Technical-Economic impact of UWB personal area networks on a UMTS cell: Market-driven dynamic spectrum allocation revisited

Virgilio Rodriguez, Friedrich Jondral
Institut für Nachrichtentechnik
Universität Karlsruhe (TH)
Karlsruhe, Germany
email: vr <at> ieee.org

Abstract— **Recently, ultra-wide-band (UWB) technology has been approved for communication applications, utilising spectrum in use by other technologies. Recent studies have evaluated the technological impact of UWB on UMTS, but not the corresponding economic impact. This is of paramount importance, given huge investments already made on UMTS. Those studies also target "traditional" spectrum allocation. Dynamic spectrum allocation (DSA) exploits temporal/spatial variations in the "loads" of various networks. A recent proposal implements DSA by periodically selling or auctioning short-term spectrum licenses, and solves the problem of a participating CDMA cell populated by delay-tolerant terminals with dissimilar "willingness to pay" operating at various data rates, on the downlink. In the present work, UWB personal/body area networks (PAN/BAN) are introduced in the aforementioned DSA environment. The UWB networks utilise the spectrum for free, and do not compete for customers against the CDMA networks, but do increase the noise experienced by the CDMA terminals. The present work studies the economic impact of UWB on a CDMA cell, and its terminals. Before considering DSA, the techno-economic management of a CDMA cell with a fixed spectrum allocation (relevant to present day networks) is studied. The analysis reveals that neither the service priorities nor the technological operating point of the data terminals is affected by UWB. Consequently, a served terminal's contribution to network revenues remain unchanged. The network bears the brunt of UWB interference, because the network can fit fewer terminals in a given spectrum allocation, yet receives an unchanged amount of revenue from each served terminal.**

I. INTRODUCTION

Recently, ultra-wide-band technology (UWB) has been approved for communication applications in the USA[1]. Europe has signalled movement in the same direction, and other world regions are expected to follow along similar lines in the near future. Often-mentioned favourable features of the UWB technology, in particular its impulse-radio variety, include: noise-like signalling, transceivers of potentially low complexity and cost, resistance to severe multipath impairment, and exceptional location and tracking capabilities due to excellent time domain resolution[2], [3], [4]. Additionally, UWB technology enables communication over segments of the radio spectrum that are being used through other technologies, leading to a form of “creation” of wireless bandwidth[5].

Present regulations impose on UWB applications severe power-emission limits over certain spectrum bands[1]. These limits are intended to offer certain incumbent technologies a degree protection against UWB interference. But even with these restrictions, incumbent technologies can be adversely affected by UWB. In particular, the possible impact of UWB interference on UMTS networks have attracted significant attention recently. One reason for this interest is the fact that in many localities UMTS networks obtained radio spectrum after paying enormous sums of money in auctions. For instance, over 22 billion Great Britain pounds (at the time, the equivalent to $2\frac{1}{2}\%$ of the UK’s gross domestic product, and enough for the building of 400 hospitals) were raised by the British Government in a recent auction of 5 UMTS licenses [6]. Thus, determining the economic impact of UWB services on UMTS is of paramount importance.

Several recent works have focused on the impact of UWB networks on CDMA (especially UMTS) networks. Some have based their studies on simulation experiments[7], while others have relied on laboratory measurements [8], [9]. These references and related ones differ from the present analysis in that they have focused on purely technological performance measures (such as the bit error rate). These measures are important and relevant to our aims. Nevertheless, they do not capture the entire story. Spectrum allocation is as much an economic problem as it is an engineering one. Reference [10] appears to be the only recent work that shares this interest with us.

Another significant difference between the present work and the literature concerns the underlying spectrum “regime”. Reference [10] and all other studies of UWB/UMTS interaction of which we are aware have focused on the “traditional” spectrum allocation. Spectrum bands are first allocated to specific radio-access technologies, such as GSM, UMTS, and DVB-T. Subsequently, the spectrum devoted to a technology is suballocated, on a very-long-term basis (up to decades), to specific business entities interested in marketing communication services. The traditional spectrum regime can be very inefficient when the demand for various spectrum-dependent services ("loads") varies widely along time and/or space. Thus, several recent spectrum management proposals envision a spectrum management regime based on dynamic spectrum allocation (DSA). DSA seeks to exploit the temporal/spatial variations in the "loads" of various radio-access networks to allocate the spectrum more efficiently[11].

In a specific recent DSA proposal available in the scientific literature, a spectrum manager implements DSA by periodically selling or auctioning short-term spectrum licenses. all of which simultaneously expire at the end of a pre-specified short period [12], [13]. The problem of CDMA network populated by delay-tolerant terminals operating at various data rates, on the downlink, and representing users with dissimilar "willingness to pay" is solved. The network finds revenue-maximising internal prices and a service priority policy, along with a bid or an optimal amount of spectrum to purchase. Simple, closed-form expressions are given for the network’s optimal operating point (signal-to-noise ratio), optimal bid or efficient amount of spectrum, a terminal’s "revenue per Hertz" service priority, as well as its contribution to revenue and spectrum consumption, if served. Reference [14] introduces a digital video broadcast network in this market-driven DSA scheme, while also providing a comprehensive overview of recent relevant literature. However, these references do not address the possible existence of UWB networks operating over the spectrum being dynamically allocated.

