Interference-aware Power Coordination Game for ISM Bands

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Abstract — **The use of wireless equipment in the already-overcrowded ISM bands has heavily increased in recent years. This increase leads to a high interference level which causes unstable communication and an average throughput reduction in heavily-used channels. Given this, there is a need for more robust, interference-aware means of resource allocation in ISM bands. In this paper, we propose a Game Theory (GT) based power allocation mechanism for IEEE 802.11 networks, which might incorporate some aspects of Cognitive Radio (CR) functionality. Operation of 802.11 devices is constrained at the regulatory level in terms of maximum transmission power, in order to limit the extent of interference from uncoordinated emissions of such devices in ISM bands. Through our proposed mechanism, we additionally consider GT as a way to allow for lighter regulatory rules or outright self-regulation for power allocation in ISM bands. Our mechanism assumes interaction between devices, and enables fine tuning of the power transmitted by the devices based on dynamic changes in the radio environment.**

Keywords—Interference, transmit power allocation, game theory, radio-spectrum access rules, ISM, Wi-Fi, Cognitive Radio.

I. Introduction

The early moves by regulators to allow general access to ISM bands such as the 2.4 GHz ISM band [1] by innovative wireless consumer systems has led to a worldwide flourishing of wireless ecosystems, with Wi-Fi (IEEE 802.11) technology being the most notable example. Much hope is pinned on further growth of Wi-Fi and other similar technologies in this and other bands [2]; however, there are significant associated challenges, due to unmanaged nature of operating radio equipment in spectrum commons.

This paper builds on the proposed idea of "ISM-Advanced" regulatory framework [3] towards developing a solid proof-of-concept for operation of self-managed power coordination game between Wi-Fi (or similar) radio transceivers in ISM bands. Such framework would bring the benefits of Cognitive Radio (CR) paradigm that could be incorporated in new and future products for ISM bands, such as IEEE 802.11ac[4] or LTE in ISM bands [5].

The transmit power of current wireless equipment in ISM bands is limited under strict rules. Whereas the recent ECC studies [6] showed that industry requires shared license-exempt spectrum scenarios with increasingly higher operating powers. This would allow improving link budgets by overcoming harsh propagation conditions and increasing data throughput capacity of the wireless links. However in order to allow introducing higher operating powers in the future, the ISM band equipment should use some intelligent power allocation mechanism, as e.g. enabled by CR technological solutions. In this paper we analyze in detail the Game Theory (GT) based power allocation mechanism [3], which would handle power control for each device based on the current state of devices. Importantly, we develop this further to address the issue of fairness in getting access to the spectrum by unmanaged radio devices.

The rest of this paper is structured as follows. Section II delineates the technical problems to be resolved as well as the key tenets of the proposed GT algorithm to address them. This is backed by an initial feasibility analysis and simulations. In Section III we further develop the algorithm to address the fairness issue and show the results of experimental evaluation. The final section summarizes our findings and outlines directions for further work.

II. Problem Formulation and GT-based Solution

A comprehensive overview of the various problems and limitations associated with inefficient use of ISM commons in general and Wi-Fi technology in particular is offered in our previous work [3]. In the context of this paper we focus on only one aspect, namely the deficiency of channel access mechanisms and associated power control issues.

The IEEE 802.11 standard encompasses two MAC mechanisms namely: Distributed Coordination Function (DCF) and Point Coordination Function (PCF). The DCF is the only mechanism certified by the Wi-Fi alliance and, as a result, had been deployed in all Wi-Fi branded devices. The key premise of DCF is the use of CSMA/CA mechanism. However, this mechanism, albeit well suited for distributed control operations, exhibits poor performance in highly interfered environment. The alternative solution is PCF - a polling mechanism – in which a coordinator, usually an Access Point (AP), manages its slave devices during a "contention free period (CFP)" (to be distinguished from the contention period used with DCF). During the CFP, no collision occurs between the terminals served by the AP, which offers potentially huge savings of air time that might be otherwise wasted in DCF due to collisions and the collision recovery periods. The PCF was envisioned as a solution for delay sensitive traffic, but did not attract much attention from manufacturers and has not been extensively implemented. Some of the reasons can be due to the polling overhead [7] or the requirement that a station that has nothing to send must anyway send a null frame.

