An Extended Alternating-Offers Bargaining Protocol for Automated Negotiation in Multi-agent Systems

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Abstract. This paper focuses on the study of bilateral bargaining protocol for competitive agents within the context of automated negotiation. Some modifications are proposed to improve the classical alternating-offers bargaining model and corresponding experimentation is designed to study the advantages/ disadvantages of this modified bargaining.

1 Introduction

Negotiation in multi-agent system (MAS) is one of the most active research areas in MAS. For instance, approximately 19% of the full papers accepted in the AAMAS 2002 conference, which is the most prestigious conference in MAS, are related to negotiation. And 7 out of 16 agent-related papers in the AAAI/IAAI 2000 conference and 13 out of 27 agent-related papers in IJCAI 2001 are also related to negotiation in MAS. This is a relatively fast growing research area since it only accounted for 6% of all agent-related papers indexed in BibTeX up to 1997. In the early 1990s, the role of negotiation in MAS was to solve conflicts of interest among agents during task allocation in distributed problem solving and resource allocation among agents. However, with the birth of e-commerce in the mid 1990s, the study of negotiation became broader, especially the study of open electronic marketplaces where humans can delegate their agents to negotiate with other agents. This paper will focus on one of the negotiation mechanisms used in e-commerce: bargaining.

Bargaining is among the oldest negotiation mechanisms in human history, even before the emergence of market or money as a means of finding a resolution among interested parties in the presence of conflicts of interest (cooperative behavior in a competitive situation). Basically, there are three elements as a prerequisite for bargaining: bargainers, conflict(s) and protocol. The protocol will tell the bargainers about how they can resolve the conflict, such as when the bargaining start or end, who move first and next, what kind of information allowed in exchange, etc. However, there is no guarantee for the existence of solution(s). In section 2, after some brief description of automated negotiation mechanisms the conditions for the existence of solution(s) will be studied. Some modifications to the standard alternating-offer bargaining protocol (and their advantages) are described in section 3. Finally, some conclusions will be derived in section 4.

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2 Automated Negotiation

2.1 Negotiation Mechanisms

A negotiation can be classified in many ways, based on the items being negotiated, the character of the negotiators, the negotiation protocol, the characteristics of information (completeness and symmetry), the negotiation period (continuous, one-step, multiple stage), and other factors (openness, with penalty, etc). Based on the negotiated items, negotiation could be differentiated into negotiation of single-attribute items or multiple-attribute items. An example of a multiple-attribute item is when negotiators consider price, quantity, quality, delivery time, and payment methods as a bundle. Moreover, negotiation can be categorized into one-to-one, one-to-many, or many-to-many negotiations. An English auction for antiques is a one-to-many negotiation (one auctioneer and many bidders), for example. Generally, a negotiator represents an individual/groups of individuals with specific/common goal(s). If a group of individuals is considered, it should take a single collective action or decision at any time and the negotiation results apply to all members of group. For example, the result of collective bargaining between workers and a company would apply to all workers.

Based on the character of the negotiators, a negotiation can be classified as cooperative or competitive. Cooperative negotiation is characterized by aiming for mutual social benefit (maximizing joint utility) for the negotiators. And competitive negotiation is characterized by seeking individual benefit for the negotiators (maximizing individual utility). Negotiation among agents in distributed problem solving usually falls into the former category, while negotiation in e-commerce falls into the latter. With the growth of various services in e-commerce, the trade of services among unknown problem solvers becomes possible. For instance, our agent might pay $10 to an agent from the US for estimating the NASDAQ stock index next week, and pay another $10 to another agent from Hong Kong for estimating the Hangseng stock index next week, and so on, in order to help in financial planning.

