# Balanced geometric model for uplink power control in industrial wireless networks

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**Abstract**

Industrial networks now are trying to implement wireless technologies, following the tendencies in communication networks. This task is complicated because of the nature of the industrial environment. Wireless connections hardly achieve the same stable quality of service (QoS) parameters as traditional cable ones. Interference is one of the reasons for that and effective solutions should be developed for its reducing in order to maximize the throughput of the wireless media. Balanced geometric model, which reduces interferences between end-users and access points, is proposed. It is based on Nash Equilibrium Theory and gives opportunity to control the output power of wireless devices in optimal way. The use of vectors in the model helps to analyse in details, impacts between the neighbour points – their power and direction. At the end, there is a sample for using balanced geometric model in industrial network.

*Keywords:* interference, Open-loop, closed loop, uplink power, industrial networks

## 1 Introduction

The information translated into modern industrial networks is characterized by its multimedia nature. Unlike the industrial traffic in the past, today not only sensor data and commands into a symbol form are transmitted to the actuators. The transfer of entire files, sound, voice and video requires new approaches and policies for network management. The ultimate goals of such management aim maximum benefits from the transmission medium, providing a high level of security when transferring critical workflow data, adequate scaling of services in the terms of variable load and mobility endpoints.

Besides the multimedia nature of transmission, new challenges arise from the tendency to replace cable connections with wireless in the terminal segments of the industrial networks. Some of these problems are related to uplink power management in such a network.

## 2 Traffic management models in industrial networks. Priority based models. Equilibrium models

There exist different management models and approaches in industrial networks. One of them tolerates priority. The nature of industrial applications supports priority transition of some data compared to the other, due to their higher degree of significance for the industrial management processes. Usually this data requires to be transmitted into shorter time intervals (in real time) and is called critical data. However, not all data transmitted in industrial networks meet this characteristics and this implies the use of models that take into account these features. These are priority-based models.

Priorities in industrial networks, however, may be set not only according to the type of the transferred information. The criteria for priority may be also different sources of the information stream. For example, the video stream from the quality control system on the assembly line should be priority transferred, according to a video stream from the surveillance system cameras in the same production space. In both cases, the information is a streaming video, but surveillance systems allow recording and buffering of the data. The video-stream, from quality control cameras must be transmitted in real time in order to be avoided latencies and scrapping production as a result or mixing of standard products with substandard.

One stage in the management of such models is a current state analysis of the network - the count and the type of transfer requests, channel load (occupied bandwidth), participants in the communication process at the analyzed moment. As a result of the analysis, priorities shall be appointed and according to them, different bandwidth parts to the different participants are provided for a specific time intervals.

Priority management according to the type of end nodes is hampered to somewhat by the mobility of the these nodes in wireless industrial networks.

All these circumstances make priority network management difficult to implement. Although there are established protocols and technologies, like MPLS for example, that can be used for implementation of such policy, the efficient management of the whole system requires use of multi-level criteria for evaluation of the priorities. Comprehensive assessment of the information on these criteria can introduce additional delays and decrease network performance. On the other hand the complicated analysis requires expensive and complicated hardware platform.

In contrast of priority models, there exist another type that explore the principles of equality. These models are called equilibrium models and tolerate even distribution of communication resources between the various actors in the communication process. Basically, the application of equilibrium models is used in the field of economic analysis, but their application in the field of communications is also possible. They use the principles of "fair play". The policy in this case is limited to ensuring equitable access to the channels for each of the end nodes.

In this case, time slots analysis is used. It is realized through equal time intervals ΔT. Within this period the current state of the network is get into account, reports are analyzed and specifically decision is taken in accordance with the accepted policy. End nodes are competitors for the network resources. From physical point of view, these resources are limited and therefore the occupation of a larger share of a single participant automatically takes shares of the other participants. However, in practice the communication process is not one-sided and involves information exchange between multiple participants. This excludes tolerating scenario where only one or a few end-nodes occupy the entire physical network capacity.

