Simple decentralised market-oriented allocation of sub-channels and power for access-point to terminal multi-carrier communication

Virgilio Rodriguez, Rudolf Mathar
Institute for Theoretical Information Technology
RWTH Aachen
Aachen, Germany
email: {rodriguez, mathar}@ti.rwth-aachen.de

***Abstract*—Common auction formats are well-understood, relatively simple mechanism which have long been used for allocating an indivisible good to the party that values it the most, for such reasons as speed of allocation, discovery of the true "value" of the object, and fraud prevention. Various auction schemes have been proposed for the allocation of telecommunication resources. The Dutch auction (the price progressively falls until a participant buys the object) has several major virtues: (i) a bid-processing protocol that automatically and simply prioritises the highest bid(s); (ii) possibility of distributive (auctioneer-free) implementation for synchronised terminals; (iii) confirmation of transmitter-receiver pairs at auction time, with smooth continuation if the pair is infeasible; (iv) exceptional signalling economy (the only strictly necessary signal is the winning bid). Below, we utilise this auction for sub-channel allocation in the access-point to terminal link of an orthogonal frequency-division multiple-access (OFDMA) network. Concurrently, we utilise a pricing scheme for power allocation. This results in a relatively simple, decentralised scheme for sub-channel and power allocation. Secure software inside each terminal may record transactions for eventual payment collection, or the auction can be interpreted as a prioritised decentralised allocation algorithm, without real money exchange.**

I. INTRODUCTION

In an orthogonal frequency-division multiple-access (OFDMA) system, the total bandwidth B is divided into N sub-carriers, and the base station simultaneously serves K terminals. We shall initially focus on forward link (base-station (BS) to terminal communication). The OFDM signal is time slotted, and the resource manager makes a resource assignment once at every slot. Channel-state information (CSI) at the transmitter (BS) enables several adaptive resource allocation strategies[1]:

- Dynamic sub-carrier assignment (DSA): Since channel characteristics for different users are virtually independent, a sub-carrier experiencing deep fading for one terminal may be in good condition for another; hence, the resource manager can dynamically assigns sub-carriers to terminals according to CSI or/and quality-of-service (QoS) considerations. However, the optimal sub-carrier allocation problem is NP-hard or NP-complete; thus, practical algorithms seek good but sub-optimal solutions.
- Adaptive power allocation (APA): Power levels may be varied to improve performance. This often involves some form of multi-user water filling.
- Adaptive modulation and coding (AMC): Higher transmission rates can be sent over the sub-carriers with better channel conditions to increase the throughput, while considering appropriate constraints.

In principle, each of these strategies can be employed at each sub-carrier, but large overhead may result. As a practical matter, several sub-carriers may be grouped into a cluster forming a "sub-channel", and adaptive techniques may be performed per sub-channel.

The critical OFDMA resource management issue is how to exploit CSI and traffic characteristics in order to efficiently allocate sub-carriers and power to improve the network's performance as much as practically possible, while considering appropriate constraints. To accomplish this, we take below an "economorphic" approach, based on the Dutch auction.

II. AUCTIONS FOR TELECOMMUNICATION RESOURCE ALLOCATION

A. Motivation

Since time immemorial, auctions have been employed as a practical mechanism for the transfer of ownership of articles of value, for such reasons as: (i) speed of allocation, (ii) discovery of the true "value" of the offered object, and (iii) transaction "transparency" (fraud prevention)[2]. Relevant auction applications to telecommunications include [3], [4], [5], [6], [7], [8]. In particular, [7] seeks a fair allocation of OFDMA sub-channels through an auction algorithm in which a terminal's bid equals the throughput difference between its best and second-best OFDMA sub-channel, while [8] seeks the same objective by applying the Vickrey-Clarke-Groves (VCG) mechanism to induce the terminals to truthfully report their channel valuations.

For telecommunication resource allocation, auctions provide a form of "prioritised allocation" in that the resource is allocated to the terminal that most values it. A terminal's valuation of the resource could either (a) represent the "true" monetary "willingness to pay" of a (selfish) human user, or (b) be a network-specified quantity ("priority index") computed/adjusted by software inside the terminal using local information (e.g., [3], [7]). A terminal's priority may be "adaptive", depending on such factors as its "importance", packet type, location, channel state, distance travelled, battery status, etc.

Furthermore, auctions enable an "incentive compatible" allocation, in the sense that they need not rely on "altruistic" or "courteous" behaviour by "selfish" users [9]. In this scenario, secure software inside each terminal may record transactions for eventual payment collection and system parameter tuning.

