Market driven dynamic spectrum allocation over space and time among radio-access networks: DVB-T and B3G CDMA with heterogeneous terminals

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Abstract— **The radio frequency spectrum is a naturally limited resource of extraordinary value, as the key to the provision of important communication and information services. Traditionally, spectrum has been allocated first to specific access technologies, and then sub-allocated to specific access networks, on very long term basis (up to decades). The traditional scheme can be very inefficient when demand patterns ("loads") exhibit high temporal and spatial variations. Dynamic spectrum allocation (DSA) improves radio spectrum efficiency by adjusting the allocation as demand changes in time and/or space. In previous work, we introduced a DSA scheme in which a spectrum manager periodically auctions short-term spectrum licenses. The scheme can be supported by a realistic "pooling" business model, and can work with many radio-access technologies. But our previous analysis only considers a code-division multiple access (CDMA) technology; and DSA provides the greatest benefits with the participation of networks having complementary "busy hours", such as video entertainment services and cellular telephony. Here, a digital video broadcast (DVB) terrestrial network joins the scheme. A typical DVB terrestrial cell is (much) larger than a UMTS cell. This brings to the forefront inter-cell interference, and inter-related auctions in different cells. To capture the essence of these issues we focus first on a situation where one DVB terrestrial cell overlays two adjacent CDMA cells. Subsequently we discuss extensions to richer scenarios. The contributions of the present work over our previous publications include to : (i) address the impact of inter-cell interference among several CDMA cells, (ii) introduce the DVB access technology into the DSA scheme, (iii) modify the auction scheme to consider that a DVB cell overlays several CDMA cells, (iv) characterise analytically the marketing and bidding behaviour of the DVB network.**

I. Introduction

Over 22 billion Great Britain pounds were raised by the British Government in a recent auction of 5 licenses covering the relatively small fraction of the radio spectrum devoted to UMTS services. That is an enormous amount of money by many measures. For instance, it is equivalent to $2\frac{1}{2}\%$ of the United Kingdom's gross domestic product (GNP) at the time, and enough to build 400 hospitals [1]. This fact highlights the extraordinary social and economic value of the radio spectrum. Its enormous value stems from its inherent scarcity, and from the importance of current and future services that depend on it .

A scarce and highly valuable resource needs to be managed very efficiently. However, traditional spectrum management can be very inefficient. Current practise is to allocate a segment of the spectrum to a specific radio access technology (e.g., TV broadcast, 2nd-generation digital telephony (GSM), UMTS, etc.) on a long-term basis. The fraction of the spectrum allocated to an access technology is further divided among individual licensees, who commercialise services based on the specific technology. The licenses are awarded on long term basis (up to decades), and may cover a very large geographical area, such as an entire country. Such static (fixed) long-term spectrum allocation can be very inefficient in the presence of service demands that vary highly along the space dimension (from region to region) and/or along the time dimension (from hour to hour). For various reasons, under a traditional spectrum allocation regime, at a given time and place a network may be lightly loaded, whereas another may be congested to the point it is forced to under-supply or decline service requests from paying customers. Dynamic spectrum allocation (DSA) seeks to exploit the variations in the "loads" of various networks to allocate the spectrum efficiently, as needs change with time and/or space.

In [2], we introduce a scheme in which a spectrum manager implements DSA by periodically allocating short-term spectrum licenses, through economic tools. Just before the start of a DSA period, a network operator acquires spectrum rights, on the basis of the current state of its network. But all the awarded spectrum licenses

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simultaneously expire at the end of a specified short period, after which the allocation process is repeated.

It is clear that a government agency could become the spectrum manager mentioned above. But this scheme can also be supported by a realistic "pooling" business model. Spectrum owners in a geographical demarcation could create a “spectrum managing firm”. They could transfer their spectrum rights to the managing firm, while maintaining ownership of this firm. And they may instruct the firm to use economic tools to allocate short-term spectrum rights to the original spectrum owners themselves, (and, possibly, to other communication firms that they may approve). Of course, the managing firm’s profits would eventually be distributed among its owners (the original spectrum licensees themselves).

In [2] we take the simplifying view that the spectrum manager sells spectrum at a unit price (presumably the one that makes demand equal supply). Such arrangement may be plausible under certain scenarios, 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 appear to be a more reasonable arrangement in other cases. Thus, in [3], the spectrum manager utilises auctions, instead. Choosing the “right” auction format can itself be the object of research. However, [3] assumes that the interested parties have voluntarily adopted the multi-unit version of the auction proposed by [4]. In the original “second price” or Vickrey auction, “sealed bids” are submitted for an object. The highest bidder wins, but pays an amount that equals the highest *losing* bid. It is well known that, in this auction, an agent’s optimal bid equals the value that the object has in the bidder’s “own mind”. In practise, special provisions must be made to avoid certain types of malicious behaviour under this or any auction format. Along this line, a relevant discussion can be found in [5].

Our DSA scheme can be implemented in the presence of many radio-access technologies. But in our previous work, all participating networks utilise a code-division multiple access (CDMA) technology. This is a significant limitation, because DSA is most beneficial when networks that exhibit complementary demand patterns (“opposite busy hours”) participate. Examples of such networks are those operating under the DVB-T and UMTS standards. Presumably, the demand for video-broadcast entertainment is highest when the demand for wireless telephony is relatively low, and vice versa. Thus, in [6] we add the presence of a DVB-T network to the situation analysed in [3]. But even a simple model of DVB-UMTS interaction must account for the fact that generally many UMTS cells can fit inside a single DVB cell (20 UMTS cells per DVB-T cell in [7]). Reference [6] focuses on the simplest non-trivial model capturing this issue : a “two island” geography, in which *each* CDMA network has one cell per island, but a single DVB-T cell covers both islands. It eventually becomes transparent that extending the analysis to consider certain, much richer scenarios is straightforward.

