INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2020, VOL. 66, NO. 4, PP. 679-685
Manuscript received April 30, 2020; revised October, 2020. DOI: 10.24425/ijet.2020.134027

Policies for Transmit Power Control in the Conditions of Jamming in Clustered Wireless System

Jarosław Michalak

***Abstract*—This article presents a consistent solution of Transmit Power Control in centralized (clustered) wireless network with and without jamming. Depending on the policy assumed, appropriate solutions are applied to minimize the power used in a system or to satisfy expected Quality of Service. Because of specific nature of the system there is no optimal solution which can be applied in practice. Correctness and effectiveness of four proposed Transmit Power Control algorithms was presented in the form of computer simulation results in which the system capacity, mean power used and the number of successful links were described.**

***Keywords*—clustered network, transmit power control, jamming, wireless system**

I. Introduction

DIFFERENT wireless systems have various features, behaviors and there are also different user expectations in regard of e.g. the node speed, its resources, services, policies etc. As a result, the literature is full of TPC (Transmit Power Control) proposals to fulfil different objective function. We usually look for optimal solutions but in many cases finding one is impossible.

TPC is expected e.g. to:

a) avoid or to minimize (reduce) the interference level,
b) maximize throughput (on the link and/or overall),
c) maximize the spectrum system efficiency,
d) avoid "near-far" effect,
e) maximize the system capacity,
f) minimize the energy used by the system,
g) save the battery energy,
h) satisfy the QoS,
i) preserve connectivity,
j) maximize the LPI/LPD properties.

Some of the expectations listed above are convergent but some of them are mutually exclusive . When a user is moving and/or propagation conditions are changing, the adaptive TPC can be applied.

We always expect TPC to react quickly and with high accuracy. Unfortunately, we have to take into account the TPC errors as a result of latency in regulation loops. They can be a reason for a lower throughput and/or higher interference levels in reality.

II. Related works

The TPC can be applied centrally (e.g. by Cluster Head) or in a distributed way. TPC algorithms can, in general, be based on statistical assumptions [1-3] or they can work "on-line" [4].

What is more, a new important area of the TPC proposals for CR (Cognitive Radio) and CRN (CR Network) has been emerging in recent years.

We can find two different approaches to the power control problem in practice:

1. The TPC is applied in some degree as an stand-alone procedure [5-7].
2. The TPC is tightly connected with and is a part of the Radio Resource Management algorithm [8-11].

The second approach is important and popular because of immediately obvious connection of the transmitted power with modulation type, coding scheme, frequency used, antenna type etc. and their possible adaptation process. One has to remember about it, but RRM (Radio Resource Management) problems will be omitted in this paper.

In [12] an inter-cluster communication scheme for self-organized TPC in MANET clustering was proposed. Each cluster member within a cluster is adjusted according to the estimated cluster density. Energy consumed by nodes in the cluster is reduced. In [7] the authors proposed a power reduction algorithm for open and closed loop in a clustered network. Maximum power is used only at the initial stage of clustering. Next, the CH adjusts its transmitted power to the regular node (RN, later it appears under the name Own Node (ON)) at the maximum distance and sends information to start a closed loop TPC algorithm. ON reports an error rate level. Centralized approaches of TPC [13-15] are not suited for mobile Ad-hoc systems where TPC has to be dynamically adjusted according to a system topology and environment changes but the clustered network provided here is locally centralized. In [16] the distributed joint power control and rate scheduling algorithm based on the SINR was proposed. The algorithm maximizes the sum of weighted link rates.

This work was carried out in the framework of the MAENA EDA Project No B-1476-IAP4-GP.

The Author are with Military University of Technology in Warsaw, Poland (e-mail: jaroslaw.michalak@wat.edu.pl).

In military communications the TPC can be connected with a special approach. In [5] the author proposed a decentralized power management algorithm for frequency reuse in connection to HF ALE (Automatic Link Establishment). Another approach is presented for FH (Frequency Hopping) systems. In [17] two TPC algorithms for adaptive LPI FH were proposed. One for minimizing the initial BER for every data frame, and another one for good LPI properties distributing the power for all channels individually to have the same SNR at the receivers. In [18] and [19] the authors consider combined power and code adaptation for FH. It was pointed out when the code rate should be changed rather than the power and vice versa. In [20] the authors presented CIR based TPC for slow FH working slot-by-slot. RRM (voice activity, antenna type, coding scheme) with TPC for FH was presented e.g. in [21].