B. Sealed-bid auctions

There exist a large number of possible auction formats. A practical auction-based scheme for the temporary allocation of telecommunication resources (such as allocating OFDMA sub-channels for the length of a time slot) must be relatively simple and rapidly produce a winner, since resources must be allocated quickly, and repetitively. Thus [3], [5], [7], [8] propose the equivalent of a "sealed bid" auction. In such auction, each bid is independently submitted in a "sealed envelope", the auctioneer "opens" all envelopes simultaneously, the highest bidder wins, and pays as pre-specified by the rules. A participant computes her bid considering her own valuation, what she may know (statistically) about the valuations of other participants, and the specific rules of the auction.

However, telecommunication sealed-bid actions do have disadvantages. They require an auctioneer (controller) — which could be a problem in certain scenarios — as well as a special MAC protocol to receive the bids. This protocol may be problematic with a large, possibly variable number of bidders. If it is contention-free, it may be wasteful of resources; and if it is contention-based, as an aloha variant, the highest-value terminals may be unable to make a bid, and, consequently, a suboptimal allocation may result.

C. The Dutch auction format

As an alternative to the sealed-bid formats, the Dutch auction utilises a "price clock" which displays a progressively falling price. Each participant watches the clock while waiting for the price to reach a desired level. At some point, a participant indicates its willingness to pay the current price (the first participant to do so is the one that most values the object) [2].

Figure 1 shows a real-life Dutch flower auction in progress, in Aalsmeer, the Netherlands. The hand on the clock starts at the top, at what — for the given product — is believed to be a high price, and moves counter-clockwise to lower prices. When the price matches a bidder's desired level, s/he pushes a button to stop the clock, and speaks into a microphone to state the desired quantity, at the current price. After the transaction is registered, the price clock briefly moves clockwise to a slightly higher price, before resuming its counter-clockwise movement to lower prices. The next bidder to stop the clock proceeds similarly, and so on until the lot of flowers is completely sold. Prices form about once every four seconds on a given price clock[10]. A different clock-based ("ascending price" and combinatorial) auction is discussed by [11] in a dynamic-spectrum access scenario.

D. Advantages of the Dutch format

For telecommunication purposes, the Dutch auction retains the relative simplicity and allocation speed of other simple auction formats, and add several fundamental advantages: (i) A built-in bid-processing protocol that automatically and simply prioritise the highest bid(s); (ii) the possibility of a distributive (auctioneer-free) implementation (start times, initial price, and rate of decrease can all be pre-specified, so that a terminal can determine from its own clock the current status of the auction); (iii) Possible confirmation of transmitter-receiver pairs at auction time, with smooth continuation if the pair is infeasible; (iv) exceptional signalling economy (only one bid signal, the winner's, is strictly necessary in a single resource scenario). The Dutch auction is discussed further in [12], where it is proposed for medium-access allocation in an infra-structureless ("ad hoc") synchronised wireless network. Reference [13] extends [12] to consider network-layer issues, while [14] particularises [12] to a location/tracking application.

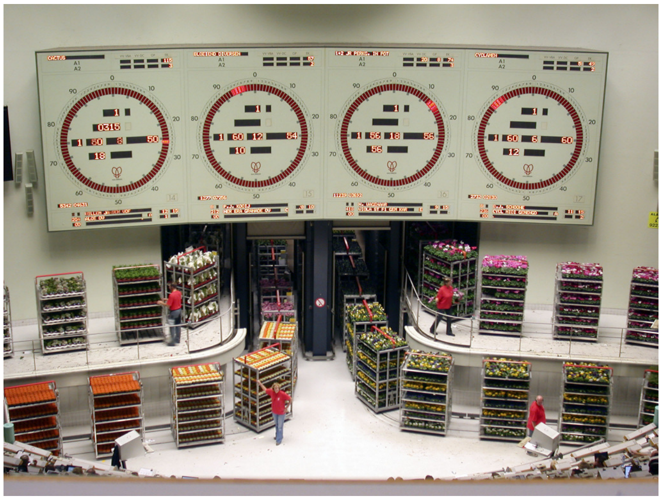

Figure 1. A real-life Dutch flower auction

E. The optimal Dutch bid

In any auction, the optimal bid depends on but need *not* equal the bidder's "valuation" of the object being auctioned. The valuation is the object's "worth" to the bidder; that is, the largest monetary amount that the bidder would pay for the object, in a direct purchase.