It is worth to mention that even in the ad hoc mode of Wi-Fi where no AP is deployed and which normally requires a distributed channel access mechanism such as DCF, it is still possible to use PCF. Some recent works have been done to adapt PCF to a distributed environment without AP where the point coordinator is chosen among all the participants and becomes the master of the cluster [8]. Both DCF and PCF have their flaws, which requires more robust way to handle interference by implementing robust power allocation based mechanism, which would help to solve interference problem between co-channel devices and remove the requirement to use DCF or PCF mechanisms.

Over the time that the Wi-Fi standard has been in place, many attempts have been made to improve the CSMA/CA protocol in a variety of ways [9, 10, 11, 12]. However, the benefits of these changes, such as RTS/CTS, remain questionable [13, 14], whilst proprietary changes to the protocols (outside the IEEE 802.11 standard) can further deteriorate performance [15]. Performance gains are highly dependent on the radio environment or loading conditions where measurements were undertaken. Real world testing of Wi-Fi networks [16] reveals that networks working in congested interference environments can suffer considerable throughput degradation. A typical example of this is shown in Fig. 1, which depicts the maximum total throughput achieved in a Wi-Fi (IEEE 802.11g) hotspot. These results were obtained for a network consisting of 3 client terminals and an AP, operating within line-of-sight of each other, in an urban city environment [17].

The throughput of the network is shown to be highly dependent on its operational radius, regardless of the fact that the signal strength at all locations (-45 to -62 dBm) of the terminals was maintained at levels that would have sustained the maximum achievable throughput of ~28 Mbps (operating at 54 Mbps IEEE 802.11gmode). The network was loaded using TCP/IP input streams containing variable packet lengths (64-1,514 Bytes). The congested channels (channel 6 with > 200 interferers) faired considerably worse than less congested channels (channel 9 with < 50 interferers). What the experiment shows is that in such dense urban environment the throughput capacity of a Wi-Fi network is dominated by the congestion and interference that it sustains rather than the signal strength it operates under [8, 18].

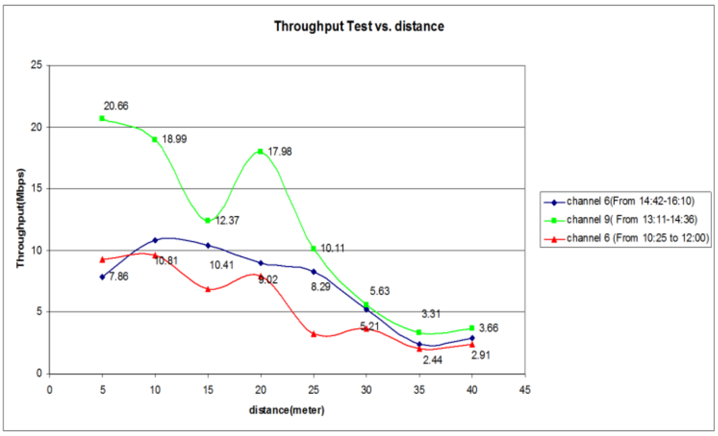

Fig. 1. Throughput of a four-node Wi-Fi IEEE 802.11g network as a function of network radius (congested outdoor environment, all terminals at line-of-sight and RSSI always >-70 dBm)

This observation forms a basis of our further consideration in this paper, as we look at intelligent self-managed power control as possible mechanism to reduce interference and improve the throughput of Wi-Fi and other devices in ISM bands, including solving the problems associated with current CSMA/CS-based framework.

