Simple adaptively-prioritised spatially-reusable medium access control through the Dutch auction: Qualitative analysis, issues, challenges

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***Abstract*—The Dutch auction (the price progressively falls until a buyer "takes" the object) is proposed as a foundation for decentralised medium-access control. 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, including medium access control (MAC). But previously proposals require a controller, and, to receive the bids, an alternate protocol which could waste resources, or miss important bids. For MAC, the Dutch auction 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). Secure software inside each terminal may record transactions for eventual payment collection, or the auction can be used as a prioritised-access algorithm, without real money exchange. Below we evaluate *qualitatively* the MAC potential of this auction, emphasising the distributed version, which can arbitrate medium access among synchronised terminals in an infrastructureless network.**

I. Introduction

Since time immemorial, auctions have been employed as a practical mechanism for the transfer of ownership of articles of value. Common contemporaneous applications include the sale of (i) art, antiques and other rare objects, (ii) used durable goods, such as vehicles, (iii) property which has fallen in loan or tax default, as well as (iv) many "government items", such as foreign currency, mineral rights, firms to be privatised, and, of course, the radio spectrum. Auctions may also be used in procurement contracts, in which the auctioneer seeks a low price for goods or services, and the world-wide web enables auctions without geographical constraints (eBay, Priceline, etc) [1]. Works describing interesting auction applications in telecommunications include [2], [3], [4], [5], [6], [7], [8], [9], [10].

General reasons for choosing auctions include (i) speed of allocation, (ii) discovery of the true "value" of the offered object, and (iii) transaction "transparency" (fraud prevention)[1].

For medium-access control (MAC), auctions provide a form of "prioritised access" in that the channel is allocated to the terminal that most values access. A terminal's valuation of access could either (a) represent the "true" monetary "willingness to pay" of a (selfish) human user, or (b) be a "priority" index computed/adjusted by software inside the terminal using local information (e.g., [2], [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 "incentive compatible" MAC schemes, in the sense that such schemes need not rely on "altruistic" or "courteous" behaviour by users [8]. Secure software inside each terminal may record transactions for eventual payment collection and system parameter tuning.

There exist a large number of possible auction formats. A MAC auction should be relatively simple and rapidly produce a winner, since access must be granted quickly, and repetitively. Thus [2], [6], [7] 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 his bid considering his own valuation, what he may know (statistically) about the valuations of other participants, and the specific rules of the auction.

However, MAC sealed-bid actions do have disadvantages. They require an auctioneer (controller), as well as an alternate MAC protocol to receive the bids. This protocol may be problematic with a large, possibly variable number of bidders. If it is contention-free, such as TDMA, 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.

The Dutch auction provides an alternative to the sealed-bid format. A public "clock" displays a progressively falling price, which each participant watches while waiting for the price to reach a desired level. At some point, the participant that most values the object indicates its willingness to pay the current price [1]. Below we examine the MAC potential of the Dutch auction, emphasising its distributed (auctioneer-free) implementation, which can control medium access of *synchronised* terminals, in an infrastructureless wireless network.

II. Synchronicity in infrastructureless networks

Infrastructure-based wireless networks typically utilise synchronous, contention-free multiple-access schemes, such as TDMA and CDMA, in the data channel, and random access for the uplink control channel. For infrastructureless wireless networks, asynchronous and distributed MAC protocols, such as CSMA/CA (standardised as DCF[11]), are typically assumed. But recently, it has been recognised that a distributed and synchronous MAC solution can be practical and beneficial to infrastructureless wireless networks [12]. While proposing a solution based on a *binary* count-down, [12] argues that wireless terminals may achieve and maintain synchronicity by listening to signals from cellular networks, or through the global positioning system, when available.

Initiatives such as the cognitive pilot channel may also be helpful to achieving synchronous operation [13]. Furthermore, portable terminals could be synchronised prior to deployment, and be required to periodically connect to appropriate time servers through the wired infrastructure in order to maintain synchronicity (and for certain money transactions, if applicable).

Ultimately, the degree of difficulty with which terminals of infrastructureless networks can achieve synchronisation depends heavily on the specific application scenario. For many scenarios, synchronicity seems well within reach, whether now or in the immediate future.

III. Dutch auction with spatial reuse

A. The Dutch auction for MAC

For MAC purposes, the Dutch auction retains the relative simplicity and allocation speed of sealed-bid auctions, 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) 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 channel scenario).

Despite the above, [3] seems to be the only previous application of the Dutch auction in a telecommunication context (for bandwidth allocation, *not* MAC).

B. The optimal Dutch bid

The bid depends on but needs *not* equal the bidder's "valuation". Characterising the optimal (selfish) bid is difficult in general. However, if each of N bidders knows that all valuations are distributed uniformly over the same interval, the optimal bid for a bidder whose valuation is V_i takes the simple form [14]:

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

Evidently, for large N the optimal bid $\approx V_i$.

