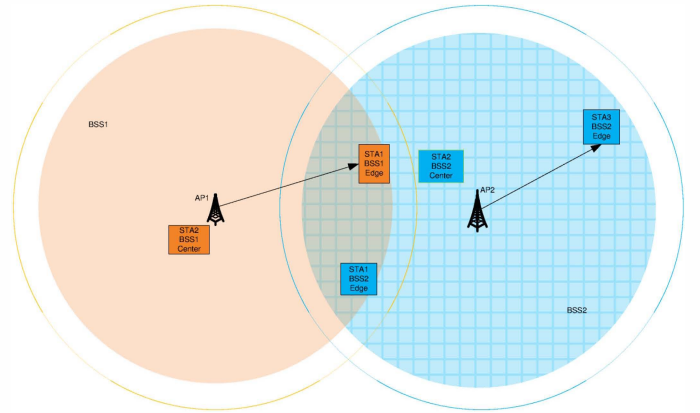

Figure 1: Transmission in Overlapping BSS

In this paper, we introduce enhanced Transmit Power Control (TPC) techniques, and inter-BSS coordination methods, to improve the performance of an 802.11 WLAN network in an OBSS scenario such as the one described above. The schemes presented in this paper may be suitable for WLAN systems that are considered in the future.
Transmit power control has been studied in 802.11 WLANs in many scenarios. These include power savings [8], interference

management [9], and improving the download duration of an FTP transfer [10]. This paper will demonstrate the use of enhanced TPC to improve both the MAC goodput, and the network energy efficiency, for a WLAN in an OBSS scenario. To further improve the MAC goodput and energy efficiency, we present an inter-BSS coordination technique that adjusts the coverage of a (primary) BSS (i.e. the STAs that may send and receive data) to reduce the amount of interference to a neighboring BSS in the event the (neighboring) BSS is transmitting to a STA located at the BSS edge. The primary BSS may also modify its maximum transmit power to an appropriate power level for the duration of the (neighboring) cell edge transmission. The designation of primary and neighboring BSS may be switched in a coordinated manner in the entire network. This scheme reduces interference during neighboring BSS-edge transmission while working seamlessly with CSMA/CA multiple access. Inter-BSS coordination techniques in WLANs have only just been introduced in IEEE802.11ah [5]. However, these schemes work with sectorized antennas at the AP, and are mostly meant to improve the CSMA/CA multiple access for a very large number of STAs (up to 6000 per BSS). Inter-cell coordination schemes are common in cellular networks, and include Fractional Frequency Re-use (FFR) with Inter-cell Interference Coordination (ICIC), Cooperative Multipoint Transmission (CoMP), and enhanced Inter-cell Interference Coordination (eICIC) for Heterogeneous networks [10]. However, with cellular, the coordination schemes are based upon deliberate multiple-access scheduling by a scheduler over time and frequency in a fraction of the transmission bandwidth, whereas the scheme introduced in this paper leverages the random access nature of CSMA/CA across the entire transmission bandwidth. This paper will demonstrate a further improvement in both the MAC goodput, and energy efficiency, using this scheme.

This paper is organized as follows: In Section II, we present an overview of 802.11 WLANs, and existing TPC methods. In Section III, we introduce an advanced TPC scheme necessary for nomadic systems, and a combined TPC/Fractional CSMA/CA method to mitigate interference in OBSS WLANs. We present simulation results in Section IV and then conclude in Section V.

II. OVERVIEW OF 802.11 WLANS AND TRANSMIT POWER CONTROL

A WLAN in Infrastructure Basic Service Set (IBSS) mode has an Access Point (AP) for the BSS, and one or more stations (STAs) associated with the AP. In IBSS mode, peer-to-peer traffic within a BSS is delivered through the AP, with the source STA sending traffic to the AP and the AP delivering the traffic to the destination STA. The AP typically has access or interface to a Distribution System (DS), or another type of wired/wireless network that carries traffic in and out of the BSS. Traffic to STAs that originates from outside the BSS arrives through the AP, is delivered to the STAs, and vice versa.

