Dynamic Transmit-Power Control for WiFi Access Points Based on Wireless Link Occupancy

Carlos Gandarillas, Carlos Martín-Engeños.
Access Network Initiative, Telefonica I+D
Madrid, Spain.
{cgd, cmp}@tid.es

Héctor López Pombo
European FAE, Quantenna Communications
Madrid, Spain
hpombo@quantenna.com

Antonio G. Marques
King Juan Carlos University
Madrid, Spain
antonio.garcia.marques@urjc.es

Abstract— **Dynamic transmit-power control (DTPC) is critical to improve spectral efficiency and reduce interference in wireless local area networks (WLANs). DTPC schemes typically use signal-to-noise-ratio (SNR) information and require exchange of information between transmitters and receivers. However, that is not always easy to implement in actual WLAN deployments. In this paper, we present a simple but novel DTPC scheme for 802.11n Access Points (AP). The method, which is run by each AP without exchanging signaling information with other APs and associated Stations (STA), seeks for transmitting with the minimum power provided that the link is not overloaded. In lieu of using the SNR at the receiver side, the power is adapted based on the wireless link occupancy (rate load). As a result, no signaling exchange between stations and the AP is required. Reducing the transmit-power reduces both co-channel and adjacent channel interference and, hence, entails benefits for all nearby WLANs. The DTPC scheme was tested in a simulator and implemented in an actual 802.11n deployment, which confirmed the theoretical benefits.**

Keywords— 802.11 Power control; interference reduction; CCA; channel sharing; WiFi Dynamic transmit power control

I. INTRODUCTION

Transmit-power control (TPC) methods are critical to reduce interference and improve network performance in wireless systems [1]. However, most wireless local area networks (WLANs), and WiFi networks in particular, do not take advantage of TPC. As a result, network devices transmit at their maximum power level, generating high interference to both co-channel and adjacent channel devices. Increasing the interference entails decreasing the quality of the received signal, increasing the packet loss, and decreasing the spectral efficiency -provided that terminals implement adaptive modulation and coding scheme (MCS). In addition to this, if several APs are operating in the same band then the probability of accessing the channel will decrease due to the Clear Channel Assessment (CCA) [2] method.

There are different approaches to reduce interference, improve throughput performance and increase the coverage on WLANs. Apart from functionalities based on digital processing (channel coding, multiple input multiple output (MIMO), spatio-temporal block coding…), out of the scope of this paper, there are methods that dynamically adapt the allocation of available resources based on real-time network state information [1],[3]. Among those resources one finds the channel (frequency) where the transmission takes place as well as the power transmitted by the devices, which is the focus of this paper. These techniques have also been incorporated to WiFi networks. The IEEE 802.11h amendment was developed to increase the available frequencies by allowing transmissions in the 5 GHz band [2],[4],[5]. Moreover, both Dynamic Frequency Selection (DFS) and TPC mechanisms are defined in the IEEE 802.11 Standard [2]. But the IEEE Standard only defines some TPC rules and functions which leaves an open way for DTPC implementations.

There exists a vast literature on dynamic resource allocation and power control for wireless systems. The most formal approaches use nonlinear optimization and control to design dynamic schemes that adapt the channel and power based on channel and/or queue state information [2],[3]. Differently, other works implement a more heuristic approach, proposing designs tailored to the particularities and operating conditions of the wireless system of interest. Some of them, in the context of (802.11) WLANs are reviewed next. A well-explored way is to control the AP transmitted (Tx) power level based on the RSSI (Receiver Signal Strength Indicator) [6]. The idea is to estimate the path insertion losses (IL) and adapt the AP Tx power level accordingly. However, the RSSI values are not always precise, so that estimating the IL can be nontrivial [7]. A way to fix this is to implement a TPC report element in both AP and associated stations (STAs), which requires additional exchange of control information. In MiSer [8] –an algorithm based on the link-quality estimation– other parameters (such as MCS) are considered. This is reasonable because automatic MCS takes into account both SNR and RSSI values. However, MiSer also requires exchanging control information between the STAs and the AP in order to complete its data table (as well as software running not only in the AP, but also in the STAs). Contour-Slotted [7] manages different WLANs APs Tx power levels working in the same area. The algorithm defines a controlled WLANs communication scheme, which is AP independent and requires the APs of different WLANs to be synchronized. In particular, [9] assumes GPS synchronization, which is an important weakness for indoor deployments. Symphony [10],[8] considers a combination of power control and rate loading for meeting the link quality requirements. However, it requires the existence of a central controller and it is not suitable for an uncoordinated and independent scenario, where each AP self-adjusts the transmitted power.