Even in the 2-island, 2-access-technology world, there are two significant challenges which do not arise in [3]: (i) inter-cell interference, and (ii) concurrent, interrelated auctions in different cells. Reference [3] focuses on one “small island”, which every participating network can serve with a single-cell system. As it turns out, the results of [3] for the downlink of a single CDMA cell can be applied to a system of many “small islands”, under a UMTS-like two-layer-spreading interference-control scheme [8]. Under such scheme, a given frequency band may be allocated to different CDMA networks, even in adjacent cells, provided the long spreading code used by a network for a given cell is *not* re-used by any network operating in the same frequency band in a neighbouring cell. Thus, among CDMA networks, we can conduct our auctions in parallel, independently, one auction per island (cell). But with a DVB cell covering both islands, the DVB network cannot consider both auctions independently. This is so, because a license to use a spectrum band over one island has no value to the DVB network unless it comes with a license to use the same band over the other island. That is, for the DVB network, both licenses are “perfect complements” (one has no value without the other). Dealing with this “perfect complementary” is a significant objective of the present work.

The present work builds upon [6]. Below, we first address similarities and differences between our proposal and other approaches to spectrum management available in the scientific literature. Subsequently, we describe the auction format to be used. Next, we summarise the results of [3], for CDMA networks competing in a “small island”. Subsequently, we address the two key issues at the core of the present work: (i) inter-cell interference control, and (ii) the “perfect complementary” issue. Afterwards, we characterise the bidding behaviour of a participating DVB-T network. After addressing briefly implementation issues, the final part of the paper discusses our results, and addresses possible extensions, and future directions.

II. Connection to alternative spectrum management proposals

The efficient management of the radio spectrum has attracted many proposals which could be termed "dynamic spectrum allocation", under some interpretation or another of this phrase. For instance, almost 100 works were presented in [9], and most, if not all, could be considered to involve some form of (or at least be relevant to) dynamic spectrum allocation. The present work is a specific dynamic spectrum management proposal, as opposed to a comprehensive survey of this literature. Thus, we shall primarily focus on those works we deem most relevant to ours.

Distinguishing features of our proposal that help differentiate it from related alternatives is that it (i) is based on licensed (as opposed to open/free) spectrum usage, (ii) focuses on the allocation of the spectrum among access networks (that is, from regulator/manager to network, as opposed to from regulator or network to end users), (iii) allocates spectrum via market tools, and (iv) is oriented to network architectures that are significantly similar to present ones (UMTS, DVB-T). In fact, the present proposal has strong similarities with auction-based spectrum allocation as done today, with two main differences: (i) the duration of the licenses (years or even decades versus minutes, or seconds in our proposal), and (ii) the fact that spectrum bands are not pre-reserved for a specific access technology (networks with different access technologies compete to win a share of the same block of spectrum). The present proposal is most similar to, and historically evolved from [10]. Important differences between [10] and the present work include: (i) our emphasis on a market-driven solution, as well as our consideration of (ii) data-transmitting terminals over CDMA, (iii) physical layer issues, and (iv) the value of the service to a user ("willingness to pay"). Our suggestion of the creation by spectrum licensees of an intermediary firm owned by them to serve as spectrum manager (in fact becoming a facilitator of real-time spectrum license trade as advocated and motivated by [11]) has connections to both previous and more recent work. The "joint spectrum management consortium" discussed in [12] seems to develop and extend the same idea further. Both the spectrum broker of [13], and the spectrum policy server of [14] have a role similar to that of our spectrum manager, offering also spectrum for short-term usage. The spectrum manager scheme is also related to "spectrum pooling" as discussed in [15]. The related idea of "real-time secondary markets" is proposed by [16], with a license holder (a GSM operator) selling to a low-priority user the right to use portions of the licensed spectrum at those moments when the quality-of-service requirements of both can be met. Similarly, in [17], an "ad hoc secondary network" utilises the bandwidth left unused by a cellular system.

Additionally, there are several works that apply Vickrey-like schemes in relevant contexts. For instance, [18] makes a similar proposal for bandwidth allocation in a wired network (which [19] later applies to CDMA power control). But [18] assumes that each bidder can choose "bands" of an arbitrary width, which complicates implementation and analysis. Reference [20] applies auctions for medium-access control, and allocates sub-carriers in an OFDM environment. Reference [21] studies auctions involving signal-to-interference-ratio and power in spread-spectrum systems.

We now provide a panoramic view of the literature addressing general radio spectrum"policy". Reference [22] discusses some of the general approaches that have been employed or can be considered for the management of the radio spectrum, and summarises the main advantages and disadvantages of the alternatives. Some of the economic tools available to the spectrum manager (such as auctions, economic value analysis, trading, etc) are discussed in [23] and [24]. Strategic planning for spectrum management is addressed by [25], which advocates four fundamental principles: (i) market driven allocation, (ii) competitive service promotion, (iii) regulatory flexibility and technological advances, and (iv) international coordination. After discussing the inefficiencies caused by "administrative" allocations of the spectrum, [26] argues forcibly for spectrum management based on property rights, provides some key "building blocks" for implementing this approach, and describes specific applications of this approach in Guatemala and New Zealand. The building blocks provided by [26], which should lead to a "working market in tradable spectrum permits", are: (a) right to property, interpreted as right to sell, fragment or lease, (b) right to use as opposed to right to provide service, and (c) prevention of "trespassing", i.e., causing undue interference. By contrast, [27] holds the provocative view that advances in technology, in particular "intelligent" radios such as those introduced in [28], will make "open" (unlicensed) spectrum the most efficient allocation. To combat congestion in the open spectrum, [27] proposes a user-run "clearinghouse" to adjust instantaneous prices, depending upon demand in a specific time, place and spectrum location. Also concluding that there are reasons to believe that unlicensed operation may be the most efficient spectrum allocation, [29] presents an engineering/economic argument grounded on the advantages of combining intelligent radios with a "peer-to-peer" network architecture supporting multi-hop routing. Reference [30] follows the general approach of [29] in seeking, from an economics viewpoint, answers to the questions of when is a policy of open spectrum more efficient than one based on licenses, and how to set up an efficient market for licensed spectrum.