C. Core protocol

For synchronised terminals, the distributed Dutch auction can provide medium access, with spatial reuse. At t_0 the first auction starts with the pre-specified initial price, and time-rate of decrease, and lasts τ. At time $t_0+\tau$ the first winner(s) access the medium for a length of time T (even if a winner is selected in less than τ, channel access starts at $t_0+\tau$). At time $t_0+\tau+T$ another auction of length τ starts, with pre-specified parameters, followed by a period of channel usage of length T, and so on.

When a terminal wishes to "take it", up to 3 short messages may be sent: (1) the winner sends its ID and that of the desired receiver (2) the receiver, if available, sends a short confirmation message (3) the winner sends a 2nd short message confirming the successful pairing. These 3 messages are reminiscent of the RTS/CTS messages in DCF[11]. If the transmitter-receiver pairing is not successful, the auction continues. Evidently, for *each* price value, the "tick" of the auction "clock" must allow sufficient time for the possible exchange of these 3 messages before moving on to the next lower price. The example below explains the process further.

D. Specific example

Figure 1 shows a situation in which 7 terminals wish access to a single communication channel. A row in table I shows the index of a transmitter, its desired receiver, and bid. Conceivably, a terminal could have a buffer with several possible messages each with its own valuation and hence associated bid (see rows 2 and 3).

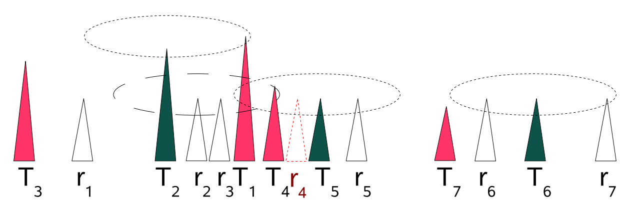

Figure 1. The distributed Dutch auction for MAC with spatial reuse

Table I
Potential transmitters, receivers and bids

T_i	r_j	*bid*
1	**1**	**10**
1	**4**	**9**
2	**2**	**7**
3	**1**	**6**
4	**3**	**5**
5	**5**	**4**
6	**7**	**3**
7	**6**	**2**

At t_0, each terminal (regardless of the physical location) knows that the (distributed) Dutch auction starts, at a pre-specified price, say 11, which will fall at a predetermined rate, say 0.1 every ε. $\varepsilon \ll \tau$ is long enough to allow the 3 messages mentioned above. Thus, after a length of time of 9ε the price has fallen to 10.1, which is still too high for everyone. After one more ε, the price becomes 10. Terminal 1 immediately sends its "I take it" message but r_1 is out of range, and does not respond. Thus, the clock continues to "tick" without a winner. 10ε later, the price drops to 9, and T_1 sends another "I take it" message this time with intended partner r_4. r_4 is in range, but in sleeping mode (indicated by a dotted red outline in fig. 1). Again, the pairing fails, and the clocks continues to tick (at this point, T_1 has no additional potential partners, and "drops out" of this auction). Eventually the price reaches 7, which triggers an "I take it" from T_2 (heard by T_1 , r_1, r_2 and r_3); r_2 confirms (heard by T_1, T_2, T_4 and r_3), and T_2 confirms the successful pairing (heard by T_1 , r_1, r_2 and r_3).

Notice that T_3 has not heard *any* of the previous messages, and continues to behave as if there has been no winners. Thus, 10ε later, T_3 assumes it has won, when the price has reached 6, and sends its "I take it" (heard only by r_1). But r_1 declines, because it knows about the $T_2 \rightarrow r_2$ pairing (notice that r_1 would *not* have known this without the second message from T_2).

The process continues similarly with T_5 and T_6 setting successful pairings, but *not* T_7. Similar to T_3 before, T_7 has not heard *any* of the preceding messages, and 'thinks' it has won when its clock indicates that the price is 2. But r_6 declines because it knows of the successful $T_6 \rightarrow r_7$ pairing (without T_6's 2nd message r_6 would *not* have known this).

IV. Main implementation challenges

Evidently, the distributed implementation requires tight synchronisation among terminals, i.e., a "common clock", which, as discussed in section II, may or may not be a major challenge.

Notice however that asynchronous terminals can be easily accommodated when there is an auctioneer (controller). The auctioneer can announce the beginning of the auction and its (possibly adaptable) initial price and time-rate of decrease. In fact, if the participating terminals lack an accurate clock, the auctioneer could even broadcast the new price at every "tick" of the auction "clock".

As any engineering solution, the MAC protocol must be judiciously designed. In particular, the parameters of the protocol (initial price, rate of decrease, τ, T, and ε) should be chosen judiciously. Processing and signal travel time, clock "drift", and the statistics of the terminals' "valuations" are among the factors to be considered in choosing the protocol parameters.