As we showed in [3], using game scenarios and GT offers a suitable tool for modelling the environmentally-aware and re-configurable power allocation mechanism that includes aspects of CR functionality. Whereas the standard analytical models might no longer cope with the increasing complexity and chaotic dynamics of wireless systems in ISM bands, GT provides the framework in which the paradigm shift to more flexible and efficient resource sharing may eventually materialize.

CR interactions are strategic interactions (in the sense defined by GT): one player’s payoff depends on the other players’ actions. Within the GT framework, the key problem is to design distributed resource allocation rules that lead to a Nash equilibrium that is efficient and possibly fair [19, 21]. Most importantly in the context of current discussion is that these rules would be self-enforcing and therefore not requiring external intervention to verify compliance [21].

In the considered case the power allocation is determined as the outcome of a game: a distributed, interference-aware, power allocation game. Given a wireless network of N transmit-receive pairs (Tx_i-Rx_i), where a ”pair” is referred to as a “player”, the objective is to find stable points of power allocation for each player such that the players’ global utility is maximised while the cumulated power levels are kept to a minimum.

These aggregated goals are meant to ensure an efficient use of the CRs’ transmission powers, thus building a foundation for spectrum access rules, in which a fixed, low EIRP limit would become superfluous factor for containing interference.

In practice, CRs would not need cooperating for power decision making purposes; each CR would decide its transmission power independently, based on its estimation of the environment and other CRs’ choices. Each CR is selfinterested, aiming to maximize its payoff. With these considerations in mind, we model the power allocation problem as a non-cooperative game.

More formally, given a set of N players (or i CR Tx-Rx pairs) $i = \{1, 2, ..., N\}$ and their corresponding strategies (i.e. power allocation profile) $P = \{p_1, p_2, ..., p_N\}$, the utility function of each player (Tx-Rx pair) would be given by

$$u_i = log\left(1 + \frac{h_{ii}p_i}{n_0 + \sum_{j \neq i} h_{ji}p_j}\right), \qquad (1)$$

knowing that CR i's received SINR is:

$$r_i = \frac{h_{ii}p_i}{\sum_{j \neq i} h_{ji}p_j + n_0} \qquad (2)$$

where: p_i, p_j are the transmit powers of players i and j, h_{ii} is the direct channel gain, h_{ji} is the channel gain between transmitter j and receiver i, and n_0 is the noise power.

The payoff function represents a difference between the utility function (1) and a cost function, $c_i p_i$, [22]:

$$\pi(p_i, p_{-i}) = log\left(1 + \frac{h_{ii}p_i}{n_0 + \sum_{j \neq i} h_{ji}p_j}\right) - c_i p_i, \qquad (3)$$

where c_i is the power cost. This parameter can be utilized to adjust the trade-off between network utility and power efficiency and is the limiting factor precluding the player to raise its power indefinitely.

The objective of the coordination game is to maximize the global utility function, $max \sum_i u_i$, while minimizing the globally allocated power, $min \sum_i p_i$, where $p_i \in [0, P_i^{max}]$.

Some further details on implementing the power control algorithm under the premises of above GT principles may be found in [3]. Based on that model, we built a software tool for simulations of the proposed algorithm. The software tool may be freely accessed at [23].

By using the software tool, a set of theoretical simulations has been performed as reported next. Parameters used for simulation are as follows: $n_0 = 1^{-12}$ W, $c_i = 1$ for all users, h_{ij} are calculated using ITU indoor propagation model P.1238 [20] and assuming co-channel operation. The number of links was varied between 2 and 10 and the main result was expressed as a function of total system capacity (i.e. sum of capacities of all individual links) on a number of users in the system. Transmitters, each paired with one receiver, are distributed uniformly in a 10×10 m square. The simulation was made of 5000 randomly generated snapshots and average total capacity was derived as shown in Fig. 2.

It can be clearly seen from Fig. 2 that removing the 100 mW limit does have positive consequences on the overall capacity of the links sustained in a given bandwidth. This is especially striking noting the rather small scale of the simulated scenario of just 10×10 m, where the higher power would not be normally considered necessary based on purely link distance necessities. This shows that allowing higher power would lead the devices to use the additional power margin in order to increase the SNR and thus improve the quality of the link. At the same time it is shown, that given the clear rules, the system would converge and no excessive over-exploitation of power would occur.

