Market-driven regulation for next generation ultra-wide-band technology: Technical-economic management of a 3G cell with coexisting UWB devices

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***Abstract*—Existing regulations for ultra-wide-band technology make negligible its impact on incumbent networks. But compliant UWB devices are severely range-limited, and hence useful for a limited class of applications. More powerful UWB devices could be allowed in exchange for some form of "economic mitigation" to incumbents. Fortunately, world-wide UWB regulations have *not* yet been set, and those set may be adjusted. We explore the technical-economic impact of *higher-power* UWB on a 3G CDMA cell populated by data-downloading terminals. Performance is measured by the ratio of actual to potential revenue. Each *served* terminal continues to operate at the original service quality (signal-to-interference level), and does *not* alter its contribution to revenue. But fewer terminals may be served, resulting in reduced total revenue. This reduction (given by a simple expression) would be a fair dynamic monetary compensation to the cellular network. As an alternative, such network may receive additional spectrum, and/or base stations to restore its original performance. As interference rises, so does the cost of the mitigation. Thus, there is an economically-efficient level. Other incumbent technologies can be similarly considered, and a regulatory radio-spectrum "mask" can be fully determined by market forces.**

I. Introduction

Ultra-wide-band technology (UWB) has numerous virtues, such as transceivers of potentially low complexity and cost, resistance to severe multipath impairment, exceptional location and tracking capabilities, and noise-like signalling[1]. Additionally, UWB can coexist over segments of the radio spectrum in use by other technologies, possibly increasing spectrum efficiency. The incumbent networks can be adversely affected to a greater or lesser extend depending on many factors.

The approach taken until recently by regulators to protect incumbents was very simple: to effectively outlaw UWB, except for a very limited number of (mostly military) uses. Recently, UWB has been approved for civilian communication in both the USA and Europe, with other regions expected to soon follow [2], [3]. But this flexibility has come under very severe power emission restrictions. Useful devices that are essentially "invisible" to the incumbent can indeed be made [4], [5]. However, such devices can only be employed in a limited class of applications, such as "cable replacement", short-rage multi-media transfer, sensor networks and medical body networks. Much wanted/needed applications, such as wireless local-area networks supporting ultra-high data rates, cannot be pursued with UWB, not because of any inherent technological limitation, but owing to the artificial limits imposed by regulations.

As an alternative, higher-power UWB could be allowed on the basis of "economic mitigation"; that is, a regulatory framework under which the beneficiaries of the more powerful devices appropriately compensate "injured parties". Direct monetary transfers could be made. But also an affected network could be "upgraded" so that it can achieve its original performance, under a higher interference level. This approach is consistent with views long held by renown economists [6, Ch. 24]. In fact, similar schemes are in present use today. In Spain, the "Canon por copia privada" establishes that buyers of recording equipment (CD/DVD burners, blank CDs and DVDs, etc) pay a special fee, whose proceeds are devoted to "mitigating" the revenue losses of authors/artists resulting from unauthorised recordings. The canon is an imperfect solution, but it is certainly preferable to outlawing or "crippling" the recording equipment available to consumers.

Fortunately, many world regions do not yet have UWB regulations, and those that have may be receptive to opening a "second round" of regulations. Thus, it is desirable to estimate the technical-economic effect on 3G of UWB devices emitting *higher* power levels than allowed today.

Other researchers (e.g. [4], [5]) have evaluated the UWB impact on 3G exclusively on technological terms (e.g., error rate performance), with the apparent sole exception of [7]. In [8], besides providing a more extensive literature review, we develop an analytical framework to assess the technical and economic impact of UWB on the downlink of a 3G CDMA cell when UWB does not offer competing 3G services. The present work complements [8] by: (i) explicitly considering a different noise level per terminal (useful when UWB does not equally affect all cellular terminals), and (ii) providing results of some relevant numerical experiments.