Furthermore, the possibility of simultaneous winners needs to be dealt with. If several "I take it" messages are simultaneously sent, the potential receivers would be unable to decode them, and hence would not respond. Each winner would then assume that its desired receiver is unavailable, and the auction would continue. Thus, if ties are infrequent, they would cause no significant damage.

If the possible valuations can be idealised as continuous random variables, then the probability that 2 terminals have the same valuation (and associated bid, consequently) is negligible. On the other hand, if the valuations ("priorities") are members of a relatively small discrete set, then the probability of tied winners can be high. In this case, some randomisation can help. For instance, suppose the valuations are integers between 1 and M. Then, at the start of the auction, each terminal may draw a random number between $-1/2$ and $1/2$, with as many significant digits as possible (considering ε above), and add it to its "true" valuation. Thus, the terminals whose "true" valuations were equal to 2, would have new valuations in the range 1,5 to 2,5. The probability that two terminals remain tied after such randomisation is negligible.

V. Access valuations for data terminals

The auction could involve real (selfish) human users, or software agents "trained" by them. In such case, a terminal's valuation will depend on the "preferences" of the human user, and the application for which access is wanted.

A. General form of access valuation

For delay-tolerant (data) traffic, it is reasonable to assume a valuation of the form $\beta_i B_i$ where (i) β_i is the monetary value (or "priority") of one information bit successfully transferred (for whoever pays, of the transmitter/receiver pair), and (ii) B_i is the (average) number of information bits the terminal can successfully transfer during the access period. It is straightforward to show that

$$B_i(x_i) = T(L_i/M_i)R_i f_i(x_i) \tag{2}$$

where (i) T is the duration of access, (ii) L_i is the number of information bits in a data packet of length M_i, (iii) R_i is the data rate and (iv) $f_i(x_i)$ gives the probability that a data packet is received correctly, as a function of the signal-to-noise ratio (SNR) at the receiver, x_i (f_i is highly influenced by modulation and coding, and generally exhibits an S-shaped graph [15]). The received SNR is $x_i = h_i P_i/\sigma_i^2$ with h_i the pertinent channel gain, σ_i^2 the average noise power, and P_i the transmission power.

B. Energy limited terminal

It is reasonable to expect an energy-limited data terminal to set power to achieve certain specific SNR, x^*, which maximises bits per Joule (x^* is a property of the link-layer configuration, and is easily found by drawing a tangent from the origin to the graph of f_i [15], [16]). Then, the valuation is:

$$\beta_i T(L_i/M_i)R_i f_i(x_i^*) \tag{3}$$

If all terminals have the same link-layer configuration (modulation/coding, L_i/M_i), then, the valuation takes the form $\hat{T}\beta_i R_i$, where

$$\hat{T} := T(L/M)f(x^*) \tag{4}$$

$\hat{T}$ can be absorbed into the units of measurement, and the valuation put in the simple form: $\beta_i R_i$.

C. Terminal with unlimited energy

If the transmitter has an "inexhaustible" energy supply (such as a vehicle's engine or the power grid), it can set its power to the maximal available level, say $\hat{P}_i$. Then, the valuation is

$$T(L_i/M_i)f_i(h_i\hat{P}_i/\sigma_i^2)\beta_iR_i \tag{5}$$

With $\hat{P}_i/\sigma_i^2 = \hat{p}$ for all i, and common link layer configuration, and convenient units, the valuation can be written as $f(h_i\hat{p})\beta_iR_i$.

Notice that if the data is equally important to all terminals ($\beta_i = \beta$ for all i) and they all operate at the same data rate ($R_i = R$ for all i), then the terminal that values access the most if the one that has the best channel (highest h_i), which makes intuitive sense.

VI. Conclusion

Previous work has shown the feasibility and effectiveness of auctions for simple, adaptively-prioritised medium-access allocation. However, the auction formats in earlier proposals require an auctioneer (controller), as well as an alternate MAC scheme to handle bids. With a potentially large number of access-seekers, contention-free bidding could be resource-wasteful, while a contention-based bid protocol could leave the potential highest bidders without an opportunity to make a bid. We have proposed the Dutch auction as a foundation for MAC. The Dutch auctioneer is optional for synchronised terminals, which enables distributed implementations with spatial reuse. The Dutch auction has a built-in bid-making protocol that automatically and simply ensures that the highest bids are made. Furthermore, this auction exhibits exceptional signalling economy (only one bid signal (the winner's) is strictly necessary in a single channel scenario). We have analysed *qualitatively* the potential of the Dutch auction for medium access allocation, and conclude that it retains the favourable features of previously proposals, while remedying their most serious limitations, and expanding the set of scenarios where MAC auctions can be used.

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