In an infrastructure mode, the AP, and associated STAs compete for the primary channel to enable them to transmit their data. For CSMA/CA operation every STA, including the AP, will sense the primary channel. If the channel is detected to be busy, the STA backs off. Hence only one STA should transmit at any given time in a given BSS. The carrier sensing mechanism may be physical, i.e. dependent on the energy detected in the channel. It may also be virtual, and dependent on special control frames (for example a Request-to-Send (RTS) and Clear-to-Send (CTS) frame sequence). Access may be improved using enhanced TPC methods.

A. Transmit Power Control in IEEE802.11

Current TPC procedures are MAC based, and involve the transmission and reception of TPC MAC packets. The procedures support the adaptation of the transmit power based on several information elements including path loss, and link margin estimates (see [1]). This TPC procedure is open loop in which the transmitting STA (AP or STA) may determine its transmit power independently of the STA's procedures.

In most 802.11 WLAN specifications, with the exception of 802.11ad, the receiving STA sends out a TPC Report element [1], that includes the transmit power and link margin (the ratio of the received power to that required by the STA to close the link). The transmitter may use the information received in the TPC Report to decide on the transmit power, for example the STA may use any criteria to dynamically adapt its transmit power to another STA based on information it receives via the TPC report from that STA. Specific methods to estimate the TPC are usually proprietary. A TPC report may be solicited by the transmitter in which an explicit TPC Request Frame may be sent by the transmitter [1]. Alternatively, a TPC Report may be unsolicited, for example, an AP in a BSS or a STA in an IBSS. For low duty cycle STAs that need a very low overhead during TPC information exchanges, IEEE802.11ah has proposed an open loop link margin index to improve the accuracy of the TPC estimate by including the receiver sensitivity or minimum required received power for a specific modulation coding scheme (MCS) [5].

Using directional multi-gigabit, mmW WLAN transmission modes (for example 802.11ad [2]), the Directional Multi-Gigabit (DMG) Link Margin element contains a field that recommends an increase or a decrease in transmit power [2]. In this case, the transmitter sends a DMG Link Adaptation acknowledgement to indicate whether it will implement the recommendation or not.

III. TRANSMIT POWER CONTROL AND FRACTIONAL CSMA/CA

A. Enhanced Transmit Power Control for WLANs

The current open loop TPC in IEEE 802.11 requires the transmission and reception of the TPC request/response frames to estimate the correct transmit power. In addition, it suffers from inaccuracies due to the dependence on receiver sensitivities and the number of antennas used at the APs/STAs

[12]. In an outdoor, nomadic scenario such as that in Case 3 for IEEE 802.11ah [13], or HEW [5] the possible change in the channel may require estimation of the transmit power for each transmission. To reduce this inefficiency, we consider an enhanced TPC scheme that may be implemented in one of the following ways:

1. Mandate that the TPC request/response frame be aggregated and transmitted with the RTS/CTS frames to ensure the resulting data transmission is at the correct TPC level.
2. Add a field to the physical layer (PHY) signal field (SIG) to indicate the transmit power and link margin needed in every frame. Based on this modification, each STA/AP is able to estimate the path loss from the transmitter and estimate the instantaneous power needed.

In this paper, we will assume that an enhanced TPC scheme is used.

B. Fractional CSMA/CA and TPC for Interference Mitigation

In dense OBSS networks, the use of TPC to improve performance may not be adequate. In this section, we describe a technique to adjust the coverage of a BSS to reduce the amount of interference to a neighboring BSS. In a dense, OBSS network deployment; independent operation of CSMA/CA in each OBSS may result in:

a) Simultaneous transmissions from multiple APs resulting in collisions (as illustrated in *Figure 1*) or
b) Prevention of transmissions due to collision avoidance, resulting in the reduction of throughput.

However, with appropriate TPC mechanisms and inter-BSS coordination, it may be possible for the two APs to transmit simultaneously with few or no collisions. We propose a fractional CSMA/CA scheme in which only a fraction of the total STAs are permitted to access the channel at a specific time. The access duration is coordinated between multiple BSSs to limit the amount of interference experienced. TPC is incorporated to ensure that the interference resulting from the coordinated transmissions is limited. The technique implicitly reduces the coverage of a subset of the BSSs in the network, reducing the amount of overlap and hence improving the system performance.