There are a lot of publications concerning TPC indicating a game theory as a key concept (TPC for CR based on non-cooperative game theory was described in general in [22]). In [23] cooperative game, Nash Bargaining and SINR utility function were used for power control resulting in a good balance between fairness and the efficiency in CDMA system. In [24] the non-cooperative TPC Nash Game on the basis of SIR for different users throughput got increased in MC-CDMA system. In [25] the new pricing function based on double-interference punishment for non-cooperative TPC in CDMA system was proposed. The authors proved the existence of the Nash Equilibrium. An optimal TPC allocation for OFDMA system using Lagrangian dual decomposition method was described in [26]. Two phase algorithm for maximizing the throughput in OFDMA link was described in [27]. In the first stage subcarrier assignment and equal transmitter power allocation are made, while in the second stage, a fine sensing (cooperative) and power allocation are performed aiming to maximize the throughput. Optimal power control policies that maximize the achievable rates of underlay cognitive radio systems with arbitrary input distributions under both peak/average transmit power and peak/average interference power constraints for general fading distributions were proposed in [28]. Beside QoS, interference constraints are assumed as well in [29]. An optimal TPC was investigated.

This article presents a proposal of solution for the Transmit Power Control in centralized (clustered) wireless network with and without jamming. Depending on the policy assumed, solutions are applied to minimize the power used in a system or to satisfy expected Quality of Service. Paragraph III includes a description of the network structure. The TPC concept with different policies was presented in paragraph IV. Simulation results can be found in paragraph V.

III. THE NETWORK STRUCTURE

The system is organized in clusters and on the assumption that there is one frequency used in each cluster at a given moment of time (Frequency Hopping mode is not considered, Fig.1).

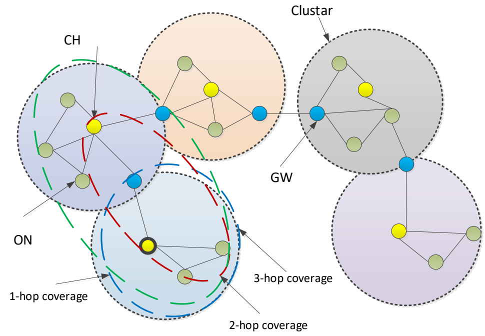

Fig. 1. An example of a clustered network
Legend: ON – Own Node, CH – Cluster Head, GW – Gateway

System assumptions:

1 The CH is responsible for resource management in its own cluster.
2 The TPC algorithm proposed is related to chosen policy (see section IV).
3 The CH knows a level of additive disturbances (environmental noise and jamming power) at each node in own cluster σ^2_i (from Hello messages)
4 The CH knows expected SINR at each ON (from resource request).
5 The CH knows the attenuation at each potential link in own cluster (from Hello messages, Fig. 2).

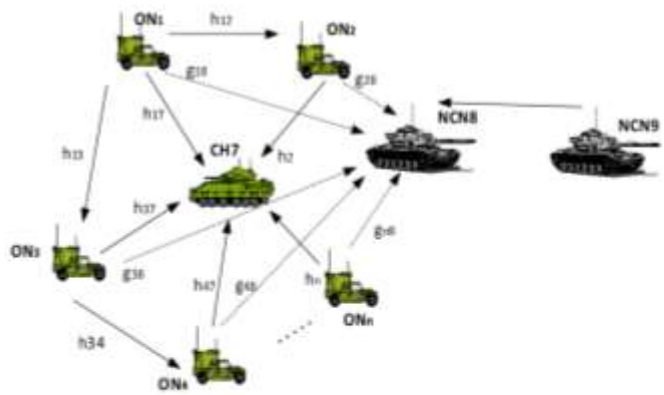

Fig. 2. An example of a system structure and communication links
Legend: Link gains between nodes in a cluster and the NCN8 (Not Connected Node, the node which is not a member of our cluster and can interfere) and between nodes. Only own nodes are tagged as gij and hij respectively (for clarity of drawing, not all link gains are marked)

IV. TPC CONCEPT

According to the above mentioned assumptions, a set of 4 policies for TPC was selected (Table I).

Remark: Power assigned cannot exceed maximum transceiver power P_{max} as well as the power permitted within the cluster (in connection to frequency reuse assumption) P_{cl}). As a result, for one link in a cluster example, we can write down the node power limit as $P_{limit} = \min\{ P_{max} , P_{cl} \}$.