III. The basic multi-unit Vickrey auction

The choice of the "best" auction format to perform dynamic spectrum management can itself be the object of research. However, as in our previous work, we assume that the interested parties have voluntarily adopted a format based on the multi-unit version of the auction proposed by [4].

The multi-unit second-price (Vickrey) auction, when applied to spectrum allocation over one cell, works as follows. The available spectrum is divided into K "small" bands, all of the same width. It is assumed that a participating radio-access network cares about *how many* but not *which* bands it is assigned (all bands are equally good for the participating radio access technologies). Each network submits a vector bid with K components. The first component means how much the bidder offers to pay for the first band *assigned* to the bidder (whichever band it is). The kth component means how much the bidder offers to pay for an *additional* band if $k-1$ bands have *already been assigned* to this bidder. The spectrum manager receives all the bid vectors and assigns the bands as follows: first, the top overall bid gets one of the bands. Next, the second highest overall bid (by looking at the components of all bid vectors) wins another band. And so on, until the K bands have been assigned. If necessary, ties are broken at random. Notice that several winning bids could be components of *the same* vector. Thus, several bands (possibly all) could be won by the same bidder.

A critical detail in the Vickrey scheme is that what a winner pays for a won band is determined, *not* by the winning bid, but by the *losing* bids of its opponents. Thus, for the first won band, a bidder pays the highest *losing* bid submitted by the other bidders; for the next won band, the bidder pays the *second-highest losing* bid submitted by others, and so on. Thus, a bidder that has won k bands pays the sum of the k *highest losing* bids submitted by *the other* bidders.

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 proceeds as follows: one of the bands is assigned to bidder 1 (5 is the highest bid, over all components), the next band is assigned to bidder 2 (second highest (component) bid is 4.5), the last band is also assigned to bidder 2 (the third highest bid is 4, the second component of b^2). For the only band won by bidder 1, it must pay the highest *losing* bid submitted by bidder 2, which was 1. Bidder 2 won two bands, and must pay the sum of the two highest *losing* bids submitted by bidder 1, that is, 3+2=5. Thus, the auctioneer receives a total of 6.

IV. The single CDMA island: Recapitulation

In [3], we focus on a "small island" served by several CDMA radio-access networks (each network covering the island with a single-cell system). Our DSA scheme is applied to the downlink spectrum (presumably the spectrum devoted to uplink communication is managed by other means). A "spectrum manager" periodically auctions short-term spectrum licenses, as described in section III. Each network is populated by delay-tolerant data terminals. A terminal is characterised by its data rate, R_i, channel gain h_i, and "willingness to pay", β_i (the most the terminal would pay for a successfully transferred information bit).

The interests of the network (maximising profit) and terminals (maximising utility, which is defined as benefit minus cost) meet at a specific operating point: the signal-to-noise ratio x^*. This is a specific value easily found by drawing from the origin a tangent to the graph of the packet success rate function (the packet success rate equals one minus the packet error rate).

Employing convenient units of measurement, at the optimal operating point, a served terminal's contribution to revenues is $\beta_i R_i$, the amount of "effective spectrum" it consumes is R_i/h_i, and its "revenue per Hertz" service priority is $\beta_i R_i \div (R_i/h_i) = \beta_i h_i$. The network optimal bid for a (an additional) band of spectrum, takes the simple form $\sum \beta_i R_i$, with the sum covering the (additional) terminals that could be served, if the band is won.

For example, suppose there are 3 total bands and a particular network has 6 active terminals. For notational convenience, suppose also that $\beta_1 h_1 > \cdots > \beta_6 h_6$ (hence, terminal 1 offers the most "revenue per Hertz", if served). A bid vector may look like :

$$\left[\ (\beta_1 R_1+\beta_2 R_2+\beta_3 R_3) \quad (\beta_4 R_4+\beta_5 R_5) \quad \beta_6 R_6\ \right] \quad (1)$$

Thus, this network would serve terminals 1,2, and 3 if it wins at least one band (the "spectrum consumption" of these terminals, $R_1/h_1+R_2/h_2+R_3/h_3$, does *not* leave room inside a spectrum band for additional terminals). If the network wins two bands, terminals 4 and 5 would also be served (the sum $R_4/h_4+R_5/h_5$ uses up another spectrum band). The sixth terminal would only be served if the network wins all 3 bands.