We partition the STAs into BSS-edge STAs and BSS-center STAs. We define a BSS-edge STA as a STA that is adversely affected by a neighboring BSS during reception or adversely affects a neighboring BSS during transmission. A BSS-center STA is a non-BSS-edge STA. In *Figure 2*, the scheme ensures that in the case of transmission of a BSS-edge STA {AP1 to STA1, BSS1}, the neighboring BSS limits its transmission to BSS-center STAs with added power control, thus ensuring that the STA in BSS1 is not affected {AP2 to STA2, BSS2}.

The scheme is described below:

1. Prior to proceeding, the STA's TPC capabilities must be checked using the TPC capabilities signaling fields. If the STA either does not support the feature, or is

otherwise instructed not to use the feature, the remainder of the technique is skipped and packet transmission follows the specification for legacy operation in existing 802.11 specifications.
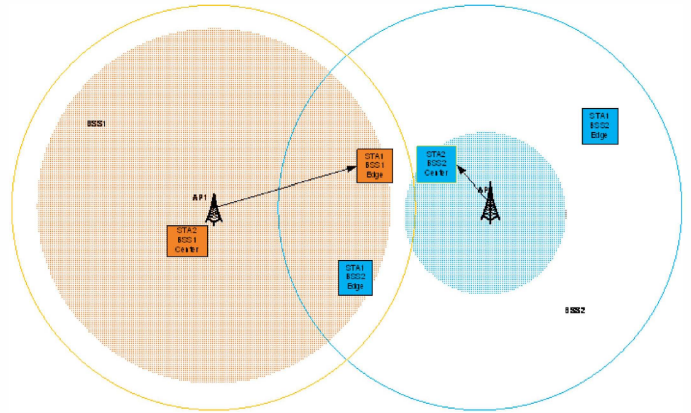

Figure 2: Overlapping BSS with Fractional CSM/CA and TPC

2. Each AP then identifies the BSS-edge STAs and non BSS-edge STAs under its control. BSS-edge STAs may be identified using a variety of different techniques such as (a) path loss; (b) geographic location; (c) STA assisted (d) genie aided as follows:
   a) Path loss method: The AP estimates the path loss from the difference of the channel to the STA and the RSSI of the individual STAs. This may be done by using TPC request and TPC response frames between the AP and STAs. The AP then ranks the STAs based on path loss and designates the bottom x% as BSS-edge. The percentages of STAs that are designated as center or edge are an adjustable design parameter.
   b) Geographic Location: The AP uses the geographical location of STAs, if available, to identify cell edge STAs and signals STAs accordingly. This may be based on Global Positioning System information or other location-based techniques.
   c) STA assisted: The STAs signal the difference between the RSSI of associated AP and next strongest AP(s). STAs with differences less than a threshold are elected as cell edge STAs
   d) Genie Aided: The AP is Genie-aided i.e. the information is derived from a network management tool.

3. The AP transmits a BSS-edge flag to STA at BSS edge. The BSS Edge indicator may be signaled as a new MAC information element or as a flag to a modified CTS frame.

4. In each BSS, the STAs are grouped based on a desired criterion e.g. cell edge, cell center. As an example,
   a) Group 1: cell center STAs in all BSSs
   b) Group 2: cell edge STAs in odd numbered BSSs

c) Group 3: cell edge STAs in even numbered BSSs

5. Multiple APs coordinate to allow access of each to the pool of STAs performing CSMA/CA based on the BSS index. For example:
   a) Group 1 is always placed in the active CSMA/CA pool
   b) Group 2 and 3 are placed in the CSMA/CA pool in a coordinated manner. The coordination may be such that groups 2 and 3 are in orthogonal pools i.e. when group 2 is in the pool, group 3 is not.

