Review of Some Fundamental Approaches for Power Control in Wireless Networks

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Abstract— An advanced tutorial on power control issues in wireless networks is provided, covering work published since circa 1992, the beginning of the systematic study of the area, to this date. We present and comment on what we consider are the most fundamental contributions in the area pointing out relationships and differences in approaches and their consequences and applicability. We consider wireless networks as collections of directly interfering wireless links. I.e., we consider single hop configurations, but we do not assume that there necessarily is centralized control, or a single common goal for the network. We explicitly deal with voice and "data" networks, which have differences in perspective that lead to different methodologies.

Index Terms— SIR balancing, power and admission control, base station assignment, wireless cellular networks.

I. INTRODUCTION

POWER control was, is and (we strongly believe that it) will remain one of the most important radio resource management techniques in wireless networks, as it mitigates the consequences of two fundamental limitations of wireless networks:

- Radio spectrum, though non exhaustible, is both a limited and–often–underutilized resource. This makes interference and interference mitigation critically important for wireless networks.
- Mobile wireless devices, such as mobile phones, Personal Digital Assistants (PDAs) etc., have significant limitations on the duration of their "talk time," as the "life" of their battery is limited. As technology improvements in the direction of prolonging battery life are slower than advances in communications, this constraint continues to have dramatic impact, particularly for uplink transmissions (from mobile nodes to base stations).

Applying transmitter power control (i.e., controlling the transmission power so as to achieve high performance–we shall explicitly specify what "high performance" stands for later) is a classical and widely adopted practice. The reasons for that are the following: Firstly, the results from the adoption of power control algorithms so as to mitigate the interference and increase the network capacity are very promising. Secondly, as power control is incorporated in widely used standards (e.g., Code Division Multiple Access-CDMA), efficient performance evaluation of proposed schemes is feasible. Last but not least, power control is smoothly combined with other interference mitigation techniques (such as channel assignment and directional antennas).

Though the quantitative analysis of the benefits from the adoption of power control techniques needs to be done carefully because the results are impacted by the assumptions of each proposed methodology and the studied environment, we would like to briefly present some illustrative statistics. For example, it was shown early on that applying power control doubles the capacity of a CDMA system compared to the non-power control case [1]. Further improvement (up to 50%) can be achieved by suitably adjusting the update rate of a power control algorithm [2]. More recent studies by Olama *et al.* [3] estimated that the signal-to-interference plus noise ratio (SINR) gains from the adoption of power control exceed 10 dB compared to a non-power control policy, for various interesting values of the outage probability (i.e., the probability a link to achieve SINR lower than a threshold required for communication). This result is similar to early findings on the advantages of using power control in TDMA/ FDMA networks [4]. Moreover, the combination of power control with base station assignment (and beamforming) increases two to four times the capacity of a CDMA network, compared to one that uses only power control techniques [5]. As far as the energy consumption or battery lifetime is concerned, studies show that power control offers a significant improvement (orders of magnitude) compared to the constant power approach. The exact value of the gain is strongly dependent on the transmission rate [6]. For Mobile Ad Hoc NETworks (MANETs), the adoption of power control leads to an over 50% improvement to the energy expended compared to the standard IEEE 802.11 [7]. However, after having presented this set of promising data, in this paper we will focus mostly on the qualitative aspects of the analyses rather than precise results for specific environments.

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The motivation for this advanced tutorial paper is threefold: a) to provide a taxonomy of approaches to power control in cellular networks into some fundamental subareas, b) to review and comment on some key power control approaches, and c) to provide inter-area and intra-area comparisons. We characterize this paper as an advanced tutorial because we believe that it will not only be useful to new researchers getting into this area, but will also serve to clear some slight (historical) misconceptions and solidify the past important contributions at a point in time where it seems that significant understanding of the area has been achieved. Note that we do not intend to provide a full traditional survey of the area (we would have to refer to hundreds of papers), but we restrict our attention to what we consider the seminal and most influential papers in the area. For the papers we cite we try to present briefly, but we hope completely, the important and lasting contributions to the area and we try to justify our selection and views.

We focus our discussion on cellular networks, as this is the type of wireless networks considered in the majority of power control schemes in the literature (and also the type with the most significant commercial and societal impact at present) and in order to limit the length of the paper. We also claim that this has no negative impact on the study of the development of this area and even its future development. However, we do mention and discuss issues and applications in other modern networks. Our discussion covers power control papers in cellular networks since 1992, when the area started to develop in a systematic way.[2] Additional, alternative efforts should be considered for less traditional environments, such as Mobile Ad hoc NETworks (MANETs), Wireless Local Area Networks (WLANs) based on Wi-Fi technology and Cognitive Radio Networks.

The remainder of this paper is organized as follows: A discussion about the need for a tutorial or survey paper in this (now rather traditional) area, outlining some previous works and our differences from them is presented in section II. A mini tutorial on the fundamental metrics of power control schemes, along with the notation that will be used in this paper is provided in section III. The central taxonomy of power control techniques is presented and discussed in section IV. Power control in voice networks where noise is not considered is discussed in section V. A taxonomy of power control approaches in noisy voice networks is given in section VI. Power control in data networks is analyzed in section VII. A discussion on some approaches on power control in modern types of cellular networks is provided in section VIII. Some directions for future research are suggested and discussed in section IX and the main conclusions from this work are presented in section X.

II. WHY A(NOTHER) SURVEY/ TUTORIAL PAPER ON POWER CONTROL

As we mentioned in the introduction, the goal of this article is not to provide an exhaustive list of references in each subarea of power control (even for just cellular networks). We decided to keep the references to a minimum, by choosing to present only some of the most cited articles that influenced to a great extent the evolution of this area. Our fundamental goals are the following:

- To present the "big picture" of this research area by classifying the pivotal works into its main research subareas.
- To discuss in fair depth these selected references that define these subareas.
- To compare point-by-point the papers in these subareas by defining some key characteristics for each subarea and by examining with which of these defining characteristics or constraints each methodology is compatible.
- To discuss some aspects of research in this area that should be given further attention.

Throughout the last two decades that power control in cellular networks has been studied, there were papers surveying the area. In our opinion, three are the most important ones. In 1998, Nicholas Bambos, one of the pioneers of this research field, provided an excellent overview [10] focusing mostly on his own previous work. Consequently, except for a couple of papers of other researchers (i.e., [9] and [11]), many interesting approaches were not analyzed in that paper. Moreover, as a decade has passed since that publication, some important modern power control ideas and techniques cannot be found in that paper. The work by Koskie and Gajic [12] is a more up-to-date attempt to survey the research area. Though a preliminary classification is presented, most of the 150 references that are cited are simply mentioned, without discussing most of them in more than a sentence. Moreover, internal taxonomies of each subarea and comparisons of the various papers are totally missing. Even more recently, Chiang *et al.* [13] presented a 170-page chapter (like a monograph) in a volume that deals with power control in cellular networks. A more detailed classification is given here and a discussion of open issues is provided. However, even though the authors had plenty of space to describe the key ideas of all the about 200 papers that they included in their reference list, they chose to discuss only a small portion of them, with focus in their own previous works. Moreover, hardly any discussion on the pros and cons of approaches in the same subarea (or between subareas) is presented.

Our paper shares eight common references with [10]. However, in practice, only [9] and [11] are fully discussed in [10] (as well as previous versions of the author's work in [14]). From the 13 common references with [12], only 3 ([4], [15], [16],) are fully discussed ([8] and [9] are also analyzed–in more than a couple of sentences each–but with some shortcomings). Finally, [13] discusses 13 common papers with us. However, only [5], [16], [17] and [18] are completely thrashed out. Five more references ([4], [9], [10], [14] and [19]) are covered at fair depth, but their analysis lacks in some points.

From the above, it is obvious that a paper that presents a comprehensive description of some classical and modern

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[2] 1992 is the year the two seminal papers and by Zander have been published and in 1993 the area shaping paper by Foschini and Miljanic appeared. Before that, some very preliminary ideas were presented in papers in the 70's and 80's—see references [2] and [4]-[9] of paper in our references.

power control approaches in cellular networks, commenting on the lessons learnt and providing some directions for further study is missing. Especially Ph.D. students may significantly benefit from our work, as this advanced tutorial article offers an opportunity to resolve inconsistencies and discrepancies that they may have noticed reviewing the literature.