A new method for managing the AP Tx power is proposed in this paper. Leveraging the fact that in most WiFi networks High Data-Rate (HDR) communications (e.g., HD video) take place from the AP to the STAs, the method is embedded only in the AP. Moreover, to facilitate its implementation in actual networks, it does not need centralized management either special communications with associated STAs or other surrounding APs. The method is based on real-time measured channel occupancy. Other parameters of the physical and link layer (MCS, RSSI, packet retries…) are also considered. The last part of the paper discusses briefly different ways to improve the proposed method (including dynamic channel selection) and preliminary test results.

The rest paper is organized as follows. Section II relies on some actual measurements to quantify the impact of interference in network performance. Section III describes the new DTPC method. Section IV presents both

and actual measurements in different indoor scenarios, comparing WLAN throughput measurements with and without DTPC. Section V briefly discusses ways to improve the proposed method. Conclusions in Section VI wrap up the paper.

II. QUANTIFING THE EFFECTS OF INTERFERENCE.

Since 802.11n terminals implement advanced signal processing techniques -MCS, MIMO, LDPC coding…-, theoretical analysis of the performance is not trivial. For this reason, we run some preliminary experiments to gain intuition on how interference affects throughput.

A. Adjacent channel and co-channel interference

Two indoor scenarios were analyzed. The first one was composed of one AP and one STA and it was tested for gaining intuition on adjacent-channel interference. The interference generated was a WLAN 802.11n signal working in the adjacent lower channel at its maximum data rate. Figure 1 shows the throughput and received power at the STA as a function of the interfering power for different system configurations. Clearly, the results confirm that throughput is severely affected by interference. The higher the adjacent channel interference is, the more degraded the WLAN performances are. Raising the noise levels causes a decrease in received SNR and performances degradation.

The second scenario focuses on testing co-channel interference. Results for this scenario are shown in Figure 2. Performances of three different infrastructure WLANs (AP1, AP2, AP3) working in the same channel and located in an office building were measured. Measurement settings are: three APs with their three associated STAs, working always at their maximum allowed throughput. As it is shown in Figure 2, when other WLAN APs start to work in the same channel, AP1 throughput is reduced by 50%. The same behavior is observed in AP2 and AP3. In this case, the WLANs CCA mechanism detects other WLANs APs and STA working on the same channel, having to share the transmission times in the radio interface. Any incoming WiFi frame whose Physical Layer Convergence Procedure (PLCP) header can be decoded will cause CCA mechanism to report medium as busy, delaying communication for the time required for detected frame transmission.

In the first scenario, a reduction of adjacent channel interference levels caused by surrounding APs can be achieved by reducing their Tx power, which will improve WLAN SNR, increasing MCS and throughput in adjacent channels WLANs. In the second scenario, a decrease in the WLANs transmitted power may avoid CCA detection, enabling simultaneous transmissions of close-by (non-interfering) WLANs. Based on these observations, one can conclude that reducing to Tx power is critical not only to reduce interference, but also to enhance spatial, frequency and time channel reuse and, hence, increase capacity and throughput.

