ADMISSION CONTROL FOR AUTONOMOUS WIRELESS LINKS WITH POWER CONSTRAINTS

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ABSTRACT
An admission control algorithm for power-controlled wireless networks, proposed previously for the case of linear interference functions, is considered in this paper. We analyze the properties of the algorithm using the framework of standard interference functions, which makes it applicable to many system designs. Furthermore, we introduce individual power constraints into the system. The key property of the algorithm is the protection of active users, which guarantees that as new users attempt to join the network, the quality of the established links is sustained. We present conditions under which this key property is preserved under power constraints and analyze the convergence properties of the scheme.

Index Terms— Admission control, power control, interference functions, cognitive radio

1. INTRODUCTION
In this paper we address the problem of admission control in power-controlled decentralized wireless networks, in which the quality of service (QoS) requirements are expressed in terms of the signal-to-interference ratio (SIR). We analyze the admission control algorithm proposed previously in [1] for the case of linear interference functions. The algorithm was designed to maintain the SIR of the operational (active) links above some given threshold at all times. In previous work [2] we showed that the considered algorithm preserves the protection property under any standard interference function. In this work, we introduce individual power constraints into the system and derive conditions under which the protection of active users is maintained. In particular, we prove a sufficient condition for the protection property to hold at all times. Alternatively, if the protection cannot be guaranteed at all times, we design a transmission scheme in which active users broadcast a so-called distress signal whenever their SIR requirements could potentially be violated. We further show sufficient conditions for the distress signal to be broadcast only finitely long which results in all users being admitted in finite time.

The introduction of power constraints is of high significance for the applicability of the scheme in practice. On the other hand, the protection property is also highly relevant in the context of cognitive radio, where the fundamental premise is that secondary users may be granted channel access only if it does not cause disturbance to primary users. The considered algorithm may be thus applicable to some cognitive radio networks.

Most proofs in the paper are omitted for space reasons, sketches of proofs are provided instead. Full proofs can be found in [3].

2. SYSTEM MODEL, ASSUMPTIONS AND DEFINITIONS
We consider an arbitrary power controlled wireless network with $K$ (logical) links that are referred to as users. Let $\mathcal{K} := \{1, \ldots, K\}$ and let $\mathbf{p} = (p_1, \ldots, p_K) \geq 0$ be the power vector (allocation), whose $k$th coordinate is transmit power of user $k$ at some time instant. Power constraint on the links are taken into account by additionally assuming that $\mathbf{p} \in \mathbb{P}$, where $\mathbb{P} \subset \mathbb{R}_+^K$ is a compact and convex set with $0 \in \mathbb{P}$. For simplicity, we consider individual power constraints on each link so that $\mathbb{P} = \{\mathbf{p} \in \mathbb{R}_+^K : \forall k \in \mathcal{K} : p_k \leq \bar{p}_k\}$ for some given $\bar{\mathbf{p}} := (\bar{p}_1, \ldots, \bar{p}_K) > 0$. In this paper, we assume that the wireless channel is arbitrary (chosen randomly) but fixed. This is a reasonable assumption for a broad class of networks in which channels vary slowly so that optimization algorithms need significantly less time than the coherence time. The performance measure of interest is the signal-to-interference ratio (SIR), which is defined to be

$$\text{SIR}_k(\mathbf{p}) = \frac{p_k}{\text{I}_k(\mathbf{p})} \geq 0.$$  

Here and hereafter, $I_k : \mathbb{R}_+^K \to \mathbb{R}_+$ is any standard interference function that fulfills the following axioms:

**Definition 1** (Standard Interference Function [4]). We say that $I_k : \mathbb{R}_+^K \to \mathbb{R}, k \in \mathcal{K}$, is a standard interference function if each of the following holds.

A1 \quad I_k(\mathbf{p}) > 0 \text{ for all } \mathbf{p} \geq 0 \text{ (positivity)}.

A2 \quad I_k(\mu \mathbf{p}) < \mu I_k(\mathbf{p}) \text{ for any } \mathbf{p} \geq 0 \text{ and } \mu > 1 \text{ (scalability)}.

A3 \quad I_k(\mathbf{p}^{(1)}) \geq I_k(\mathbf{p}^{(2)}) \text{ if } \mathbf{p}^{(1)} \geq \mathbf{p}^{(2)} \text{ (monotonicity)}.