The present work revisits the DSA scheme of [12], [13] to determine the effect of introducing UWB personal and/or body area networks (PAN/BAN) over the spectrum being dynamically allocated. It is specified that UWB is used in support of PAN/BAN to emphasise that UWB does not directly compete against CDMA for customers wishing data services. The UWB networks do not participate in the market-driven DSA scheme, either, because they are presumed to co-utilise all the spectrum, all the time, for free. However, the UWB networks do impact the DSA, as they increase the "noise floor" of the terminals operating in the downlink of the CDMA networks. The present work analytically characterises the economic impact of the presence of these UWB PAN/BAN on the CDMA networks, on the terminals ("customers") and, indirectly, on the revenue raised by the spectrum manager. Although the focus is ultimately on a market-driven DSA regime, the analysis also provides valuable insights on the economic impact of the introduction of the UWB, under a traditional spectrum regime.

The rest of the paper revisits, clarifies, re-interpret and to a modest degree extends the analysis of [12], [13], seeking to understand the techno-economic impact of UWB PAN/BAN. In section II, the physical model and the basic rationale of the terminals are specified. Section III performs techno-economic resource management for the downlink of a CDMA cell populated by data terminals. Section III assumes a fixed allocation of spectrum, as in present-day networks, and provides the foundation for the subsequent analysis. Section IV utilises the preceding results to derive the optimal amount of spectrum that the CDMA network should purchase if it can obtain any desired amount at a unit price (as in [12]). Subsequently, also on the basis of the analysis of section III, section V revisits the participation of the CDMA network in the DSA auction scheme of [13]. After each of sections III , IV , and V the main objective of the present work is directly addressed, through an examination of the "sensitivity" of the results to a change on the "noise level", which is the chief technological effect of the UWB PAN/BAN. The present work concludes with a summary and discussion of key findings, and comments on future directions for this line of research.

II. GENERALITIES

A. Physical Model

Before proceeding with the analysis, we specify in greater detail the physical model.

1) N is the number of terminals *receiving* data simultaneously *from* a CDMA base station (BS) (downlink operation). The BS has a total downlink power constraint of $\bar{P}$.
2) R_i bps is the data rate of terminal i
3) R_C cps is the chip rate of the channel, common to all terminals. For convenience, we set $R_C = W$, where W is the total bandwidth (spectrum) allocated to the cell.
4) $G_i = W/R_i$ is the spreading (processing) gain of terminal i.
5) Information is sent in M-bit packets carrying $L < M$ information bits.
6) $f_S(x_i)$ is the packet-success-rate function (PSR) giving the probability of correct reception of a data packet as a function of the signal-to-interference ratio (SIR) at the receiver. Below, $f(x) := f_S(x) - f_S(0)$ replaces $f_S(x)$ to avoid certain technical problems. As an example, for non-coherent FSK modulation, with packet size M=80, independent bit errors, no forward error correction, and perfect error detection, the PSR is $f_S(x) = \left[1 - \frac{1}{2}\exp\left(-\frac{x}{2}\right)\right]^{80}$. However, we stress that our analysis does *not* rely on this or any specific PSR. We assume that *all we know* about the physical layer is that the PSR has the "S" shape shown in figure 1. The technical characterisation of an "S-curve" and some useful results are given in [15].
7) Following [16], we assume that in the downlink, the CDMA signatures retain their orthogonality, and effectively eliminate intra-cell interference (or that it is included as part of the random noise). Thus, the received SIR is obtained as $x_i = G_i h_i P_i / \sigma^2$ with P_i the downlink power, h_i the path gain, and σ^2 the average noise power at the receiver.
8) Packets received in error which cannot be corrected result in ideal retransmissions until correctly received and confirmed.

A relatively simple analysis tells us that, on the average, the number of information bits successfully transferred by a terminal over the time interval τ is:

$$B_i(x_i) = \tau(L/M)R_i f(x_i) \qquad (1)$$

B. Behaviour of the terminals

We must specify the behaviour of a data terminal that can choose resources, in the presence of pricing. We focus strictly on the downlink of a single CDMA cell.

We assume a utility function of the form $\beta_i B_i + y_i$ where (i) β_i is the monetary value to the terminal of one information bit successfully transferred (a constant for a given terminal), (ii) B_i is the (average) number of information bits the terminal has successfully transferred within a reference length of time, say τ, and (iii) y_i is the amount of money the terminal has left after any charges and rewards are computed. This model is grounded on the micro-economic concepts of quasi-linear utility function, and partial-equilibrium analysis [17, Ch. 10].