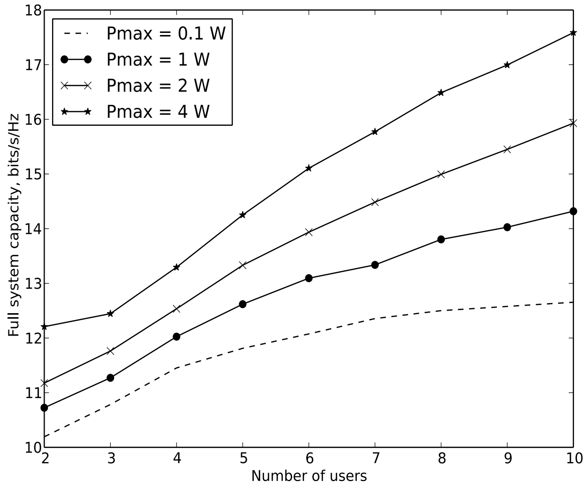

Fig. 2. Total system capacity for simulated devices with interference-aware power control game (10×10m area, frequency 5500 MHz)

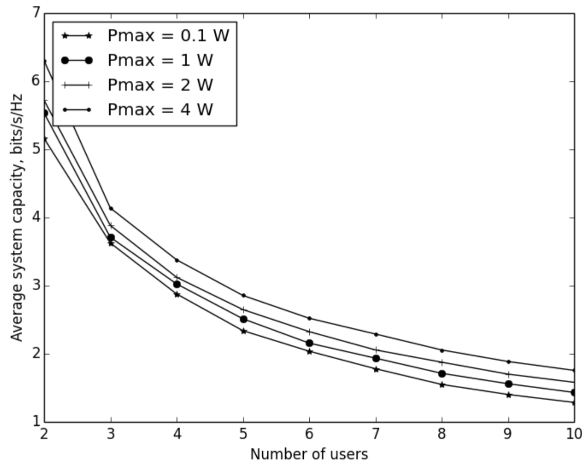

Fig. 3. Average link capacity in the simulated system as function of total number of users

On the other hand, same theoretical simulations also highlighted the issue of fairness in power allocation. This is illustrated by the simulation results presented in Fig. 3. These results indicate an average capacity per user, which deteriorates proportionally with the growth of the number of supported users in the band. It may be observed (Fig. 3) that the individual links would suffer of spectrum congestion regardless of the power limit. It is especially illustrative that the 100 mW EIRP limit is not really a solution to address that problem. Yet, even in very congested situations having the higher power limits as an option would allow achieving higher link capacities.

III. Model Adjustment and Experimental Testing

In this section we proceed by further developing the GT model presented in the previous section in order to improve it and make it more suitable for practical implementation. The model adjustment also addresses the channel access fairness issue.

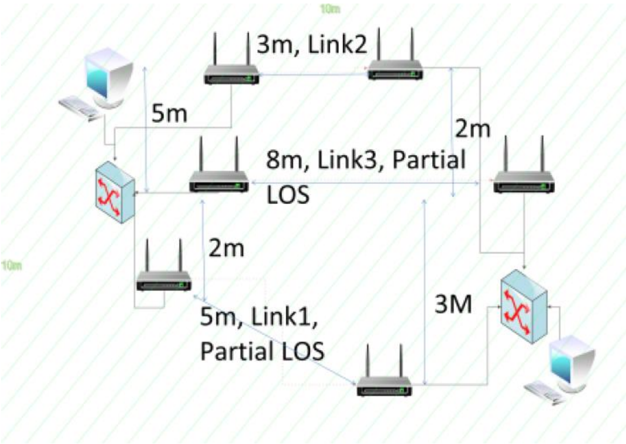

Fig. 4. The experimental setup for testing power coordination algorithm

The first improvement to the theoretical approach would be to add a threshold for operational received signal level, i.e. as measured by the Received Signal Strength Indicator (RSSI). Most of the wireless devices can operate at lower signal levels and still keep the optimal throughput. Adding RSSI ceiling to the proposed algorithm would allow limiting the overall interference level and improving fairness between users. It is suggested that RSSI value of -35 dBm could be a suitable balance, below which Wi-Fi device can still operate at a high data rate and above which the signal would start impacting the linearity and efficiency of RF front ends.