The main advantages of the equilibrium communication models are related to their significantly easier implementation, simplified computational logic and correspondingly lower cost of the hardware devices. Another advantage is driven by their higher performance boost. The simplified analysis shortens decision-making. It also allows pro-active management – it is sufficiently fast response to meet the requirements of industrial applications and at the same time adequate to the environment to such an extent as to provide the desired quality of service.

The equilibrium models are suitable for upload power control in industrial wireless networks with high density and for maintaining the interference in the network on minimum-eligible equilibrium levels.

## 3 Interference impact in the industrial wireless networks

The interference is a phenomenon that describes a complex influence of two or more waves with the same frequency at certain points. As a result of the interaction of these waves, in the tested points can be obtained attenuation or amplification of the waves. The interaction between two waves is easy to analyze, but many disturbing sources make the task considerably more complex.

In the context of wireless industrial networks this phenomenon is affecting the distribution of radio waves. The range of the wireless zones is vulnerable to internal and external interfering sources (Figure 1).

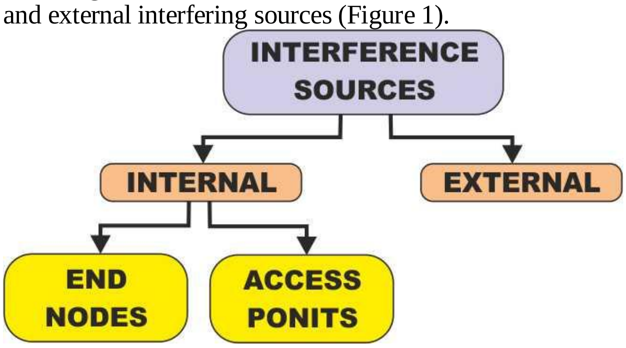


FIGURE 1 Classification of the interference sources in wireless industrial networks

External interfering sources are common in the industrial environment can be often observed in the industrial environment and their impact can be limited through a proper network planning, use of shields and / or directional antennas. Examples of such sources are powerful electromagnetic devices like transformers, contactors, electric motors, coils and others. The interference caused by these sources will not be dealt with in this report.

The other groups of interference impacts are internal for the network and can be divided into interference caused by near situated access points, working on the same or near frequencies and interference caused by end users into the area of the same access point. The accepted standards for wireless communication use bandwidth, divided into a separate channels. Each separate channel differs with a specific main carrier frequency and own frequency range (band). The standards allow partially overlapping bands of neighboring channels (Figure 2).

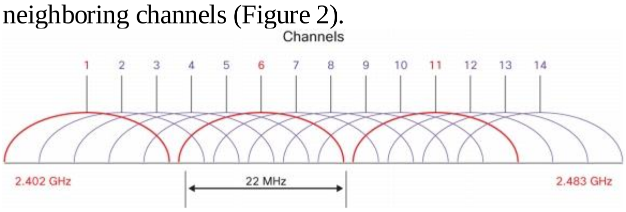


FIGURE 2 Channel bandwidths for 2.4GHz in the USA

This suggests the occurrence of interference in the adjacent access zones using adjacent frequency channels. The prevention against this type of interference includes administrative setting of distant frequency channels for the geographical neighboring access zones.

The interference between end users in a common zone arises due to the fact that they all use the same channel and respectively the same carrier frequency.

The end users, situated near the access point suffer less of interference impacts. Respectively the end users at the periphery of the zone are more vulnerable to an interference and at the same time, they are potentially more likely to generate similar impacts. The explanation for this is based on the amplitude of the signals at the points where end-users are positioned. The attenuation of radio signals for the used frequencies is realized on an exponential law.

End users situated near the access point receive significantly stronger signal from it and disturbing waves of other users are less likely to affect this link. In this situation, it is not necessary end devices to increase their output power in order to be connected to the access point. When end subscribers are placed on the periphery of the wireless zone, the signal from the access point is significantly weaker and more susceptible to interference impacts. In this case the end subscriber device tries to increase its uplink power in order to compensate for the attenuation of the signal caused by the long distance to the access point.