Characterising the optimal (selfish) bid in a Dutch auction is difficult for the general case. However, if each bidders knows that there are K bidders, and that all valuations are (statistically) uniformly distributed over a common interval, then the optimal Dutch bid for a bidder whose valuation is V_i takes the simple form [15]:

$$(1 - \frac{1}{K})V_i \tag{1}$$

Evidently, for large K the optimal bid is approximately equal to V_i.

III. THE DUTCH AUCTION FOR THE OFDMA FORWARD-LINK

A. *Basic idea*

The OFDMA resource manager makes a resource assignment once at every slot. Just before assignment, the manager sets up simultaneous Dutch auctions, one per sub-channel (as in figure 1, where several auctions are held in parallel).

The manager broadcast to the terminals the necessary information, so that each terminal can, from its own internal clock, determine the current price for each auction, and its bid. This information includes the starting price of each "clock" (which may or may not be the same for all clocks, and which may or may not change from an auction to the next), as well as the reduction in price after each "tick" (which also could vary from clock to clock, and from an auction to another).

Just before start of the auction, each terminal has an estimate of the anticipated channel state over each sub-carrier during the upcoming time slot. The terminal can, thus, compute for each sub-channel the "value" of using it during the upcoming time slot. Each terminal then waits for the price for its "best" sub-channel to be low enough. When this happens for the first time, the concerned terminal sends an appropriate signal to indicate its willingness to buy the given sub-channel at the current price. If there is no reason to decline this request, the BS broadcast an allocation confirmation, along with any relevant information. After this, confirmation, each terminal may re-calculate its valuations of the remaining sub-channels. The parallel auctions continue, with each "clock" decreasing its price at each tick, until another terminal determines that the price of one of the sub-channels is "low enough". The process continues in the obvious way.

B. *Sketch of bid calculation*

In this sub-session we only sketch the calculations necessary for a terminal to determine its bid for a given sub-channel. We assume below that each-sub-channel has one single sub-carrier. This may not be realistic, and it is unnecessary; however, it simplifies the exposition. Thus, below, SC may be read as sub-carrier or sub-channel.

A terminal's valuation of a given SC is determined by the difference between the benefit of using the SC, and any associated cost. The benefit is the value of the maximal amount of information it can transfer over that SC during the upcoming time slot. This value should in principle depend on the terminal's channel estimate, its application, and its "willingness to pay" (how much the terminal values one correctly transferred information bit). The terminal may have to set optimally certain link-layer parameters, such as power, modulation order, and the symbol rate.

Since the BS has a limit on the total power available for all the sub-carriers, it makes sense for the BS to give each terminal the opportunity to choose the power to be used over a won SC, at a price per Watt (which could conceivably change from a terminal to another, and from a time slot to another). This price is included in the information broadcast to the terminals at the start of each auction.

If the terminal has not yet won any SC, it may perform the valuation of each SC independently, as if it was the only available one. Let $\mathcal{V}(p)$ be the value of the information that the terminal could transfer with power p and the "ideal" link-layer configuration (modulation, symbol rate, etc.) over the given sub-channel, and $c(p)$ be what the terminal must pay for using p Watts during the upcoming time-slot. The terminal can find the p^* that maximises $\mathcal{V}(p) - c(p)$. Then, its valuation for that sub-channel is $\max(0, \mathcal{V}(p^*) - c(p^*))$. From this valuation, the terminals determines its bid as discussed in sub-section II-E. The terminal performs this calculation for each of the available sub-channels. When a terminal sends the winning signal, it includes the amount of power it desires, p^* . When the BS confirms the assignment, it broadcasts the amount of remaining power.

If the terminal has already won one or more sub-channels, its valuation computation is only somewhat more complicated.

C. *Simple example*

Table I displays a simple example in which there are 2 terminals, T1 and T2, and 5 sub-channels (SC). The column corresponding to a terminal has its initial bids for each SC. For simplicity, we will assume that after a sub-channel has been won, *no* terminal changes its valuation of the remaining SC's.

Suppose that both price clocks start at 10,0, and the price drops 0,1 each "tick" of the clock. The clocks start moving to lower prices each tick, as 10,0 , 9,9 , 9,8 , 9,7 , etc. After 4 ticks, the price of SC2 has reached 9,6 which is attractive enough for T2. Thus, T2 sends the buying signal. The BS broadcast the confirmation of the allocation (in principle, each terminal could at this point re-calculate its bid for the remaining sub-channels, but we have assumed none does so). After 6 additional ticks, the price of SC 2 has reached 9,1, and accordingly T1 sends the buying signal for SC1. After 20 total ticks the price of SC4 has reached 8,0 and T1 buys it. The process continues similarly, with T2 getting SC5 (after 25 total ticks), and eventually also SC3.