It is also proposed to implement a "fairness indicator", linked to packet loss factor. Thus, after each interaction between wireless nodes, the transmission power would be adjusted, triggered by packet retry rate %, RSSI levels at different nodes, link quality indication % and packet loss.

During initial experimental set-up (see Fig. 4), the first measurements were done following the original algorithm in order to determine the reference packet loss. A total of 100,000 packets of 1500 bytes each were being sent during each packet generator session. Average loss was then calculated.

The testing environment was a 10 by 10 m room with randomly placed 6 IEEE-802.11n devices operating in the same channel (we used 5 GHz devices as samples for this test, operating at 5500 MHz), two "Cisco" layer 3 switches and PCs for packet generation. All devices are off-the shelf commercial devices with 802.11n based proprietary protocol, which allowed us to completely disable CSMA algorithm and Automatic Power Control options. In order to determine algorithm operation in different link situations devices were placed at different distances, in both LOS and NLOS conditions. Link3 devices used 5 dBi antennas while all the rest used omni antennas. The PCs acted as both packet generator machines and central controlling system which did calculations and power adjustments of Wi-Fi devices.

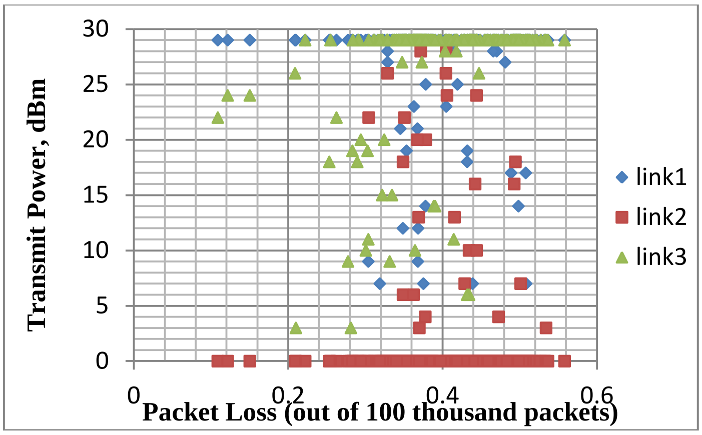

Fig. 5. Packet loss distribution at different transmit power levels on three experimental links

The prototype algorithm [23] was implemented using Python programming language; however it can be easily back ported to Lua programming language in order to decentralize the system in such a manner that devices would operate on their own without the central coordinating system. However we stayed with Python based version for easier maintenance and faster changes in testing phase.

Test flow was started by taking initial measurements of total PPS (Packets per second) in each link. During the testing constant traffic of 5 Mbps duplex was flowing through each link, which later was increased to maximum capacity of the link. After each measurement, algorithm either increased or decreased the transmit power and repeated the measurement again. If the throughput, in terms of PPS, increased and loss decreased, it was considered that current settings were correct. However if the loss increased compared to previous iteration, the control system sent command to all other operating nodes to decrease their transmit power. This allowed maintaining fairness between different links in order to obtain and maintain the highest capacity. The resulting distribution of packet losses is shown in Fig. 5. As expected, short LOS Link2 required much less power to maintain high data rate.

Also notable is that the algorithm ensured keeping the power of Link2 close to 0 dBm at which devices can still obtain desirable RSSI levels to maintain the proper link quality. Link1 and Link3 often tried using maximum transmit power, apparently as a result of larger link distances and NLOS effects. The RSSI difference when Link3 is in complete LOS vs. partially obstructed LOS is approx.. 5…10 dB.