III. SOME FUNDAMENTAL NOTIONS

Before starting the review of our papers, we would like to clarify some important points. Power control is generally adopted for at least one of the following reasons: i) to mitigate the interference in order to increase the capacity of the network, ii) to conserve energy in order to prolong battery life and–nowadays–“to green” the Internet/ mobile networks, and iii) to adapt to channel variations in order to support Quality of Service (QoS). All the above are fully (or partially) correlated with the Signal to Interference (plus Noise) Ratio–SI(N)R–metric. We shall provide an example by using a wireless cellular network, however, the description stands for ad hoc network and wireless local area networks too, provided that nodes can exchange feedback messages.

Fig.1 presents a part of a single channel cellular topology with three Base Stations (BSs) and two Mobile Nodes (MNs). MN_1 is connected with BS_1 and MN_2 is connected with BS_2. We only present and discuss the downlink case (transmission from BSs to MNs)–the uplink is similar. As the same channel is used for the transmission of all BSs considered, the signal, for example from BS_1 to MN_1 interferes with the signals from BS_2 and BS_3 to MN_1. This is depicted in the definition of SINR (we use SINR rather than SIR, since we consider a noisy environment). The numerator expresses the MN’s received power from the BS to which it is connected, whereas the denominator is the sum of the received power from all the interfering BSs plus the noise of the channel. The coefficients G_{ij} express the link gain from BS i to MN j. In general, these coefficients belong to the range $(0,1]$ and incorporate the path loss of the power of the signal. This means that, depending on the channel conditions, the power of the signal that will be received by MN i will be 100 $(1 - G_{ij})$% smaller than the transmission power of BS i. Other phenomena such as fading or shadowing and their relevant parameters may be also expressed by these coefficients.

The higher the SI(N)R of a link, the better the quality of the signal. Let us consider a topology where all links except one transmit with a common power P, whereas that one link is allowed to use any transmission power. The SI(N)R for this link increases as this link increases its transmission power (we shall describe the process in the following paragraph). One idea for that link is to increase its power to the maximum possible level to achieve the maximum SI(N)R. However, this has the disadvantage that this link will spend much energy to achieve a quality signal which may be higher than the one that it really needs for a particular application. Consequently, it should be better for that node to increase its transmission power only up to the level needed to achieve its desired SI(N)R target. As a final note, it is worth mentioning that an increase in the transmission power does not necessarily lead to an improvement of the SI(N)R. Other nodes may also increase their transmission powers and this extra interference may lower the SI(N)R.

It is interesting to notice that each BS can change its transmission power to improve the SI(N)R that its attached MN perceives. However, this value of the SI(N)R (at the MN) is not directly known to the BS. A BS knows only its transmission power. On the other hand, the MN knows the total received power. This information may be communicated to the BS through the reverse channel. Thus, the BS can simply subtract its own contribution to the total power and compute the current value of SI(N)R. This assumes that the BS knows its link gain to the MN. If this is not the case, we can consider reciprocal systems, i.e., systems where uplink and downlink link gains coincide. Consequently, the link gain is estimated from the reverse channel too. All the above are necessary for the functioning of a power control scheme (and are always implied in the analysis of each scheme).

For generality of exposition, instead of changing the roles of transmitters and receivers to MNs and BSs in uplink and downlink, we prefer to write transmitter, receiver and link respectively. When necessary, we explicitly mention whether it is an uplink or downlink transmission.

IV. POWER CONTROL IN CELLULAR NETWORKS: THE BIG PICTURE

Fig. 2 illustrates the power control taxonomy that we are going to analyze in the following sections. The left part of Fig. 2 corresponds to power control in voice networks, where the target metric is SIR for noiseless systems (and SINR for noisy systems, respectively). For the noisy systems, we further define the following three subareas: Power Control and Base Station Assignment, Power Control and Admission Control, and Discrete Power Control. The first subarea provides room for improvement on the performances of the links, as the links are allowed to associate with different Base Stations. The second subarea deals with the interesting problem of the application of power control with a view to protecting the QoS that a link has attained. The third subarea concerns power control approaches that take into account that the transmission power levels are not continuous, but they take only discrete (predefined) values. The right part of Fig. 2 depicts power control categories in data networks, where further distinction is based on whether a cost function is used (which is introduced as a pricing mechanism), or not. Accordingly, utility based and net utility based approaches are discussed. The difference is that with the former set of schemes each link tries selfishly to maximize its own utility function without having to “pay” for the transmission power that it will choose. Apart from a thorough description of some representative papers for each subarea, we shall provide both inter-area and intra-area comparisons (power control in data networks vs. power control in voice networks, SIR based approaches vs. SINR based approaches, net utility based vs. utility based approaches). Moreover, we shall discuss some thoughts for the unification of the power control algorithms that will be suitable for both voice and data networks. This is the reason why we choose to join these rectangles with a line.

V. POWER CONTROL IN VOICE NETWORKS: NOISELESS SYSTEMS

A. Literature Review

Zander is one of the pioneers of this research area, being among the first in the early nineties that studied power control techniques in cellular networks ([4], [8]). In these successive papers, he considers a TDMA/ FDMA system where *M* links, with common SIR threshold γ^t for successful communication, share the same channel in a noiseless system. He is interested in applying transmitter power control so as to find a transmission power vector $\boldsymbol{P}^*$ (without placing a limit on the maximum power of each transmitter) that maximizes the minimum SIR of the links (in either the uplink or downlink). In [4], a centralized power control scheme is proposed. It is shown that there is a unique solution, which is always feasible and leads to SIR balancing, i.e., all links converge to the same SIR, γ^*. This SIR (γ^*) is derived from the spectral radius λ^* (i.e., the max. eigenvalue) of the normalized gain matrix *G* shown in (1); $\boldsymbol{P}^*$ is the corresponding eigenvector. Consequently, independently of the initial power vector, knowledge of all link gains is a sufficient condition to compute γ^*. Of course, an obvious drawback of this scheme is its centralized nature, because knowledge of the full link gain matrix is difficult to be achieved in practice.

$$G=\begin{Bmatrix} \dfrac{G_{ij}}{G_{ii}},\ i\neq j \\ 1,\ i=j \end{Bmatrix} \qquad \gamma^*=\frac{1}{\lambda^*-1} \tag{1}$$

In [8], a partially distributed power control scheme is proposed–see (2). Each link updates its power by taking into account its previous transmission power, its previous SIR and a positive normalization parameter, *b(k)*. It always converges to γ^* from every initial strictly positive power vector (i.e., power of each link is positive).

$$P_i(k+1)=b(k)P_i(k)(1+\frac{1}{SIR_i(k)}) \qquad b(k)=\frac{1}{\sum P_i(k)} \tag{2}$$

This synchronous (i.e., all links update concurrently their transmission power) iterative power update process is similar to the power method, fact which is not surprising, since γ^* is dependent on the maximum eigenvalue (and the power method is a classical method to compute it). Though this iterative scheme is applied autonomously from each transmitter in each time slot, it is not a fully distributed algorithm, as the normalization parameter *b(k)* (which is necessary to avoid extremely high transmit powers) demands cooperation among links in each time slot of the algorithm (as all transmission powers during the previous iteration of the algorithm should be known to each transmitter). The way to choose *b(k)* is not unique, see [20] for another choice.

Even though it is always possible to maximize the minimum SIR in each system, this γ^* may be below the target SIR γ^t which is the threshold for successful communication. In this case, all links would suffer from unacceptable performance. To combat this problem, the notion of “cell removal” is introduced [4]. The goal is to remove the best combination of cells in order to find the optimal set of links that achieves the maximum γ^* above the target SIR. As the optimal policy increases dramatically the complexity of the process, a suboptimal but faster solution is to remove in each step one cell (i.e., one transmitter–the one with the worst SIR–powers off each time, as in TDMA/ FDMA there is only one MN per channel per cell) until the remaining ones have acceptable SIRs. This process goes on until an acceptable solution is achieved. In [8], cell removal is applied if, after a predefined number of iterations, the partially distributed algorithm (2) has not converged to an acceptable solution. Then, the cell with the worst initial SIR is removed and the iterative scheme is reapplied for the *M-1* links. It is worth mentioning that, during the decision process for which cell should be removed, there is a violation of the distributed nature of the process, as cooperation among links is–again–necessary.