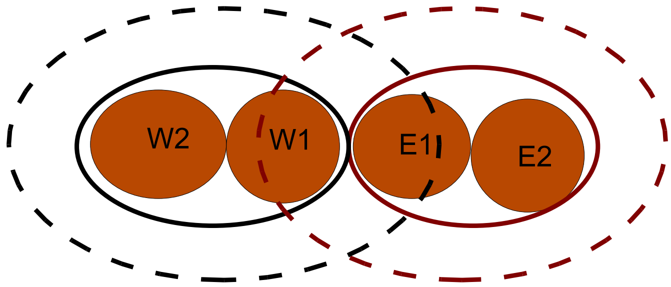
V. Multi-cell considerations

A. Geographical scenario

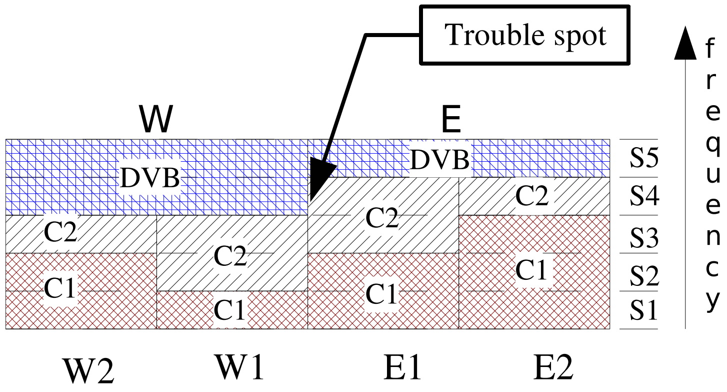
Figure 1 depicts schematically a plausible spectrum allocation along the space dimension, over four neighbouring small islands: E1, E2, W1 and W2. Two CDMA networks (C1 and C2) are active, each having its own cell per island. A DVB network is active over 2 "large" cells: E and W, covering respectively the eastern and western islands. The diagram shows a plausible allocation of 5 spectrum bands at a moment in time. For example, S1 is allocated to C1 in all 4 islands, whereas the DVB network has S5 over the entire system, with other bands changing hands along the space dimension. Assigning a band to a CDMA network system-wide is the usual situation in CDMA ("reuse factor of 1"). Assigning a given band to contiguous DVB-T cells presents no difficulties if both base stations transmit the same information ("single frequency network"). Other cases could be more complicated. For instance, in this example, band S4 is being allocated to DVB on the West, but to CDMA on the East. Such arrangement may be tolerable only under special circumstances, such as when all terminals operating on this band in the neighbouring cells happen to be near their respective base stations, or far from the conflicting border. Another possibly troublesome spot on the same boundary as before involves band S2, which is assigned to C1 on the East side, but to C2 over island W1. However, as discussed below, this latter case can be dealt with via a UMTS-like interference-control scheme.

B. UMTS interference control

In a UMTS system, two-layered spreading is used, in which a shorter and a longer spreading sequence are applied sequentially. A user's binary data stream is first multiplied by the shorter spreading sequence (such as a Walsh code), which is orthogonal to the spreading sequence assigned to any other user in the given cell. Subsequently, the already-spread signal is multiplied by the longer spreading code, which is a pseudo-noise sequence shared by all users in a given cell, but different from cell to cell [8]. Under this scheme, the fact that the same frequency band may be allocated to different UMTS networks in adjacent cells may not cause any significant problem. However, the long code used by a network for a given cell may *not* be re-used by any network operating in the same frequency band in a different cell. These longer sequences are quite plentiful (for example Gold codes); thus, their availability should *not* become a limitation.



(a) Planar view. The solid-line ovals represent DVB cells, and the broken-line ovals denote the region where interference from the corresponding cell can be sensed.



(b) Schematic digram showing a conceivable, but problematic, spatial spectrum allocation of 5 spectrum bands at a moment in time.

Fig. 1. Four neighbouring small islands: E1, E2, W1 and W2. Two CDMA networks (C1 and C2) are active, each having its own cell per island. A DVB network is active over 2 "large" cells: E and W, covering respectively the eastern and western islands.

VI. DSA auctions with two radio-access technologies

Let us focus on only one half (say the West side) of figure 1. There are two small "islands". Each CDMA radio-access network has a cell per island, but a single DVB-T cell covers both islands. In view of the discussion on UMTS interference control in section V-B, without the presence of DVB, we could conduct parallel independent auctions, one for each island (cell), allowing the possibility that a band assigned to a given CDMA network in one island be assigned to a different CDMA network in an adjacent island. Thus, among CDMA networks, dynamic spectrum auctions of downlink spectrum can be conducted in parallel, in such a way that spectrum is allocated on a "cell by cell" fashion. But with a DVB network servicing both islands with a single cell, the allocation scheme of [3] must be modified. The DVB network has no use for winning a band on only one auction.

A. Bids

Below, we address separately the bidding behaviour of the CDMA and the DVB networks. We again assume that the entire system consists only of the West side of figure 1.

1) CDMA bids: From the standpoint of the CDMA networks, there are two independent auctions, one covering island W1 and the other covering island W2. Each parallel auction works as described in section III. Each CDMA network submits independent vector bids to each auction as discussed before. That is, the CDMA network treats each auction as if it was the only one, separately taking into account the active terminals in each island, and producing bids as discussed in section IV for a single auction.

2) DVB bids: The DVB network submits a vector bid to the system, at the same time as the CDMA networks. It is understood that what a DVB network offers for a band involves its exclusive use over both islands, simultaneously. The process by which the DVB network generates its bids is discussed in section VII.

B. Allocation

The system receives a vector bid from each CDMA network interested in exclusive use of spectrum bands over island W1. The system also receives a vector bid from each CDMA network interested in spectrum bands for use over island W2. And the system receives a vector bid from the DVB network which wants to use any given band over both islands, simultaneously.

1) Intuition: The intuition of the allocation process is easier to capture when there is only one band available (vector bids are of length one). Over each island, the highest CDMA bidder is declared the "interim" winner of the band. These two interim winning bids are added and the result is treated as a "CDMA bid". This bid is compared to the (highest) DVB bid, and the technology providing the highest bid wins the band.

When many bands are available, they are allocated sequentially, one by one, following a procedure similar to that described in section III. Each band is treated, when it is its turn to be allocated, as the only band was treated in the previous paragraph: (i) interim CDMA winners are declared per island (by considering in each island the CDMA bids that have not yet won any band in previous rounds), (ii) the interim winning bids of the current round are added, and (iii) this sum (the current "CDMA bid") is compared to the highest DVB bid (of those that have not won in previous rounds) to determine which technology wins the current band.

TABLE I

DATA FOR THE ALLOCATION PROCESS IN THE 2-ISLAND 2-TECHNOLOGY SPECTRUM AUCTION

b1	by	b2	by	CDMA	DVB
5	**C1**	**4.5**	**C2**	**9.5**	**8**
4.5	**C2**	**4**	**C2**	**8.5**	6.5
4	C2	3	C1	7	4.5
3.5	C1	2.5	C1	6	-
2	C1	2	C1	4	-
1	C2	1	C2	2	-

2) Formal specification: More formally, in each island the components of the bid vectors are sorted, to form a "column" vector of bids in descending order. These two column vectors are added, resulting in a new column vector of "CDMA bids". The highest "CDMA bid" is compared to the highest DVB bid, and the technology providing the highest of these two bids is allocated the first band. If CDMA is the winner, each of the two CDMA bidders (one per island) that make up the winning CDMA bid ("interim winners") receives a licence to use the concerned band in its respective island.