B_i depends on the SIR, x_i (a physical index of quality of service) . When the terminal must pay $c_i(x_i)$ for QoS level x_i, it chooses x_i to maximise $\beta_i B_i(x_i) + [D_i - c_i(x_i)]$. $\beta_i B_i(x_i)$ is the "value" to the terminal of the bits it gets to transfer over the reference period (the terminal's "benefit"), and D_i is the terminal's monetary budget. D_i is just a constant for a

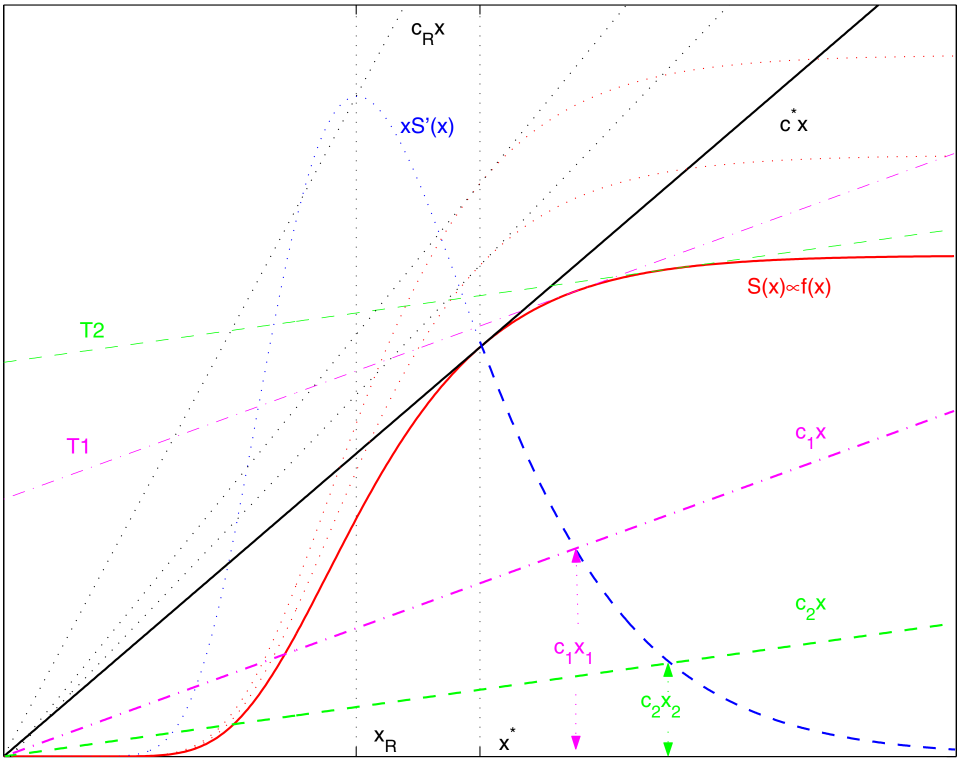

Fig. 1. Pricing for revenue maximisation: With an SIR of x, $S(x)$ represents the terminal's "benefits", or the monetary "value" of the bits it gets to transfer over a reference period. $S(x) \propto f(x)$ (the packet-success rate function (PSR)). When QoS is costly, the terminal maximises benefits minus costs, that is $S(x) - cx$. With $c = c_k$, it chooses $x = x_k$ to satisfy $S'(x_k) = c_k$ (e.g., $T1$, the tangent of S at x_1 is parallel to $c_1 x$), provided that its cost $c_k x_k$ does not exceed its "benefit" $S(x_k)$. The largest c for which the terminal will operate is c^*, the slope of the only tangent of S that goes through the origin. For $c_k \leq c^*$ network's revenues are $c_k x_k \equiv x_k S'(x_k)$ (blue dash curve). The graph $xS'(x)$ is single-peaked. With the constraint $c \leq c^*$, the curve $xS'(x)$ (revenues) is maximised at $x = x^*$ corresponding to $c = c^*$. x^* does not change when S is replaced by a multiple of S; thus, the same x^* is shared by all terminals with common PSR.

given terminal, which limits its total expenditure. If D_i is relatively "large", it needs not be considered. Thus, the terminal chooses QoS to maximise benefits minus cost:

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

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III. TECHNO-ECONOMIC RESOURCE MANAGEMENT OF A CDMA CELL

A. Optimisation problem of a network

Regardless of the spectrum regime, the network is interested in managing its spectrum efficiently. A key aspect of efficient spectrum management is pricing. Pricing is the key to revenue generation (with which spectrum can be payed), as well as a tool to encourage a conscientious use of network resources. Once the network has set an appropriate price rule, it can determine the terminals' "demand" for services, as well as the revenues that can be obtained from a given amount of spectrum. With this information, the network can then determine how much spectrum to purchase (under the scenario of [12]), or how to bid for spectrum (under the scenario of [14]). Below, we neglect the effect of the competition among networks. The monopoly analysis provides some useful "bounds": it is the "best case scenario" for the network, and the "worst case scenario" for the end-user. Additionally, this analysis is a useful approximation of the "oligopoly" situation often observed in practise, in which relatively few firms dominate the market in a given region.

B. Terminal choice under linear pricing

1) Selling power or SIR?: For a fixed amount of spectrum, it is natural for the network to charge each terminal per unit of allocated downlink power (the limited "resource" to be allocated). However, for a given bandwidth, a price per Watt can be easily converted to a price per received SIR. To see this, suppose that the terminal must pay $\hat{c}$ per downlink Watt. Since the received SIR is obtained as $x_i = G_i h_i P_i / \sigma^2$, in order to enjoy an SIR of x_i, the terminal must order $(\sigma^2 / G_i h_i) x_i$ Watts of downlink power, for which it must pay $(\sigma^2 / G_i h_i) \hat{c} x_i$. This payment can be written as $c_i x_i$ with $c_i := (\sigma^2 / G_i h_i) \hat{c}$. Likewise, the network can convert a price per SIR to an equivalent price per Watt: $\hat{c} = c_i G_i h_i / \sigma^2$. Thus, one can assume that the network charges the terminal per delivered SIR (QoS).