6. The transmit power is adjusted based on the group in the active CSMA/CA pool. Note that the maximum transmit power is important as this determines the power at which "control" frames needed by all the STAs are sent.
   a) If group 1 only is in the pool, then the maximum transmit power is limited to the "worst" STA in the limited group i.e. the STA that requires the maximum transmit power in group 1. This maximum transmit power is used for both data and control frames.
   b) If all STAs are in the pool, then the maximum transmit power is limited to the "worst" STA in the BSS i.e. the STA that requires the maximum transmit power in the BSS.

To manage the amount of interference between OBSSs, the STA grouping and timing between the different groups must be coordinated between overlapping BSSs. This coordination may be centralized, with control managed by an AP controller connected to all the APs in the network, or distributed, with control and coordination managed by the APs themselves. The coordination procedure decides on the number of groups, the criteria for assigning STAs to each group, and a timeslot structure used to ensure non-overlapping transmit opportunities for the interfering groups. These transmit opportunities may be fully or partially orthogonal. The coordination, whether centralized or distributed, may require some changes to the WiFi specification. In this paper, we assume a common timeslot structure between groups and orthogonal transmissions between groups 2 and 3.

Figure 3 shows a 16 BSS network with STAs placed in groups 1, 2 and 3 as discussed. *Figure 4* shows the 3 groups and the timeslot structure that governs their placement in the active CSMA/CA pool: Group 1 is always in the active CSMA/CA set while Groups 2 and 3 are placed in the active CSMA/CA set during specific time-slots in a manner to ensure orthogonal transmission. The scheme is combined with TPC to limit interference.

IV. SIMULATIONS

We present simulation results using an NS3-based simulator showing the effect of the TPC and the Fractional CSMA/CA on the MAC goodput and energy efficiency of an overlapped BSS WLAN. We will use parameters that simulate an IEEE802.11ah network. We simulate both uplink and downlink transmissions between the AP and the STAs.
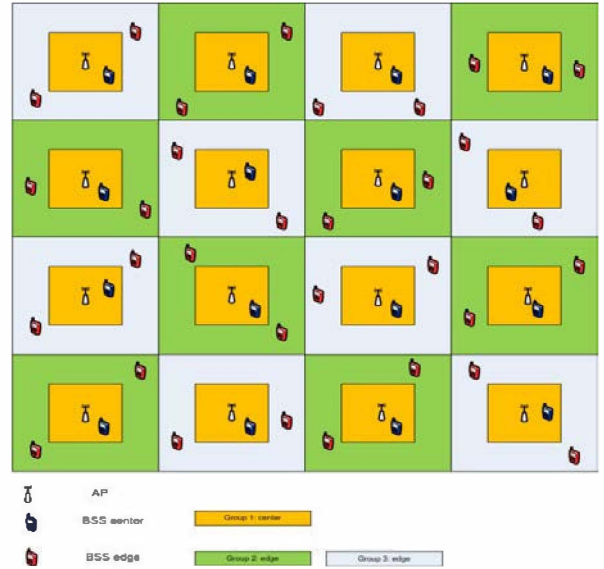
A. Simulation Parameters

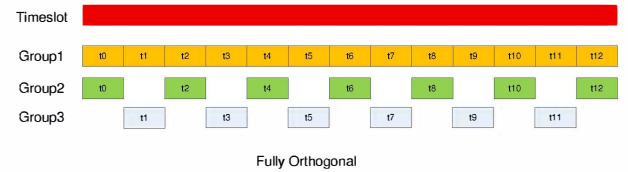*Figure 3: 16 AP system with BSS-edge/BSS-center partitioning*

Figure 4: Active CSMA/CA Sets

For the network topology, we use a grid position allocator with 16 APs set in a square 4 x 4 grid with BSS(x,y), ($x = 1,..,4$, $y = 1,...,4$) indicating the BSS in horizontal position, x, and vertical position, y. In this model, BSS ($1,1$) is at the bottom left hand corner. The STAs are uniformly distributed in each BSS and each BSS has an effective radius of 600 m with an inter-AP spacing varying from 1200m (normal minimally-overlapping BSS) to 800m (OBSS scenario). As we are in a sub 1 GHz environment, the path loss is given by [14].

$$PL=8+37.6*log10(distance)$$

The TPC interval update specifies the rate at which TPC estimates are made. We specify two options

1. Packet Update Interval: In this case, the TPC estimate is made on every packet transmitted to a dedicated receiver. This update rate models the enhanced TPC scheme discussed earlier.
2. Beacon Update Interval: In this case, the TPC estimate is made only once during a beacon interval of 1.024 seconds.