## 4 Known methods of preventing interfering influences

Bluetooth standard uses hopping carrier frequency in the defined frequency band (figure 3). The hopping frequency is changed automatically and synchronously, both in transmission and in the host side. This transmission method has been used since World War II, as the focus then was placed on the increased security of which provides. However, according to the subject matter of this paper, it may indicate the advantages in terms of safety from interference.

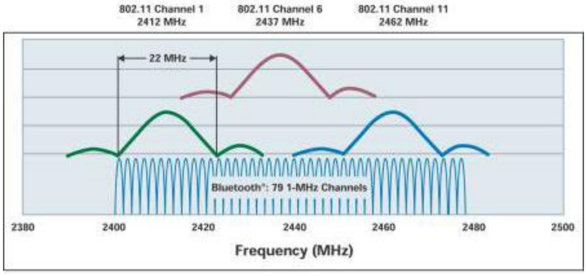


FIGURE 3 Hopping frequency channels in Bluetooth [16]

Hopping of the carrier frequency supposes that in occurrence of interference between two devices at a certain point, at the next moment the interference will be terminated due to the change of frequency in both interfering participants. The technology called Adaptive Frequency Hopping (AFH) relies on this principle, as it detects interfering devices, using different standards and protects them from setting the same carrier frequencies. There are used 79 frequencies with the interspace of 1 MHz. Bluetooth standard is used in the industrial wireless networks, but under certain conditions. Slower operating speeds and short-range distances mainly dictate its limited implementation.

Other method for minimizing the interference uses especially dedicated antennas for access points. When end users are static, their mutual influence can be suppressed by use of directional antennas. However, the access points often serve multiple subscribers distributed over a given territory, as some of them may be mobile. This limits the use of directional antennas. However, there exist antennas, constructed of multiple elements, as every one of them has a certain orientation. The antenna has an intelligent management and at work process can switch on and off some of its elements. The switching process is performed synchronously in time, according to which end subscriber communicates the access point at the given moment. So the antenna can effectively manage its beam.

## 5 Basic methods for uplink power control

One of the methods, specified by the standard organization 3GPP (3rd Generation Partnership Project), is known as Open Loop Power Control (OLPC) or also Fractional Power Control (FPC) [10, 13]. This method intends partial or full compensation of different values of SINR parameter for the subscribers with different allocation (Figure 4).

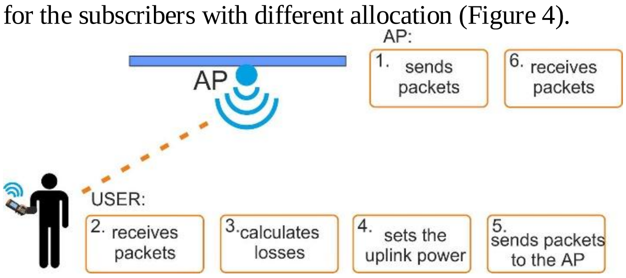


FIGURE 4 OLPC operation

In this method the end subscriber monitors the levels of the received signals and according to them determinates the necessary uplink output power on back direction. So the emitted signals can reliably reach the access point.

This method is called also "without feedback" because the access point does not have control over the output power of the end users. This method is not effective against interference and allows their appearance in a high density request environments. Due to this specification, it is not proper for uplink power control in a wireless industrial networks.

More reliable for implementation in this case is the other basic method known as Interference Based Power Control (IBPC). It uses the mechanism of Close Loop Power Control (CLPC) [2, 4, 7, 9, 13]. In this method, subscribers are not treated independently, but through management of uplink power on every subscriber it tries to increase the performance of the closed cells (serving access points) system as a whole. In other words it searches maximization of the total uplink throughput, through limiting the intercellular interference when it seeks a way to compensate the losses for the subscribers located in the border cell zones. [5,12]. The method is also known as "method for management and coordination with feedback", because the decision for uplink power is taken on basis of the received back into the access point signals.