Both schemes proposed by Zander increase the capacity of the system, as the outage probability (i.e., the probability a link to achieve SIR lower than γ^t) is decreasing compared with non-power control policies.

In [21], Lee and Lin present a fully distributed power control scheme that leads to γ^* (3), provided that the positive constant *Y* is greater than (or equal to) γ^*. As this constant can be predetermined, it is easy to notice that no interlink communication is necessary so as to compute $\boldsymbol{P}^*$ (equivalently γ^*).

$$P_i(0)=1 \qquad P_i(k+1)=\frac{\min(SIR_i(k),Y)}{SIR_i(k)}P_i(k),\ Y>0 \tag{3}$$

However, during the cell removal phase (which is not part of the power control algorithm), the cooperation among links is inevitable, as the target is not to remove a random link (which could be done with a predefined criterion too), but the “worst” link, and this cannot be done autonomously. A plus of this synchronous iterative scheme is that a P_{max} limitation is also imposed, as power vectors cannot exceed (component-wise) the initial power vector–in that case[3] $\mathbf{P_{init}=1}$. Moreover, this scheme is faster than Zander’s distributed scheme [8], as the latter is based on the power method, whose convergence to the max. eigenvalue is–generally–slow.

Wu in [22] extends Zander’s centralized scheme [4] for CDMA. Contrary to a TDMA/ FDMA set-up, in CDMA there is only one channel that is shared by all links in each cell. So, whenever cell removal is necessary, this means that all links in that cell would power off (instead of only one in TDMA/

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[3] A vector with all its elements 1.

FDMA). Consequently, another idea should be adopted so that only a single link powers off at a time. Wu proposes a scheme that leads to a link removal, instead of a cell removal, guaranteeing that only one link powers off at a time (the one that leads to the maximum γ^* for the other *M-1* links).

In [20], Wu studies topologies where the SIR thresholds of the links are both heterogeneous and variable (for example, due to mobility or fadings). His goal is to invent centralized and distributed power control algorithms that lead to the maximum possible SIR for each link, provided that each target γ_i^t is known every time. (One way to know that in CDMA, is by considering that the outer loop control works perfectly.) He shows that there always exists a unique power vector that leads to SIR for each link i which is δ times γ_i^t. In case that $\delta \geq 1$, no link removal is needed. Otherwise, by applying the same mapping as in [22], link removal is used until an acceptable solution is found. For the distributed case, the maximum possible SIR target for each link can always be achieved by applying the partially distributed algorithm in (4). In general, the main drawback of this approach is the demand for the same δ for each link.

$$
\begin{aligned}
P_i(k+1) &= b(k)P_i(k)\frac{\gamma_i^t(k)}{SIR_i(k)} \\
b(k) &= \frac{1}{\max P_i(k)}
\end{aligned}
\qquad (4)
$$

B. *Power Control in Noiseless Systems: The Big Picture*

Table I helps us depict our taxonomy of this subarea by checking with which criteria each paper is compatible. Besides our comments on the previous paragraph, it is worth mentioning that all approaches lead to the same SIR, γ^*, for both uplink and downlink, though power vectors may differ as downlink and uplink gain matrices are generally different [20].

VI. POWER CONTROL IN VOICE NETWORKS: NOISY SYSTEMS

A. *Introduction*

In noisy systems (where the noise level v_i at each link is non zero), the normalized gain matrix cannot be applied to compute the maximum eigenvalue that maximizes the minimum SINR of each link. This is because of the noise term in the denominator of the SINR. So, the target is modified as follows: Can we find a power vector $\boldsymbol{P^t}$ (t stands for "target") so that $SINR_i \geq \gamma_i^t$ for each link i of the cellular system? (From this section on, the algorithms are applied to all multiple access schemes of cellular networks, i.e., TDMA, FDMA and CDMA.) In practice, most papers set the same γ^t for each link during the performance evaluation of their method. This is reasonable because, in voice networks (which is the traditional case), the QoS target and the need for resources are thus the same in each (voice) link.

In [9], Foschini and Miljanic were the first who answered the question: Given the common γ^t for each link and provided that a "genie" informs us that there is a feasible unknown power vector $\boldsymbol{P^t}$ that achieves this SINR target, can we find it in a fully distributed way? The answer is positive and the iterative scheme that leads to γ^t is presented in (5).

$$
\begin{aligned}
P_i(k+1) &= FP_i(k) + \eta_i, \\
F &= \begin{cases} \gamma^t \dfrac{G_{ij}}{G_{ii}}, i \neq j \\ 0, i = j \end{cases} \\
\eta_i &= \gamma^t \frac{\nu}{G_{ii}}
\end{aligned}
\qquad (5)
$$

This algorithm is fully distributed, as there is no normalization factor that demands communication (and cooperation) among links to be determined. In [10] this algorithm is further simplified to the formula of (6), which we refer to as the *simplified* Foschini-Miljanic algorithm. (Actually, this was first suggested in [6], which is referred in the additional reading section of [10].)

$$
P_i(k+1) = \gamma_i^t \frac{P_i(k)}{SINR_i(k)} \qquad (6)
$$

Though many authors refer to (6) as the Foschini-Miljanic algorithm, this is not actually the case, and leads to misunderstandings as it is not trivial to see the equivalence of (5) and (6). An obvious shortcoming in the analysis in [9] is that if γ^t is infeasible (as no "genie" informed us about its feasibility), then the powers of the transmitters diverge to infinity. So, there is no discussion about the circumstances under which their scheme converges to a feasible solution. Moreover, no P_{max} limitation is imposed. The first shortcoming is discussed by Mitra in [11]. He shows that a sufficient and necessary condition for the convergence of the power vector $\boldsymbol{P^t}$ to γ^t is for the spectral radius of matrix $\boldsymbol{F}$ in (5) to be smaller than 1. Moreover, he shows that this power vector $\boldsymbol{P^t}$ is Pareto optimal, in the sense that any power vector $\boldsymbol{P}$ that satisfies the target SINR for each link demands at least as much power for every transmitter and at least one transmitter's power to be greater. I.e., $P \geq P^t$ component-wise. Furthermore, he proposes an asynchronous (i.e., all links do not necessarily have to update their transmission power concurrently) version of the Foschini-Miljanic algorithm that satisfies the target SINR under the above mentioned condition. In [15], Grandhi, Zander and Yates incorporate a P_{max} constraint for each link and restate the simplified Foschini-Miljanic formula with a P_{max} constraint by presenting a Distributed Constrained Power Control (DCPC) scheme. Synchronous, i.e., (7), and asynchronous versions are provided.

$$
P_i(k+1) = \min\{P_{\max}, \gamma_i^t \frac{P_i(k)}{SINR_i(k)}\} \qquad (7)
$$

Moreover, the authors propose a centralized algorithm that, by iteratively increasing the target SINR, finds the maximum γ^t

that can be achieved by all links (in that case $\gamma^t=\gamma^*$). Contrary to the noiseless case, this cannot be done "on the fly," as a number of iterations are needed for the maximization of this quantity.

In [16], Yates studies the following interesting problem: If somebody devises an iterative power update scheme $P(k+1)=I(P(k))$, where $I(P)$ stands for the interference that each link must overcome, is there any way to know whether this scheme is going to converge to a power vector (if that exists) that satisfies the SINR target for each link? The answer was positive, provided that the–so called–Interference function $I(P)$ is standard, i.e., it fulfils the following properties: positivity $-I(P)>0-$, monotonicity $-P \geq P' \Rightarrow I(P) \geq I(P')-$ and scalability $-aI(P) > I(aP),\ a>1$. Yates showed that this framework holds for:

- Power Control in both the uplink and the downlink, under fixed BS assignment
- Power Control and BS Assignment in the uplink, when single channel systems are used

In the above cases, the framework is valid under very general settings, including support for P_{max}, P_{min}, or no power constraints, synchronous or even asynchronous updates, as well as for joint power control and admission control techniques. The importance of this paper is that it functions as a "convergence guarantee" for every proposed power control algorithm that is valid for that framework.