Additional simulation parameters can be found in Table 1 below.

Parameter	Value
Mobility	3 km/hr
Carrier Sensing Mechanism	RTS/CTS on
Traffic	UDP Constant bit Rate
Traffic Direction	Uplink/downlink
Bandwidth	2 MHz
Packet Size	500 bytes
AMC	Adaptive Automatic Rate Fallback (AARF)
Path loss exponent	3.76
Reference path loss (dB)	8.0
Shadow fading Std dev	8.0
TxGain and RxGain	3.0 dB
CCA threshold	-92.0 dBm
Energy detection threshold	-88.0 dBm
Max Tx Power	30 dBm
Target TPC power	-85 dBm
Energy Model	WifiRadioEnergyModel
BasicEnergySupplyVoltage	3.3 V
TxCurrentA	0.144 Amp
RxCurrentA	0.088 Amp
IdleCurrentA	0.017 Amp
CcaBusyCurrentA	0.0017 Amp
SwitchingCurrentA	426e-6 Amp

Table 1: Simulation Parameters

B. TPC and Fractional CSM/CA Modeling

We model the following TPC schemes:

1. **No TPC:** All STAs and APs transmit at the maximum transmit power.
2. **Basic TPC:** The AP uses a transmit power sufficient to reach the farthest STA in its BSS. STAs transmit power to satisfy the link of the farthest STA in the BSS at a target received power to allow for reception of the lowest MCS. The target has been established experimentally at -85 dBm based on our platform. The transmit power used is based on a single TPC request/response frame.
3. **Unfiltered TPC:** The AP and STAs transmit at a transmit power required to satisfy the link at that point in time. In the case where the packet is not directed at a specific STA (e.g. the beacon), the AP transmits at a power to satisfy the link of the farthest STA in the BSS.
4. **Filtered TPC:** The AP and STAs transmit at a power derived from the transmit power required to satisfy the link at that point in time. The power use is estimated by a unit norm, single pole IIR filter of the form

$$y(n) = a\, y(n\text{-}1) + (1\text{-}a)\, x(n),$$

where $y(n)$ is the transmit power, $y(n\text{-}1)$ is the transmit power used in earlier transmissions, and $x(n)$ is the instantaneous power needed. We set $a=0.8$.

Note that in the case that the TPC is updated on a beacon interval (filtered or unfiltered), this scheme maps to the open loop link margin method in 802.1l ah while with a per packet update rate, this scheme maps to the enhanced TPC method discussed earlier. In all cases, we obtain the results with and without Fractional CSMA/CA.

C. Absolute Performance

In *Figure 5, Figure 6, Figure 7*, and *Figure 8* we show the Energy Normalized MAC Goodput (in kbps/Joule) plotted