TABLE I
POLICIES FOR TPC

Policy no.	Basic assumptions	Description
1	T, QoS, max C	Maximization of cluster capacity on condition T and QoS
2	T, QoS, min P	Minimization of Tx Power on condition T and QoS
3	QoS, max C	Maximization of cluster capacity on condition QoS
4	QoS, min P	Minimization of Tx Power on condition QoS

C – cluster capacity during data slot
QoS – Quality of Service
T – the maximum accepted interference power at NCN (if NCN exists)

The following situations can indicate the use of a specific policy:

1. When NCN is present and own system can maximize its capacity in the conditions of Low Probability for Intercept and/or if nodes power consumption is not an issue – use Policy No.1
2. When NCN is present and own system works in the conditions of Low Probability for Intercept and/or if nodes power consumption is an issue – use Policy No.2
3. When NCN does not exist (or own system does not take it into account) and own system can maximize its capacity in the conditions of Low Probability for Intercept and/or if nodes power consumption is not an issue – use Policy No 3
4. When NCN does not exist (or own system does not take it into account) and own system works in the conditions of Low Probability for Intercept and/or if nodes power consumption is an issue – use Policy No.4

A. Policy no. 1 (T, QoS, max C)

Input parameters: resource request list (direction, QoS ($SINR_{min}$, min throughput)), T, s.t. maximize cluster capacity.
For each link request assign Tx Power max ensuring condition P_{limit} and T.

1. If assigned Tx Power satisfies QoS for requested link – success
2. If assigned Tx Power does not satisfy QoS for requested link – Best Effort (MCS (Modulation and Coding Scheme) ensuring max C with assigned Tx Power)

Pseudocode

Input parameters: P_{limit}, T, $SINR_{min}$, σ_i^2, link gains $h_i(i = 1, \dots n)$ between own nodes (ON) and $g_i(i = 1, \dots m)$ in relation to NCN, k – number of links to assign. The number of assigned links within one frame will not exceed d - the number of data slots within frame.

For each data slot and link request taken from the queue:
$P_i = T/g_i$
If $P_i * \frac{h_i}{\sigma_i^2} \geq SINR_{min}$ for assumed throughput and $P_i \leq P_{limit}$ – success
Else if $P_i * \frac{h_i}{\sigma_i^2} \geq SINR_{min}$ for assumed throughput and $P_i > P_{limit}$ => $P_i = P_{limit}$ – best effort
Else if $P_i * \frac{h_i}{\sigma_i^2} < SINR_{min}$ for assumed throughput and $P_i \leq P_{limit}$ – best effort
Else if $P_i * \frac{h_i}{\sigma_i^2} < SINR_{min}$ for assumed throughput and $P_i > P_{limit}$ => $P_i = P_{limit}$ – best effort
End

B. Policy no. 2 (T, QoS, min P)

Input parameters: resource request list (direction, QoS ($SINR_{min}$, min throughput)), T, s.t. minimize Tx Power.
For each link request assign Tx Power min ensuring condition P_{limit} and T.

1. If assigned Tx Power for requested link and QoS satisfies condition P_{limit} and T – assign this Tx Power for the link - success
2. Otherwise, assign lower Tx Power ensuring condition T and P_{limit} – Best Effort

Pseudocode

Input parameters: P_{limit}, T, $SINR_{min}$, σ_i^2, link gains $h_i(i = 1, \dots n)$ between own nodes (ON) and $g_i(i = 1, \dots m)$ in relation to NCN, k – number of links to assign. The number of assigned links in one frame will not exceed d - the number of data slots in frame.

For each data slot and link request taken from the queue:
$P_i = SINR_{mini} * \sigma_i^2 / h_i$
If $P_i * g_i \leq T$ and $P_i \leq P_{limit}$ – success
Else if $P_i * g_i > T$ and $P_i \leq P_{limit}$ (condition T is not fulfilled) => $P_i = T/g_i$ - QoS is not fulfilled
Else if $P_i * g_i \leq T$ and $P_i > P_{limit}$ (condition P_{limit} is not fulfilled) => $P_i = P_{limit}$ – QoS is not fulfilled
Else if $P_i * g_i > T$ oraz $P_i > P_{limit}$ => take min(P_{limit}, T/g_i) - QoS is not fulfilled
End

C. Policy no. 3 (QoS, max C)

Input parameters: resource request list (direction, QoS ($SINR_{min}$, min throughput)), s.t. maximize cluster capacity.
For each link request assign Tx Power max ensuring condition P_{limit}.

Assigned Tx Power = P_{limit}

1. If assigned Tx Power satisfies QoS for requested link – success
2. If assigned Tx Power does not satisfy QoS for requested link – Best Effort (MCS ensuring max C with assigned Tx Power)

Pseudocode

Input parameters: P_{limit}, $SINR_{min}$, σ_i^2, link gains $h_i(i = 1, \dots n)$ between own nodes (ON), k – number of links to assign. The number of assigned links in one frame will not exceed d - the number of data slots in frame.

For each data slot and link request taken from the queue:
$P_i = P_{limit}$
If $P_i * h_i / \sigma_i^2 \geq SINR_{min}$ for assumed throughput – success
Else if $P_i * h_i / \sigma_i^2 < SINR_{min}$ for assumed throughput – Best Effort
End

D. Policy no. 4 (QoS, min P)

Input parameters: resource request list (direction, QoS ($SINR_{min}$, min throughput)), s.t. minimize Tx Power
For each link request assign Tx Power min ensuring QoS and P_{limit}.