B. *Power Control in Noiseless vs. Power Control in Noisy Systems: A Comparison*

Before presenting some special power control problems in noisy systems, we would like to compare the approaches in noiseless and noisy systems under the assumption that their target SI(N)R is common for each link (which is the norm for voice networks, and this is the case in most papers that deal with power control in noisy systems). Table II helps us identify some important differences. Firstly, whereas finding γ^* is always possible, it may be unacceptable if it is below γ^t. On the other hand, γ^t is not always feasible. However, if this target is feasible, the following two properties are always true.

- $\gamma^t \leq \gamma^*$
- Both schemes ("maximize the minimum SIR" and "SINR greater or equal than a target") lead to *SI(N)R balancing*, though $\gamma^t \leq \gamma^*$

We remind the reader that in noiseless systems the goal of power control was not SIR balancing, but to maximize the minimum SIR of the links. This process led to SIR balancing. Moreover, in noisy systems with homogeneous SINR needs, the initial goal set, i.e., "SINR greater or equal than γ^t for each link," was restated as "find the minimum power vector that satisfies γ^t for each link" and, whenever a feasible solution existed, this led to the target SINR (γ^t) for each link, i.e., SINR balancing, again. We emphasize these points because some authors claim inaccurately some of the following:

- Power control in noiseless systems focused on SIR balancing, whereas in noisy systems, to achieve a SINR target. (Note that both these claims are somewhat inaccurate: For the noiseless system, the difference is that there are many power vectors that lead to SIR balancing, not only the one that maximizes the minimum SIR. For the noisy case, the target is different, as we explained above.)
- In both cases, the goal was to have SI(N)R above or equal a target value. (This was not the case in noiseless systems.)
- The goal was to satisfy SI(N)R targets *by minimizing the total power.* (This is totally inaccurate in a noiseless system. Even in a noisy system, the power vector $\boldsymbol{P}^t$ is the *smallest component-wise power vector* [11], not simply the one that minimizes the *total* power. But more importantly, minimizing the total power does not have any special meaning for the uplink since different entities are involved— except in the general "green" power sense…)

Moreover, an important difference between these two systems is that there cannot be applied admission control policies in the noiseless systems. This is due to the fact that a power control algorithm simply tries to maximize the minimum SIR of the links (and not to achieve the SIR target of a link). As this was the goal for the noiseless systems, we cannot apply an admission control policy with a view to protecting the links that have already achieved their SIR targets so as not to fall below their SIR targets. Of course, the approach of the "cell removal" that we discussed in the subsection V.A aims at finding a solution that maximizes the number of links that have achieved their SIR targets. However, this does not guarantee that a link that has achieved its SIR target will remain its target if a new link enters into the system or a link changes its transmission power. We shall discuss joint power control and admission control schemes in subsection D.

Lastly, in case that links have heterogeneous SI(N)R thresholds, power control approaches in noisy systems are more flexible compared to noiseless systems. This property is possible in the latter systems, but with the demand for the same δ for each link, as we discussed in [20].

C. *Power Control and Base Station Assignment in the Uplink*

Yates and Huang in [23] and Hanly in [19] study the joint power control and BS assignment problem for a single-channel cellular system in the uplink. They are interested in finding the optimal power vector (component-wise) that satisfies SINR constraints, provided that each MN can switch to a different BS. They independently show that, by applying the *simplified* Foschini-Miljanic formula, but allowing each MN to know the interference at each BS and to connect to the one for which the least power is needed to transmit, the algorithm converges to a unique power vector $\boldsymbol{P}^t$, provided that this is feasible. It is worth mentioning that, even though $\boldsymbol{P}^t$ is unique**,** the assignment BS-MN that leads to $\boldsymbol{P}^t$ may not be unique (for example, in case there is symmetry in the topology).

These works differ in the following points: Hanly's approach in [19] predetermine the set of BSs that each MN could connect to. This set may be adjusted dynamically throughout the process. In [23], this knowledge is not necessary. Moreover, Yates and Huang in [23] present both synchronous and asynchronous versions of their algorithm, whereas Hanly deals only with the synchronous case. Lastly, Hanly discusses the case where a MN notices rapid oscillations back and forth between two BSs and proposes a small modification of the algorithm to alleviate this phenomenon. A limitation of these works is the absence of a P_{max} constraint.

Further power control issues such as joint power control, BS assignment and beamforming, as well as downlink extensions, are discussed in [13].

D. Power Control and Admission Control

An important disadvantage of all the above mentioned power control schemes is that links suffer from fluctuations during the evolution of the power updates. In other words, there is no guarantee that when a link becomes active, i.e., its SINR is above γ_i^t, it will remain so in the following iterations of the algorithm, as new links may desire to enter the network and some active links may not be able to absorb this extra interference imposed by the newcomers. A consequence of this problem is that these power control schemes lead to the following type of error: A new link is admitted even though the new link could not safely be admitted. This is the well known dropping probability error (type I error), which is very annoying for users [24]. Let us discuss some important works that address this issue that hold for both uplink and downlink. It is worth mentioning that, as shown in Table II, admission control in SIR based schemes does not make sense.

Bambos and his colleagues [14] were the first that dealt extensively with the joint power control and admission control problem (see also [10] and references therein for their successive works). They divide links into two categories: admissible (set: A_k) and inadmissible (set: B_k). For the former, they used a modification of the *simplified* Foschini-Miljanic formula as seen in (8) with a parameter, δ, where $\delta = 1+\varepsilon,\ \varepsilon \to 0^+$:

$$P_i(k+1) = \begin{cases} \delta\gamma_i^t \dfrac{P_i(k)}{SINR_i(k)}, \text{ if i } \in \text{A}_\text{k} \\ \delta P_i(k), \text{ if i } \in \text{B}_\text{k} \end{cases} \tag{8}$$

This parameter, δ, allows each active link to set its target to $\delta\gamma_i^t$, so as to provide an ε protection margin for their communication. This scheme has this nice property for each admissible link (9):

$$SINR_i(k) \ge \gamma_t^t \Rightarrow SINR_i(k+1) \ge \gamma_t^t \tag{9}$$

Consequently, $A_k \subseteq A_{k+1}$ and $B_k \supseteq B_{k+1}$. However, in cases where a link remains inadmissible for many iterations of the algorithm, chances are that it will remain so in future iterations too. For these cases, it may be better for some links to follow a so-called voluntary drop-out policy, i.e., to power off for a while (until channel conditions change) and after some iterations of the algorithm to retry to power up. More specifically, they propose two policies: A time-out drop-out policy and a SINR saturation drop-out policy. The former dictates that if a link remains inadmissible for K iterations of the algorithm, then it will try only up to M more times–this number will grow inversely proportionally to the difference between γ_i^t and SINR(K)–to achieve its target, before powering off. The latter proposes that if the SINRs of some links do not present a significant improvement for K successive steps of the algorithm, then they flip independent coins to decide whether to power off in the next iteration of the algorithm. Again, the smaller the difference between γ_i^t and SINR(K) for a link, the higher the chance to go on updating its power.

A great advantage of the approach in [14] is that all the above mentioned approaches are fully distributed. However, in case that a P_{max} limitation exists, then some cooperation among links is considered necessary, as an already admissible link should inform the inadmissible ones to power off (forced drop-out policy) when its P_{max} constraint would be violated to remain admissible. Moreover, some cooperation is necessary to find the maximum allowable initial power that a link can transmit without "impacting" the already active links. If this does not happen, then an active link may instantaneously become inactive. Authors eloquently use the motto "once active, always active!" to describe the power update policy for these cases.

An important problem of the scheme in [14] is that it may (rarely) lead to type I errors, as a link may become admissible but its power would eventually diverge to infinity. Moreover, since a voluntary/ forced drop-out policy is used, it is possible that a link is rejected wrongly, as it could have been become eventually active (blocking probability error, or type II error). In [24], Andersin, Rosberg and Zander invent a partially distributed soft and safe (SaS) joint power control and admission control algorithm under a P_{max} constraint, which is type I and type II error free. The key idea of the algorithm is the following: Each time a new link powers up, all other transmitters scale their powers uniformly (this step demands cooperation among the links) to overcome the extra interference. If this is possible, then all links (including the not yet admitted one) apply the DCPC (with a view to finding a solution that both demands less power for at least some of the admitted links and the new link becomes admissible), with two stopping conditions:

- An admitted link becomes inadmissible or gets assigned power higher than P_{max}
- The new link becomes admissible, or its power is set higher than P_{max}

This iterative process converges to the desired solution, though this happens–in general–quite slowly. For this reason, the authors proposed a fast version of the SaS algorithm (F-SaS), where after only one iteration of the DCPC, either the new link becomes active, or it powers off. Though this version is very fast, it is only type I error free, as type II errors may arise. However, in general, blocking a new call is less annoying than dropping an ongoing call.