against the inter-AP spacing (in meters) for the four middle BSSs in the 16 AP network (so as to eliminate the edge-effects on the performance). The Energy Normalized MAC Goodput is the ratio of the data payload successfully delivered at the MAC layer to the total transmission time and the energy expended by all the elements of the network during the simulation. It includes the effect of MAC retransmissions. It is a combined capacity and energy efficiency metric and captures two characteristics desired in IEE802.11ah networks [5]. We desire an increase in this metric. The inter-AP spacing ranges from no minimal-overlap (at 1200m) to significant overlap (at 800m). *Figure 5* and *Figure 6* show the downlink and uplink performance assuming a packet update interval while *Figure 7* and *Figure 8* show the downlink and uplink performance with the update occurring once every beacon interval (or 1.024 seconds). The textured bars indicate the results with fractional CSMA/CA enabled.
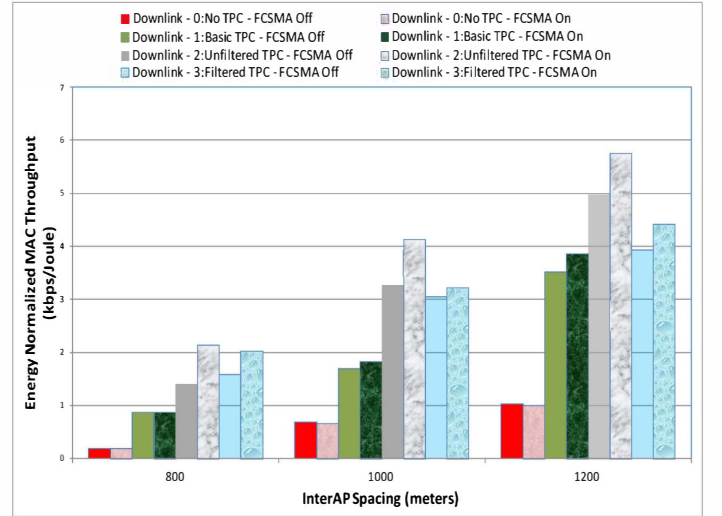

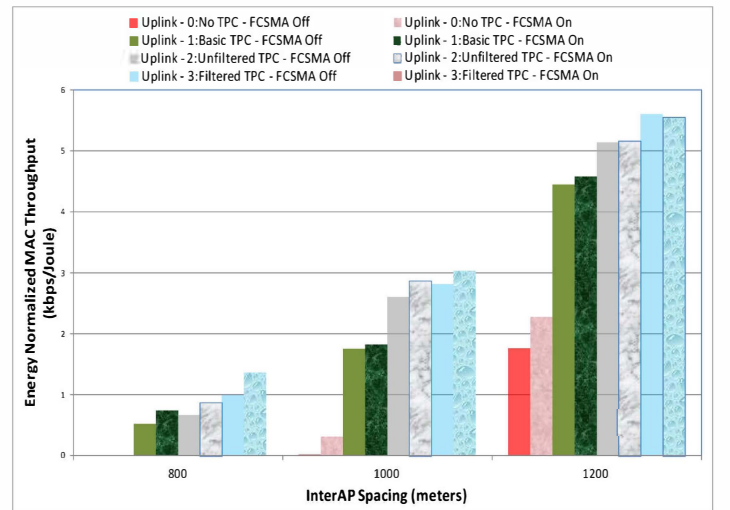
Figure 5: Downlink Performance (Packet Interval Update)

Figure 6: Uplink Performance (Packet Interval Update)
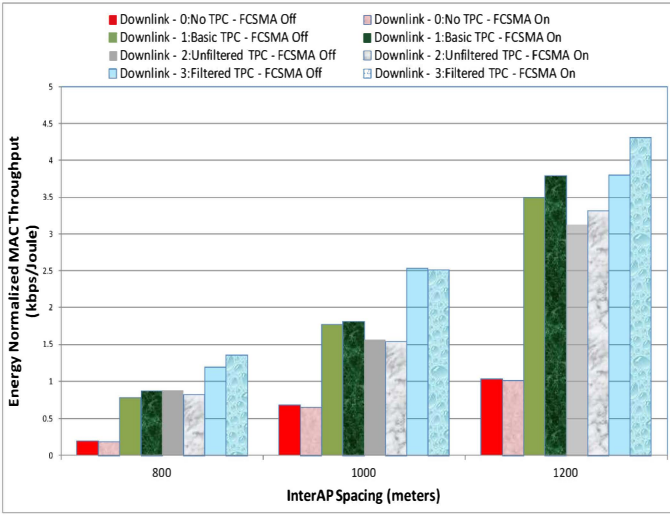
Figure 7: Downlink Performance (Beacon Interval Update)
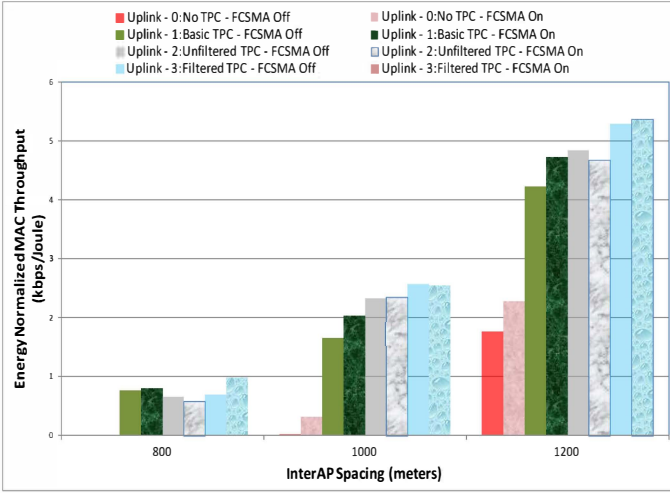

