A Mutual Compensation Mechanism
for Efficient Decentralized Network Management:
The Case of Power Control in Wireless Networks

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Abstract

A “mechanism” is a set of rules governing the interaction of selfish entities, which attempts to lead these entities to a desirable outcome. This work applies a relatively simple mechanism, available in the economics literature, to achieve an efficient decentralized allocation of power among data-transmitting terminals. The resulting operating point is “efficient”, because terminals end up “fairly” compensating each other for the interference each one causes. The same ideas can be fruitfully applied in more general networks, and even outside the engineering context.

It has long been recognized that decentralized control algorithms offer many advantages over their centralized counterparts. Reasons include complexity, signaling overhead, and unavailability of local information to a central controller. Besides, certain modern communication and/or computing paradigms, such as ah-hoc wireless networks, and peer-to-peer computing, are inherently decentralized, which make central controllers highly impractical, if not outright impossible to implement.

With minimal or no intervention by a central authority, many economic agents, each acting independently, in its own interests, and making relatively simple decisions, can achieve sensible outcomes. Thus, a free economic market provides the engineer with a useful paradigm for decentralized control, and microeconomics and game theory can provide a solid scientific foundation. For instance, power control in wireless data applications has been formulated as a “game”; i.e., a situation in which each of several selfish agents choose a “strategy” in order to maximize its own “payoff”, which depends on the chosen strategies by all players. The strategy is a power level, and the payoff is quality-of-service (QoS) (e.g., bits per Joule), which depends on the choices of *all* terminals, because the power chosen by a terminal becomes interference for others. The actual decisions may be made by “software agents”, which may be controlled and/or tuned or trained by an actual human operator, acting on his self-interests. Or these agents could be entirely programmed by the network administrator to its own advantage. Either case can be handled by this framework.

A key solution concept is a Nash equilibrium (NE); i.e., an allocation (a strategy per player) such that no player would be better off by *unilaterally* changing strategy. In the data terminals game, a NE specifies a power level per terminal, such that no terminal could increase its QoS by unilaterally adjusting its power. It is well understood that, if transmission power is limited, a NE does exist [3, 4]. But NE are generally "inefficient". Thus, the terminals settle on power levels that are “too high”. The challenge is to get selfish entities to move toward a more efficient operating point “on their own”.

An option is to design an appropriate “mechanism”; i.e., a set of procedures, penalties and rewards intended to guide these entities toward a desired outcome. In order to achieve an efficient decentralized allocation of power among mutually interfering terminals, this work applies a relatively simple mechanism introduced in [5]. This mechanism requires a “transferable good” (e.g., money, or some form of service credits) with which terminals can compensate each other. The intuition of this mechanism can best be captured by considering a 2-terminal situation in which only terminal 1 interferes with terminal 2 (but *not* vice-versa), which can actually happen with successive interference cancellation. Terminal 2 must declare the amount of the transferable good it wishes to *charge* terminal 1 as compensation for each unit of interference. Likewise, terminal 1 must quote the price it offers *to pay* terminal 2 as compensation. But terminal 1 faces a penalty increasing with any difference between its offered price and what terminal 2 demands. At equilibrium, the interfering terminal will pay the true cost caused on the other terminal by its interference, which is precisely the “fair” thing to do. If the amount paid by terminal 1 exceeds the cost its interference causes on terminal 2, then terminal 2 is in fact “making a profit” per unit of interference. But then, it is optimal for this terminal to induce terminal 1 to *increase* its interference, and to do so, terminal 2 must *decrease* what it charges.

When both terminals interfere each other, each terminal must quote two prices: one to *be paid to* the other, as compensation for each unit of interference it creates; the second to *be charged* as compensation for the interference caused *by the other*. But each terminal faces a penalty if its offered price differs from what the other wants as compensation. At equilibrium, the terminals end up fairly compensating each other, which is “socially optimal” in a reasonable sense.

The mechanism can be described in greater details as follows. Terminal 1 needs to choose three values: c^1_{12} : unit compensation to be *offered to* terminal 2; c^1_{21} : unit compensation to be *charged to* terminal 2; transmission power, p_1. Equivalently, terminal 2 chooses c^2_{21}, c^2_{12} , p_2. The “payoff” to terminal 1 is (some unit conversion constants are implicit) :

$$\underbrace{u_1(p_1;p_2)}_{\text{bits/Joule}} + \underbrace{c^2_{21}p_2}_{\text{paid BY 2}} - \underbrace{c^1_{12}p_1}_{\text{paid TO 2}} - \underbrace{\left(c^1_{12}-c^2_{12}\right)^2}_{\text{Penalty}} \tag{1}$$

Terminal 2 chooses c^2_{21}, c^2_{12} , p_2, and faces an identical situation.

The mechanism is implemented in two stages: (i) announcement: the terminals announce c^1_{12}, c^1_{21}, c^2_{21}, c^2_{12} . (ii) choice: each terminal chooses its power level to maximize its payoff. It can be shown that the equilibrium strategies of this 2-stage game are efficient.

We are currently exploring the impact of this mechanism on several issues involving communication networks. For instance, we know that mobile terminals using a cellular system from “bad locations” can stress the system, and reduce its capacity. This can be more severe if the poorly-situated terminal transmits media content (e.g., video) that demands a high data rate, and an inflexible signal-to-interference target. These terminals should, ideally, defer transmission pending a better location, unless their information is “urgent”, which is only known to the transmitter. Implementing a mechanism such as this should induce a more judicious use of the network by these terminals.

This framework can be extended to accommodate many mutually-interfering terminals, and can be applied outside the cellular architecture. With many terminals, the exchange of pricing signals between terminals becomes an issue. However, the fact that terminals only care about the total interference, helps because a terminal’s charge per unit of interference should be independent of the source of the interference. But each terminal may, in principles, quote a different value. The rate of converge toward the equilibrium prices and power levels is also a concern. But it can be shown that a simple updating algorithms exists that leads to the equilibrium, even when users don’t know “everything” about each others. In an ad-hoc scenario, the main challenge may be to set up an accounting system to track down the compensations among terminals. We intend to explore these an other interesting issues in our research program.

References

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