II. Physical and Behavioural Model

For greater detail see, please, [8]. The index i identifies a terminal. (i) N is the number of terminals *receiving* data simultaneously *from* a CDMA base station (BS). (ii) $\bar{P}$ is the BS downlink power constraint. (iii) R_i is the data rate of terminal i (iv) R_C is the chip rate. For convenience, $R_C = W$, with W the available bandwidth. (v) Information is sent in M_i-bit packets carrying $L_i < M_i$ information bits (vi) Packets received with errors that cannot be corrected result in ideal re-transmissions until correctly received and acknowledged. (vii) As common in the literature, we assume that in the downlink, the CDMA signatures retain their orthogonality, and effectively eliminate intra-cell interference. The received signal-to-interference ratio (SIR) is $x_i = (W/R_i)(h_i P_i/\sigma_i^2)$ with P_i the downlink power, h_i the channel gain, and σ_i^2 the average noise power at the receiver.

Furthermore, $f_S(x_i)$ is the packet-success-rate (PSR) as function of the received SIR. $f(x) := f_S(x) - f_S(0)$ replaces $f_S(x)$ for technical reasons. A*ll we assume* about the physical layer is that the PSR has the "S shape" shown in fig. 1.

The average number of information bits transferred by a terminal over the interval τ is:

$$B_i(x_i) = \tau(L_i/M_i)R_i f(x_i) \tag{1}$$

Following [6, Ch. 10], if a terminal (with a "large" monetary budget) must pay $c_i(x_i)$ for SIR x_i, it chooses x_i to maximise benefits minus cost:

$$\beta_i B_i(x_i) - c_i(x_i) \equiv S_i(x_i) - c_i(x_i) \tag{2}$$

β_i is the terminals "willingness to pay", the most it would pay for a successfully transferred information bit.

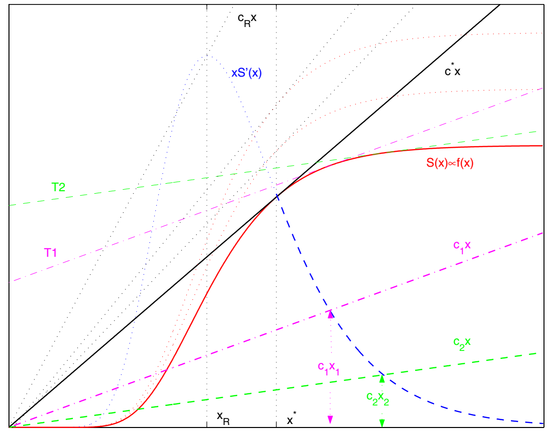

Figure 1. Terminal maximises benefit minus cost: $S(x) - cx$. Network chooses $c = c^*$ and terminal $x = x^*$. Revenue is $c^* x^* \propto \beta R f(x^*)$

III. Technical-Economic resource management for CDMA

Pricing can serve as a tool for both generating revenue, and encouraging efficiency. The network needs (i) a pricing rule, and (ii) a criterion to prioritise terminals when not all can be served. Two key assumptions are (i) the $\beta' s$ are known to the network, and (ii) the network can charge an individual price to each terminal.

A. Optimal linear pricing

Figure 1 summarises an analysis found in [8]. The key conclusions are:

- (i) the network chooses for terminal i a price c_i^* (the slope of the only tangent to S_i from the origin). The service SIR is x_i^* (at the tangency point). If the PSR, f, is common, $x_i^* = x^*$ for all i.
- (ii) the revenue from terminal i, if served, is:

$$\tau(L_i/M_i) f_i(x_i^*)\beta_i R_i := \tau_i \beta_i R_i \tag{3}$$

  When the link layer configuration is common, $\tau_i = \tau_0$ for all i, and can be "hidden" in the units.
- For reasons given below, all terminals have the link layer configuration with the largest $(L/M) f(x^*)/x^*$.