Figure 8: Uplink Performance (Beacon Interval Update)

In downlink transmission with per packet updates, (see *Figure 5*), the performance demonstrates that some manner of TPC is necessary especially with increasing overlap based on the performance of the no TPC scheme. In the case where F-CSMA/CA is off, unfiltered TPC performs best with little or no overlap in the BSSs while filtered TPC performs best when there is overlap. This may be due to the effect of the interference on the transmit power estimation algorithm. With increasing overlap, the estimation algorithm is less reliable based on the effect of both channel fading and interference variation from adjacent overlapping BSSs. Filtering helps average the interference and reduce the effect of the variation. As expected the basic TPC performs the worst of all TPC schemes. With F-CSMA/CA, all the TPC schemes show an improvement in performance and unfiltered TPC has the best performance at all levels of overlap unlike without F-CSMA/CA. This is because it coordinates the BSS-edge users effect that causes the variation in interference.

In uplink transmission with per packet updates (see *Figure 6*), it can be seen that with increasing overlap and no TPC,

there is no throughput at all at both 800m and 1000m. In this case, the filtered TPC method performs best. This is because in the uplink, the interference from STA to AP transmission in adjacent BSSs is larger than in the downlink and as such, filtering is needed to mitigate the effect of a mis-estimation of the transmit power needed due to the constantly varying interference. Interestingly, F-SCMA does not help as much in the uplink with a large AP separation. This is because the receiver (the AP) is far away enough from the edge STAs in this case to not need the additional scheme. However, as the overlap increases, the value of F-SCMA can be seen, even in the case where there is no TPC (at 1000m separation).

In downlink transmission with Beacon interval updates (see *Figure 7*), filtered TPC performs best for the scenarios with and without F-CSMA/CA. Interestingly, the non-filtered case performs even worse than the basic TPC.

In uplink transmission with Beacon interval updates (see *Figure 8*), filtered TPC performs best as 1200m and 1000m overlap but the basic TPC performs best at 800m for the scenarios without F-CSMA/CA. This may be due to the use of outdated TPC estimates. In addition, the non-filtered case performs even worse than the basic TPC. With F-CSMA/CA, the filtered TPC performs best even with large overlap.

In general, combining filtered TPC with fractional CSMA/CA can be used to obtain the best energy normalized goodput performances in any scenario. The adaptation of the filter parameter (a) enables the use of unfiltered or heavily filtered TPC estimates based on the direction of transmission (uplink/downlink) and the rate of update in relation to the channel Doppler and interference variation.

D. Relative Performance

In this subsection, we show the relative performance of the proposed schemes with an IEEE802.11ah network modeled by a filtered TPC scheme with beacon interval updating and F-CSMA/CA off. We will look at four cases; downlink and uplink with no overlap (1200m inter-AP separation) and downlink and uplink with overlap (800m inter-AP separation). The legend indicates the TPC type (filtered vs. unfiltered), the update rate (packet interval vs. beacon interval), and the F-CSMA/CA[1] state (on/off). The y-axis is the percentage gain in energy normalized MAC throughput of the different schemes over the 802.11ah TPC baseline performance.
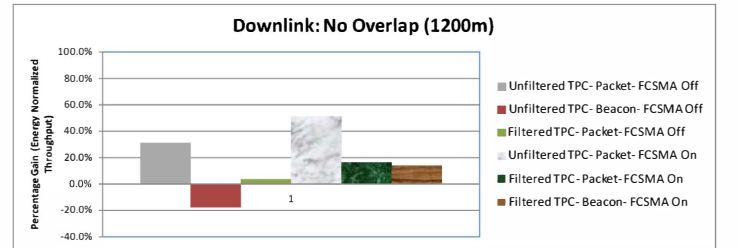