Fig. 6 presents a graph of PPS distribution for different transmit power over time. The initial PPS values, measured at transmit power 0 dBm, are much lower compared to the ones achieved after starting the proposed algorithm operation. Over time the PPS is dynamically changing responding to different transmit power values. During the experiment it could be seen that system under test moved towards optimal values and only little deviated from them due to signal reflections and dynamic environment at which the devices operated, the stability condition [22] was only temporal and devices constantly re-adjusted the transmission power after short transmit power stability.

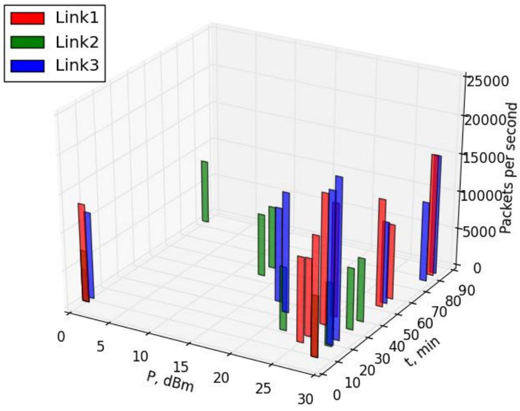

Fig. 6. Power allocation and throughput distribution

In order to achieve a more controlled environment, the experiment was repeated in a hardwired test-bench arrangement containing two links. “Yantel” attenuators (set to 60 dB) were used to model path loss along with RF switches and coaxial cables. Continuous 5 Mbps (duplex) traffic was maintained using “*nepim*” traffic measurement tool. This assured continuous traffic over links during the entire experiment. Again all CSMA and power control options were disabled in order to evaluate the functioning of the proposed algorithm. The program code was started on PC which sets randomly primary transmit powers on each device. Using “*pkt-gen*” tool allowed collecting information about maximum and minimum PPS, BPS, and loss. Other aspects of algorithm operation and experiment were unchanged.

The results of second experiment are given in Fig. 7. It shows that link throughput is constantly changing due to link budget dynamics. However from the graph it can be seen, that throughput difference between two links was never greater than 20%. The fluctuations of transmit power in both links can be seen in Fig. 8. The transmit power of both transmitters was mostly kept within 25…30 dBm range, where highest throughput results were achieved. This shows the stability of the proposed power control algorithm.