Notice that direct SIR-pricing is even more natural in the scenario of section IV, where it is implicit assumed that the network can buy any necessary amount of spectrum from the manager.

2) Terminal's response to linearly priced SIR: Per section II-B, the terminal chooses its received SIR x_i to maximise benefits minus cost: $\beta_i B_i(x_i) - c_i x_i$, with B_i given by eq. 1. $\beta_i B_i(x_i)$ is just a multiple of the PSR and inherits its shape. Thus, we need to understand the maximisation of an expression of the form $S(x) - cx$, where S is some S-curve.

Figure 1 illustrates the solution procedure. First, if the line cx lies entirely above S, except at the origin, the terminal should choose $x = 0$ (decline to operate), since its cost would exceed its benefit for any positive x. Otherwise, the maximising choice is a point at which the derivative of the S-curve equals c. The derivative of the S-curve is "single-peaked" (similar to the curve $xS'(x)$ shown in fig. 1). Therefore, if c is sufficiently large, no value of x can satisfy $S'(x) = c$. Otherwise, two values of x satisfy $S'(x) = c$, and the maximiser is the largest of the two, that is, the one to the right of the inflexion point of S, where the second derivative $S''(x)$ is negative.

The largest value of c for which the problem of maximising $S(x) - cx$ has a positive solution is denoted as c^*, and as shown in fig. 1, is obtained as the slope of the unique tangent line of S that goes through the origin. It is easy to see that replacing S with a multiple of S will change c^*. On the other hand, basic analytical geometry tells us that x^* must satisfy $S(x^*) = x^* S'(x^*)$, which immediately implies that replacing S with a multiple of S has no effect on the value of x^*. Thus, if S_1 and S_2 are multiple of *the same* PSR, they share the same x^* (shown also in fig. 1); that is, x^* is determined by the physical layer, through the PSR. c^* and x^* are related by $c^* = S'(x^*) = S(x^*)/x^*$

C. Optimal linear pricing

Section III-B tells us how the terminal reacts given a linear cost function set by the network. As c grows, the terminal chooses smaller values of x. Thus, a higher c may actually lead to lower network revenue. Hence, it is not obvious from the network's point of view what is the "best" c. To determine such c, the network needs to understand how its revenue varies as a function of c. In addressing this issue, we shall first assume that a single terminal is active. Subsequently, we will generalise.

1) Only one terminal : As discussed above, and illustrated by fig. 1, for a given $c_k \leq c^*$, the terminal will choose an SIR (QoS level) x_k satisfying $S'(x_k) = c_k$; that is, at x_k the tangent to S is parallel to $c_k x$ (e.g., $T1$, the tangent of S at x_1, is parallel to $c_1 x$). Then, the resulting network's revenue is $c_k x_k \equiv x_k S'(x_k)$. Thus, the network's revenue follow the curve $xS'(x)$.

The curve $xS'(x)$ has a "bell shape" (same as $S'(x)$) with a single "peak" at x_R. In principle, the network would like to drive the terminal to choose x_R, the point at which the curve $xS'(x)$ reaches its maximum. But this curve crosses S at the point x^*, which lies to the right of x_R, and it has already been established that the terminal will not operate to the left of x^* ($c > c^*$). For any $x > x^*$, $xS'(x) < x^* S'(x^*)$ as shown in fig. 1. Thus, the best the network can do is to set $c = c^*$, and receive revenue equals to

$$c^* x^* \equiv x^* S'(x^*) = S(x^*) \qquad (3)$$

The network is interested in maximising profit, not revenue. It is in principle possible that the revenue-maximising choice may differ from the profit-maximising choice, because of cost considerations. However, by setting its price to c^*, the network drives the terminal to operate at x^*, the lowest SIR which the terminal finds acceptable. The smaller the SIR, the smaller the spectrum needs (for a given power constraint). Thus, by setting a price c^* the network is both maximising revenues and minimising spectrum costs. This provides the highest achievable level of profit, while serving this terminal. But below it will become clear that it is not necessarily optimal for the network to serve a given terminal.

2) Many terminals: The analysis in the preceding section identifies clearly the revenue-maximising linear price, c^*, and the utility-maximising SIR value, x^*. But the analysis focus on a single terminal, and assumes that the network knows the terminal utility function (specifically the β coefficient, which denotes the monetary value to the terminal of a correctly transferred bit). When the $\beta's$ are known to the network, it is straightforward to extend the preceding analysis to a many-terminal situation, provided that the network can set an individual price per terminal ("price discrimination"). The case in which terminals are non-identical, but the network is forced to offer the same price to all terminals is more complex. And if the network does not know the $\beta's$, all cases (even the single-terminal one) become more complicated. Below we shall continue to assume that the network has full knowledge of the terminal's utility functions, and can set individual prices.

From the analysis summarised in the caption to fig. 1, we know that the network will choose for terminal i a price c_i^* obtained as the slope of the only tangent to S_i that goes through the origin. ($S_i(x_i) = \beta_i B_i(x_i)$ with B_i given by equation 1).