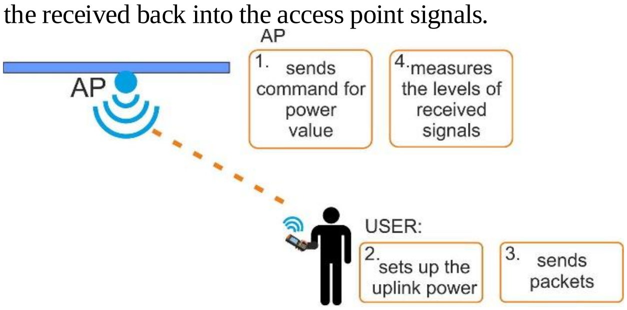


FIGURE 5 CLPC operation

The cycle shown on figure 5 repeats about 1000 times per second, which ensures precision and flexibility (short response time) of the mechanism. CLPC answers in a much higher degree of the requirements for high density industrial networks.

The methods for uplink power control, mentioned above use static analyses and do not represent reality from the point of the theory of service. Users constantly change their position and ongoing services requested. This requires development and research of dynamic uplink power management methods for wireless industrial networks and evaluation of the current density of service requests in base stations.

## 6 A vector model for equilibrium management of the interference

If it is necessary to analyze the interference between two access points, the factors affecting in this case would be:

- The output power of a signal for each of the points;
- Distance between the points;
- Direction of signal propagation.

The output power of a signal for each of the points is a function of the power sent from the final stage amplifier of the point transmitter and gain antenna used. On equal other circumstances, the dependence between output power and interference is directly proportional.

The distance between the two points in inverse proportion according to the interference.

In the theory of radio-wave signals except with its amplitude are described with its direction of propagation.

According to the topic of this paper, direction is detected to the geographical location of both access points (and the direction of transmission of their antennas, if they are directed).

These features show that for mathematical analysis, the most suitable geometric object to describe the interference is the vector. It also has size and direction, which adds greater visibility in the analysis.

For management of the energy estimation for uplink power in industrial environments is possible to use a relatively simple but effective approach based on a game theory. It aims by geometric (vector) analysis of the working environment to be achieved "Nash equilibrium" of interference between the separate zones. In his dissertation John Nash [11] explores situations of "game theory". According to this work, games can be divided into two main groups – cooperative and non-cooperative games. Non-cooperative games are those in which participants can make decisions only at its own discretion and interest, but by their actions a consequences arise for other players in the game. Nash considers a case with captured prisoners-accomplices, isolated from each other, which can confess their own and/or foreign wines and according to confessions made to get different sentences. According to the theory in terms of isolated interrogation, the lowest sentence prisoners will receive equal, if all plead guilty.

Brought in a field of high-density industrial networks, the Nash theory can be designed to interference influences. There are participants in the network connections. "The fault" or "confession" could be interpreted as own uplink transmit power to a particular participant and interference from other participants represent "punishment". In a case of inconsistency, each subscriber can emit high-power signal (not recognized wines), but afterwards the others will do the same. As a result, the total interference level will increase (greater penalty). According to the “Theory of Nash”, the equilibrium of the system can be achieved, when participants limit their output power in such a manner, as they will generate minimal interference with each other. In this case there is a "non-cooperative game" because participants coordinate their uplink power only with access points. Every user suspects the interest of others, but only can take decisions on its own interest and shares the risk.

In this model are analyzed the interference impacts in the system, during equal time slots with an optimal duration and after that they are presented in a vector form. This form allows in real situations to receive, if necessary, a visual representation of the situation. The vectors coincide with the direction of the interference impacts, and according to the length indicate power of the influence. The ultimate goal is to achieve an equilibrium system in which interferences between separate zones are in a balance.

For example, the approach may be used for analysis of the interferences in the range of three adjacent access points in a high density industrial wireless network and customers located in them. On a figure 6 can be observed the mutual disposition of the analyzed wireless access points.