The framework of standard interference functions can be used to describe many system designs. An important example of a standard interference function is the linear (affine) interference function assumed in [5, 1] and given by

$$I_k(\mathbf{p}) = (\mathbf{V}_k \mathbf{p} + \mathbf{z}_k) = \sum_{i \in \mathcal{K}} v_{k,i}(p_i) + z_k. \quad (1)$$

Here, $\mathbf{V} = (v_{k,i})$ is the so-called gain matrix, $v_{k,i} \geq 0$ with $v_{k,k} = 0$ are (effective) power gains determined by the transceiver structure, wireless fading channel etc, and $\mathbf{z} = (z_1, \ldots, z_K) > 0$ is the noise vector. Note that $v_{k,i} = V_{k,i}/V_k \geq 0$, where $V_k > 0$ is the signal power gain and $V_{k,i}$ denotes the interference power gain, is independent of the power allocation.

Other important examples of receiver designs which are captured by standard interference functions include optimal linear receivers (in the sense of maximizing the SIR) or linear successive interference cancellation receivers. For more details we refer to e.g. [4] or [2].
Let \( I(p) = (I_1(p), \ldots, I_K(p)) \). This vector-valued interference function is referred to as standard if \( I_k \) for each \( k \) is a standard interference function. At this point we recall a useful result from \cite{2}:

**Proposition 1.** Let \( I : \mathbb{R}_+^K \to \mathbb{R}_+^K \) be a standard interference function. Then, \( I \) is component-wise continuous.

Let \( \gamma_k \geq 0 \) be the SIR target of user \( k \) in the sense that this user is satisfied with the quality-of-service provided by the network if \( \text{SIR}_k(p) \geq \gamma_k \) for some power vector \( p \). If this holds for every user, then the power allocation is also said to be valid. We define also \( J(p) := (J_1(p), \ldots, J_K(p)) = (\gamma_1 I_1(p), \ldots, \gamma_K I_K(p)) \).

### 3. POWER CONTROL WITH ACTIVE LINK PROTECTION

Let \( n \in \mathbb{N} \) be a time index and let \( A_n = \{ k \in K : \text{SIR}_k(n) \geq \gamma_k \} \) be the index set of users that satisfy their SIR targets at time \( n \). Furthermore, we define \( B_n = K \setminus A_n \). We say that user \( k \) is active at time \( n \) if \( k \in A_n \). Otherwise, it is said to be inactive. Each inactive user aims at becoming an active one. The core of the admission control problem is thus the design of a suitable power control algorithm which will provide means for inactive users to join the network. Without loss of generality, it is assumed that \( A_0 = \{1, \ldots, M_0\} \) and \( B_0 = \{M_0 + 1, \ldots, K\} \) for some \( 1 \leq M_0 < K \).

#### 3.1. Summary of the case of unconstrained transmit powers

In previous work \cite{2} we analyzed the case of unconstrained transmit powers, and in this section we summarize the most important results. The end of the section it is therefore assumed that any \( p \in \mathbb{R}_+^K \) is a feasible power allocation. Under this assumption, the following admission control algorithm with active link protection (ALP) for power-controlled networks \cite{1} was considered:

\[
    p_k(n + 1) = \begin{cases} 
    \delta \gamma_k I_k(p(n)) & k \in A_n \\
    \delta p_k(n) + \delta^n p_k(0) & k \in B_n 
    \end{cases}
\]  

(2)

where \( \delta \in (1, \infty) \) is some given constant, \( I_k \) is any standard interference function (according to Definition 1) and \( p_k(0) > 0 \) is arbitrary for each \( k \in B_0 \). As \( k \in A_n \), if and only if \( p_k(n) \geq \gamma_k I_k(p(n)) \), the iteration (2) can be equivalently written as

\[
    p(n + 1) = \delta T(p(n))
\]  

(3)

where \( T = (T_1, \ldots, T_K) : \mathbb{R}_+^K \to \mathbb{R}_+^K \) is given by

\[
    T_k(p) = \min \{ p_k, \gamma_k I_k(p) \} = \min \{ p_k, J_k(p) \}.
\]  

(4)

The key property of the control scheme (2) is the active link protection (ALP) property \cite{4}, which states that for any \( \delta > 1 \), \( A_n \subseteq A_{n+1} \). In words, the property guarantees that as long as all users update their transmit powers according to iteration (2), the SIRs of the active users will never drop below their corresponding SIR targets.