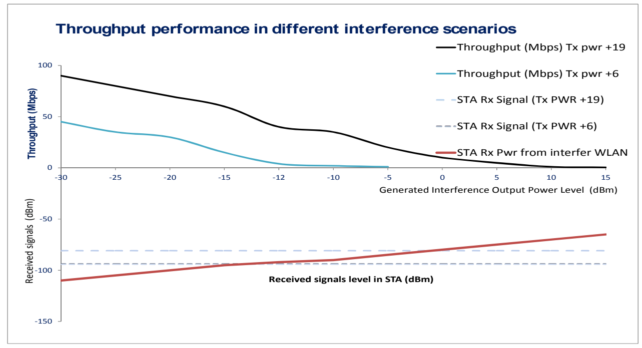

Figure 1. WLAN performances degradation because radio interferences

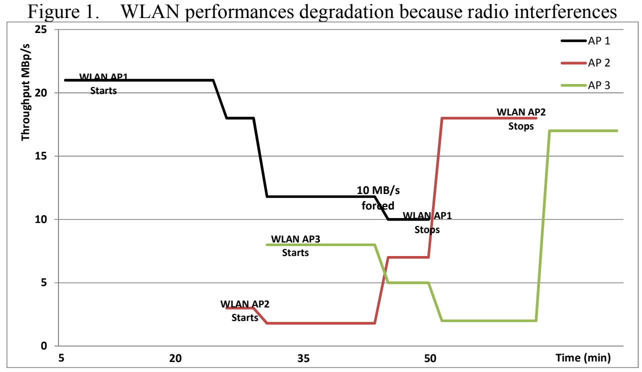

Figure 2. WLAN performances degradation because co-existence. WLAN Channel sharing

B. Measuring the effects of decreasing Tx power

In another test setup, throughput measurements were taken in a WLAN indoor scenario without any interference (co-channel or adjacent-channel). Throughput was measured with different AP Tx power levels. Measurements showed that for instance, in order to achieve a target throughput of 30Mbps (allowing two HD-TV streaming), the AP Tx power can be reduced from 18 to 9dBm. In other words, the AP Tx power can be reduced maintaining good throughput performances. Clearly, this AP Tx power reduction without degrading carried data, entails a decrease on RF interferences in the adjacent-channels working WLANs. Moreover, in several tests, it also entails a reduction of CCA detection of WLANs working in the same channels, which means less occupancy collisions and more available time for current transmission. More specifically, there are tests for which the power coming from neighboring WLANs is below the detection threshold used by the CCA mechanism, the frequency band is declared free and hence it is reused.

III. DTPC METHOD

As discussed in the previous section, reducing the power Tx by the AP improves the SNR of neighboring WLANs and, in certain cases, allows for frequency reuse. For that reason, our DTPC method tries to reduce the Tx power by the APs. However, reducing the Tx power by a AP also reduces the quality of the link of the specific WLAN the AP belongs to. To guarantee that the quality of the link is preserved, the DTPC dynamically manages the AP Tx power, the method keeps track of real-time link state (conditions) and automatically reacts to changes in the wireless link (or RF environment). Moreover, the proposed DTPC does not affect management frames. To acquire the link status the method uses real-time (and statistics) information available at the AP, but, different from most approaches [8], it does not exchange specific information between AP and clients (STAs). As a result, the DTPC method can be used for any STA. Since it does not use information from other APs, nor exchange of information among APs, neither the existence of central scheduler/manager [9][10] are needed.

IEEE 802.11 MCS and data throughputs are directly related to SNR. Specifically, reducing the Tx power can reduce SNR, MCS and data throughputs. The developed method considers a perspective for managing Tx power level in a wireless link without disturbing the required real-time data rate. The method considers both the real time transmission data rate and physical medium conditions. The parameters for controlling the transmitted power are obtained following rules defined in IEEE 802.11n. This implies that this method can be implemented independently of any other specific IEEE 802.11 amendment and number of clients. APs with the DTPC method embedded can obtain the parameters from all IEEE 802.11 standard-based devices, so that the method will work for any STA. The specific parameters used by our DTPC method are described in Section III.A, the method itself is described in Section III.B, while the procedure to set the maximum/minimum values of such parameters is detailed in Section III.C. The parameters selected account mainly for the state of the physical channel, but also for the state of upper layers, giving our design a slight comprehensive (cross-layer) touch.

A. DTPC method: input parameters

1) Tx power parameters: The current AP Tx power at a given time is *TXPW*. $STEPPW_{UP}$ defines the value in dBs that the power Tx by the AP is increased; $STEPPW_{DOWN}$ the dBs that power Tx by the AP (*TXPW*) is decreased. The initial Tx power value is always the AP max. Tx power (as if no DTPC).