1. If assigned Tx Power satisfies QoS for requested link and $P_i \leq P_{limit}$ – success
2. Otherwise (condition P_{limit} is not fulfilled) => $P_i = P_{limit}$ – QoS is not fulfilled, Best Effort

Pseudocode

Input parameters: P_{limit}, $SINR_{min}$, σ_i^2, link gains $h_i (i = 1, \dots n)$ between own nodes (ON), k – number of links to assign. The number of assigned links within one frame will not exceed d - the number of data slots in frame.

For each data slot and link request taken from the queue:
$P_i = SINR_{min i} * \sigma^2_i / h_i$
If $P_i < P_{limit}$ - success
Else if $P_i = P_{limit}$ – Best Effort, QoS is not fulfilled
End

V. SIMULATION RESULTS

A. Assumptions

Algorithms for TPC were implemented in Matlab using node location as in Fig.3. There was one NCN node (red) and 10 ON (green) with 1 CH (blue). Simulations verified TPC efficiency as a functions of changing $SINR_{min}$, P_{limit} or T.

The default values of parameters are as follows:

- additive disturbances level (environmental noise and jamming power) at each node in own cluster σ^2_i.=1.5470*10^(-14)
- channel bandwidth: 25kHz
- number of nodes including NCN: 11
- $SINR_{min}$: 10dBW
- P_{limit}: 1W
- T= 1*10^(-11)

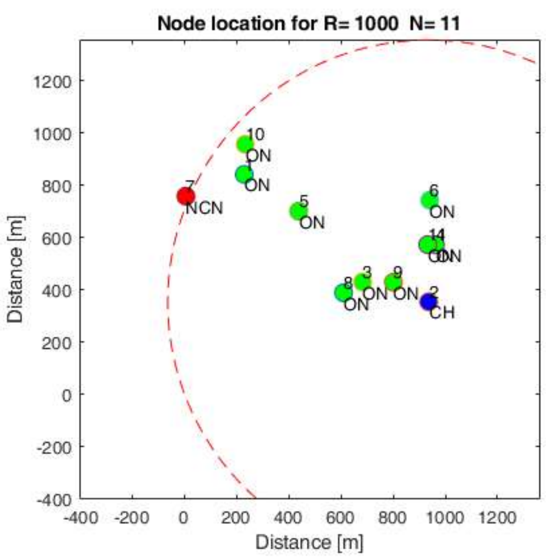

Fig. 3. An example of node location
Legend: ON – Own Node, CH – Cluster Head, NCN – Not Connected Node

B. Metrics

Cluster capacity C (the sum of capacity in all data slots in one frame).
The potential rate in a slot can be defined as

$$R_{slot} = \log\left(1 + \frac{h_i p_i}{\sum_{j \neq i} h_j p_j + \sigma^2}\right), \quad (1)$$

where:

σ^2 - environmental noise and jamming power,
p_i – Tx power,
h_i – link gain,
i, j, number of link.

The overall cluster rate is the sum of rates in all data slots in one frame.

$$C = \sum_{i=1}^{d} \log\left(1 + \frac{h_i p_i}{\sum_{j \neq i} h_j p_j + \sigma^2}\right), \quad (2)$$

where d – the number of data slots in one frame.

If there is only 1 link active in one data slot, the capacity of the frame can be expressed as:

$$C = \sum_{i=1}^{d} \log\left(1 + \frac{h_i p_i}{\sigma^2}\right). \quad (3)$$

The power used within a cluster can be written down as:

$$P_{cl} = \sum_{i=1}^{d} p_i, \quad (4)$$

where p_i is a Tx Power in data slot.
The number of links fulfilling QoS condition in a cluster (for all data slots in one frame)

$$Links_{no} = \sum_{i=1}^{d} link_{QoS}. \quad (5)$$

Relative number of links fulfilling QoS condition in a cluster.

$$Links_{rel} = \frac{links_{no}}{links_{req}}, \quad (6)$$

where $links_{req}$ is a number of requested links for one frame cycle.

C. Results

1) *Number of successes, percentage of successful links, mean cluster capacity and mean power within the cluster versus $SINR_{min}$ (Fig. 4, Fig. 5, Fig. 6, Fig. 7)*

If $SINR_{min}$ grows, the capacity and power disposal rises (with different slope) as well as in all the policies but Policy no.3 in which P_{limit} maximizing capacity (1W) is accepted (with no NCN; Fig.6.,Fig.7). When NCN is present, in the function of growing $SINR_{min}$, we should expect decreasing number of served links (Fig. 4, Fig. 5).