B. Which terminals to serve?

1) Basic resource constraint : For a given bandwidth, W, the allocated downlink powers must satisfy:

$$\frac{W}{R_i}\frac{h_i P_i}{\sigma_i^2} = x^* \Rightarrow P_i = \frac{R_i}{h_i}\frac{\sigma_i^2}{W} x^* \tag{4}$$

The power constraint requires that

$$\sum_{i=1}^{N} P_i \equiv \frac{x^*}{W} \sum_{i=1}^{N} \frac{\sigma_i^2 R_i}{h_i} \leq \bar{P} \tag{5}$$

or equivalently:

$$\sum_{i=1}^{N} \frac{R_i}{\hat{h}_i} \leq \frac{W}{x^*/\bar{P}} := \frac{W}{W_0} \tag{6}$$

with

$$\hat{h}_i := h_i/\sigma_i^2 \tag{7}$$

$W_0 := x^*/\bar{P}$ is the bandwidth "consumed" per unit of "amplified" data rate, $R_i/\hat{h}_i$. Thus, i, if served, consumes:

$$W_0(R_i/\hat{h}_i) \tag{8}$$

2) The knapsack problem and solution: The network wants to choose, from all the sets of terminals that satisfy constraint (6), the set that yields the most revenue. Such decision problem is a version of the well-known "knapsack problem". There is a finite set of items, each characterised by a "weight" and a "benefit" (measured as a positive number). One seeks the combination of items that maximises the sum of the benefits, without exceeding a total weight constraint (the "knapsack capacity"). The problem is in general NP-hard (although a number of solution algorithms perform well in practise). However, the "fractional" version of the problem, which allows the inclusion in the knapsack of any desired "fraction" of an item, admits a very simple and intuitive solution. To solve this case, one simply sorts the items by their "benefit to weight" ratio, and starts inserting whole items in order. When no space is left for an additional whole item, one adds the necessary fraction of the next item to completely fill the knapsack [9]. In our problem, serving "a fraction" of a terminal means to admit it at a fraction of its data rate, which seems both possible and reasonable.

3) The revenue per Hertz criterion: A terminal's "benefit to weight" ratio is its contribution to revenue per unit of used resource. From equations (3) and (8), a terminal's "revenue per Hertz" contribution is:

$$\propto \frac{\beta_i R_i}{R_i/\hat{h}_i} = \beta_i \hat{h}_i \tag{9}$$

With terminals' labels such that $\beta_1 \hat{h}_1 \geq \cdots \geq \beta_N \hat{h}_N$, and I^* the largest index such that

$$\sum_{i=1}^{I^*} \frac{R_i}{\hat{h}_i} \leq \frac{W}{W_0} \tag{10}$$

a reasonable and simple service criterion emerge:

(i) serve terminals 1 through I^*, each at its full rate

(ii) admit terminal I^*+1 at a fraction of its data rate to fully exhaust the resource [9].

4) Impact of channel gains: A terminal's own noise level simply reduces its channel gain (eq. (7)). And the channel gain "amplifies" the terminal's data rate (constraint (6)). Thus, a data rate of R_i with a channel gain h_i is (for consumption purposes) equivalent to $\hat{R}_i := R_i/h_i$ with a perfect channel ($h_i = 1$).

The other effect of the channel gain is to "attenuate" the terminal's willingness to pay (eq. (9)). β_i with a channel gain h_i, is equivalent to $\hat{\beta}_i := \beta_i h_i$ with a perfect channel. Notice that, conveniently, $\hat{\beta}_i \hat{R}_i \equiv \beta_i R_i$

5) "Optimal" link layer: The constants W_0 and τ_0 provide some useful information. From subsection III-B3, revenue per Hertz is proportional to the ratio τ_0/W_0 which is itself proportional to $(L/M)f(x^*)/x^*$, which is determined by the link layer configuration (modulation/coding). Other things being equal, the configuration with the largest $(L/M)f(x^*)/x^*$ should be chosen in order to maximise revenue per Hertz.

IV. UWB IMPACT

UWB may increase "the noise floor" of "victim" terminals. If higher-power UWB were widely adopted, each data terminal could face the same level of increased noise, and $\sigma_i^2 = \sigma^2$ for all i. The conclusions in this case are given in [8]. If UWB affects different terminals differently, its impact must be re-examined.