2) Channel occupancy parameters: Channel occupancy is the result of comparing the wireless data communication measured bits (data rate) to the available physical capacity of the wireless link (given by the active MCS [5]). THR_{MAX} and THR_{MIN} are thresholds that define the maximum and minimum channel occupancy values. TX_{BYT} is the number of bytes sent in one second and TX_{AVG} is the number of bytes sent during T_{AVG} (T_{AVG} is the time for last n measurement periods, used for average calculations). TXB_{MIN} is the minimum TX_{AVG} value below which the method will continue retrieving statistics without taking any decision on the transmit power.

3) Link status parameters: MCS_C is the index for the active MCS (real-time). This value is translated into a maximum physical layer transmission rate according to the tables defined in [5]. *PKT_S* is the number of packets sent to the network, and *PKT_R* the number of retried packets. RET_{AVG} is the ratio of retries over sent packets (averaged across the last n periods). $THRET_{MAX}$ defines the maximum percentage of retries above which the method does increase Tx power. $THRET_{MIN}$ is the minimum ratio of retries below which the method decreases Tx power. Finally, *PanicRETTHR* is the RET_{AVG} threshold above which the algorithm declares that the performance is severely disturbed and enacts a channel change. In other words, for the cases where the number of terminals and/or the traffic load is so high that interference cannot be reduced, our DTPC method is strengthened with a simple (but effective) dynamic channel change mechanism.

B. DTPC method: description and flowchart

The method is formally described by Figure 3 and by the pseudo-code given at the end of Section III.B. A more intuitively description is given next. The proposed DTPC method periodically takes as input the real-time parameters accounting for the state of the wireless link. Then, it compares them with some pre-established thresholds, previously assessed to guarantee that the link is reliable. The thresholds can be adapted dynamically, but they must be initially set by the AP. (See Section III.C to check how the parameters are set.) Finally, these comparisons activate some triggers, based on which decisions about how to manage the Tx power are made.

The MCS rate, percentage of packet transmission retries as well as the calculated data communication channel occupancy are used as input parameters. The channel occupancy is the main input in the method. It provides information about whether the communication bit rate on the current wireless data link is close or far from its maximum capacity for the physical layer -given by the current obtained MCS-, which will make it possible to evaluate an upcoming decrease in Tx power. As already mentioned, the fact of taking into account the wireless link occupancy status makes our DTPC different from most TPC approaches, which only consider the wireless link status (physical layer).

The main steps describing how to adapt the power Tx by the AP is summarized as follows:

1. A calculation is performed to determine whether the number of bytes sent exceeds a threshold defined in the algorithm in order to consider that there is a WLAN data communication (TXB_{MIN}).
2. A check determines whether a first set of conditions are met. $RET_{AVG} > THRET_{MAX}$ or $TX_{AVG} > THR_{MAX}$.
3. If the conditions are met, the Tx power is increased in a given step ($STEPPW_{UP}$). Return to 1.
4. A new check determines whether a second set of conditions are met. $RET_{AVG} < THRET_{MIN}$ and $TX_{AVG} < THR_{MIN}$.
5. If the new conditions are met the Tx power is decreased in a given step ($STEPPW_{DOWN}$). Return to 1.
6. If neither the criterion in 2 nor the one in 4 are met, the transmitted power remains the same. Return to 1.

The above mentioned calculations include averaging smart verification of unconditional extreme value, as well as some considerations between MCS and packet retries relationship in order to avoid unnecessary changes on AP Tx-power.

Figure 3 depicts a flowchart describing the DTPC. In fact, the flowchart considers as well the option of allowing Tx power management per STA (note that the required parameters are obtained for each STA link). The Tx power control per-packet is implemented in the *TxVector_txpower_level* frame which contains the information of the Tx power level attributes in the current transmission.