Table I
BIDS BY TERMINALS 1 AND 2, FOR THE VARIOUS SUB-CHANNELS. THE FOURTH COLUMN INDICATES THE TERMINAL THAT WINS THE CORRESPONDING SUB-CHANNEL.

SC	T1	T2	W
1	9,1	6,5	1
2	5,1	9,6	2
3	3,5	4,0	2
4	8,0	2,0	1
5	3,5	7,5	2

IV. VALUATIONS AND BIDS FOR DATA TERMINALS

A. *Physical model: further detail*

Below we assume a common physical model from the literature, utilised, for instance, in [16]. There are N sub-carriers and K terminals downloading data. The base station (BS) transmitter must obey a total transmit power constraint.

Each transceiver has a single antenna. The frequency response is flat within a given sub-carrier. Let $h_{k,n}$ denote the *quotient* resulting from dividing the channel gain corresponding to terminal k and sub-carrier n, by the pertinent receiver noise value.

B. Single sub-carrier valuation for data

For a terminal that has a "long" queue of delay-tolerant (data) information to transfer, it is reasonable to assume a valuation of the form $\beta_i R_{i,n}(p) - c_i(p)$ where (i) β_i is the monetary value of one information bit successfully transferred multiplied by the SC bandwidth, (ii) $R_{i,n}(p) = \log_2(1 + ph_{i,n})$ yields information bits/Hertz successfully transferred over SC n when power p is used (with ideal link layer configuration), and $c_i(p)$ is the associated cost. For simplicity, we assume that the power cost is linear: $c_i(p) = c_i p$.

The terminal can find the optimal amount of power for SC n as the solution x^* to the single-variable equation $R'_{i,n}(x) = c_i/\beta_i$. Of course, the amount ordered by the terminal cannot exceed the total amount of power that remains at the transmitter (considering any amount allocated to previous winners), say P. Thus, with $p^*_{i,n} := \max(P, x^*)$, the terminal valuation of this SC equals $\beta_i R_{i,n}(p^*_{i,n}) - c_i p^*_{i,n}$, and from this, under the assumptions of sub-section II-E, the bid follows directly (equation 1). Since the price clock will never reach negative numbers, a negative bid simply means that the terminal has no interest in this SC.

It is intuitively clear that at a given moment, i highest bid will correspond to its "best" SC of those available. If the starting price, "tick" duration, and price "step" per tick are common to all price clocks, then all indicate the same price at given moment. Thus, although all SC are simultaneously auctioned, terminal i can focus on its best SC, until it is won by someone. At this point, it can calculate its bid for its next best of the remaining SC, and focus on that until someone gets it, and so on.

C. Sub-carrier valuation after previous winnings

The terminal can update its valuation of the remaining carriers, after anyone has won. If someone else wins a SC, certain amount of power is allocated to it. Thus, a terminal may have to re-calculate its valuation of SC n, if $p^*_{i,n}$ exceeds the amount of power now available.

If terminal i has won SC m, then to determine its valuation for SC n it should find the power levels x, y that maximise $\beta_i(R_{i,m}(x) + R_{i,n}(y)) - c_i(x+y)$. Of course, $x+y$ must be less than the available (not already allocated) power. It is tempting to think that the terminal should allocate to m the same amount of power it reserved at the moment of winning it. But this need not be optimal. The correct procedure is to solve the bi-variate problem above. After finding $x+y$ the terminal should "remember" that it has already bought a certain amount of power $p^*_{i,m}$, thus, it only needs now $x+y-p^*_{i,m}$.

The benefit of winning sub-channel n is the difference between the benefit of having both m and n versus that of m alone: $\beta_i(R_{i,m}(x) + R_{i,n}(y) - R_{i,m}(p^*_{i,m}))$. Then, the valuation of sub-channel n after m has been won equals: $\beta_i(R_{i,m}(x) + R_{i,n}(y) - R_{i,m}(p^*_{i,m})) - c_i(x+y-p^*_{i,m})$ or

$$[\beta_i(R_{i,m}(x) + R_{i,n}(y)) - c_i(x+y)] - [R_{i,m}(p^*_{i,m})) - c_i p^*_{i,m}] \quad (2)$$

The first bracket represents the utility (benefit minus cost) of the pair m and n as if both were won simultaneously, while the other bracket is the utility of sub-channel m alone (used previously to calculate the bid for m when the terminal had not yet won anything).