A. Impact at the terminal level

As discussed further in [8], the pricing results of section III-A do not depend on the specific level of noise. From this, it immediately follows that a "victim" terminal will : (i) continue to operate at the signal to interference ratio, x^* (and hence enjoy unchanged quality of service), but (ii) necessitate a higher level of power (see eq. (4)), and (iii) increase its demand for "bandwidth" in direct proportion with noise ($R_i/\hat{h}_i \equiv R_i\sigma_i^2/h_i$, eq. (8)), yet (iv) pay the network the same amount, for a given service time (eq. (3) does not depend on σ_i^2), and (v) see a decrease in its revenue per Hertz contribution, $\beta_i\hat{h}_i$, which may alter its ordinal service priority.

B. Impact at the system level

"Capacity" (the right-hand-side of (6)) remains unchanged, but each term on the left ("consumption") may be raised by UWB. Thus, I^*, the largest index for which (10) is satisfied, could register a significant drop, resulting in fewer terminals served, yet each paying the original amount.

This analysis reveals the answer to an important question: if UWB is allowed power emissions high enough to make this effect noticeable, what would be a “fair” monetary compensation to the network? This amount is the difference between the revenues raised by the network at the original noise level and those raised after the noise rise (over each reference time period). For instance, with convenient units and assuming that no terminal needs to be served “fractionally”, if after noise rises, terminals 1 through $i^* < I^*$ exhaust capacity, then the network revenue loss takes the simple form :

$$\sum_{i=i^*+1}^{I^*} \beta_i R_i \tag{11}$$

This is the former revenue contribution of the terminals that can *no longer* be served.

V. Numerical illustrations and experiments

A. Simple illustration

A network has 9 terminals wishing access to 90 units of bandwidth (BW). The critical data is given in table I, with rows sorted by revenue/Hertz. Convenient units are assumed.

Table I

R_i	h_i	β_i	$\beta_i h_i$	R_i/h_i	$\beta_i R_i$
1	1	3	3	1	3
1	1/3	3	1	3	3
1	1/8	2	1/4	8	2
3	1/9	2	2/9	27	6
1	1/5	1	1/5	5	1
2	1/5	1	1/5	10	2
3	1/10	2	1/5	30	6
2	1/6	1	1/6	12	2
3	1/40	5	1/8	120	15

The first 7 terminals consume 84 units of BW. The 8th terminal is admitted at 1/2 its data rate to “fill” the channel. The terminal with the highest β is not served, because its channel state makes its revenue/Hertz contribution too low. Actual revenue is 24 versus a “potential revenue” ($\sum \beta_i R_i$) of 40, so “efficiency” equals 24/40 = 3/5. Untransferred bits are worth 1+15=16.

B. Numerical experiments

The following experiments are conducted: (i) vary level of uniform UWB interference (by multiplying noise by certain factor) for fixed bandwidth, (ii) vary spectrum for fixed uniform UWB noise factor, (iii) vary UWB “density” (a terminal’s probability of “falling victim” to UWB) for given noise factor, (iv) vary the cell radius for fixed bandwidth and UWB noise factor. To obtain a “reference” amount of spectrum, we divide the “average”

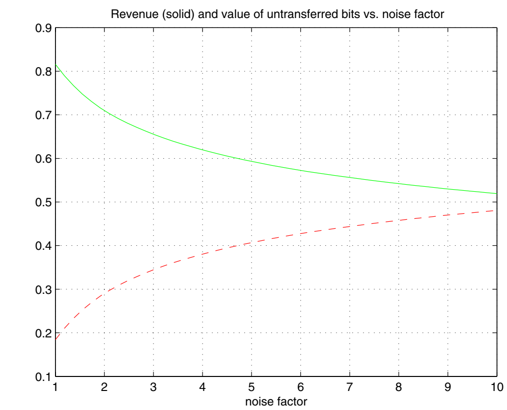

Figure 2. Noise is amplified everywhere by the factor shown. After noise doubles (3 dB) normalised revenue falls from ≈ 0,8 to ≈0,7