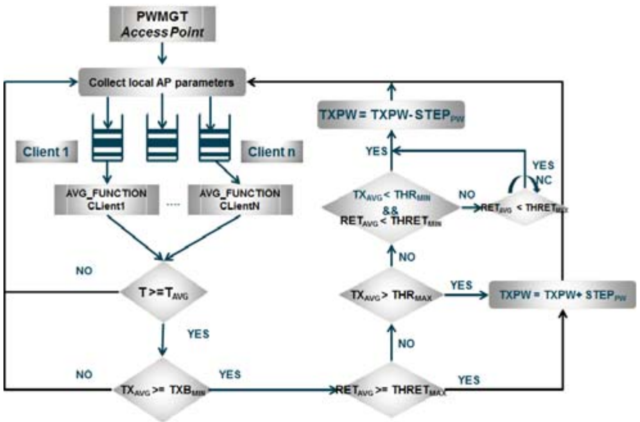

Figure 3. DTPC Method Algorithm Scheme

C. *DTPC method: Parameter setting*

The values set for the thresholds defined in the previous section will clearly affect the performance of the DTPC method. Hence, such values have to be selected (either analytically or empirically) to optimize/guarantee performance. In this paper, the thresholds have been set empirically (via exhaustive simulation and measurements), to guarantee a minimum rate performance -HD video streaming jointly with HDR WLAN transmissions-. The effects of some parameters are currently studied in simulations. Clearly, the degrees of freedom (number of parameters) are enough to being able to make the algorithm more or less conservative and/or accurate (even in real-time), as well as being adapted to the type of wireless data communicated. To guarantee HD video streaming the parameters were initialized as follows: TXB_{MIN}<1000bits; THR_{MIN}=20% of associated real-time MCS throughput. THR_{MAX}=75% of associated downlink MCS throughput. $THRET_{MIN}$=1% and $THRET_{MAX}$=10% of sent wireless packets. $STEPPW_{UP}$=3dB, $STEPPW_{DOWN}$=1dB, PW_{MAX}=18dBm and PW_{MIN}=6dBm with the number of average iterations (cycles) for estimating power management in different conditions is 15. *PanicRETTHR*=30% of sent packets, above 30% the HD image was disturbed. If the average packet retries were higher than 'Panic retries', the wireless link was highly degraded and the system performed an automatic channel change (a more detailed description of this feature will be given in Section V). The next section presents simulation and measurement results that illustrate the benefits of the DTPC method proposed.

IV. SIMULATION AND MEASUREMENT RESULTS

A. *Simulating the DTPC method in an indoor scenario*

DTPC performances were first simulated using an indoor scenario and assuming that all traffic was from APs to STAs. This scenario was evaluated by an in-house WiFi planning and simulation tool developed by Telefónica I+D. AP main characteristics, real 3D location sites and detailed scenario plan have been used; considering average propagation losses from one to other apartment of 16dB due to signal wall penetration. The path loss, coverage and indoor SNR-Throughput were estimated with a based empirical propagation models [11] and ray tracing propagation algorithms. WLAN performances were simulated with and without DTPC installed in both APs.

Figure 4 shows the simulated layout (two neighbouring apartments: apartment 1, with an area of 110 m^2, and apartment 2, with an area of 50 m^2), the location of the two APs, and the coverage areas estimated by the simulator. The channels for AP1 and AP2 were set to CH40 and CH48, respectively, both with 40MHz BW. The upper subplot assumes that APs do not implement DTPC and transmit using their maximum power level (+20dBm). Simulation shows the coverage for achieving a target WLAN throughput of 30Mbps in AP1 and 50Mbps in AP2, (SNR mapped values obtained from [12]). Red area shows the area of target throughput coverage for AP2, yellow colour is the area of target coverage for AP1. As it is illustrated, when both APs transmit at maximum power level (without DTPC), adjacent channel interference from AP2 degrades apartment 1 AP1 coverage: roughly, only 50% of area achieves the objective throughput. The lower subplot assumes that APs implement our DTPC algorithm. In this case, the AP2 Tx-power is adjusted to +9dBm maintaining coverage range and the target 50Mbps throughput. With DTPC in AP1, the AP1 Tx-power is reduced to +15dBm. Tx power reduction in AP2, maintaining 50Mbps, provides adjacent channel interference reduction in AP1, improving SNR, coverage and throughput. DTPC improvements in coverage are around 70% for target in AP1 -Figure 4, for close located WLAN adjacent-channel interfered scenarios.