Figure 9: Downlink: No Overlap

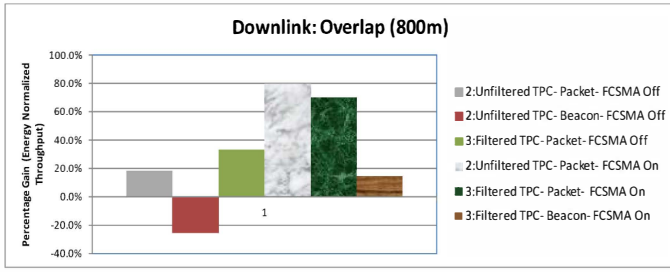
[1] F-CSMA/CA is represented by FCSMA in the legend

Figure 10: Downlink: Overlap

In downlink transmission with no overlap (*Figure 9*), gains may be obtained by using enhanced TPC only (up to 30%). Combining both enhanced TPC and F-CSMA/CA realizes gains of up to 50% over the baseline scheme. With overlap in BSSs (*Figure 10*), the benefits of TPC and F-CSMA/CA are apparent with gains of up to 80% over the baseline.
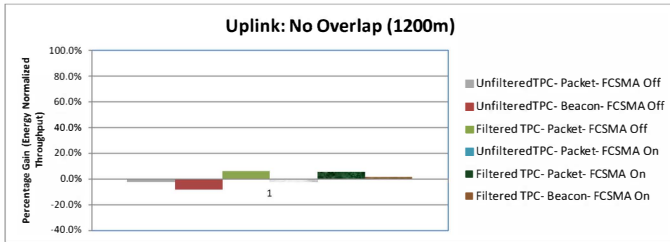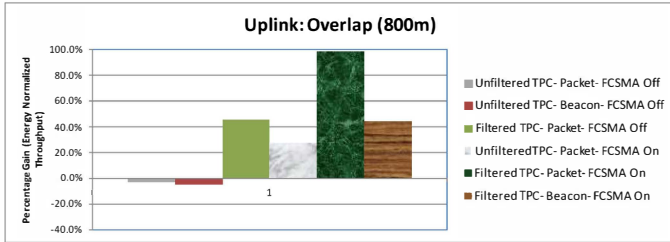

Figure 11: Uplink: No overlap

Figure 12: Uplink: Overlap

In uplink, with no overlap (*Figure 11*), the benefits of the schemes are limited as the receiver (the AP) is far away from any transmitter. In the OBSS scenario (*Figure 12*), gains of up to 100% are achievable.

V. CONCLUSION

In this paper we demonstrate the effect of TPC and a new fractional CSMA/CA scheme on the system performance of a dense, overlapped network with multiple BSSs. Fractional CSMA is a technique which uses a combination of user grouping, enhanced transmit power control and inter-BSS coordination to improve the energy normalized MAC goodput of an overlapped BSS WLAN. The new scheme improves performance by reducing the effect of BSS edge transmission on neighboring BSSs in a coordinated manner thereby increasing throughput and energy efficiency. The scheme works seamlessly with CSMA/CA and is suitable for future wireless systems such as evolutions of IEEE802.11ah and High Efficiency Wireless LANs. Numerical results show gains over the baseline TPC methods in IEEE802.1l ah. In dense, highly-overlapped networks, gains of up to 80% in the downlink and 100% in the uplink are achievable with the addition of F-CSMA/CA to enhanced TPC providing a significant portion of the gains. In minimally overlapped networks, there are minimal gains in the uplink and up to 50% in the downlink. In this case, enhanced TPC provides a significant portion of the gains.

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