It is interesting to compare the main characteristics of the joint power control and admission control algorithms in [14] and [24]. Table III helps us depict them. Apart from our comments in the previous paragraphs, we would like to mention that a disadvantage in [14] is some loss of capacity due to the safety margin that is defined by parameter δ. Of course, as δ approaches 1, this capacity loss decreases. However, the smaller the δ, the more difficult is the admission of new links, as active links have a lower safety margin to tolerate extra interference. Furthermore, algorithms in [24] assume that only one link desires to power up every time (which is compatible with the Poisson assumption for arrivals made in the paper). Thus, in order to further minimize the probability of two concurrent inadmissible links, the authors use only the synchronous version of DCPC (because even though the asynchronous version of DCPC would–theoretically–fit the algorithms, it is not desirable as it increases the probability of two concurrent inadmissible links). Note that the demand for synchronous updates is also present in [14].

As a final note, recently, Gitzenis and Bambos [25] propose a variation for the power update of inadmissible links (8). By introducing some mini slot time periods as guard bands, they periodically offer the opportunity to inadmissible links to test any desired transmission power–in these mini slots–(for example, they may even decide to choose the power so that they become active in the next iteration of the algorithm). If, during that mini slot, all the active links can tolerate this extra interference, then, during the next slot of the algorithm, these links deviate from (8) and transmit with the power of the previous mini slot period. It is obvious that this process will converge faster compared to [14]. Moreover, (partially) asynchronous convergence may be achieved. However, it remains an open issue whether this scheme will prove even more beneficial if links cooperate in order to decide when each one will try to update its power to a higher level than the one that is imposed by (8). Of course, this will destroy the fully distributed notion of the algorithm, even in the unconstrained case (i.e., with no P_{max}).

E. Discrete Power Control

Apart from introducing a P_{max} constraint, a practical power control scheme should take into account the fact that transmitter power is updated only at discrete levels. This was the motivation for discrete power control algorithms ([26], [27]), a subject that has not been developed much all these years. It is worth mentioning that the following approaches are valid for both uplink and downlink. In [26], Andersin, Rosberg and Zander use the synchronous and asynchronous versions of DCPC (7) and take the ceiling or floor of the DCPC to the nearest higher or lower discrete power so as to try to satisfy the target SINR γ_i^t of each link. It is rather obvious that the floor DCPC (unless the powers are at exactly the discrete levels) leads always to a solution where no transmitter is satisfied. (We shall explain its relevance below.) On the other hand, by applying the ceiling DCPC, it is proven that convergence to a unique power vector is not guaranteed, as oscillations between power vectors may appear. Andersin *et al.* first prove that if there is a distributed discrete power control algorithm (DDPC) that leads to a feasible solution, then, there is an equally good ceiling DCPC. Then, they show that if the initial power vector is **0 / P$_{\mathbf{max}}$** (a power vector with all its elements 0 or P$_{max}$, respectively) and there exists a feasible solution, the ceiling DCPC converges to the smallest / biggest discrete power vector, respectively. In case the initial power vector is arbitrary, ceiling DCPC either oscillates in a region that is defined by the above mentioned power vectors, or it converges to one of them. But, in case that floor DCPC is applied until the oscillations start and then ceiling DCPC, this DDPC converges to the smallest power vector.

We complete the discussion of this paper by mentioning that, contrary to the case with continuous power, it is the first time that we discuss a paper where the convergence to a power vector is not guaranteed from every initial power vector. Moreover, when convergence in discrete power control is feasible, it happens faster than in the continuous case (when the stopping condition, in the continuous case, is small enough). Apparently, the outage probability is higher in the former case. Last but not least, we mention that the DCPC power vector is (component-wise) smaller than the DDPC power vector (in the extreme case, i.e., when the transmit powers are at exactly the discrete levels, these vectors coincide).

Another approach in discrete power control was presented in [27]. Sung and Wong firstly prove that if $\boldsymbol{P^t}$ converges to γ_i^t for each link**,** there exists a quantized power vector that converges to the region $\left[\delta^{-1}\gamma_i^t, \delta\gamma_i^t\right]$, where δ>1. Then, they proposed the update scheme in (10) and showed that it converges in this region, provided that this is feasible. Moreover, they incorporate an admission control scheme by showing that if $SINR_i(k) \geq \delta^{-2}\gamma_i^t$, this inequality will also hold in the following updates of the algorithm. Of course, this extra δ margin leads to some loss of capacity for the system.

$$P_i(k+1) = \begin{Bmatrix} \delta P_i(k), \text{ if } \mathrm{SINR_i}(k) < \delta^{-1}\gamma_i^t \\ \delta^{-1} P_i(k), \text{ if } \mathrm{SINR_i}(k) > \delta\gamma_i^t \\ P_i(k), \text{ otherwise} \end{Bmatrix} \tag{10}$$

Comparing the schemes in [26] and [27], we remark the following: The main advantages of DDPC [26] are the inclusion of a P_{max} constraint, as well as the possibility for asynchronous convergence. On the other hand, it is a quite complex algorithm and does not incorporate any admission control mechanism. The algorithm in [27] is simpler and permits the admission control process (sacrificing some capacity), but its performance worsens when P_{max} is taken into account. As a last note, the performance of discrete power control algorithms depends on the number of power levels. The more the power levels, the smaller is the loss of capacity, but the slower is the convergence to a power vector. The opposites hold for fewer power levels. However, the distance between two consecutive power levels should not be defined arbitrarily, but it should arise from the type of the cellular network technology that is used.

F. Power Control in Noisy Voice Systems: The Big Picture

We shall complete our analysis for this section by providing Table IV, which presents the big picture, i.e., we provide some properties and examine which of them are satisfied by the power control algorithms of the papers that we discussed. The only exception has to do with [16], as no algorithm (but a framework) was presented. It is interesting to note that paper [9] does not fit to this table because of the properties that we chose to compare these papers against. However, that paper was the basis for most of the approaches of the papers that were discussed in this section.

VII. POWER CONTROL IN DATA NETWORKS

In voice networks, the target is the maximization of the number of links that can achieve a specific SI(N)R. In data networks the target can be loosely described as the minimization of the transmission errors for each link. I.e., for a data link, in principle, there is no specific acceptable performance level, below which the link is considered useless and above which improved performance is indifferent (as in voice links), but a continuous tradeoff between achieved SI(N)R and the cost to achieve it. Thus, there is (in general) never a question whether a link should be removed from the system. Just a question of how to decide on transmission power levels to best optimize various metrics. And in this case, all the active links, if the design allows it, may exhibit selfish (rational) behavior. I.e., they may try to optimize their own performance (or utility), possibly taking into consideration potential repercussions of their actions by competing links.

Note that in the voice network case, the role of individual link consideration is almost non-existent. All (traffic loaded) links desire to be in operation and if a feasible power vector is found then all links, if seen as independent agents are as a happy as they could be. Also from a system (telecommunications operator or social welfare) perspective, this situation is the best possible. (Note that cost has not been considered here.) When a solution with all links active is not feasible, the traditional proposed approaches implicitly took an operator's (or social welfare perspective), trying to maximize the number of operating links (i.e., to minimize the links removed). There was no consideration for importance or identities of the links, *my* link vs. *your* link etc. With data links being able to operate (in principle) at all SI(N)R levels and all (loaded) links remaining in the system, the questions of independent or not agents and their goals come to the forefront. For example, a good, traditional, approach would be to take an operator's profit maximization perspective, assuming that the operator can dictate power levels. However, if the operator (e.g., through the base stations) cannot dictate power levels, but transmitters can set their transmission powers independently, then a game theoretic treatment seems more natural, with the various entities competing among themselves.