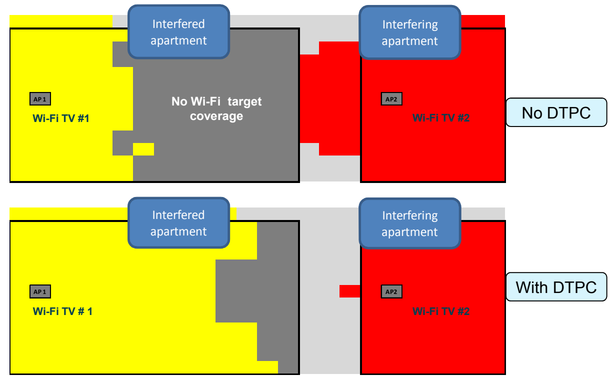

Figure 4. Simulation of DTPC in WLAN Adjacent-Channel Interference.

B. *Improvements of DTPC: Measurement results*

To assess the benefits of the proposed DTPC method an indoor (office) building scenario was selected. Many different test were performed, here below are displayed a subset of measures that are illustrative of the behavior and strength of DTPC. The idea was to emulate a typical collective home building, so that the position of APs and STA for achieving RF isolations between different WLANs devices about 85dB. It was further assumed that the link from the AP to the STAs was the one with highest load (e.g., HD video streaming).

The scenario layout is depicted in Figure 5. The test scenario description is as follows. Four AP-STA pairs were deployed: W1, W2, W3 and W4. W1 (AP1-STA1) transmits 2HDTV (between 13Mbps and 30Mbps) in channel 100 (CH100); W2 (AP2-STA2) is used at higher utilization rate (50Mbps) in CH108. W3 (AP3-STA3) and W4 (AP4-STA4) are sharing CH60, W3 transmits 50Mbps and W4 2HD-TV + 20Mbps. BW is 40MHz and devices implement MIMO 4x4. Wireless isolation between devices belonging to W3 and devices in W4 is higher than 95dB. Test results were divided in 2 different cases: adjacent channels and co-channel interference.

1) DTPC test in adjacent channels. WLANs (W1, W2)

The results are reported in Figure 6, which shows the evolution of different performance measures (rate, retries and power) across time. Initially, the APs were configured so that DTPC was not implemented, then, as time progressed, DTPC at each of the APs was activated, first in AP1 and then in AP2. Specifically, up to time 0, both AP1 and AP2 transmit at their maximum (fixed) Tx power. W1 interferes W2, inducing the fraction of retries by W2 to be above 40%, rendering W2 useless. Then, DTPC method is activated on W1, which reduces the power Tx by AP1 to +7dBm (check interval 0-8 in the bottom subplot of Figure 6 –red dotted line), while maintains the packets retries below 2% (see middle subplot). The decrease in Tx power in AP1 due to DTPC also entails interference and retries decrease in W2, leaving retries below 1.8% now, according to that environment, throughput in W2 can be increased now up to 80Mbps (>60% of initially 50Mbps maximum allowed), maintaining low packet retries. Finally, if DTPC is applied now to W2 (transmitting its 50Mbps wireless data rate), AP2 Tx power decreases down to +6dBm (Figure 6, bottom graph, green line from time 4 to 10 minutes).

Figure 6 demonstrates that the DTPC method adjusts Tx power in WLANs in real-time. It is shown that there is a strong relationship between the power transmitted by APs that are neighbors and work in adjacent channels. It is also shown how reducing the transmit-power of one of the APs improves the quality of service of the links involving the neighboring APs. In Figure 6 it is shown how DTPC works, AP Tx power is initially reduced for both APs in W1 and W2, always maintaining their wireless data rates. When the wireless link is disturbed (i.e. in time min. around 18 and 46, because there were physical obstacles put in middle of their AP-STA wireless link) the DTPC method detects the wireless link degradation, increasing the power transmitted by both AP1 and AP2. In this case scenario, if no DTPC is applied in W1 AP, the wireless interference from W1 creates high wireless retries due to its high wireless data rate required and disturbs W2 performances.