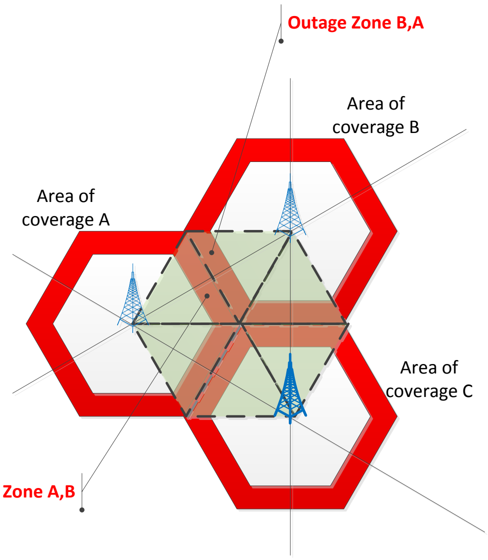


FIGURE 6 A part from wireless industrial network with three access points

Although the coverage zones are spherical in shape for the separate points, for the analysis purposes, on the figure they are presented as equilateral hexagons. On figure are marked the axes, on which interacts signals from the points, respectively on which will lie vectors. Highlighted in green area is the zone of interaction (interference). The border area of each cell is represented by a red line, as the subscribers located in this area generate significant interference in comparison with the others, located in the white access point area. As it was mentioned before in a point 3, as closer are users to the access point - the less power they need to support the communication and correspondingly feeble interference influences. This applies in the vector approach, visually distinguishing of the two types of subscribers identified by this criteria - near and peripheral situated.

If the scheme should represent interferences generated only between access points, ignoring for the moment influences from end users, the network will look like depicted in Figure 7.

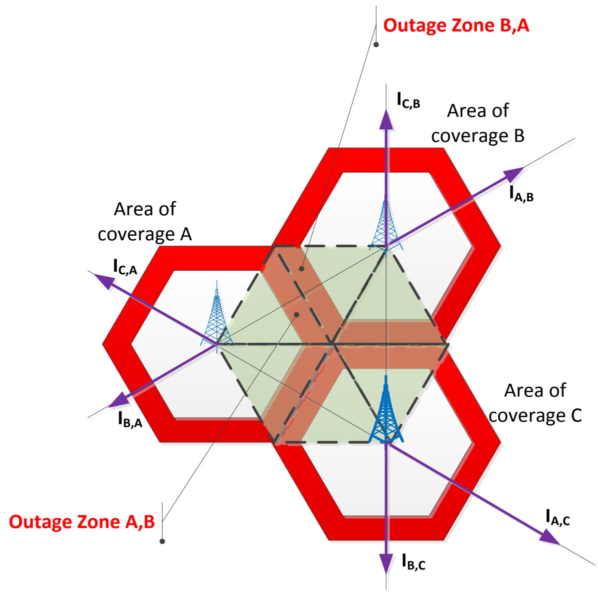


FIGURE 7 Interferences between access points

The vectors couple at each point represents interference in this place, generated by its neighbour access points. At this stage, it is easy to sum vector couples, but the results will not be credible if do not take into account the positions of subscribers, located in the separate areas (cells) of the access points.

On the figures above, the zone of interference influences (marked in green) is divided into triangles. They are important for the sectoral analysis caused of interference by customers. For example, the coverage area of point A has two sectors of influence (in a triangular form) – customers located in the north-positioned sector of figure, have an intensive influence on the access point B. Respectively customers located in the south-positioned sector of figure, have an intensive influence on the access point C.

Classification and grouping of customers according to their position is shown on Figure 8.

Having in mind the possibilities of mobility and transience of some subscribers is necessary for the analysis to take into account the relative values regarding the number of subscribers in the border areas of the sectors. The formula for obtaining this value is:

$$KI_{X,Y} = QXY_{out} / QXY_{all} \,, \quad (1)$$

where

$KI_{X,Y}$ - relative number of customers in the border area between cells X and Y, in the sector near by X.

$QXY_{out}$ – absolute number of customers in the border area between cells X and Y, в in the sector near by X.

$QXY_{all}$ – total number of clients in the sector with interfering influences of cell X to the side of cell Y.