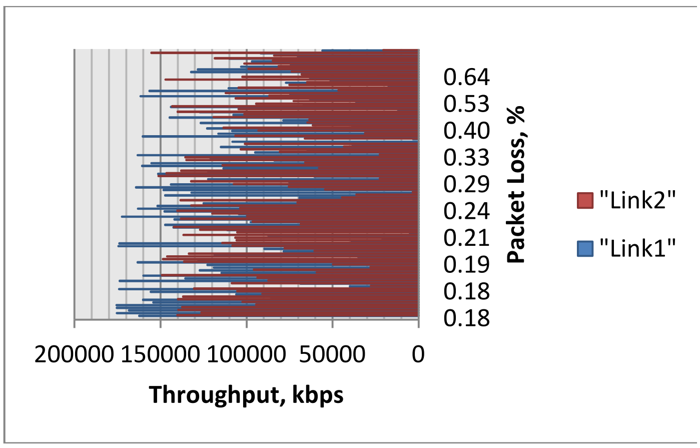

Fig. 7. Throughput measurement results in Test #2 as packet loss graph

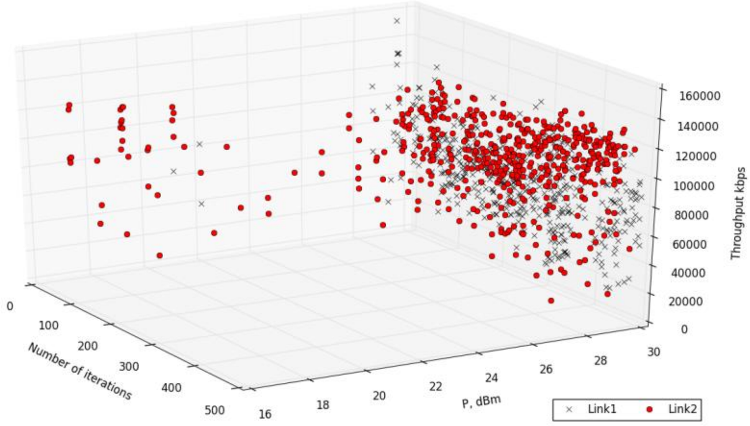

Fig. 8. Power allocation and throughput distribution

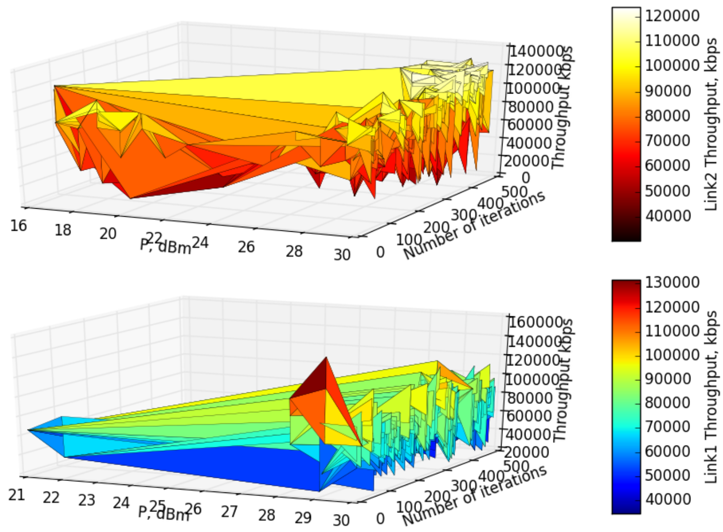

Fig. 9. Transmit power and throughput between iterations on Link1 and Link2

The experiment was continued by increasing the number of iterations from 100 to 500 in order to get more accurate results. From Fig. 9 one can see that the power on both links concentrated at 24…30 dBm.

The throughput during each iteration was hardly changing on both devices, which allows making assertion that 24…30 dBm was a self-established optimal transmit power range for both links. Note that it exceeds the current (European) regulatory limit of 20 dBm.

IV. SUMMARY AND FUTURE WORK

This paper proposes that Wi-Fi and other wireless devices using ISM bands may benefit of a new CR-like power allocation algorithm based on the GT model. The algorithm was tested in both theoretical simulations and practical experiment with 6 wireless nodes in indoor environment. Both the simulations and practical experiments confirmed that the proposed algorithm allows significant increase of the total capacity of co-located co-channel links in ISM band.

Although operation in non-stationary realistic radio environments was shown to make it difficult reaching stable Nash equilibrium, the algorithm allowed achieving reasonable stability of transmit power and fairness of channel access between neighboring devices. It is especially notable that the proposed algorithm allowed achieving exceptional throughput while CSMA/CA was completely disabled, as seen in Fig. 9. This suggests that the proposed intelligent interference-aware power control mechanism may be even used as a substitute for CSMA/CA.

The experiments further allowed establishing relation between transmit power and packet loss in a composite "cost of the link" - c - value, which is needed as an input to GT-based operation.

Ultimately, the proposed implementation of proposed power coordination algorithm may allow completely removing the regulatory limit on maximum transmit power of Wi-Fi and other devices in shared bands, as it could be left as a matter for self-regulation. It may also replace both DCF and PCF mechanisms, while achieving increased total capacity of co-channel wireless links.

For future work it is planned to continue investigation of various practical aspects of the proposed algorithm with the objectives of its further optimization and adaptability to different environments. One of other possible avenues would be to explore use of more directional antennas.

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