Finally, in this first scenario it was also checked that the WLAN adjacent RF interference is strongly related to adjacent channel utilization, and DTPC allows a reduction in adjacent channel interference according to WLAN time occupancy and wireless link status.

Figure 5. DTPC test Scenario.

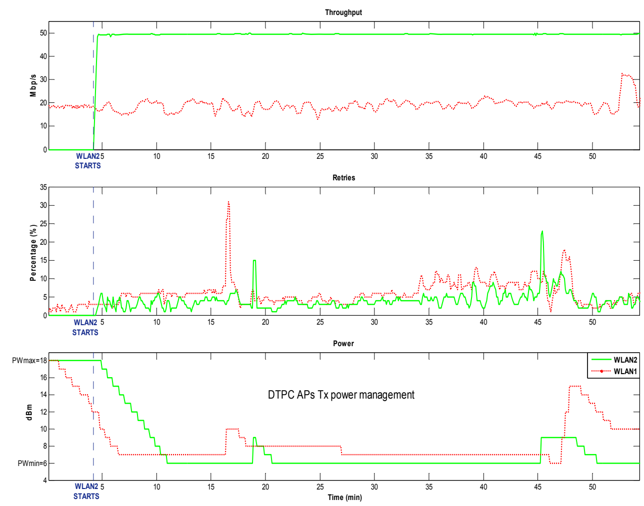

Figure 6. DTPC performance (WLANs close located in adjacent-channels).

2) DTPC test in WLANs sharing channel

In this case, both W3 and W4 work in CH60, deferring their transmissions due to WLAN medium access methods and CCA detection. When W3 and W4 do not implement DTPC, the corresponding APs transmit at their maximum power. W3 is able to transmit TCP at 50Mbps with a retries rate around 3%, and W4 is able to transmit 2HDTV+20Mbps at very high retries rate (>40%) including packet losses and TV interruptions. Clearly, in this scenario WLAN W4 is highly affected by W3 channel utilization.

When DTPC is implemented in the AP in W3, its Tx power goes down to +6dBm, keeping constant its data rate (50Mbps). When W3 AP is lower than 10dBm, W4 802.11 CCA does not detect ever W3 transmissions. At that point, W4 does not need to share the wireless medium access, neither to defer transmissions. In this case, DTPC improvement is so outstanding that W3 still transmits at 50Mbps (and higher) with only 2% retries rate and W4 is able to transmit at 50Mbps (2HDTV+20Mbps) and higher with retries rates lower than

2%, without interrupting HDTV. Afterwards, if DTPC is applied to AP4 in W4, its transmit-power is reduced as well. In this case scenario, no DTPC benefits were detected when isolation between different WLANs devices working on the same channel is lower than the CCA threshold (-85dBm) added to transmit-power reduction range. In this case, it means that the benefits of reducing the Tx power by an AP are significant only for neighboring WLANs working in the same (or an adjacent) channel and not very closed located. These measurements are samples and valid in the described scenario.

V. Improving the algorithm: Preliminary results

To facilitate implementation, the DTPC scheme presented was fairly simple. Nonetheless, both simulations and actual measurements demonstrated that network performance improves significantly. In this section we briefly discuss ways to improve the algorithm. The idea is to improve performance further, while keeping complexity low. Although preliminary simulations (and actual measurements) are encouraging, the modifications have not been yet tested extensively. Two meaningful ways to modify our scheme are: a) considering Dynamic Smart Channel Selection (DSCS), and b) control the transmit power of the different network terminals in a coordinated fashion.

Regarding a), DSCS schemes would clearly increase reliability, reduce interference and improve performance. As a first step (already implemented), the DSCS algorithm can use the same parameters than the DTPC scheme uses, switching automatically, without cutting WLAN communications, to another channel when the link load is too high or performances are degraded. In a more elaborate design, the new channel should be selected in an efficient manner (e.g., taking into account parameters like the long-term occupancy of the channels using off-load channel scanning tools). According to our preliminary test results, it is critical to track the activity not only in the active channel but also in adjacent channels.