From the discussion in section III-B, we know that if the terminals share an identical PSR, f, then each S_i is a multiple of the common f, and the terminals will choose an identical SIR x^*(that is, the network will choose c_i^* such that each terminal's best response is to choose $x_i = x^*$).

D. Service priority: Revenue per Hertz

The preceding analysis indicates that all terminals (having the same link layer configuration) should operate at the same SIR value. But with fixed spectrum allocation and power constraint, it is not necessarily possible for the network to serve all terminals.

The network must allocate the available downlink power among all served terminals. For a given bandwidth, W, the allocated powers must satisfy:

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

The power constraint requires that

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

Given system parameters and the network state, it may not be possible to serve all terminals and obey constraint (5). Thus, the network must determine a service priority that specifies which terminals are served under a given network state.

Given our interest in spectrum management, we can rewrite constraint (5) as:

$$\sum_{i=1}^{N}\frac{R_i}{h_i} \leq \frac{W}{W_0} \tag{6}$$

with

$$W_0 := \frac{x^*}{\bar{P}/\sigma^2} \tag{7}$$

From constraint (6) we notice that the effect of the channel gains on resource consumption is equivalent to an "amplification" of the data rates. That is, a data rate of R_i with a channel gain h_i is (for resource usage purposes) equivalent to a data rate of $\hat{R}_i$ under a perfect channel ($h_i = 1$), where $\hat{R}_i := R_i/h_i$.

The amount of bandwidth consumed by terminal i, if served, is then:

$$W_0\frac{R_i}{h_i} \equiv W_0\hat{R}_i \tag{8}$$

W_0 is then the amount of bandwidth required by a terminal per unit of "amplified" data rate. For notational convenience, the units of measurements can be chosen such that $W_0 = 1$ (bandwidth can be measured as a multiple of W_0).

A reasonable techno-economic criterion to choose the set of terminals to be served is to choose among all the set of terminals that satisfy constraint (6), the set that yields the most revenue.

From equations (1) and (6), the revenue provided by terminal i, if served, is given by

$$\tau(L/M)f(x^*)\beta_i R_i \tag{9}$$

For a fixed link layer, shared by all terminals, the expression $\tau(L/M)f(x^*)$ is simply a constant that can be absorbed in the (time) unit. Thus, the revenue provided by terminal i if served can be written as simply $\beta_i R_i$.

A relevant piece of information that can help the network choose which terminals to serve is the amount of revenue a given terminal contributes per unit of resource it consumes, that is, its "revenue per Hertz" contribution. With convenient units, terminal's i contribution to revenue per unit of resource is simply

$$\frac{\beta_i R_i}{R_i/h_i} = \beta_i h_i \tag{10}$$

Notice that the other effect of the channel gains is to "attenuate" the "willingness to pay" of the terminals. That is, a willingness to pay of β_i with a channel gain h_i is (for priority purposes) equivalent to a willingness to pay of $\hat{\beta}_i$ under a perfect channel ($h_i = 1$), where $\hat{\beta}_i := \beta_i h_i$.

Now, with the terminals' labels such that $\beta_1 h_1 \geq \cdots \geq \beta_N h_N$, a reasonable and simple service criterion emerges: serve terminals 1 through I^*, with I^* the largest index such that,

$$\sum_{i=1}^{I^*} \frac{R_i}{h_i} \leq \frac{W}{W_0} \tag{11}$$

More formally, what the network needs to do is to choose out of all the combinations of terminals that satisfy the resource constraint, (11), the combination that maximises revenue. It turns out that such decision problem is a version of the well-known "knapsack problem". In this problem, there is a set of n items, each characterised by a "weight" and a "benefit" (measured as a positive number). The objective is to find the combination of items that maximises the sum of the benefits of the chosen items, without exceeding a total weight constraint (the "knapsack capacity"). The problem is NP-hard, but for its solution, there are many well-studied algorithms that perform well in practise [18]. In fact, the service criterion described above provides an optimal solution under two scenarios: (i) inequality (11) is (luckily) satisfied as an equality, or (ii) we are allowed to choose, in addition to terminals $1 \dots I^*$, "a fraction" of terminal $I^* + 1$ in order to use up all the available resource [19]. Notice that serving "a fraction" of a terminal can be interpreted as admitting it at a fraction of its data rate (which could very well be possible and reasonable). Further discussion of the knapsack problem and its solution is beyond the scope of the present work. Below, we assume that the "revenue per Hertz" service criterion described above is, for our purposes, sufficiently close to the optimum.

E. UWB impact

The chief technological impact of the presence of UWB PAN/BAN is an increase in "the noise floor", that is, our parameter σ^2. However, depending upon the "popularity" of the UWB networks, it is possible that some data terminals are sufficiently far from any such network, that the noise level experienced by any such terminal remains unchanged. Other data terminals may be only moderately close to UWB networks, while some others may be "surrounded" by several UWB PAN/BAN. To capture this situation, we must reconsider the preceding analysis in a model in which each terminal faces its own noise level, σ_i^2. This is tedious, but straightforward.

On the other hand, if the UWB technology becomes very popular, one can envision a situation in which all data terminals face the same level of increased noise level (wherever a data terminal goes, there are UWB networks nearby). This situation would leave the preceding analysis unchanged, except that the parameter σ^2 would represent a significantly larger value.