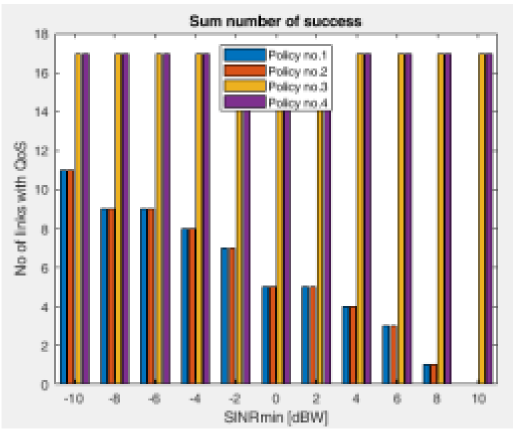

Fig. 4. Aggregate number of successes as a function of $SINR_{min}$.

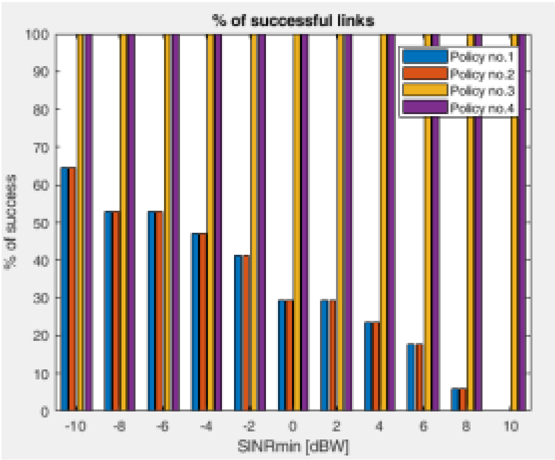

Fig. 5: Percentage of success as a function of $SINR_{min}$

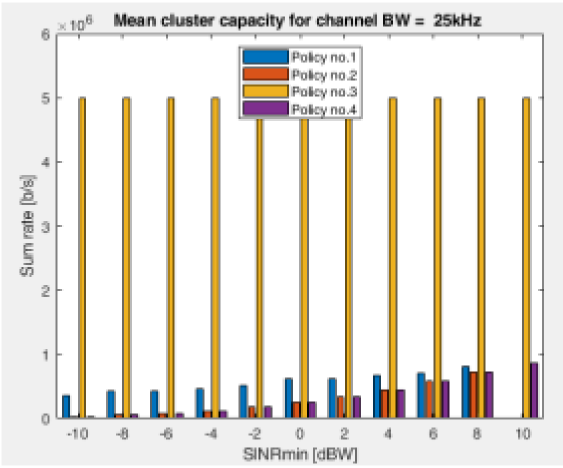

Fig. 6: Mean cluster capacity as a function of $SINR_{min}$

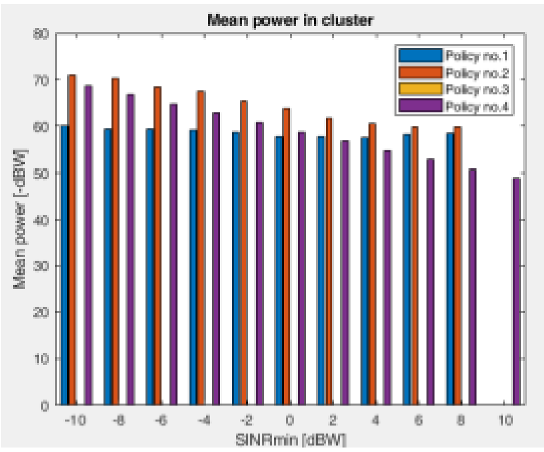

Fig. 7: Mean power in cluster as a function of $SINR_{min}$

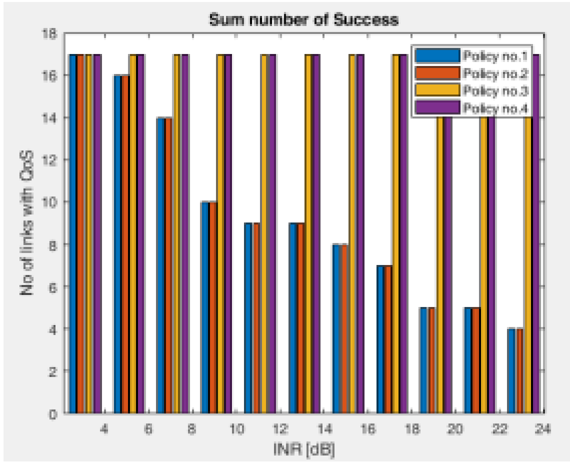

Fig. 8: Aggregate number of success as a function of *INR*

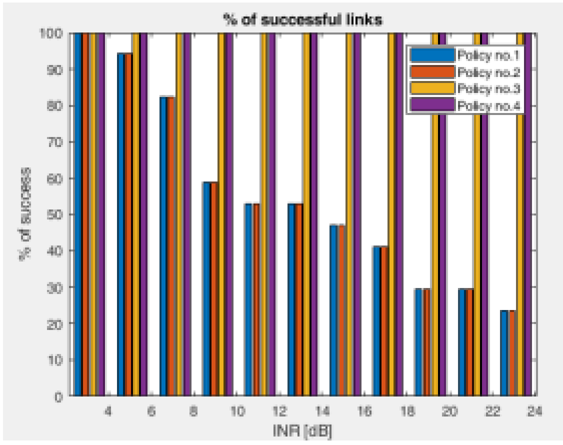

Fig. 9: Percentage of success as a function of *INR*

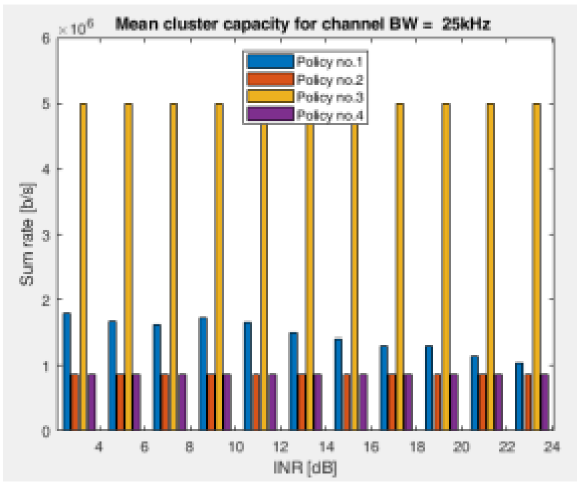

Fig. 10: Mean cluster capacity as a function of *INR*

2) Number of successes, percentage of successful links, mean cluster capacity and mean power in the cluster as a function of interference to noise ratio (Fig. 8, Fig. 9, Fig. 10, Fig. 11)

If the relation of T/σ^2 (INR (Interference to Noise Ratio)) is changed we can observe of the NCN node limiting influence. (look on policy no. 1 and no. 2 only because the NCN is not assumed in policy no.3 and no.4).

3) Number of successes, percentage of successful links, mean cluster capacity and mean power in cluster as a function of P_{limit}.(Fig. 12, Fig. 13, Fig. 14, Fig. 15)

If policy application effects connected with changing level of P_{limit} is discussed, its limiting influence is observed with all policies. The influence on the system capacity and Tx power is presented in Fig. 14 and Fig. 15. A special impact can be observed if NCN is present (policy no 1 and no. 2).