Notice that the terminal must solve this bi-variate problem, only after it has won a SC, and — when clocks parameters are common as discussed in section IV-B — only for its best of the remaining SC . Once this SC is won, then the terminal should repeat this calculation for the best of those still remaining, and so on.

More generally, if the terminal has won $\mu - 1$ sub-carriers, it should solve the optimal power-allocation problem for μ sub-carriers with a per-Watt price, which leads to "water-filling" with costly power. Besides space limitations, this problem is sufficiently interesting to merit an independent discussion[17].

V. SOME IMPLEMENTATION ISSUES

Evidently, the auction requires tight synchronisation among terminals, i.e., a "common clock". For 4G networks this is not a problem, because this requirement is already in place, since these networks are time-slotted by design.

The parameters of the auction (initial price, the clock "tick", and price "step" per tick) should be chosen judiciously. The statistics of the terminals' "valuations" are among the factors to be considered in choosing the system parameters.

Because the SC valuations (and corresponding bids) are channel dependent, they can be idealised as continuous random variables. Therefore, the probability that 2 terminals have the exact same bid can be neglected; that is, the possibility of simultaneous winners can be ignored in our scenario.

Finally, the entire auction process could take place at the base station, with a software agent playing the role of each terminal. To implement this, the resource manager would only need each terminal's channel state and β (value of an information bit). At the end of the process, the manager would report to each terminal its sub-carrier and power allocation, as with any other OFDMA resource-management scheme.

VI. DISCUSSION

We have presented a low-complexity decentralised sub-channel/power allocation scheme for the forward-link of an orthogonal frequency-division multiple-access (OFDMA) wireless access network. The scheme is based on a simple descending-price auction run in parallel for each sub-channel by the access point for each time slot. A terminal´s bid for a given sub-channel is monotonically increasing in the value of the information it can transfer over that sub-channel. Thus, the system tends to allocate a given sub-channel to the terminal that can transfer the "most valuable" information through it. Other things being equal, the terminal that anticipates the highest quality for a given sub-channel will make the highest bid for it. However, each terminal has its own "willingness to pay" (that is, the value of one transferred information bit), which reflects the fact that different users may be performing tasks of different levels of "importance" (social messaging versus school work versus financial information downloading, etc). Thus, a terminal transferring very "important" information may win a given sub-channel over another terminal that anticipates higher channel quality but that is transferring less "important" information.

The auction can be taken literally as involving real money to be paid by users as service fees. However, the bids may also be interpreted as "priority" indices that software within each terminal computes according to a network-imposed criteria, and without the intervention of the human using the terminal (who presumably pays the network according to a conventional service contract). As long as a terminal's bids are increasing with the importance of the information it transfers, and its channel quality estimates, the scheme yields a reasonable allocation.

Whether or not the scheme involves real money, it can be entirely implemented inside the base station, with a software agent representing each terminal. This agent only needs the terminal's channel state and monetary parameter. In this case, the scheme is an OFDMA resource allocation algorithm, which is of low complexity, in the sense that it makes no attempt to solve the global (NP-hard) sub-channel/power allocation problem.

Whether the scheme is implemented by the resource manager entirely, or with the terminals directly performing the bidding, the only significant computation is bid calculation/update. Such computation becomes more complex, as a given terminal wins more sub-channels, but is very similar to the standard water-filling algorithm[17]. Portable computers should have no difficulty with these calculations, and pocket devices capable of high-speed wireless data transfer typically have embedded processors comparable to those of desktop PC's of the recent past.

We have assumed that terminals transfer delay-tolerant ("best effort") data traffic (e-mail, web browsing, file transfers, video-clip downloading, etc), so that at a given time slot, each may get more, less or no resources, depending upon their bids, without this creating a major problem. Our scheme could in principle be applied even if certain terminals require to transfer a fixed amount of information per time slot. In this case, the terminal must simply bid high enough to ensure that it (almost) always wins enough resources to satisfy its requirements. Alternatively, the applications that have stringent data rate constraints could be separated and handled in a parallel "logical network" under a conventional service contract, while best-effort traffic is handled under our proposal.