A good methodology to model and address these issues is to consider utility and cost functions. A utility function *U(.)* expresses the (dis)satisfaction of a link that utilizes system resources. In the case of power control games, the general form of a utility function is $U_i(P_i, SINR_i) = V_i(P_i, SINR_i) - C_i(P_i)$, where V(.) is a value function that expresses the value that (an owner of) a link perceives and C(.) is a cost function that expresses the resources that it has to spend to achieve this value. Adopting the standard notation in the literature of power control games, in case of a non zero cost function, $U_i(P_i, SINR_i) \equiv NU_i(P_i, SINR_i)$ and we call this quantity a *net utility* function. Otherwise (i.e., when the cost function is zero), we use the term *utility function*. We are going to present some fundamental approaches in this direction. Further material can be found in [13] (mainly in chapters 5 and 6).

A. Literature Review

In [18], Saraydar, Mandayam, and Goodman propose a utility function that approximates the number of information bits that were successfully received per Joule of energy expended (11).

$$\max_i U_i(P_i, SINR_i) = \max_i \frac{LR}{MP_i} f(SINR_i) \tag{11}$$

L is the number of information bits per frame, *M* is the total number of bits in a frame, *R* expresses the bit rate, P_i is the transmission power of each link and f(SI(N)R$_i$) is a function that approximates the probability of correct reception of a frame. They model the problem as a non-cooperative game, where each link tries selfishly to maximize its own utility function. As it is known from game theory, some questions concerning the solution of such a game arise: Has this game Nash Equilibrium (NE) solutions, i.e., a point from which no link has motivation to move, provided that all other links will not change their transmission powers? Is the NE unique? Is it an efficient solution? By solving the maximization problem in (11), we end up with (12).

$$\frac{f(SINR)}{SINR} = \frac{df(SINR)}{dSINR} \tag{12}$$

As long as each link uses the same function *f*, it is obvious that the achieved SI(N)R will be the same (and also, the maximum possible) for each link. Though this operational point was the desired target in voice networks, in data networks this NE is not efficient. This means that there is another power vector that leads to the same value of the utility function for all links and, at least for one link, there is an improvement to its utility function. In other words, it is preferable for a link to achieve a lower SI(N)R, as the value of its utility function will be higher. So, "this SI(N)R balancing" operational point is simply a local optimum of the utility function, not the global optimum one. The reason for that is the following: in voice networks, the motivation for the *simplified* Foschini-Miljanic formula was that the higher the interference a link receives, the higher the transmission power needed to overcome it. However, by applying the same policy in a data network, we do not take into account the interference that a link causes to the others (due to its transmission power so as to achieve its target SI(N)R), which is a crucial parameter for the target of the minimization of the transmission errors. For this reason, the authors introduce the concept of maximizing the net utility function, which, as we mentioned above, is defined as the difference between a utility function and a cost function (here, a linear pricing function of the transmit power) (13).

$$\begin{aligned}&\max_i NU_i(P_i, SINR_i) = \\ &\max_i \{U_i(P_i, SINR_i) - Cost_i(P_i)\} \\ &= \max_i \{U_i(P_i, SINR_i) - c_i P_i\},\ c_i > 0\end{aligned} \tag{13}$$

By applying supermodularity theory, they show that this maximization problem has many NEs and the NE with the smallest powers can be computed in a (synchronous or asynchronous) distributed way. This NE is more efficient than the one of (11), though it leads to different SI(N)Rs for each link, so it is unfair in that sense. Moreover, they find out the linear pricing coefficient *c* (provided that it is the same for each link) that leads to a max min fair distribution of the net utilities of the links. As a final note, it is worth mentioning that linear pricing is not the optimal pricing policy. However, introducing a general pricing function complicates the problem and destroys its distributed solution aspect.

Xiao, Shroff and Chong in [28] propose an alternative algorithm for the non-cooperative game in (13) by using a more natural utility function than the one in [18]. They reformulate the *simplified* Foschini-Miljanic formula as (14), where $SINR_i^+(k)$ is the target SINR that each link should achieve at each step of the algorithm (update):

$$P_i(k+1) = SINR_i^+(k)\frac{P_i(k)}{SINR_i(k)} \tag{14}$$

Contrary to the hard SINR targets that (6) imposes, this is a ‘soft’ SINR, which changes with time. It is computed by taking the inverse function of the derivative of the utility function of each link. This utility function is sigmoid, (15), with parameters α_i and β_i. By adjusting the values of these parameters, utility functions that are suitable for either data links (higher SINR target but acceptable to power off for a while), or voice links (lower SINR target but not desirable to power off even for a while) may be constructed.

$$U_i(SINR_i) = \frac{1}{1+e^{-a_i(SINR_i - \beta_i)}} \tag{15}$$

By applying Yates’ framework [16], (14) converges (synchronously or asynchronously) to a unique power vector from every initial power vector, provided that a feasible power vector exists. Lastly, the authors present even better results for the utility functions of the links by applying adaptive pricing i.e., by taking into account both the channel conditions and the distance between transmitter and receiver to decide the pricing coefficient for each link. However, a complete analysis of the optimal linear pricing policy is left as an open issue.

In [17], Leung and Sung propose the concept of opportunistic power control. This means that not only do they decrease SINR targets when channel conditions worsen (as shown in [28] too), but they also decrease their transmit powers in this case. The algorithm is depicted in (16) and converges to a unique power vector from every initial power vector, if it does converge. It is worth mentioning that this scheme may also arise from various non-cooperative game formulations, where the goal is to maximize the net utility function. An interesting property and significant advantage of this approach is that if some voice links follow (6) and can converge to a unique power vector, they can coexist without falling below the target SINR with links that follow (16).

$$\begin{aligned}&P_i(k+1) = \zeta_i \frac{SINR_i(k)}{P_i(k)} \\ &P_i(k)R_i(k) = \zeta_i \\ &R_i(k) = \frac{\sum_{j \neq i} G_{ij} P_j(k) + \eta_i}{G_{ii}}\end{aligned} \tag{16}$$

B. *Power Control in Data Networks: The Big Picture*

Table V presents a comparison of the schemes that we discussed in the previous subsection. In addition to our previous comments, we mention that the main drawback of [18] is that it is only suitable for data links. A major limitation of [28] is that no P_{max} constraint is included in the analysis. Lastly, [17] does not discuss an asynchronous version of the proposed algorithm.

VIII. Power Control in Modern Wireless Networks

In this section, we shall briefly discuss some power control approaches that focus mostly on various types of modern wireless networks using a representative paper for each type.[4]

In [29], Kawadia and Kumar propose various algorithms that focus on either maximizing the network capacity or minimizing the energy consumption of a wireless ad hoc network. They firstly present *COMPOW*, an algorithm that finds the minimum (common) transmission power that can be used by all nodes of the network so as to maximize the network capacity. This is feasible provided that the distribution of the nodes is homogeneous. If this is not the case, they propose *CLUSTERPOW*, an algorithm that dynamically creates clusters of nodes that use the same transmission power. They show that this process is optimal in terms of network capacity too. Afterwards, they focus on the energy consumption minimization, by using a variation of the Bellman-Ford Algorithm (*MINPOW*) that manages to globally minimize the total energy. Finally, authors present *LOADPOW*, a scheme that applies power control based on the network load, i.e., nodes increase their transmission power when the load is low and vice versa. We have already seen an application of this idea in [28].

It is worth mentioning that these schemes correspond to a cross-layer design, using properties of both the physical layer and the MAC layer of the IEEE 802.11 protocol. A common limitation of these ideas is the demand of synchronization

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[4] An interesting discussion of earlier papers that apply power control in the context of multihop wireless networks is presented in [30].

among links, which is both difficult to achieve and adds an overhead to each method. However, even if the implementation of many of these schemes is questionable (mainly) due to various firmware limitations, these ideas remain interesting.

In [31], Nie, Comaniciu and Agrawal deal with power control in the context of cognitive radio networks. A game theoretic model is proposed by using a utility function that takes into account both the interference that a node receives from other nodes and that it provokes to other nodes that are using the same channel. The key difference from other game theoretic works that we have discussed (e.g., [18], [28]) is that these cognitive devices are able to also adapt their transmission rate. Thus, by changing their modulation scheme, their SINR targets change too. Extensive simulations that consider power control with and without channel assignment as well as with and without power limitation are presented. They show that the joint power control and channel assignment scheme is the best policy in terms of i) throughput, ii) energy consumption and iii) fairness. However, analytical models were not developed so as to formally prove these findings.