1) UWB impact on a given terminal: Before we understand the system-wide techno-economic impact of the introduction of UWB, we need to understand how it affects a given terminal. We first notice that the development through section III-C.1 applies unchanged. Up to that point, σ^2 is just a constant of non-specified value. This allows us immediately to conclude that, after the introduction of UWB, a "victim" data terminal :

- will operate at the same signal to interference ratio, x^* it did without UWB.
- will necessitate a higher level of downlink power (to achieve this SIR). From equation (4) it follows that the increase in power is given by (with σ_U^2 the new

noise level):

$$\Delta P_i = \frac{R_i}{h_i} \frac{\left(\sigma_U^2 - \sigma^2\right)}{W} x^* \tag{12}$$

- will consume more bandwidth per unit data rate (obtained directly from equation (7))
- will pay the network the same total amount (for a given time period). This may seem puzzling. Yet, close inspection of the preceding development shows that what the terminal pays the network equals "the value" of the bits it gets to transfer over the reference period. As long as the terminal continues to operate at the same SIR, x^*, its contribution to revenues is given by equation (9), which does not explicitly depend on the particular value of σ^2.
- The network bears the brunt of the economic impact of UWB. The terminal consumes more, but pays the same.

2) Impact at the system level (high popularity): The key system level impact of UWB on the CDMA cell is a reduction in capacity. The terminals operate at the previous SIR, but each "victimised" terminal requires more downlink power (or bandwidth) to achieve that SIR. Specifically, W_0, the amount of bandwidth required by a terminal per unit of "amplified" data rate, grows linearly with noise. This has a direct impact on the capacity constraint (6). For example, if noise power doubles, the right-hand-side of constraint (6) is cut in half.

The increase of W_0 affects all terminals equally. Thus, under the new system-wide value of noise, the ordinal service priorities (the indices of the terminals in the development leading to inequality (11)) remain unchanged. But the value of I^*, the largest index such that inequality (11) is satisfied, could register a significant drop. Thus, although each served terminal pays the same to the network as in the non-UWB scenario, the total number of terminals than can be served is lower. This leads to an exact expression for the economic loss to the network. If without UWB terminals 1 through I^* can be served, but with UWB only terminals 1 through $i^* < I^*$ can be served, then the network revenue loss has the form (with convenient units):

$$\sum_{i=i^*+1}^{I^*} \beta_i R_i \tag{13}$$

IV. SPECTRUM PURCHASE UNDER A LINEAR PRICE REGIME

With the results obtained in section III one can easily obtain the optimal amount of spectrum that the CDMA network should purchase if it can obtain any desired amount at a unit price (as in [12]).

A. Which terminals to serve

Although now the network can presumably purchase any desired amount of spectrum, say at a unit cost of κ, depending upon the value κ, and the willingness to pay of the terminals, it may not make sense to serve certain terminals.

Terminal i contributes revenue of $\tau(L/M)f(x^*)\beta_i R_i$ (equation (9)), but consumes bandwidth $W_0 R_i/h_i$. This terminal should be served only if its contribution to revenue exceeds the cost of serving it. This condition can be expressed in several ways to facilitate interpretation. With spectrum sold at a unit price, the terminal should be served only if its contribution to revenues per unit of spectrum usage exceeds the unit cost of spectrum. That is, terminal i should be served, only if

$$\tau \frac{\bar{P}}{\sigma^2} \frac{L}{M} \frac{f(x^*)}{x^*} \beta_i h_i \geq \kappa \tag{14}$$

Of course, for given power parameters and link layer configuration, the units can be chosen so that the admission takes the simpler form: "serve terminal i only if $\beta_i h_i \geq 1$".

Again, it makes sense to label the terminals so that $\beta_1 h_1 \geq \cdots \geq \beta_N h_N$. Then, only terminals 1 through J^* should be served, with J^* the maximal index whose terminal satisfies the admission condition.

B. Spectrum purchase

The optimal amount of spectrum is the minimum amount that allows the service of all of those terminals that passed the admission criterion. It can be directly obtained with inequality (6) taken as equality, as :

$$W^* = W_0 \sum_{i=1}^{J^*} \frac{R_i}{h_i} \equiv \frac{x^*}{\bar{P}/\sigma^2} \sum_{i=1}^{J^*} \frac{R_i}{h_i} \tag{15}$$

C. Network profit

The difference between total revenue and total cost yields the network's profit. If we only consider spectrum-related cost, the network's profit is given by (with monetary units such that $\tau(L/M)f(x^*) = 1$):

$$\sum_{i=1}^{J^*} \left(\beta_i R_i - \kappa W_0 \frac{R_i}{h_i} \right) \equiv \sum_{i=1}^{J^*} (\beta_i h_i - \kappa W_0) \frac{R_i}{h_i} \tag{16}$$

D. Link layer configuration

The left-hand-side of (14) provides an interesting piece of information. The product of ratios $(L/M)f(x^*)/x^*$ is entirely determined by the link layer configuration (modulation/coding). If several such configurations are available, other things being equal, the configuration that yields the maximal product $(L/M)f(x^*)/x^*$leads to maximal revenue per Hertz.

E. UWB impact

Unless otherwise indicated, the conclusions of section III-E continue to apply.