Furthermore, in \cite{2} interesting convergence properties of (2) were shown. The convergence behavior depends on the feasibility of SIR targets. Considering Proposition 1, denote

\[
    C(T) := \inf_{p > 0} \max_{k \in K} \frac{\gamma_k I_k(p)}{p_k} > 0,
\]

where \( T = \text{diag}(\gamma_1, \ldots, \gamma_K) \). Note that the infimum cannot be attained due to the axiom \( A2 \) but, by the axiom \( A1 \), it must be larger than 0. Now, the SIR targets \( T \) are feasible if and only if

\[
    0 < C(T) < 1.
\]

Now it can be differentiated between the following three cases (using the terminology of \cite{1}):

(C.1) \( C(T) < C(\delta T) < 1 \): The users seeking admission to the network (inactive users) are fully admissible.

(C.2) \( C(T) < 1 \) and \( C(\delta T) > 1 \): The inactive users are fully admissible but \( \delta \)-incompatible.

(C.3) \( C(T) \geq 1 \): The inactive users are not fully admissible (totally inadmissible).

In the analysis of the convergence properties, an additional assumption on the interference functions was made in order to exclude the trivial case when one or more active users are orthogonal to all inactive users:

\[
    (C.4) \text{If } B_n \neq \emptyset \text{ for some } n \in \mathbb{N}_0, \text{ then, for each } k \in A_n, \text{ there is } l \in B_n \text{ such that } l_k \text{ is strictly increasing in } p_l.
\]

Using the above, the following statements hold \cite{2}:

(i) Let (C.1) and (C.4) be satisfied. Then, there is a finite \( n_0 \in \mathbb{N} \) so that \( A_{n_0} = K \). Moreover, as \( n \to \infty \), we have \( p_k(n) \to \delta^\gamma p_k(0) \), \( k \in K \).

(ii) Let (C.2) and (C.4) be satisfied. Then, there is a finite \( n_0 \in \mathbb{N} \) so that \( A_n = K \) for all \( n \geq n_0 \). However, \( p_k(n) \to \infty \) for each \( k \in K \) as \( n \to \infty \).

(iii) Let (C.3) and (C.4) be satisfied. Then, as \( n \to \infty \), \( \text{SIR}_k(n) \to \text{SIR}_k \in (0, \infty) \) and \( p_k(n)/\delta^n \to \delta^\gamma p_k \in (0, \infty) \). If \( k \in B = \bigcap_{n \in \mathbb{N}_0} B_n \neq \emptyset \), then \( \delta^\gamma p_k \) is strictly increasing in \( p_l \). In contrast, for each \( k \in A = \bigcup_{n \in \mathbb{N}_0} A_n \), we have \( \text{SIR}_k = \gamma_k \).

#### 4. CONSTRAINED TRANSMIT POWERS

It is important to emphasize that all the properties presented in the previous section and, in particular, the protection of active users (ALP property) have been obtained under the assumption of no constraints on transmit powers. In the rest of this paper we deal with the problem under which additional conditions the previously obtained results apply to control schemes with individual power constraints given by \( p \in P = \{ p \in \mathbb{R}_+^K : \forall k \in K, p_k \leq \bar{p}_k \} \). In this case, we propose a power-constrained version of (3) to be:

\[
    p(n + 1) = \delta T(p(n), \bar{\delta}), \quad p(0) \in \mathbb{R}_+^K
\]

where \( T : \mathbb{R}_+^K \times \mathbb{R}_+^K \to \mathbb{R}_+^K \) is of the form

\[
    T(p, \bar{p}) = \min \{ p, T(p), \bar{p} \}
\]

where the minimum is taken component-wise.