Our development has not targeted any particular communication standard. Thus, our proposal can be implemented in any present or future multi-carrier network, including — but not limited to — fourth-generation (4G) cellular networks that follow the WiMAX or Long-term Evolution (LTE) standards. We have emphasised qualitative/conceptual aspects, having provided a simple numerical example strictly for pedagogical reasons. Nevertheless, we realise that it could be very useful and interesting to implement our proposal within a simulation of a 4G network, both, to show how to apply it in a concrete practical scenario, as well as to obtain valuable performance data. Such simulation is not presently available, but it is certainly anticipated (for example, with the open Wireless Network Simulator (openWNS) — an RWTH Aachen project — which specifically targets 4G networks[18]).

ACKNOWLEDGEMENT

Financial support from the Deutsche Forschungsgemeinschaft (DFG), through the UMIC project, is gratefully acknowledged.

REFERENCES

[1] G. Song and Y. Li, "Utility-based resource allocation and scheduling in OFDM-based wireless broadband networks," *Communications Magazine, IEEE*, vol. 43, pp. 127–134, Dec. 2005.

[2] E. Wolfstetter, "Auctions: An introduction," *Journal of Economic Surveys*, vol. 10, pp. 367–420, Dec 1996.

[3] G. P. Pollini and Z. J. Haas, "E-BAMA vs. RAMA [multiple access protocols]," *IEEE Network*, vol. 8, pp. 18–25, Mar./Apr. 1994.

[4] C. Courcoubetis, M. Dramitinos, and G. Stamoulis, "An auction mechanism for bandwidth allocation over paths," in *17th International Teletraffic Congress*, Dec. 2001.

[5] C. Kloeck, H. Jaekel, and F. Jondral, "Auction sequence as a new resource allocation mechanism," in *IEEE Vehicular Technology Conf.*, vol. 1, pp. 240–244, 2005.

[6] V. Rodriguez, K. Moessner, and R. Tafazolli, "Market driven dynamic spectrum allocation over space and time among radio-access networks: DVB-T and B3G CDMA with heterogeneous terminals," *Mobile Networks and Applications*, vol. 11, pp. 847–860, 2006.

[7] S.-w. Han and Y. Han, "A competitive fair subchannel allocation for OFDMA system using an auction algorithm," in *Vehicular Tech. Conf., IEEE 66th*, pp. 1787–1791, 30 2007-Oct. 3 2007.

[8] Z. Kong, Y.-K. Kwok, and J. Wang, "Auction-based scheduling in non-cooperative multiuser OFDM systems," in *Vehicular Tech. Conference, IEEE 69th*, pp. 1–4, April 2009.

[9] N. BenAmmar and J. S. Baras, "Incentive compatible medium access control in wireless networks," in *Workshop on Game theory for communications and networks*, (Pisa, Italy), p. 5, ACM Press, 2006.

[10] "Dutch auction," in *EconPort Economics Handbook*, 2009. Retrieved 22 May 2009 from the EconPort Web Site http://www.econport.org/econport/request?page=man_auctions_dutchauction.

[11] T. Forde and L. Doyle, "A combinatorial clock auction for ofdma-based cognitive wireless networks," pp. 329–333, May 2008.

[12] V. Rodriguez and F. Jondral, "Simple adaptively-prioritised spatially-reusable medium access control through the dutch auction: Qualitative analysis, issues, challenges," in *Communications and Vehicular Tech. in the Benelux, 14th IEEE Symp. on*, vol. Supp., pp. 1–5, Nov 2007.

[13] C. Lima and G. de Abreu, "Game-theoretical relay selection strategy for geographic routing in multi-hop wsns," in *Positioning, Navigation and Communication, 5th Workshop on*, pp. 277–283, Mar 2008.

[14] V. Rodriguez, F. K. Jondral, and H. Jaekel, "Tracking a large number of tokens: A customised prioritised medium-access protocol for target responses," in *ICT Mobile Summit*, 2009.

[15] W. Vickery, "Counterspeculation, auctions and competitive sealed tenders," *Journal of Finance*, vol. 16, pp. 8–37, 1961.

[16] K. Seong, M. Mohseni, and J. Cioffi, "Optimal resource allocation for OFDMA downlink systems," in *Information Theory, IEEE Inter. Symp. on*, pp. 1394–1398, July 2006.

[17] V. Rodriguez and R. Mathar, "Generalised water-filling: costly power optimally allocated to sub-carriers under a general concave performance function," in *Conference on Information Sciences and Systems (CISS)*, (Princeton, NJ, USA), Mar 2010. Forthcoming.

[18] D. Bültmann, M. Mühleisen, K. Klagges, and M. Schinnenburg, "openWNS - open wireless network simulator," in *Proc. European Wireless Conference*, pp. 205–210, May 2009.