Under the present regime, a terminal is directly impacted through the admission condition (14). An increase in σ^2 reduces the left-hand side of (14). Thus, an originally admissible terminal may become inadmissible after UWB becomes active. Therefore, the index $J^*$of (15) may decrease.

It is not clear how the optimal amount of spectrum given by (15) varies. On the one hand, fewer terminals may be served. But on the other hand, the amount of spectrum consumed by any served terminal will be larger (because W_0, spectrum consumed per unit data rate is now larger).

Equation (16) reveals the impact on network's profit. First, if fewer terminals are served, the sum contains fewer (positive) terms, leading to a lesser total. Additionally, an increase in σ^2 leaves revenues unchanged, while increasing W_0. Thus, the profit derived by the network from each served terminal (each term inside parenthesis in (16)) decreases. The difference in the profit obtained from servicing terminal i can be written as (with σ_U^2 the new noise level) :

$$\kappa \frac{x^*}{\overline{P}} \left(\sigma_U^2 - \sigma^2 \right) \frac{R_i}{h_i} \tag{17}$$

V. AUCTION-DRIVEN DSA

Selling spectrum at a unit price seems plausible, for instance, when the state wants to allocate the spectrum reasonably efficiently without a significant concern for revenue, and when there is a relatively large number of spectrum buyers, none with enough power to influence the "market clearing price". Auctions appears to be a more reasonable arrangement in other cases. Choosing the "best" auction format to perform DSA can itself be the object of research. Below we assume that the interested parties has settled on a format in which it is optimal for each selfish participant to submit a bid that equals its true "valuation" of a short-term spectrum license. One such format is the multi-unit version of the auction proposed by [20].

A. Multi-Unit Vickrey Auction

The multi-unit second-price (Vickrey) auction when applied to spectrum allocation works as follows. The available spectrum is divided into K bands, each of width w. We assume that a network cares about *how many* but not *which* bands he is assigned (all bands are equally good for the considered radio access technologies). Each network submits a bid vector with K components. The first component means how much the bidder offers to pay for the first band *assigned* to him (whichever it is). The kth component means how much he offers to pay for an *additional* band if $k-1$ bands have *already been assigned* to him. The spectrum manager receives all the bid vectors and assigns the bands as follows: first, the top overall bid (by looking at the components of all bid vectors) gets one band, the second highest bid wins the next band, and so on, until the K bands have been assigned. Notice that the overall highest and the second highest bids could be components of *the same* vector. Thus, the first several bands (possibly all) could go to the same bidder. A critical detail is that what a winner pays for a band depends on the *losing* bids of the opponents. For the first won band, a bidder will pay the highest *losing* bid submitted by the other bidders; for the next won band, he will pay the *second-highest losing* bid (excluding his own), and so on. Thus, a bidder that has won k bands, will pay the sum of the *k highest losing* bids submitted by *the other* bidders. (Ties are broken at random).

For example, let $K = 3$. A bid (b_1, b_2, b_3) means: I offer to pay b_1 if I *end up* with a *total* of one band allocated to me (I don't care which one), I offer $b_1 + b_2$ for a *total* of two bands, and I offer $b_1 + b_2 + b_3$ for all 3 bands. Suppose that only two bid vectors are submitted: b^1= (5, 3,2) and b^2=(4.5,4,1). The assignment goes as follows: one of the bands goes to bidder 1 (5 is top overall bid), the next band goes to bidder 2 (second highest bid is 4.5), the last band also goes to bidder 2 (the third highest bid is 4, the second component of b^2). Since bidder 1 won only one band, he will pay the highest *losing* bid submitted by bidder 2, which was 1. Bidder 2 won two bands, and will pay the sum of the two highest *losing* bids submitted by bidder 1, that is, 3+2=5. Thus, the auctioneer will get a total of 6.

B. Optimisation problem of a network

The main question the network must answer is how much to bid for spectrum at a given DSA period. At the moment of bidding, the network will know (or have a reliable prediction) of the number and characteristics of the terminals wishing to (continue to) operate, including the details of the physical communication layer (modulation, error-control coding, mode of diversity, etc). A distinguishing feature of the chosen auction format is that the bidder "best response" is to bid his "true valuation" of the object being auctioned. This implies that the first component of a bid vector should equal the maximal revenue that the network could obtain if it gets a single band of spectrum (and nothing else). The second component should equal the *extra* revenue it would get if instead of only one band, it gets a total of two, etc. But the network's revenue also depends on its own pricing policies. Thus, the network must determine its own (internal) pricing policy along with the bid. Both can be determined on the basis of the analysis in section III.

In determining a network's end-user pricing, we continue to neglect, the competition among networks. This analysis may be a useful approximation of the situation often observed in practise, in which relatively few networks dominate a given region in the provision of specific data services.

C. Optimal SIR and Optimal Price

In order to determine its bid, the network must find the maximal amount of revenue that it can obtain from the various possible amounts of spectrum it may win. But section III tells us precisely how to price a fixed amount of spectrum for revenue maximisation, and in which order to arrange the terminals for service. Thus, the network just needs to apply the results of section III, with W equal to the pertinent amount of spectrum (for a single band $W = w$).