To allocate the next band the process described in the preceding paragraph is repeated, with only one change: the winning bids of the previous round are not considered. The process continues recursively until all bands have been allocated.

3) Numerical illustration: The process is further clarified through an example. Let there be $K = 3$ bands. Suppose that only two CDMA bid vectors are submitted for spectrum use over island W1: b^{11}= (5, 3.5,2) and b^{21}=(4.5,4,1). Suppose also that two additional CDMA bids are submitted in parallel for spectrum use over island W2: b^{12}= (3, 2.5,2) and b^{22}=(4.5,4,1). Finally, suppose that the DVB network submits a bid b^3=(8,6.5,4.5). It is convenient to organise the information in tabular form.

In table I, columns b1 and b2 contain the sorted CDMA bids in islands 1 and 2 respectively. The "by" column specifies the network that made the bid to the left. The "CDMA" column contains the "CDMA bids" (obtained by adding column vectors b1 and b2), and the final column contains the sorted DVB bids.

The assignment proceeds as follows: over W1, the first band is preliminarily assigned to C1 (5 is highest bid over W1), while over W2, the "interim" winner of the first assigned band is C2 (4.5 is top bid). These assignments could be overruled if the highest DVB bid exceeds the *sum* of the preliminarily winning bids, which is 5+4.5=9.5. But the top DVB bid is only 8. Therefore, the preliminary assignments of one band to C1 over

W1 and one band to C2 over W2 are *confirmed*. The process is replicated for the assignment of another band. Over W1, the next band is temporarily assigned to C2 (4.5 is the highest CDMA bid that has not yet won anything). Over W2, the next band is also temporarily assigned to C2 (4 is highest remaining CDMA bid). Thus, "CDMA" offers a total of 4.5+4=8.5 for a band over both islands. The top DVB bid continues to be 8. Thus, the preliminary assignments are again confirmed. For the final band, C2 is the interim winner over W1 (4 is highest remaining bid); while over W2 C1 is the interim winner (3 is highest remaining bid). Thus the "CDMA bid" for the last band is 4+3=7. But now the preliminary assignments are overruled because the highest remaining DVB bid continues to be 8. Therefore, the final band is assigned to the DVB network.

To recapitulate, in the first "round" CDMA network C1 obtained 1 band for use over W1, while CDMA network C2 obtained one band for use over W2. In the second "round" C2 won a band each over W1 and W2. In the final pass, the DVB network won the remaining band for use over its 2-island cell.

C. Payments

Payments should be in the spirit of the original Vickrey multi-unit auction (section III). The fundamental guiding principle is : a bidder that has won k bands should pay the sum of the k *highest losing* bids submitted by *the other* bidders. Under the present auction scheme, the application of this principle to DVB winners is straightforward. However, its application to CDMA winners is not as clear as in the original auction, and may in fact benefit from additional research.

1) Payment by a DVB winner: If there is one DVB network, and it wins k bands, it is a simple matter to determine its payment. In the allocation step (subsection VI-B) a vector of sorted "CDMA bids" is formed. Eliminating the winning CDMA bids from that vector immediately reveals the the k highest losing "CDMA bids".

2) Payment by a CDMA winner: The problem to apply the Vickrey payment scheme to CDMA winners is created by the DVB *losing* bids. A DVB bid is submitted for use of a band over both islands. Thus, it is unclear which fraction of a DVB losing bid should be "credited" to each island (to calculate the payments of the CDMA winners in a given island). We propose below a specific formula to divide the DVB losing bids among the islands. The formula appears reasonable and agrees with intuition. But a "better" formula might exist. Once a pertinent fraction of each DVB losing bid has been assigned to each island, the payments by CDMA winners are determined in each island independently, as in section III.

TABLE II
CALCULATIONS TO DETERMINE THE PAYMENTS BY CDMA WINNERS

b1	by	b2	by	sum
~~5~~	C1	~~4.5~~	C2	~~9.5~~
~~4.5~~	C2	~~4~~	C2	~~8.5~~
4	C2	3	C1	7
3.7	D1	2.8	D1	6.5
3.5	C1	2.5	C1	6
2.6	D1	1.9	D1	4.5
2	C1	2	C1	4
1	C2	1	C2	2

To determine the fraction of a given DVB *losing* bid to be "credited" to an island, we identify the "CDMA bid" nearest to it *from above* (that is, the lowest "CDMA bid" that *exceeds* the given DVB bid). If such "CDMA bid" is $b = b_1 + b_2$ (b_i corresponds to island i), and the concerned DVB bid is d, then the fraction of the DVB losing bid "credited" to island i equals $(b_i/b) * d$. For example, let a particular DVB losing bid be equal to 5, and let the CDMA bid "nearest from above" be 6=4+2 (4 corresponds to island 1). Then, this DVB losing bid is registered in islands 1 and 2 as losing bids of (2/3)*5 and (1/3)*5, respectively.

Looking again at the single-band case, suppose that CDMA wins. If the CDMA bid nearest from above to the DVB bid is precisely the winning bid (that is, the DVB bid is the highest *losing* bid), the CDMA winners collectively pay an amount equal to the DVB bid, and split this amount precisely in proportion to their respective winning bid (which agrees with intuition). But of course, it is possible that the CDMA bid nearest from above to the DVB bid is *not* the winning CDMA bid. In that case, the DVB bid is split according to this losing CDMA bid, and each CDMA winner pays the highest losing bid in its respective island, whatever it may be.