Regarding b), the first step would be to implement DTPC also at the STAs side. IEEE 802.11h [4] specifies mechanism which allows STAs to reduce their Tx power level dynamically. TPC request and report frames allow the exchange of the information between the AP and STAs of the right power level that must be set to STAs. In our case, it is used to set into STAs the same Tx power value transmitted from the AP to each STA. Our results show that the rate improvement is only significant when traffic load is high and symmetric or when a STA is very close to a neighbouring AP. (Besides the impact on the rate performance, it is worth stressing that this DTPC scheme would contribute to extend the lifetime of battery powered STAs such as smartphones or tablets.) A more elaborate design (not implemented yet) is to exchange information among APs in a collaborative model. Note however that, different from DSCS schemes, this modification entails exchange of information between terminals, which may be challenging (especially among APs, when they are not managed by the same entity). A more detailed description of the dynamic schemes and extensive (with especial focus on DSCS schemes) are left as future work.

VI. Conclusions

A simple method to control dynamically the transmitted power level in WLANs was presented, tested and evaluated. The method, which is embedded in the APs chipset, it is based on real time measurements of wireless link status and WLAN data usage. The basic idea is to reduce the transmit power (and, hence, the generated interference) guaranteeing the communicated data-rate. Both simulations and actual deployments confirm that the method reduces the overall co-channel and adjacent channel interference and, consequently, improves the coverage range of the WLAN. The aggregate throughput increment in the tested scenarios was higher than 60%, for networks working in adjacent channels, and higher than 100%, for networks far enough that share the same channel. The method is especially suitable for scenarios such as large building or residential neighborhoods, where several APs (typically managed by different operators) coexist. The last part of the paper discussed briefly different ways to modify the algorithm (including dynamic channel switching schemes).

References

[1] A. Goldsmith, *Wireless Communications*, Cambridge Univ. Press, 2005.

[2] ETSI standard EN 301 893 V1.7.0, Broadband Radio Access Networks (BRAN); 5 GHz high performance RLAN; Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive, 2012.

[3] L. Georgiadis, M. Neely, and L. Tassiulas, "Resource allocation and crosslayer control in wireless networks," Found. Trends Netw., vol. 1, no. 1, pp. 1–144, Apr. 2006

[4] IEEE 802.11h, Amendment to Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Spectrum and Transmit Power Management extensions in the 5 GHz band in Europe, IEEE Std 802.11h-2003, Oct. 2003. IEEE 802.11-2012 Standard.

[5] IEEE Standard for Information technology—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. IEEE Computer Society. IEEE Std 802.11™-2012. March 2012.

[6] Vivek Shrivastava, Dheeraj Agrawal, Arunesh Mishra, Suman Banerjee and Tamer Nadeem. "Understanding the limitations of transmit power control for indoor WLANs". In *Proc. ACM IMC,* San Diego, USA, October 2007.

[7] A. Vlavianos, L. K. Law, I. Broustis, S. V. Krishnamurthy, and M. Faloutsos, "Assessing link quality in ieee 802.11 wireless networks: Which is the right metric?" in *Personal, Indoor and Mobile Radio Communications, 2008. PIMRC 2008. IEEE 19th International Symposium* on, Sept. 2008, pp. 1–6.

[8] D. Qiao, S. Choi, K.G. Shin, "Interference Analysis and Transmit Power Control in IEEE 802.11a/h Wireless LANs", IEEE/ACM Transactions on Networking, vol. 15, no.5, pp. 1007-1020, Oct. 2007.

[9] V. Navda, R. Kokku, S. Ganguly, and S. Das, "Slotted Symmetric Power Control in managed WLANs", Technical Report, NEC Laboratories America, 2007.

[10] K. Ramachandran, R. Kokku, H. Zhang, and M. Gruteser, "Symphony: Synchronous Two-Phase Rate and Power Control in 802.11 WLANs", IEEE/ACM Transactions on Networking, vol. 18, no. 4, 1289-1302, Aug. 2010.

[11] 'Digital mobile radio towards future generation systems'. COST 231. CH4. Propagation prediction models. Final Report.

[12] Rakib Al Mahmud, Zaigham Shabbir Khan, "Analysis and planning microwave link to established efficient wireless communications," M.S. thesis. Ch 4.1 Adaptative modulation. Blekinge Institute of Tech. Sept 2009.