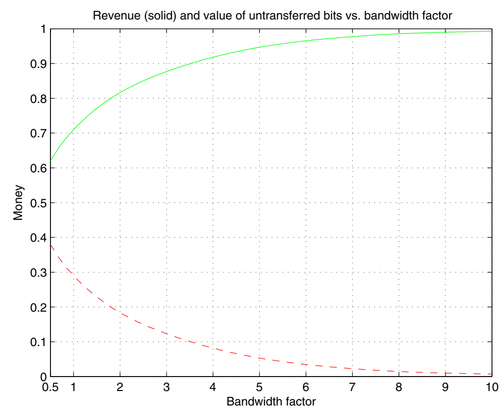

Figure 3. With twice as much bandwidth the network performs as it did before a 3dB noise rise (see fig. 2).

data rate by the channel gain half the cell radius away, and multiply the result by the average arrival rate (13 terminals per reference period). Cell radius is 1000m, when not varied. The key performance index is the ratio of revenue (the “value” of transferred bits) to the value of all traffic (transferred plus untransferred bits) during a given time interval. We emphasise that the used noise levels do *not* reflect present-day UWB regulations.

VI. Discussion

We perform the technical-economic management of a CDMA cell, in the presence of UWB devices that can emit *higher* power levels than those allowed today. We consider non-uniform device density, and provide pertinent numerical results. The ratio of actual to potential revenue is the key performance index. Different per-terminal noise level can be conveniently analysed as a reduction of the channel gains. This suggests that

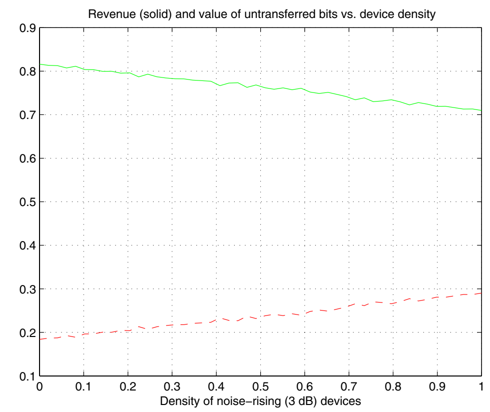

Figure 4. With a noise factor of 2 (3dB), revenue decreases as density grows from 0 to 1. When density =1 the revenue is the same as in fig. 2 for noise factor = 2, as it should.

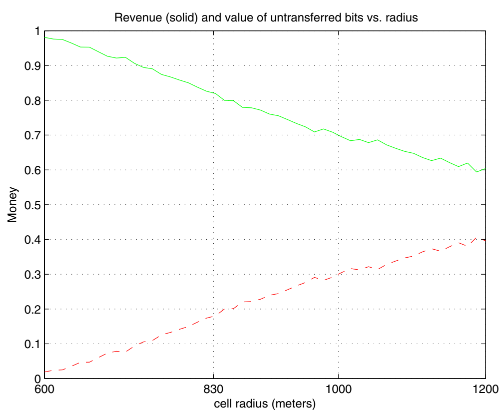

Figure 5. Under a noise factor of 2 (3 dB), the 830m cell performs like a 1Km cell prior to noise rise (see fig. 2). The cost of the redesign that can bring back the original cellular performance would be a fair "economic mitigation".

the cellular network can be brought back to its original performance level by decreasing cell size, through additional base stations (which is confirmed by experiments). The economic cost of such network redesign would be a reasonable lump sum monetary compensation from "high-power UWB" to "3G". Additionally, a closed-form expression for the "real-time" revenue reduction experienced by the cellular network is given (eq. (11)), which could provide the basis for a dynamic monetary compensation mechanism. This reduction could also be cancelled through additional spectrum (possible, for example, in the dynamic spectrum regime of [8]).

A new generation of powerful UWB devices that can satisfy a greater set of consumer needs can arise. The beneficiaries of these devices can contribute toward the "economic mitigation" of negative effects caused by the extra power on incumbent networks. Present devices might continue to be allowed (exempt from economic contribution), and manufactures and consumers could choose whether to support one or both classes of devices.

At the foundation of this analysis is a radical change of approach to radio-spectrum management: market-driven regulation. Other incumbent technologies can be similarly considered. Generally, the higher the interfering power, the greater the cost of mitigation. Therefore, there is an economically-efficient level, which depends on the spectrum band. Thus, the regulatory "spectrum mask" that specifies maximal power emissions over the frequency spectrum can in fact be entirely drawn by the "invisible hand" of the market.

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