3) Numerical illustration: Payments are further clarified with the preceding example. Assessing the payments by the DVB network is straightforward. It won a band upon overruling the preliminary assignments to CDMA networks, whose bids added up to 4+3=7. This was the final band. Thus, the overruled bids form precisely the highest losing "CDMA bid". Accordingly, the DVB network must pay 7 for use of its band over its 2-island system.

To assess the payments of the CDMA winners we must first assign to each island a fraction of each DVB *losing* bid, as discussed above. Table II clarifies the procedure. This table is similar to table I, except that we have inserted some "bids" submitted by bidder D1 to each island. These pseudo-bids are really the fraction of each DVB losing bid assigned to an island. For example, the DVB losing bid of 6.5 is split as 3.7 and 2.8. This is proportional to 4/7 and 3/7, because the "CDMA bid" of 4+3=7 is the nearest to 6.5 "from above". After a pertinent fraction of each DVB losing bid has been assigned to each island, the payments by the CDMA winners are calculated in each island, independently, as in the standard multi-unit Vickrey auction discussed in section III.

Over W1, C1 won one band, and must pay the highest losing bid submitted by others. This is 4, submitted by C2. C2 also won one band over this island, and must pay the highest losing bid submitted by others. This is 3.7, which is the fraction assigned to this island of the DVB losing bid of 6.5.

Over $W2$, C2 won 2 bands, and must pay the sum of the two highest losing bids submitted by others: 3+2.8=5.8. (2.8 is the fraction assigned to this island of the DVB losing bid of 6.5). Therefore, C2 must pay a total of 5.8+3.7=9.5 for its 3 licenses.

The auctioneer receives 7+4+9.5=20.5 for the 3 bands.

VII. Behaviour of the DVB-T radio-access network

A. An earlier service model

Our service model for the DVB network follows loosely [7]. In [7], a DVB customer can select one of several (8) available multicast "programmes". Examples of such programmes are news bulletins, weather information, sports updates, and entertainment video clips. A spectrum band devoted to DVB-T is assumed to support a fixed number of concurrent multicast services (4). A specific multicast service is only offered if a minimum number of users (500) requested the service within a specified period.

B. Our service model

1) Communication issues: We shall also assume that a fixed number of simultaneous multicast DVB programmes, say ν, can be accommodated by a spectrum band. Once a programme is chosen for multicast, there is no physical limit on the number of paying subscribers that can view it. As we envision an inter-allocation (DSA) interval as short as possible, the length of the video programmes will generally exceed the length of the spectrum license. In such scenario, the network could admit new users periodically, with a period equal to a multiple of the inter-allocation interval (for example, if spectrum is (re)-allocated every minute, and the typical length of a video programme is 5 minutes, then new users may be admitted every 5 minutes). Below, we simply assume that the length of the programmes equals the time interval between spectrum allocations, which is similar to assuming that the DVB-T network always "reserves the right" to drop a "long" video service due to spectrum shortage (that is, the network would not promise continued service beyond the length of a short-term spectrum license).

2) Economic issues: Revenues are key, as they determine how much the network bids for spectrum, which in turn determines which bands are assigned to whom. We have previously assumed that β_i is the monetary "value" of a correctly delivered information bit to a data terminal. β_i can be interpreted as the terminal's "willingness to pay". However, for DVB video services it makes more sense to speak of the "value" of an entire video clip. On the other hand, a video clip requires the successful transfer of a certain number of information bits. Thus, from the value of a video clip, we can obtain an "average value" of a DVB-T bit. The reason to do this is that we expect the value of a successful data bit, and the average value of a DVB-T bit to be of the same order of magnitude. In fact, we assume below that if β_i is terminal i's value of a data bit, and a DVB video clip contains μ bits, then $\mu\beta_i$ is the value of the video clip to terminal i. This assumption essentially "levels the playing field" between networks of different radio-access technologies.

C. Pricing and bidding

As we have assumed for the CDMA networks, we assume that a DVB-T network knows the "willingness to pay", β_i, of each active terminal, and can charge an individual price to each terminal ("price discrimination"). Thus, if a DVB video clip contains μ bits, terminal i is charged $\mu\beta_i$ for receiving it, which is exactly the monetary value of the clip to this terminal.

Under the present auction scheme, a bidder offers for an object what the bidder thinks the object is worth. Thus, as in [3](see section IV), the network's bid for a spectrum band equals the (additional) revenue generated by the (additional) terminals that can be served if that band is won. To compute this, let us define as J_k the set of the indices of all the terminals that are interested in receiving the programme k (a given terminal requests *at most* one programme at a time). Then, programme k would produce revenues of

$$\mu \sum_{J_k} \beta_j \qquad (2)$$

Let us assume for convenience that the programmes are labelled in the order of the revenue each brings (programme one brings the most revenues). Then, evidently if only one band is won, and ν programmes fit in one band, then programmes 1 through ν are shown. If an additional band is won, then programmes $\nu+1$ through 2ν are also shown, and so on.

The bid vector is such that its first component has the revenue that the first band would yield if won, the second component is the additional revenue that winning a second band would produce, and so on. For example, with 3 total bands available for auctioning, and 2 simultaneous DVB programmes fitting in one band (each programme consisting of μ bits), a bid from the DVB-T network has the form $\mu\left[\begin{array}{ccc} b_1 & b_2 & b_3 \end{array}\right]$ with:

$$b_1 = \sum_{J_1} \beta_j + \sum_{J_2} \beta_j \equiv \sum_{J_1 \cup J_2} \beta_j \qquad (3)$$

$$b_2 = \sum_{J_3} \beta_j + \sum_{J_4} \beta_j \equiv \sum_{J_3 \cup J_4} \beta_j \qquad (4)$$

$$b_3 = \sum_{J_5} \beta_j + \sum_{J_6} \beta_j \equiv \sum_{J_5 \cup J_6} \beta_j \qquad (5)$$

Thus, b_1, the bid for the first band, equals the total revenue that the first won band would yield; that is, $\mu \sum \beta_j$, with the sum covering all the terminals interested in programmes 1 and 2 (the two programmes producing the highest revenues). Likewise, b_2 equals $\mu \sum \beta_j$ with the sum now covering the terminals interested in programmes 3 and 4. And so on.