In the unconstrained case, the notions of admissibility and \( \delta \)-compatibility play crucial roles for the behavior of the control scheme (see (C.1)–(C.3)). In the presence of power constraints, however, the lack of \( \delta \)-compatibility has different implications. To see this, note that (5) is necessary but not sufficient for the SIR targets to be feasible under power constraints. A necessary and sufficient condition for feasibility of \( T \) is that

\[
    0 < C(T; P) := \inf_{p \in P} \max_{k \in K} \frac{\gamma_k I_k(p)}{p_k} \leq 1.
\]

Let \( p' \in P \) denote any minimizer in (8) so that

\[
    p' := \arg \min_{p \in P} \max_{k \in K} \frac{\gamma_k I_k(p)}{p_k}.
\]
Obviously, as \( P \subset \mathbb{R}_+^K \), we have \( C(\Gamma) \leq C(\Gamma; P) \), and thus \( C(\Gamma) < 1 \) does not necessarily imply \( C(\Gamma; P) \leq 1 \). In such cases, \( C(\Gamma; P) \) defined by (8) provides a basis for defining the notion of admissibility. In analogy to the previous definitions, we can say that the inactive users are

(C.5) fully admissible if \( C(\Gamma; P) \leq C(\Gamma; P)_1 \leq 1 \),

(C.6) fully admissible but \( \delta \)-incompatible if \( C(\Gamma; P) \leq 1 < C(\Gamma; P)_1 \),

(C.7) totally inadmissible if \( C(\Gamma; P) > 1 \).

**Proposition 2.** As \( n \to \infty \), SIR\(_n\)(n) \( \to \) SIR\(_\infty\) \( \in (0, \infty) \) and \( p_k(n) \to \hat{p}_k \in (0, \bar{p}_k] \), \( k \in K \), under (6). If (C.5) holds, then \( \hat{p} = \hat{p}' \) where \( \hat{p} > 0 \) is the unique vector satisfying

\[
\hat{p}' = \delta I(\hat{p}') \leq \hat{p}.
\]

**Sketch of proof.** The proposition can be proven by showing that there exists \( n_0 \) s.t. for all \( n \geq n_0 \) the iteration (6) is equivalent to \( p(n + 1) = I(p(n)) \). Now, it can be shown that \( I(p) \) is a standard interference function and its fixed point always exists and is unique. Furthermore, if (C.5) holds, then there exists \( \hat{p}' \) satisfying (10), which is the unique fixed point.

Thus, the algorithm (6) converges to the fixed point of \( I \), which is a valid power allocation provided that (C.5) is fulfilled. This fixed point however is not necessarily a valid power allocation if the users are fully admissible but \( \delta \)-incompatible (C.6), which stands in clear contrast to the unconstrained case. Thus, Condition (C.5) is crucial for the algorithm to be of any value, which also shows that \( \delta \) should be chosen very carefully. An open question that remains is to what extent the ALP property is preserved under (C.5) when limitations on transmit powers are taken into account. We address this problem in the remainder of this section. From [4, 1], we know that the property of protecting active users does not carry over in its full generality to the power-constrained case.

Consider the SIR of an active user \( k \in A_n \) for some \( n \in \mathbb{N}_0 \). As the user is active we have \( \delta \gamma_k I_k(p(n)) \leq \delta p_k(n) \). Furthermore, by (6) together with A2 and A3 there holds:

\[
I_k(p(n + 1)) = I_k(\delta \min\{p(n), I(p(n)), \hat{p}/\delta\}) < \delta I_k(\min\{p(n), I(p(n)), \hat{p}/\delta\}).
\]

Hence, for any \( n \in \mathbb{N}_0 \) and \( k \in A_n \), one has

\[
\text{SIR}_k(p(n + 1)) = \frac{\min\{\hat{p}_k, \delta \gamma_k I_k(p(n))\}}{I_k(\delta \min\{p(n), I(p(n)), \hat{p}/\delta\})} > \frac{\min\{\hat{p}_k, \delta \gamma_k I_k(p(n))\}}{\delta I_k(\min\{p(n), I(p(n)), \hat{p}/\delta\})}.
\]

The foregoing conditions are independent of \( m \in \mathbb{N}_0 \), and thus, if they are satisfied, the ALP property is guaranteed for all \( n \in \mathbb{N}_0 \), just as in the case of unconstrained transmit powers. Now the question is what to do when (13) and with it all the consequential conditions, cannot be guaranteed. One possible remedy is to apply the concept of distress signaling where users are prohibited from increasing their transmit powers whenever they receive a distress signal (special tone in a control slot or some separate control channel) broadcast by at least one active user. The idea was already mentioned in [1] where the distress signal is suggested to be broadcast when an active user is about to exceed its power limit at some time point, that is, when \( \hat{p}_k < \delta I_k(p(n)) \) for some \( k \in K \) and \( n \in \mathbb{N}_0 \). One problem with this approach is that the active users may be about to violate their power constraints again and again, thereby generating distress signals at many different time points. In some situations, it would be better not to deactivate the distress signal until it is guaranteed that all the inactive users can be admitted with the protection of active users.