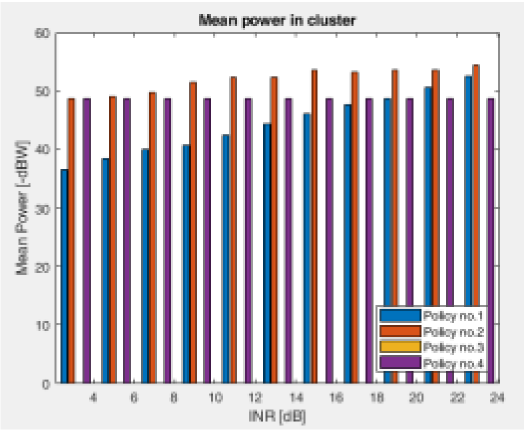

Fig. 11: Mean power in cluster as a function of *INR*

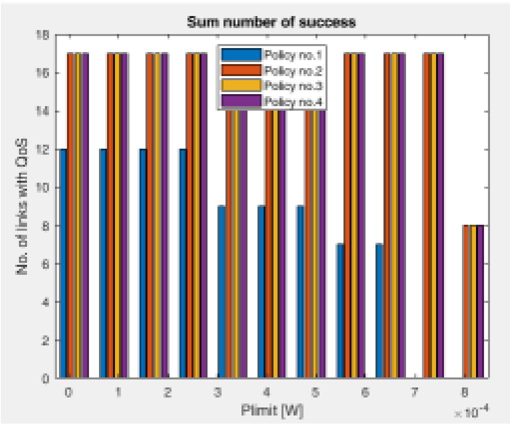

Fig. 12: Aggregate number of successes as a function of P_{limit}

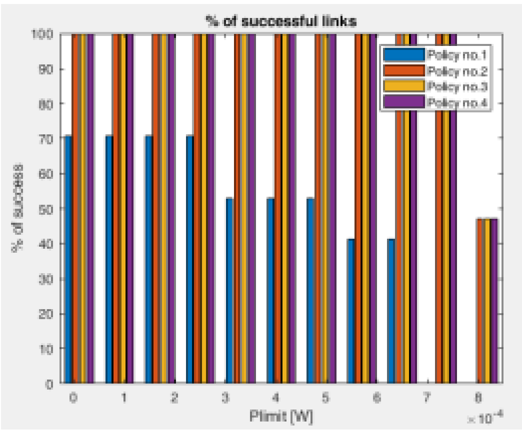

Fig. 13: Percentage of successes as a function of P_{limit}

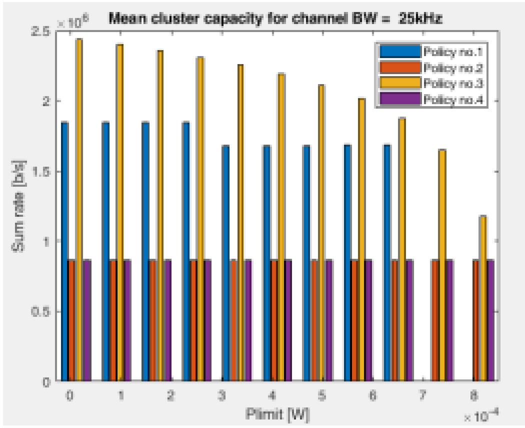

Fig. 14: Mean cluster capacity as a function of P_{limit}

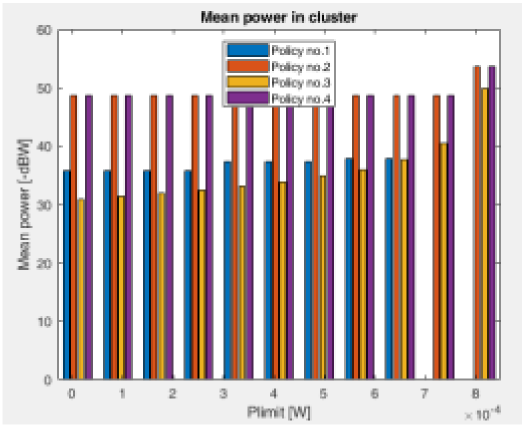

Fig. 15: Mean power in cluster as a function of P_{limit}

Conclusion

The Transmit Power Control for wireless clustered network with interference power constraint as well as QoS and P_{limit} constraints was presented.

The solution can be applied in following practical scenarios:

1. Policy no.1 – when some NCN (e.g. Primary User or the cluster using the same frequency) is present in vicinity which can have limiting influence on Tx Power level (policy is maximizing of the system capacity with avoiding interferences at the NCN or adjacent cluster).
2. Policy no.2 - when some NCN (e.g. Primary User or the cluster using the same frequency) is present in vicinity which can have limiting influence on Tx Power level and the system is trying to use minimum energy at the same time (LPI/LPD approach (Low Probability for Intercept/Low Probability for Detection) with ensuring the minimal requested throughput).
3. Policy no.3 - when there is no any NCN taken into account and the only limiting parameter is the maximal possible Tx Power which can be assigned (policy is maximizing the system capacity).
4. Policy no.4 - when there is no any NCN taken into account and LPI/LPD approach is needed (policy is minimizing the user intercept probability).

Depending on a scenario it is reasonable to use appropriate TPC policy realizing the chosen objective function. Presented solutions can be applied in military as well as in civilian systems although LPI/LPD approach is usually used in military.

During simulations we can observe that depending on policy applied, the capacity and power disposed in a cluster can be doubled.

REFERENCES

[1] S. Ulukus, R.D. Yates, „Stochastic power control for cellular radio systems," *IEEE Transactions on Communications,* pp. 784-798, 46(6) 1998.

[2] D. Das, M. K. Varanasi, „Stochastic power control with averaging," *IEEE International Conf. On Personal Wireless Communications,* pp. 325-329, Hyderabad, India 2000.

[3] N. Bui, S. Dey, „Optimal power control in CDMA over Markov fading channels," *Proc. IEEE International Symposium on Information Theory,* p. 79, Lausanne, Switzerland 2002.

[4] H. Su, E. Geraniotis, „Adaptive closed-loop power control with quantized feedback and loop filtering," *IEEE Transactions on Wireless Communications,* pp. 76-86, 1(1) 2002.

[5] C.H. Lee, , „Decentralized Power Management Algorithm for Frequency Reuse," *IEEE,* 1997.

[6] K. Kobayashi, Y. Kakuda , „An Inter-Cluster Communication Scheme for Self-Organized Transmission Power Control in MANET Clustering," *18th International Symposium on Real-Time Distributed Computing Workshops,* 2015.

[7] T. J. Kwon, M. Gerla , „Clustering with Power Control," *IEEE,* 1999.

[8] I. Wong, B. Evans, „Resorce Allocation in Multiuser Multicarrier Wireless Systems," *Springer,* 2008.

[9] S. A. Kyriazakos, G. T. Karetsos, „Practical Radio Resource Management in Wireless Systems," *Artech House, Inc.,* 2004.