D. Service priority and Bidding

1) Service priority: revenue per Hertz: The analysis and results of section III-D continue to apply. Terminals should be served in the order of their "revenue per Hertz". With the terminals' labels such that $\beta_1 h_1 \geq \cdots \geq \beta_N h_N$, the service criterion is simple and clear: serve terminals 1 through I_1^*, with I_1^* the largest index such that,

$$\sum_{i=1}^{I_1^*} \frac{R_i}{h_i} \leq \frac{w}{W_0} := \bar{w} \tag{18}$$

2) Bidding: The preceding subsection tells us immediately what the network should offer for a single band (the first component of the bid vector), namely $\sum_{i=1}^{I_1^*} \beta_i R_i$ (with convenient units, terminal i contribution to revenue is $\beta_i R_i$). To know how much to bid for an additional band, the key is to determine the additional terminals that can be served, which would tell us the additional revenue brought by the band. Assuming that the chip rate can be adjusted to match a larger bandwidth (this is *not* strictly necessary), we can multiply the right-hand side of constraint (18) by two, and obtain I_2^* as the largest index that can satisfy the new constraint, meaning that terminals $I_1^* + 1$ through I_2^* could now be served. Likewise, we can determine that terminals $I_2^* + 1$ through I_3^* could additionally be served with a third band, and so on. Then, the jth component of the bid has the simple form (with $I_0^* := 0$)

$$\sum_{i=I_{j-1}^*+1}^{I_j^*} \beta_i R_i \tag{19}$$

and represents the contribution to revenues of the additional terminals that can be served if the jth band is won.

For example, suppose there are 3 total bands and a particular network has 6 active terminals. With labels such that $\beta_1 h_1 > \cdots > \beta_6 h_6$ (terminal 1 offers the most "revenue per Hertz", if served), a bid vector has the form:

$$\left[\begin{array}{ccc} \beta_1 R_1 + \beta_2 R_2 & (\beta_3 R_3 + \cdots + \beta_5 R_5) & \beta_6 R_6 \end{array} \right] \tag{20}$$

Thus, this network would serve terminals 1, and 2 if it wins at least one band (the "spectrum consumption" of these terminals, $R_1/h_1 + R_2/h_2$, uses up a spectrum band). If the network wins two bands, terminals 3, 4 and 5 would also be served (the sum $R_3/h_3 + R_4/h_4 + R_5/h_5$ uses up another spectrum band). The sixth terminal would only be served if the network wins all 3 bands.

E. Impact of UWB

Unless otherwise indicated, the conclusions of section III-E continue to apply. The optimal operating point (the SIR x^*) is determined by the link layer, and does not change after a raise in the noise level. The total payment by a terminal over a reference period of time equals the value of the bits it gets to transfer. This value remains unchanged by UWB, because the service SIR remains unchanged. The chief impact of UWB on the auctions can be seen through constraint (18). A raise in the noise level, raises W_0 (bandwidth consumed per unit data rate), decreasing the right-hand-side of (18). Thus, fewer terminals can be served if the band is won.

The network bids equals the revenue contributed by all served terminals. The revenue contribution of any such terminal is unchanged by UWB. But the network loses the revenues of the terminals not served, which is reflected in the network's bid for the concerned band. If all networks face an analogous situation, all bids will be lower, which will reduce the auctioneer's revenues.

For example, after UWB becomes active, bid (20) may have to be modified as:

$$\left[\begin{array}{ccc} \beta_1 R_1 & (\beta_2 R_2 + \beta_3 R_3) & (\beta_4 R_4 + \beta_5 R_5) \end{array} \right] \tag{21}$$

In the redone example, only terminal 1 fits in the first band. Now, terminal 2 can be served (together with terminal 3) only if a second band is won. And if all bands are won, terminals 4 and 5 are additionally served. Terminal 6 cannot now be served. The total amount bid by the network is obviously lower, as is the value of the first component.

VI. DISCUSSION

We have revisited and extended previous work on techno-economic spectrum management. Our approach has been to examine how certain critical expressions change after a rise in the noise level (the chief technological effect if UWB personal/body area networks become wide spread). The general context has been that of a market-driven dynamic spectrum allocation regime, where networks acquire (through bidding or direct purchase) spectrum licenses for short term use. But before analysing the DSA regime, we discussed the techno-economic management of a CDMA cell with a fixed spectrum allocation. The fixed-spectrum discussion is relevant to present day networks.

Section III-E contains the core of our conclusions. The operating point of the data terminals operating on the downlink of a CDMA cell is unaffected by UWB. In turn, this implies that their contribution to network revenues remain unchanged. Thus, the network bears the brunt of an increase in noise resulting from UWB, because the network can fit fewer terminals in a given amount of spectrum, yet receives an unchanged amount of revenues from those terminals it serves.

This analysis is more relevant to a situation where UWB PAN/BAN are highly popular. In this scenario, the CDMA data terminals face increase noise regardless of their location. If the UWB networks are very disperse, then their effect would be minimal: most times, most CDMA terminals will be sufficiently far from an UWB network not to be significantly affected.

Our development has been so far entirely analytical. However we continue to examine recent experimental work on the technological impact of UWB PAN/BAN on UMTS terminals. On the basis of such experimental work we hope to provide numerical illustrations in future versions of this work.

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