In this subsection, we derive more general conditions under the assumption of standard interference functions. First we slightly strengthen the condition \( \delta \hat{p}' \geq \hat{p} \).

**Proposition 4.** Suppose that (C.5) is satisfied and \( \hat{p} \) is any power vector such that

\[
\delta I(p) \leq \hat{p} \leq \hat{p}'.
\]

Let \( \lambda : = \lambda(\delta, \hat{p}) \) be any constant for which \( I(\lambda \hat{p}) \leq \hat{p} \). If

\[
p(m) \leq \lambda \hat{p}
\]

for some \( m \in \mathbb{N}_0 \), then \( A_n \subseteq A_{n+1} \) for all \( n \geq m \).

**Sketch of proof.** The proof is conducted by showing that there exists \( \lambda \) strictly greater than 1 and that once (15) is satisfied for \( m = m_0 \) with some \( m_0 \in \mathbb{N}_0 \), it is preserved for all \( m \geq m_0 \). With the above, it can be shown that the SIR of an active user is bound below by \( \gamma_k \) even if its power constraint is reached.

Any power vector satisfying (14) is called a \( \delta \)-valid power vector allocation. Notice that if (C.5) hold, a \( \delta \)-valid power vector exists. Particular examples of such vectors are \( \hat{p}' \) and \( \hat{p}'' \) defined by (9) and (10), respectively. Also note that due to A2 and Proposition 1, there exists \( \lambda \) strictly larger than 1.

By Proposition 4, we have the ALP property if the inactive users are totally admissible and the transmit powers are sufficiently small so that (15) is fulfilled. A useful property of this result is that once (15) is satisfied, there is no need to verify this condition again, unless (14) is violated due to, for instance, fading effects or arrival of new inactive users. The main problem with (15), however, is how to efficiently obtain a \( \delta \)-valid power allocation in a distributed environment. One possibility is to bound below the the set of \( \delta \)-valid power allocation under the worst-case scenario. This problem is left open. Instead we consider the possibility of letting each user compare its transmit power with the interference power.
Proposition 5. Assume (C.5) and let \( \lambda \geq 1 \) be defined as in Proposition 4. If
\[
\frac{p(m)}{\lambda \delta} \leq \delta I(p(m)/\lambda^2) \tag{16}
\]
for some \( m \in \mathbb{N}_0 \), then \( A_n \subseteq A_{n+1} \) for all \( n \geq m \).

Sketch of proof. The proof is based on the axioms A1-A3 defining standard interference functions and the fact that if the fixed point \( p^* \) of an interference function \( I(p) \) exists, \( p \leq I(p) \) implies \( p \leq p^* \). Using the above, it can be shown that (16) implies that the conditions of Proposition 4 are met, which guarantees the protection of active users at all future time points.

Notice that by Proposition 1, A2 and (10), there exists \( \lambda > 1 \) satisfying the condition of the proposition: \( I(\lambda \delta p^*) \leq \delta \). Choosing \( \lambda = 1 \) leads us to the following corollary.

Corollary 1. If (C.5) holds and
\[
p(m) \leq \delta^2 I(p(m)/\delta) \tag{17}
\]
for some \( m \in \mathbb{N}_0 \), then \( A_n \subseteq A_{n+1} \) for all \( n \geq m \).

We point out that it is not clear whether (16), and with it (17), is preserved in general. The results solely show that once (16) or (17) is satisfied, then the ALP property is ensured for all future instances \( n \geq m \). It must be also emphasized that (16) and (17) are less restrictive than \( p(m) \leq \delta^2 I(p(m)) \) as \( x \mapsto x I_k(p/x) \) is strictly increasing for any \( p > 0 \).