Depending on the protocol type, a negotiation can be categorized as an auction, a contract-net protocol, voting or bargaining. Some examples of well-known auction types in MAS are English auction, Dutch auction, double auction, first-price sealed-bid auction and Vickrey auction. English auction, Dutch auction and double auction are characterized by sequential decision making and open-bid. First-price sealed-bid auction and Vickrey auction are characterized by simultaneous decision and sealed-bid. One of the advantages of the auction mechanism lies in its high efficiency, i.e., in terms of the trading surplus extracted and the computational cost of the strategy used by bidders. Moreover, the best strategy of bidders in an English auction (usually used in auctions for antiques) is to increase the bid from zero until their private valuation. A bidder's valuation here means her/his minimum or maximum acceptable price depending on whether her/his position is as a seller or a buyer. For example, Tom is willing to accept $5000 for his car; thus any price above $5000 (his minimum acceptable price as a seller) generates a surplus for him. And Pat is willing to buy a sculpture for at most $1000 (her maximum acceptable price as a buyer); therefore her best strategy in an English auction is to compete with others up to at most $1000. Moreover, the best strategy of bidders in a Vickrey auction (second price sealed bid auction: the winner is the one with highest bid but pays the second highest bid) is to bid their true valuation, e.g. Pat bids $1000 [24]. The simplicity of these strategies can save computational costs.

If the auction mechanism is good, why is bargaining still important? The answers are:

1. Most auctions only allow negotiation for price, not other attributes (delivery time, payment method, etc.).
2. In some cases, feedback from negotiators is important. For instance, a buyer may disagree with the delivery method and thus does not participate in the auction, while the auctioneer can solve this problem trivially.
3. Auctions usually are scheduled in advance and with time restrictions, e.g. some online auctions range from 1 hour to 1 week. Intrinsically, auctions need multiple buyers or sellers in order to work well, therefore needing some time for gathering participants. Some buyers/sellers may not want to wait until an auction opens or finalizes.
4. In some circumstances, non-attribute factors are important, e.g., trusteeships, friendships, etc. Auctions cannot accommodate these factors.
5. Most auctions extract the surplus for the benefit of the auctioneer. For instance, in the Vickrey auction if the difference between the highest and second highest valuation is small (as usually happens if there is a significant number of bidders), the auctioneer can extract the most bidder surplus.[1] This could be considered as unfair and thus restrict the participation of bidders.

Considering these limitations, bargaining still plays an important role in automated negotiations in e-commerce.

Another approach, the Contract-net protocol [15, 16, 17, 21], on the other hand, provides a simple but powerful negotiation mechanism for solving a complex task by means of distributed problem solving. The underlying mechanism of a contract-net system is to decompose a task into sub-tasks and assign them to other agents. An agent will accept a contract if its marginal cost is less than its marginal benefit [15, 16, 17]. For example, if an agent already has many tasks to do, then any additional task will generate high marginal cost (e.g., cause slower computation). Moreover, every agent can sub-contract/re-contract its (previous) tasks to others who are willing to accept them. But usually it is assumed that each agent does not know the marginal cost of these tasks for other agents. This is true especially if we consider an open MAS where our agent will assign a task to another agent (e.g. as in our previous example of estimating the NASDAQ index). The common way to assign a task is to open an auction/bargaining and assign the task to the winner. Using this self-organizing mechanism, the system would perform optimal task allocation, which is pareto optimal. "Pareto optimum" is defined to be the situation where we cannot make anyone better off without making other(s) worst of. The following example illustrates this concept. Assume there are two agents *A* and *B* who can solve two

[1] Consider 100 bidders with their valuations randomly generated from {1, 2, .., 100}; then the winner, who has highest valuation $x, will bid $x and very likely pays $(x-1), thus getting $1 surplus. However, if there are only 10 bidders in a similar situation, then the winner, who has valuation $y, very likely pays $(y-10), thus getting $10 surplus.

disjoint tasks *a* and *b* with cost vector *CostA* = ($8 $10) and *CostB* = ($10 $8), where the value of *x* and *y* in vector (*x y*) represents the cost for solving task *a* and *b* respectively. That is, *A* is good at solving *a* and *B* is good at solving *b*. So, if someone pays $20 to *A* to solve both *a* and *b*, then the best action of *A* is to solve *a* and sub-contact *b* to *B*, which generates total cost equals to $8 + $8 = $16, which is pareto optimum. But*A* might not know *CostB*. In this two agents situation, *A* will announce simultaneously several options to *B*, such as (task *a*, pay $7), (task *b*, pay $9), or (task *a* and *b*, pay $16). And *B* will counter propose with its proposals. However, if the number of agents is large, conducting bargaining will be inefficient.