VIII. Implementation issues

We envision a computerised system which allocates spectrum licenses for a time interval as short as permitted by technology. A high-level view of the system follows. The spectrum manager has a computer that performs three steps sequentially, in an infinite loop: it (1) receives the bids from the interested networks, (2) allocates the short-term licenses, and (3) registers the appropriate charges for the allocated spectrum. Likewise, each participating network has a computer set up to perform in an infinite loop the following steps: (1) to "sense" the status of the network, (2) to generate bids and send them to the spectrum manager, (3) to authorise the appropriate services according to pertinent priorities. The exchange of signals between a network and the manager is quite simple: a vector of bids goes from the network to the manager, and a spectrum allocation is returned (for example, in the form of a vector of zeros and ones, where a one denotes that a specific spectrum band has been assigned to this network).

A. Spectrum manager side

The steps to be followed by the spectrum manager's algorithm are straightforward, and of a fairly low complexity, and have been amply discussed above. The operations necessary to generate an allocation are very basic: sorting (the bids), adding (interim winning bids), comparing two numbers, removing (winning bids) from further consideration, etc. The payment calculations are also simple (with the subtlety involving the losing DVB bids discussed in subsection VI-C).

B. Network side

The steps to be followed by a network's DSA computer are relatively simple, also. Below, we comment further on the most involved: "sensing" or to collect the information from the network that is necessary to generate the bids.

In the case of a CDMA network, as discussed in section IV, the generation of bids necessitates three quantities for each active terminal: its willingness to pay (presumably a constant for a given subscriber obtained through marketing methodology outside the scope of this work, and stored in some database), its data rate (which the base station should know), and its channel gain (obtained through standard channel estimation procedures). The analysis assumes that channel gains are constant through the inter-auction period, which may be reasonable if the inter-auction period is very short, and/or the channels are largely stable (low mobility, no significant fading). Under certain scenarios, channel estimation may be inaccurate, and the resulting errors can make the operation of the network less efficient. A short inter-auction interval is very helpful in this regard.

For the DVB network, sensing reduces to knowing the willingness to pay of any subscriber wishing to view a "programme".

Once the network has the required information about the terminals, bids are generated and service priorities established through very simple algorithms, discussed in sections IV and VII-C.

IX. Discussion, extensions and future directions

Dynamic spectrum allocation (DSA) seeks to increase radio-spectrum efficiency by exploiting temporal and/or spatial variations in the demand patterns ("loads") of participating radio-access networks. In [2], [3] we introduced a DSA scheme in which a spectrum manager periodically allocates short-term spectrum licenses, via economic tools. We focused on a "small island" served by several CDMA networks populated by heterogeneous

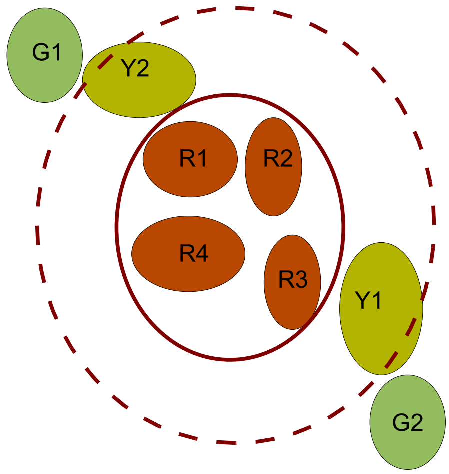


Fig. 2. A richer geography, with a single DVB cell (solid-line oval) serving four islands: $R1$, $R2$, $R3$ and $R4$. The broken-line oval is the "interference region" of the DVB cell, which affects islands $Y1$ and $Y2$. Islands $G1$and $G2$ are *not* affected by the DVB cell. An "interim" CDMA winning bid is the one that would have won the concerned spectrum band in a given island, if there was *no* DVB. A DVB winning bid must beat the sum of *six* "interim" winners: those over the four islands served by DVB ($R1$, $R2$, $R3$ and $R4$), plus those of the two islands inside its "region of interference" ($Y1$ and $Y2$).

terminals, on the downlink. We obtained closed-form analytical results for (i) the service signal-to-noise ratio, and a terminal's (iia) bandwidth consumption, (iib) revenue contribution, and (iic) service priority ("revenue per Hertz"), as well as (iii) the network's optimal bid for a spectrum band (the revenue generated by the (additional) terminals that can be served, if the given band is won). An application of our scheme to uplink spectrum is in principle possible, but requires further study, because CDMA uplink interference control is more complicated.

Section V-B makes clear that, among CDMA networks *only*, the scheme and results of [3] can be applied in an entire system of "small islands", with independent auctions per island, under a UMTS-like interference-control scheme. But DSA is most beneficial in the presence of networks with complementary "busy hours". Thus, presently we have added to the scenario of [3], a wireless broadcast network (motivated by those operating under the DVB-T standard), as well as a second "island" (to account for the fact that a typical DVB-T cell overlays many UMTS cells). This, in turn, required a substantial modification of the auction scheme of [3].

We have acquired a clear analytical understanding of the 2-island, 2-access-technology situation, including two key issues: (i) the modification of the auction format to account for the fact that the DVB network requires a spectrum band for simultaneous use over both islands, and (ii) the process by which this network markets its services and generates its bids.