The main problem with Proposition 5 and Corollary 1 is that \( I_k(p(m)/\delta^2) \) and \( I(p(m)/\delta) \) may be known not to be user \( k \) at time \( m \) even if \( I_k(p(m)) \) is known. The following proposition shows that the ALP property is guaranteed even if \( p(m) > \delta I(p(m)) \), provided that the entries of \( p(m) \) are not too large. In other words, there is always some margin around the value \( \delta I(p(m)) \) so that the protection is guaranteed whenever \( p(m) \) belongs to this margin.

Proposition 6. Suppose that (C.5) is true and
\[
p(m) \leq \delta^2 I(p(m)) \tag{18}
\]
holds for some \( m \in \mathbb{N}_0 \) and \( \beta \in [1, \beta_{\text{max}}] \). Then, there exists \( \beta_{\text{max}} > 1 \) such that \( A_n \subseteq A_{n+1} \) for all \( n \geq m \).

Sketch of proof. The proof is conducted by showing, first, that once the condition (18) is satisfied for some \( m \in \mathbb{N}_0 \), then it will be also satisfied for all future time points. On the other hand, by A2, we have \( I_k(p/m) < \delta \lambda I_k(p/m) \). This implies that \( \beta_{\text{max}} > 1 \) exists so that, if (18) holds, the conditions of Proposition 5 are fulfilled.

By the proposition, we have the protection of active users for all \( n \geq m \) if (18) holds for some sufficiently small \( \beta \geq 1 \). The main insight is that there is the possibility of choosing \( \beta \) being strictly larger than one.

In the remainder of this paper, we summarize our findings and make some suggestions as to what to do when (C.5) is not fulfilled. For brevity, we focus on condition (18) but the subsequent discussion also applies to (16) and (17) (with (18) substituted by (16) or (17)). Given some \( \beta > 1 \) and \( \delta > 1 \) (both sufficiently small), let \( P' \subseteq P \) be the set of all power allocations for which (18) is satisfied. When \( p(n) \notin P' \), the scheme prevents all users from increasing their powers by broadcasting distress signals on a common control channel. The distress signals are sent by all the active users \( k \in A_n \) such that \( p_k(n) \geq \beta \delta I_k(p(n)) \), which can be verified locally. First assume that (C.5) holds, meaning that there is an additional mechanism to ensure full admissibility of all users. Then, the admission control algorithm with distress signaling becomes:
\[
p(n+1) = \begin{cases} 
    \min\{p(n), \delta I(p(n))\} & p(n) \notin P' \\
    \delta T(p(n), p/\delta) & p(n) \in P'
\end{cases} \tag{19}
\]
where \( T \) is defined by (7). From (19), we see that the admission control algorithm (6) stops if \( p(n) \notin P' \) (at least one active user transmits a distress signal), in which case no user increases its transmit power. Therefore, active users are protected as the interference powers do not increase and each active user, say user \( k \in A_n \), decreases its transmit power if and only if \( p_k(n) > \delta I_k(p(n)) \). Moreover, since the transmit power of user \( k \) decreases as long as \( p_k(n) > \delta I_k(p(n)) \) and other transmit powers are kept constant, there must be a time point \( m \geq n \) such that \( p(m) \in P' \). Once this condition is satisfied, no distress signal is broadcast and, by (19), the iteration (6) is resumed. Now the active users are guaranteed to be protected for all \( n \geq m \), provided that (C.5) is satisfied.

Now if (C.5) is not satisfied, the problem is open but we have to differentiate between (C.6) and (C.7). In the case of (C.6), the algorithm in (19) applies, provided that the parameter \( \delta > 1 \) is reduced so as to fulfill (C.5) at the expense of extending the duration of the whole admission process. So the only issue is when and how to reduce \( \delta \) to provide full admissibility. In contrast, if (C.7) is true, then it is impossible to admit all users at the required quality-of-service, and therefore either some inactive user will reach its power constraint without attaining its SIR target and it should voluntarily leave the system, or the SIR target of some active user will be violated at some time point. In the latter case, a simple idea is to let this active user permanently send a distress signal so that no transmit powers are increased and, after some time point, first inactive users will drop out of the system. Obviously, a better approach would be to let inactive user (cooperatively) estimate \( C(\Gamma; P) \) and \( C(\delta I; P) \) so that they do not even attempt to access the network if \( C(\Gamma; P) > 1 \). However, an efficient estimation of these quantities in a distributed environment is still an open problem.

5. REFERENCES