[10] Y. Tachwali, B. F. Lo, I. F. Akyildiz, R. Agusti, „Multiuser Resource Allocation Optimization Using Bandwidth-Power Product in Cognitive Radio Networks," *IEEE Journal on Sel. Areas in Communications* , pp. 451-463, 31(3) 2013.

[11] D. J. Dechene, A. Shami, „Energy Efficient Resource Allocation in SC-FDMA Uplink with Synchronous HARQ Constraints," *IEEE ICC,* 2011.

[12] K. Kobayashi, Y. Kakuda, „An Inter-Cluster Communication Scheme for Self-Organized Transmission Power Control in MANET Clustering," *18th International Symposium on Real-Time Distributed Computing Workshops,* pp. 95-102, IEEE Computer Society 2015.

[13] S. Narayanaswamy, V. Kawadia, R. S. Sreenivas, P. R. Kumar, „Power Control in ad-hoc networks: Theory, architecture, algorithm and implementation ofthe COMPOW protocol," *Proceeding ofEuropean Wireless Conference,* pp. 156-162, 2002.

[14] G. Calinescu, I. Mandoiu,A. Zelikovsky, „Symmetric Connectivity with Minimum Power Consumption in Radio Networks," *IFIP Conference Proceeding,* pp. 119-130, Vol. 223 2002.

[15] X. Cheng, B. Narahari, R. Simha, M. X. Cheng, D. Liu, „Strong Minimum Energy Topology in Wireless Sensor Networks: NP-Completeness and Heuristics," *IEEE Transactions on Mobile Computing,* pp. 248-256, Vol. 2, No.3 2003.

[16] S. Zhou, X. Wu, L. Ying, „Distributed Power Control and Coding-Modulation Adaptation in Wireless Networks using Annealed Gibbs Sampling," *31st Annual IEEE International Conference on Computer Communications: Mini-Conference,* pp. 3016-3020, 2012.

[17] G. Bark, „Power Control in an LPI Adaptive Frequency-Hopping System for HF Communications," *HF Radio Systems and Techniques Conference,* pp. 302-305, No. 411 1997.

[18] M. B. Pursley, C. S. Wilkins , „Adaptive Transmission for Frequency-Hop Communications with Reed-Solomon Coding," *IEEE,* pp. 866-69, 1997.

[19] J. D. Kim, S. W. Kim , „Combined Power/Code Rate Adaptation in Reed-Solomon Coded Frequency-Hopped Spread-Spectrum Multiple Access Communications," *IEEE,* pp. 872-876, 2000.

[20] K. Hamaguchi, Y. Kamio, S. Sampei, N. Morinaga, „Performance of Slow-FH/16-QAM System with Interference-immunity Decoding and Transmission Power Control for Land Mobile Radio," *IEEE,* pp. 1810-1814, 1999.

[21] A.H. Hassan, S> Chennakeshu, J. B. Anderson, „Performance of Coded Slow-Frequency-Hopped TDMA Cellular Systems," *IEEE,* pp. 289-292, 1993.

[22] Z. Junhui, Y. Tao, G. Yi, W. Jiao, F. Lei, „Power Control Algorithm of Cognitive Radio Based on Non-Cooperative Game Theory," *Communications System Design,* pp. 143-154, 2013.

[23] Z. Wang, X. Wan, X. Wei, Z. Fan , „A Closed-form Power Control Algorithm in Cognitive Radio Networks Based on Nash Bargaining Solution," *3rd IEEE International Conference on Computer and Communications,* pp. 681-685, 2017.

[24] P. Li, S. Shao, L. Yang, H. Zhu , „A Novel Power Control Game Algorithm for Cognitive Radio," *International Conference on Communications and Mobile Computing,* pp. 149-153, 2010.

[25] J. Sun, Q. WU, „A Non-Cooperative Power Control Game via New Pricing in Cognitive Radio," *IEEE Proceedings,* 2009.

[26] T. Jiang, Z. Wang, Y. Cao, „Cognitive Radio Networks," *CRC Press,* 2015.

[27] S. E. Mahmoodi, S. B. Kordan, B. Abolhassani , „A New Algorithm for Joint Sensing and Power Allocation in Multiuser Cognitive Radio Networks".*Iranian Research Institute.*

[28] G. Ozcan, M. C. Gursoy, „Optimal Power Control for Underlay Cognitive Radio Systems With Arbitrary Input Distributions," *IEEE Transactions on Wireless Communications,* pp. 4219-4233, Vol.14, No.8 2015.

[29] Z. Wang, X. Wan, Z. Fan, M. Wang, „Optimal Power Control in Cognitive Radio Networks Under Interference Power Constraint and Quality of Service Constraints," *IEEE,* 2016.