The case in which a single spectrum band is available illustrates the intuition behind our scheme. In this case, each CDMA network "sees" an independent auction per island, and submits a bid to each auction reflective of the network status in the concerned island. In each island, the CDMA network submitting the highest bid is declared the "interim winner". We regard the sum of the two interim winning bids as the "CDMA bid". If this sum exceeds the DVB bid, the interim winners are confirmed. Otherwise, the DVB network gets the band for use over both islands. Payments follow the Vickrey philosophy. If DVB wins, it pays for the band the sum of the two interim winning bids (the highest *losing* bids submitted by the other bidders). If CDMA wins, payment calculations are less clear. In principle, each CDMA winner should pay the highest *losing* bid in the island it won. But it is not clear which fraction of a DVB *losing* bid should be assigned to each island (which is critical, if one CDMA networks does *not* win in both islands). To accomplish this, we propose an intuitive formula, but do not rule out the possibility that a "better" formula may exist.

Certain extensions of the present analysis to richer scenarios are straightforward. For example, in the development we have only considered one DVB network. In fact, with minimal changes, we can consider several DVB networks, each covering the same two islands. The key step in the allocation procedure is the comparison of the highest "CDMA bid" (that has not yet won a band) to the highest DVB bid (that has not yet won a band). The fact that some DVB bids may have been submitted by different bidders makes no difference in this critical step. Likewise, the impact of *losing* DVB bids on the payments by CDMA winners is exactly the same, regardless of the number of DVB networks that are bidding. Finally, a DVB network that wins k bands should pay the sum of the k highest *losing* bids submitted by others, whether CDMA (as discussed before), or DVB bids.

Likewise, the extension of the present analysis to a situation with many "small" islands, all covered by a single DVB cell, is straightforward. A minimal reflection reveals that the restriction to 2 islands is only for expositional convenience. As long as there are independent and simultaneous auctions per island among CDMA networks, each CDMA network continues to behave as in [3]. The behaviour of the DVB network is as described in section VII. Of course, in this multi-island scenario, in order for the DVB network to win a band, its bid must exceed the sum of all of the "interim" CDMA winning bids (one per island). If the single DVB cell covers only *some* of the islands, the modification is still straightforward. For example, consider the situation of figure 2. In this case, a DVB winning bid must beat the sum of *six* interim CDMA winning bids: those of the four islands served by DVB ($R1$, $R2$, $R3$ and $R4$), plus those of the two islands inside its "region of interference" ($Y1$ and $Y2$). In fact, the present analysis could cover a geography in which the situation of figure 2 is repeated many times, provided that the "interference region" of the DVB cells do not intersect with one another.

Extensions to scenarios in which there is inter-cell interference among DVB cells require further research, as they can involve complex combinatorial optimisation. To see a simple example of this, consider the scenario of figure 1, exactly as shown (assuming that the DVB network does *not* operate as a single-frequency network), and with a total of 3 available bands. The scenario presents no difficulties to the parallel, independent CDMA auctions. In principle, one could attempt to handle the participation of the DVB network as described in the body of the present work, considering the East and West sides of the picture independently. But the DVB inter-cell interference considerably clouds the analysis. For example, the DVB network bids could be high enough to win two bands on the East, and also two bands on the West. But with only 3 available bands, if 2 bands are assigned to DVB on the West, only one band is left to be assigned also to DVB on the East (because of inter-cell interference). On the other hand, a band assigned to DVB on one side of the geography *could* be reused by a CDMA network in a *non*-adjacent island. Thus, it is not really clear how to disentangle this situation, especially if figure 1 only shows a part of the geography (with many more islands to the East and West of the picture in a similar situation).

Neither in [3] nor in the present work have we considered the effect of market competition in the price-setting behaviour of network operators. Thus, we can view the present analysis as a "best case scenario" for the operators, or as an approximation of the "oligopoly" situation often observed in practise (where relatively few firms compete in the provision of similar communication services in a given region). Likewise, we have focused on relatively simple strategic behaviour. With repeated and simultaneous auctions, the networks could engage in more sophisticated bidding behaviour than we have assumed. But the fact that these licenses expire in a very short time (minutes or perhaps seconds) seems to justify the utilisation of relatively simple bidding strategies.

We have not discussed the additional functionality needed by a wireless network and its terminals in order to implement DSA. Relevant discussions can be found in [10], [31]. Evidently, current networks and standards do not support DSA. But with the steady advance of technology, the additional functionality seems within reach. Before any adoption decision, a cost-benefit analysis of the infrastructure upgrade is necessary. When the demand for services varies widely over time and/or space, the efficiency gains of any DSA scheme are magnified, but these gains are minimised under uniform demand. By considering a UMTS and a DVB-T operator participating in a DSA scheme, the work reported in [10] achieved "gains" approaching 40%.

Our research strategy has been to study analytically relatively simple scenarios, progressively adding elements to our model with the aim of ultimately obtaining a firm understanding of a relatively complex case, resembling a "realistic situation". The obvious next step along this line is to extend our analysis to an entire system of "islands", where each CDMA network continues to have a cell per island, and each DVB-T cell covers several islands, but with neighbouring DVB cells interfering one another. Once this new situation is understood, we may be in a good position to perform numerical exercises with "realistic" data. And then we could juxtapose the benefits of our DSA scheme to those that have been reported.

Our analysis rests on a microeconomic foundation, and could be applied in the presence of real business considerations. However, our scheme may also serve as an algorithmic metaphor along the lines of [32]. For instance, a telecommunication firm with several networks operating under different radio-access technologies could use our scheme to allocate its licensed spectrum internally among its own divisions: each division may use its real budget, or a software agent with a fictitious budget could play the part of each access technology in internal auctions. Likewise, a regulator wishing to dynamically allocate free spectrum could create software agents endowed with fictitious money to play the role of various networks. These agents would be fed real network information (data rates, location, priorities ("willingness to pay")) and would generate bids, from which a dynamic spectrum allocation would be made. In this case, no real money would change hands, but the algorithm could still provide a reasonable dynamic allocation. In fact, the same regulator could apply our scheme as originally described, with real money, and eventually return the revenues generated by the auctions (in a form or another) to the paying customers of the participating networks. But the regulator must be careful, not to encourage wasteful behaviour.

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