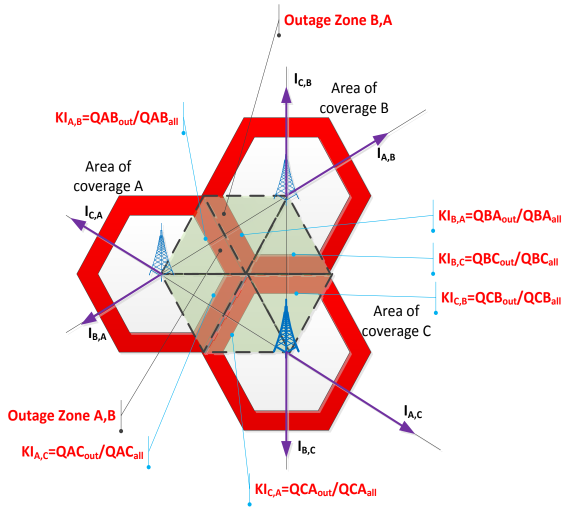


FIGURE 8 Differentiation of the clients according to their number and position

The total interference impact for individual areas (access points) and for the system at all are presented in Figure 9. The graphic analysis indicates, in the shown example, that it is necessary to increase the uplink power of cells B and C or to reduce the power of the A, in order to achieve equilibrium.

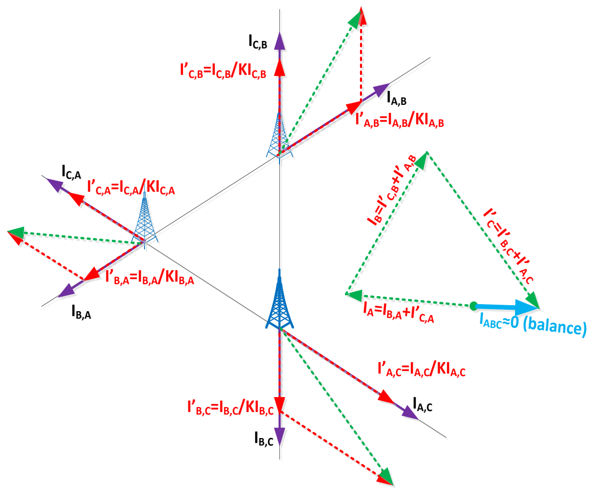


FIGURE 9 Sum of the interference for the explored zone

As it can be seen from the figure above, the relative interference impact for each of these cells can be calculated by the formula 2:

$$I'_{X,Y} = I_{X,Y} / KI_{X,Y} \,, \quad (2)$$

where

$I'_{X,Y}$ - relatively interference influence of cell X upon cell Y.

$I_{X,Y}$ - Interference of the access point in cell X upon the access point in cell Y.

$KI_{X,Y}$ - relative number of customers in the border area between cells X and Y, in the sector near by X.

After summing the vectors of the example was obtained triangle on the right side of the figure. The blue vector in the figure - I_ABC shows equilibrium by Nash. As more as this vector tends to zero, as much equilibrium system is and interference influences are balanced.

## 7 Scenarios in the case of interference imbalance

The reasons for an imbalance between the three points can be different. Mostly they are related to the mobility of subscribers, temporary occurrence of external interference, changing the density of requests, inadequate management, poor synchronization.

In order to apply the method, described in the previous paragraph, the access points should measure levels of interference and take decisions to achieve the minimization of the balance vector. The access points implement decisions by adjusting the uplink power, both for themselves and for the adjacent subscribers. Power of the subscribers can be set through a value of the coefficient α. It can vary in a range from 0 to 1 in a given step. For α=1, set capacity is the maximum possible, which can use the particular subscriber. Other management rule says that the coefficient α for anyone of the subscribers in every new time slot can be changed with only one step up or down.

In so established rules, one of the worst scenarios for behavior of the system is displayed in Figure 10.