In [32], Messier, Hartwell and Davies discuss power control in wireless sensor networks (WSNs). As it was expected, they focus on minimizing the energy consumption, which is reasonable since battery replacement is not always possible in cases where sensors are found in remote places. They present a cross-layer approach (extending many previous works) that takes into account link and physical layer. The goal is to minimize the energy that is spent per symbol transmitted at both the physical layer and at the link layer (due to potential retransmissions of the frames). Further work on reducing the complexity of the scheme is needed to ease adoption and facilitate its implementation. Moreover, the demand for synchronous nodes is a disadvantage which should be treated carefully. A framework similar to Yates' seminal paper [16] would be very useful.

Lastly, in [33], Morreno, Mittal, Santi and Hartenstein apply power control in the context of Vehicular Ad Hoc Networks (VANETs). They present a power control scheme with a view to increasing vehicular traffic safety. Messages that a VANET vehicle may send belong into two categories: i) some periodic messages that transfer standard information and are transmitted by all vehicles and ii) some safety-critical messages that are transmitted only when some emergency arises. The latter have higher priority and are transmitted by higher power (when necessary). Thus, channel saturation for priority messages due to the transmission of periodic messages is avoided. Moreover, their scheme considers fairness in the sense that it maximizes the minimum power used for the transmission of periodic messages by all the nodes of the vehicular network. It is quite interesting that this conception is similar to the key idea of Zander's early works ([4], [8]), though VANETs do not share many similarities with cellular networks. Fairness is achieved provided that there is perfect communication among all the interfering nodes. This is quite unrealistic for a VANET as nodes change position rapidly. However, simulations have shown that the results are close to the theoretical ones.

Table VI summarizes this section, depicting which of the following key characteristics apply to each of the papers that we have discussed.

IX. FUTURE DIRECTIONS

We select and discuss here some aspects that we consider important and that could be given more emphasis in this research area. Even though power control techniques for voice and data networks have evolved mostly independently, it would be very useful to combine them. This is because SI(N)R based approaches are simpler, but they demand hard SI(N)R targets and cannot incorporate other than SI(N)R metrics, whereas (net) utility based approaches are more complex, but they provide soft SI(N)R thresholds and take into account the transmit power or energy expended. Note that Internet style multimedia communication (including VoIP) are adaptive and can operate at various quality (and thus SI(N)R levels) and are becoming more and more prevalent. (For LTE–Long Term Evolution–Systems, it seems that all voice will be VoIP based with the data networks approaches above becoming more relevant and the voice network approaches becoming less–directly–applicable and less relevant.)

In [34], Yolken and Bambos pose the following interesting problem: Under which circumstances, does the non-cooperative power control game in (13) lead to a NE that coincides with the result from the *simplified* Foschini-Miljanic formula with a P_{max} constraint? They show that if the utility function follows the form (17)–which is widely used, see [13]–and the $\boldsymbol{P}^t$ vector satisfies (18), then (13) has a unique NE that could be derived through (6).

$$U_i(SINR_i) = \begin{cases} u_i \ln(SINR_i + 1), SINR_i < \gamma_i^t \\ u_i \ln(\gamma_i^t + 1), SINR_i \ge \gamma_i^t \end{cases}, u_i > 0 \tag{17}$$

$$\frac{U_i'(\gamma_i^t)\gamma_i^t}{P_i^t} \ge c_i, \forall i \tag{18}$$

Furthermore, the maximum value that each linear pricing coefficient c_i should take so that the NE coincides with *simplified* Foschini-Miljanic power vector is given by (19). This preliminary work constitutes an example for the integration of power control schemes in voice and data networks. This is a matter that demands further attention, as it leads to solutions that combine the simplicity of the fully distributed schemes of the voice networks with the powerful extensions of the non-cooperative game formulations that appeared for data networks.

$$c_{i\max} = \frac{u_i \gamma_i^t}{(\gamma_i^t + 1)P_i^t} \tag{19}$$

Until now, we discussed approaches where links (i.e., their users) have no choice, or are willing to follow any given algorithm adopted by a network (operator?). Even in non-cooperative formulations that we presented, cooperation at that level was always implied. However, consider a dynamic environment where links may not follow a given algorithm, as there is a (possibly dynamic) set of algorithms from which each link can freely choose one to update its power (at each opportunity).

Providing incentives to a link to either notify other links with which it interferes about its policy, or to convince it to change its policy in cases where this may be beneficial to other interfering links (including possibly itself) is a very timely research issue that has not received much attention yet. In the general case this would lead to mechanism design.

We can also consider more complex cases where links may even deviate from the set of the predefined policies. Consequently, the target is not only to find the optimal power control policy for each link, but also to provide the incentives to the links to follow it (incentive based power control). It will be interesting to compare the performance of these heterogeneous strategies (many algorithms to choose per link, each time) with the current homogeneous policies (one algorithm per link each time). Note that this idea is related to the "freedom" to select the transmission power that was discussed in [25].

Another topic that demands further attention is the case of the infeasible topologies, where it is impossible for all the links to achieve their SINR targets (simultaneously). Fig. 3 depicts the performance evaluation of the simulation of the *simplified* Foschini-Miljanic algorithm with a P_{max} constraint for small topologies with uniformly distributed voice links (SINR targets of each link were set from 12 to 15 dB). Even for these small topologies (which of course are not a representative), it is quite often that an inefficient state arises (grey column).

Knowing that it is impossible for the N links of the topology to achieve simultaneously their SINR targets, we should alter the goal to satisfy the SINR targets for $N-1$ (or fewer) links. An obvious solution towards that direction is to follow a policy similar to the "cell removal" one that was discussed in [4] so as to choose a link to power off (using a predefined criterion), hoping that this will help some of the other inadmissible links to achieve their SINR targets. However, as mentioned above, this case implies that links are obliged to power on/ off based on the instructions of an external entity. In practice, this is quite unrealistic (in many situations).

In [35], Douros, Polyzos and Toumpis discuss a heuristic approach focusing on the integration of the *simplified* Foschini-Miljanic algorithm with a P_{max} constraint with a bargaining-inspired phase, the so-called Bargaining Foschini-Miljanic (*BFM*) algorithm. With *BFM*, all nodes are endowed with an initial budget and after a FM phase, a pair of unsatisfied nodes (i.e., nodes that have not achieved their SINR targets) start to negotiate for the level of their transmission powers; if a negotiation leads to an agreement, a node gives some (predefined) reward to the other and the latter reduces its power to the agreed level and the process is then repeated, using the updated budgets. Simulations that compare *BFM* with the previously developed approach, where the weakest node is forced to power off completely [4], show that *BFM* finds an equal number of solutions, however it is more fair, flexible, and more realistic in modern (less rigid) environments. Further work in this subarea could include the formulation of this problem as a game with a view to finding out a NE.

Moreover, as we discussed in section VI discrete power control algorithms should be further developed. Recently, Altman et al. in [36] consider a set of N MNs and a single BS. Each MN may transmit at multiple channels, but has a constraint on the average power consumption. They propose a centralized approach where the BS assigns the transmission power levels to the MNs in order to maximize the total throughput of the system. They also propose a distributed approach where each MN chooses on its own its transmission power and the target is either to maximize the total throughput (in a cooperative setting), or for each MN to maximize its transmission rate (in a non cooperative setting). They finally examine the robustness of the system with the presence of malicious nodes. Though the performance evaluation is mostly based on numerical examples and proofs on the convergence of the proposed approaches are missing, the ideas remain very interesting. Consequently, the above discussed items could be analyzed further along with extensions that cover the downlink case, as well as the case where many BSs are considered.

Finally, it is worth mentioning that, even though power control is implemented in the core of the 3G/ 4G technology (e.g., a detailed description is provided in [13]–mainly in chapter 10), this is not so much the case currently for IEEE 802.11 networks, as the hardware and wireless driver support is very limited in most cases. IEEE 802.11h supports transmitter power control, but it is not yet supported by the bulk of the current wireless cards [37]. Wide industry adoption of power control for Wi-Fi technology remains an open issue.

X. CONCLUSIONS

This paper provided an overview of the evolution of power control in wireless networks. We briefly discussed the advantages from the adoption of power control techniques and explained the basic mechanisms for an efficient power control scheme. By reviewing some fundamental papers in the area, we presented their advantages and disadvantages, as well as their major contributions to the field. We believe that in this way we contributed a view of the big picture for the subareas that we discussed, including some important aspects of power control algorithms that could accelerate the deep familiarization of young researchers with the area. Moreover, we explained the differences in approaches between different subareas and pointed out some important research directions that could be further pursued.