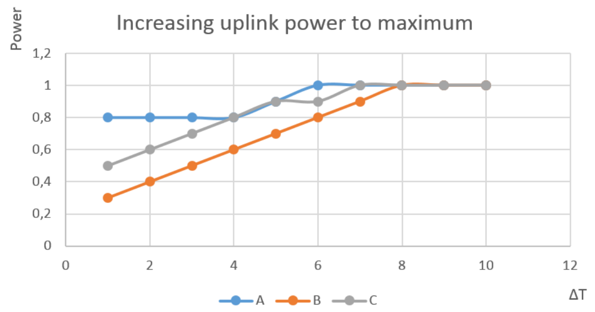


FIGURE 10 Mutual suppression

In this case, the separate access points (zones A, B and C) do not tend toward equilibrium and management in response to the increasing interference consists only in attempts for a compensatory rising of the output power. As a result, it can be observed exponential increasing of the interference and possibilities for blocking of the system. In industrial networks blocking is unacceptable and therefore, this type of control is considered as not applicable.

Another scenario is related with the inability for achieving balance, despite the possibilities of the system not only to increase the capacity of certain subscribers, but also to suppress those that generate excessive interference. Private case of this scenario can be observed on Figure 11.

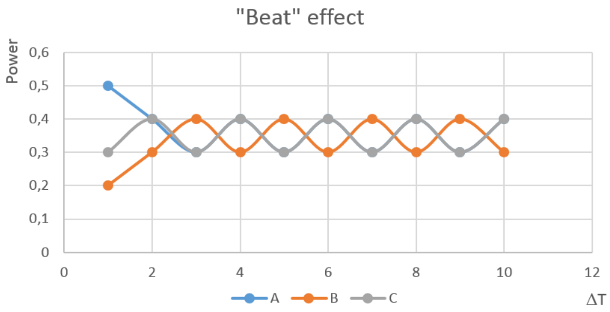


FIGURE 11 Inability to achieve balance

The figure shows pulse of power for the separate access points, two of which are in equilibrium with respect to each other (A and C), but the third is always unbalanced in relation to them (B).

The reasons this type of scenario to happen are limited mostly to incorrect selection of the length of a time slot ΔT.

At equilibrium (Figure 12) for the system shown on Figure 6, if we do not take into account external interferences and influences of the environment, the transmitted power from all three zones must be the same. The reason is that the access points are at the same distance and angle to each other.

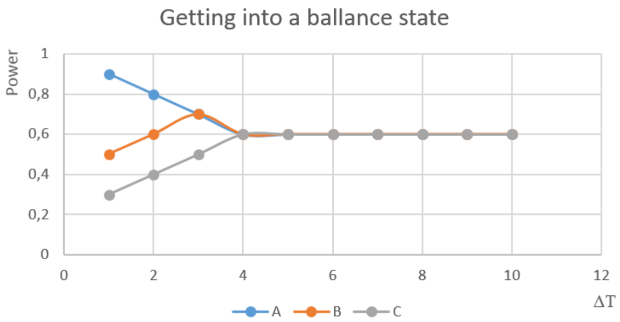


FIGURE 12 Achieving balance

In this situation, the balance vector $I_{ABC}=0$ and the access points share equal the negative interference impact. The usage of the equilibrium vector model aims exactly such a situation.

## 8 An example of using the equilibrium vector model. Results obtained

The approach explained above, can be used for analysis of a particular example of wireless industrial network. The actual location of end devices of this example is depicted on Figure 13.

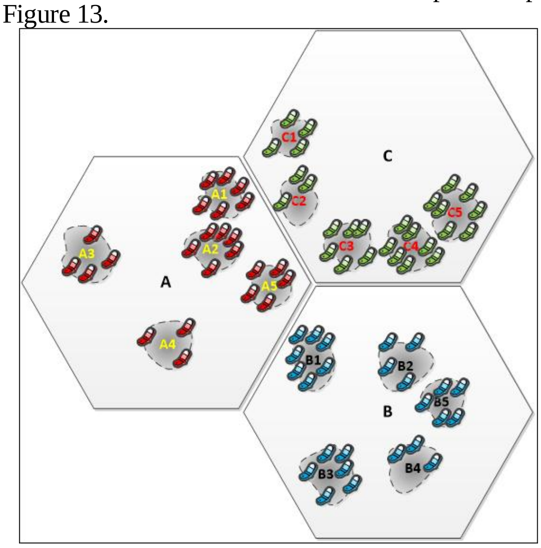


FIGURE 13 Placement of the end users in three separate areas at high density industrial network

Although, the end subscribers in the example are of different types (sensors and actuators), for the analyses purposes, they are drawn the same way and only their color is different according to their belonging to a specific cell. The individual subscribers are grouped in a subgroups depending on their location in the cell (zone). The explanation of the figure is represented in a data form on Table 1.

TABLE 1

| | A | B | C | Users in a Subgr. | | |
|---|---|---|---|---|---|---|
| | **X** | | | | **{GGIP}AB** | **{GGIP}AC** |
| A1 | **308** | 780 | 470 | 6 | **948** | **1573** |
| A2 | **148** | 618 | 563 | 6 | **575** | **631** |
| A3 | **228** | 935 | 917 | 4 | **390** | **398** |
| A4 | **210** | 680 | 812 | 3 | **371** | **310** |
| A5 | **294** | 480 | 458 | 5 | **1225** | **1284** |
| | | **X** | | | **{GGIP}BA** | **{GGIP}BC** |
| B1 | 451 | 266 | 624 | 7 | **1651** | **1194** |
| B2 | 737 | 158 | 561 | 4 | **343** | **451** |
| B3 | 676 | 211 | 881 | 6 | **749** | **575** |
| B4 | 878 | 166 | 853 | 3 | **227** | **234** |
| B5 | 826 | 162 | 667 | 5 | **392** | **486** |
| | | | **X** | | **{GGIP}CA** | **{GGIP}CB** |
| C1 | 536 | 854 | 283 | 4 | **845** | **530** |
| C2 | 438 | 627 | 270 | 3 | **740** | **517** |
| C3 | 530 | 471 | 269 | 6 | **1218** | **1371** |
| C4 | 727 | 471 | 255 | 7 | **982** | **1516** |
| C5 | 844 | 595 | 240 | 7 | **796** | **1129** |

The values in columns A, B and C represent the distances between the concrete subscriber groups and access points in the adjacent zones. In the both columns on the right is calculated the impact of every subgroup over the other cells. Visually represented, the results will look the following way:

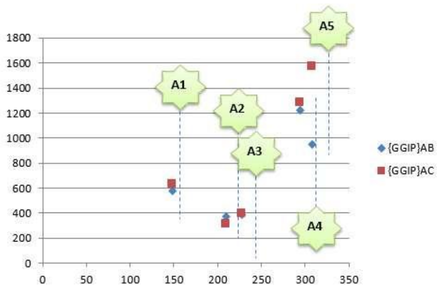


FIGURE 14 Influence of subgroups of zone A to the other subgroups

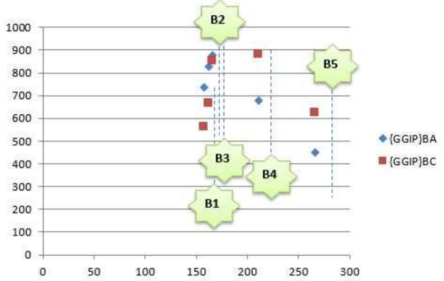


FIGURE 15 Influence of subgroups of zone B to the other subgroups

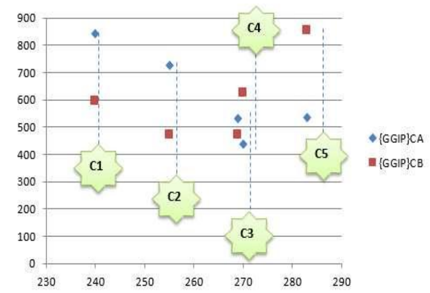


FIGURE 16 Influence of subgroups of zone C to the other subgroups

## 9 Conclusion

The analysis of the obtained results proves that every sub-group of subscribers generates higher interferences to the neighboring cells, when is situated on a maximum distance from its own base point (access point) and at the same time is maximum close to any of the neighbor access points.

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