As a final conclusion, we noted that the tremendous evolution of cellular systems had direct impact to the objectives and the complexity of the power control schemes. An ideal power control scheme should satisfy the following key characteristics: simplicity, efficiency, flexibility, scalability, and instantaneous or online operation (fast convergence). Unfortunately, these demands are counterbalancing; for example, a very simple algorithm such as the *simplified* Foschini-Miljianic is not suitable for current

3G data networks. All these tradeoffs should be taken into account for the choice of power control algorithms.

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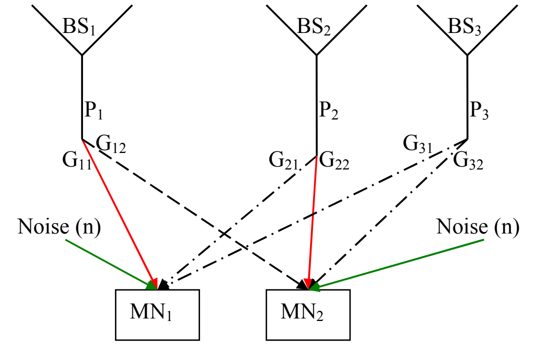

$$SINR_{1->1} = \frac{G_{11}P_1}{G_{21}P_2 + G_{31}P_3 + n} \qquad SINR_{2->2} = \frac{G_{22}P_2}{G_{12}P_1 + G_{32}P_3 + n}$$

Fig.1: Part of the downlink transmission in a single channel cellular topology. SINR definitions at receivers are also presented

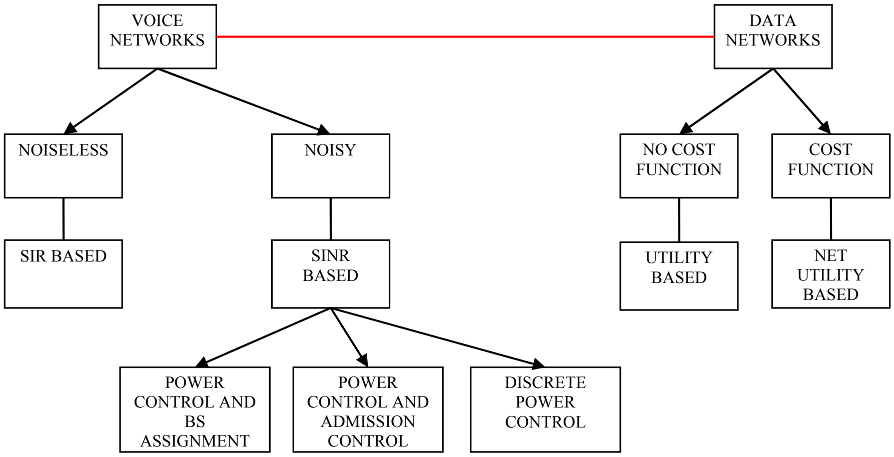

Fig. 2: A Taxonomy of Power Control Approaches in Cellular Networks

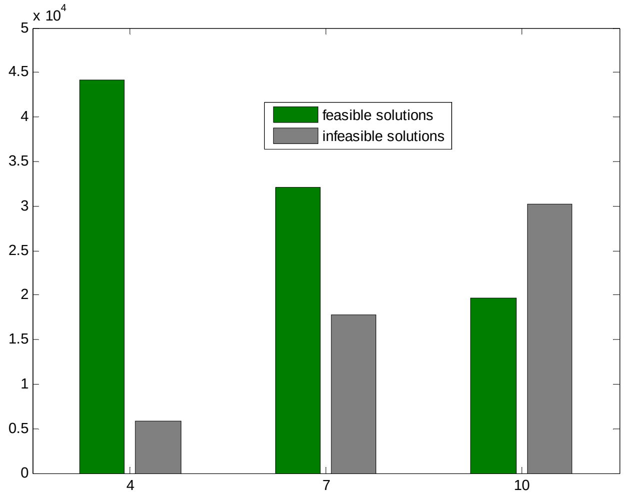

Fig. 3: Performance evaluation of the *simplified* Foschini-Miljanic algorithm with a P_{max} constraint**. Horizontal axis depicts the number of the links of the topology (4, 7, 10). Vertical axis represents the number of experiments that executed for each topology (50000). Green columns depict the number of cases where the topology led to a feasible solution, whereas grey columns depict the number of topologies where no feasible solutions exist.**

TABLE I: A CLASSIFICATION OF POWER CONTROL APPROACHES IN NOISELESS VOICE SYSTEMS

Target / Paper	TDMA/ FDMA	CDMA	Uplink and Downlink	Centralized	Partially distributed	Fully distributed	P_{max}	Hetero-geneous SIR thresholds γ_i^t
Zander ’92 [4]	✓	only in theory	✓	✓				
Zander ’92 [8]	✓	only in theory	✓		✓			
Lee & Lin ’96 [21]	✓	only in theory	✓			✓	✓	
Wu ’99 [22]	✓	✓	✓	✓				
Wu ’00 [20]	✓	✓	✓	✓	✓			✓

TABLE II: SIR BASED SYSTEMS VS. SINR BASED SYSTEMS (SINR Target γ^t is considered common for all links)

	NOISELESS SYSTEMS	NOISY SYSTEMS
Target	MaxMin SIR (noted as γ^*)	$SINR \geq \gamma^t$ (common for each link)
Feasibility of the Target	Always feasible (but maybe $\gamma^* < \gamma^t$)	Not always feasible
Admission Control	Impossible	Possible
Centralized	✓	✓
Fully Distributed	✓	✓

TABLE III: JOINT POWER CONTROL AND ADMISSION CONTROL SCHEMES: A COMPARISON

	Bambos *et al.,* 2000 [14]	Andersin *et al.,* 1997 [24]
Type I and II Error Free		✓ (only SaS)
Type I Errors	✓ (very rare)	
Type II Errors	✓ (voluntary Drop-Out)	✓ (only F-SaS)
Fast Convergence	✓ (forced/ voluntary Drop-Out)	✓ (only F-SaS)
Loss of Capacity	✓	
Fully Distributed	✓ (if no P_{max} constraint)	
One Inactive User per Time Update		✓ (necessary)
Synchronous Updates	✓	✓

Table IV: A Taxonomy of Power Control Papers in Noisy Voice Systems

Target / Paper	P_{max}	Power Control & Admission Control	Power Control & BS Assignment	Discrete Powers	Asynchronous Version	Type of Approach
Andersin et al. ’97 [24]	✓	✓			Only in theory	Partially Distributed
Andersin et al. ’98 [26]	✓			✓	✓	Fully Distributed
Bambos et al. ’00 [14]	✓	✓				Fully Distributed (if no P_{max} constraint)
Foschini and Miljanic ’93 [9]						Fully Distributed
Gitzenis and Bambos ’08 [25]	✓	✓			Partially	Partially Distributed
Grandhi et al. ’94 [15]	✓				✓	Fully Distributed (but also proposed a centralized scheme)
Hanly ’95 [19]			✓			Fully Distributed
Mitra ’93 [11]					✓	Fully Distributed
Sung and Wong ’99 [27]	Partially	✓		✓		Fully Distributed
Yates and Huang ’95 [23]			✓		✓	Fully Distributed
Yates ’95 [16]	✓	✓	✓		✓	No algorithm proposed

Table V: A Taxonomy of Power Control Papers in Data Networks

Target / Paper	maxU	maxNU	Voice Links and Data Links Coexistence	Asynchronous Version	P_{max}
Saraydar et al. ‘02 [18]	✓	✓		✓	✓
Xiao et al. ‘03 [28]		✓	✓	✓	
Leung and Sung ‘06 [17]		✓	✓		✓

Table VI: A Taxonomy of Power Control Papers in Modern Wireless Networks

Target / Paper	Max Network Capacity	Min Energy Consumption	Fairness	Congestion/ Load Control	Power Control & Channel Assignment
Kawadia and Kumar ’05 [29]	✓	✓		✓	

Nie et al. ’06 [31]	✓	✓	✓		✓
Messier et al. ’08 [32]		✓			
Morreno et al. ’09 [33]			✓	✓	