Another approach to resolving conflicts is voting. Voting is a social choice mechanism in selecting social preferences over a set of alternatives. One of the applications of voting in MAS is resource allocation by means of majority voting. For example, in order to use a common resource (e.g. a supercomputer), an agent can broadcast a request to all other agents to collect access keys from these agents. If two agents compete to use the same resource, then the first who gets the majority votes (>50% of access keys) will be able to access the resource. This mechanism is considered less effective than auctions for at least two reasons:

- Voting cannot accommodate the urgency of access. For example, if an agent *A* who very urgently needs a resource comes later than agent *B*, who has collected 50% of votes, then *A* will lose although it needs the resource more. Modification by using a multi-priorities mechanism (e.g. veto) can solve this problem but with the overhead of lower efficiency. However, in auctions urgency can be represented by private valuation. Thus, the resource will be allocated to whoever needs it most (bids highest).
- Even agents who are not concerned to use the resource reply to any request made by agents needing the resource, which increases the communication cost. But in auctions, only those who need the resource will participate.

In summary, auctions are efficient if the number of agents is large.

2.2 Bargaining

Basically, we can divide bargaining theory into two main categories: axiomatic bargaining theory and strategic bargaining theory [12, 17].

Axiomatic bargaining first sets several axioms (such as all bargainers are individually rational, the solution is invariant to independent changes of utilities, the solution is pareto optimal, bargainers are symmetric and independent of irrelevant alternatives).It then finds unique bargaining solution(s) based on these axioms.

Some of the well-known axiomatic bargaining solutions are the egalitarian solution, the utilitarian solution, the Nash solution, and the Kalai-Smorodinsky solution [8, 10, 14]. The Egalitarian solution solves the bargaining problem by splitting the surplus equally among all bargainers. The Utilitarian solution solves the bargaining problem by finding the maximum sum of bargainers' utility. For example, if a seller needs money for medication for her child while a buyer does not need money, the utilitarian solution will give the entire bargaining surplus to the seller, i.e. the buyer pays as much as his valuation to the seller. One of the applications of axiomatic bargaining is in labor arbitration, where union and company submit their proposals to an arbitrator who decides the final result.

In contrast, strategic bargaining theory does not assume a centralized decision maker (arbitrator), but allows the bargainers to solve the dispute by offer and counter-offer proposals. In this model, a bargainer *A* starts the negotiation by sending a proposal to his opponent *B*, who chooses either to accept or reject the proposal. If *B* accepts it, then the negotiation terminates. If *B* rejects it, then she must send back a counter-proposal to specify her preferences to *A*. Now *A* will evaluate the proposal and choose either to accept or reject it. The process continues until agreement is reached. Strategic bargaining uses, primarily, assumptions and techniques from game theory, such as backward induction. Currently, there are many variants of this model, such as a model with a time deadline, with various information levels (complete /incomplete, symmetric/ asymmetric), with risk of breakdown (one party walks out before negotiation ends), with risk-averse agents, etc. Most of the theoretical foundations of these various models have been studied by game theorists [2, 3, 4, 5, 12, 13]. One of the seminal works in strategic bargaining theory is Rubinstein's dividing pie problem [12, 13], where two agents offer and counter-offer proposals about how to divide a pie in the presence of the waiting cost.[2] Rubinstein uses backward induction to solve the problem and shows that the bargaining process only takes one step, i.e., an agent will send only one proposal that is accepted immediately by another agent. The outcome is based on some strict assumptions such as every agent is perfectly rational and has perfect foresight.

Generally, the bargaining model in MAS adopts the classical alternating-offers model. However, some important limitations of the game-theoretic approach come from its strict assumptions such as:

- All agents are perfectly rational, which means every agent has a preference order over available choices and always seeks the best choice (utility maximizer).
  Objection: In order to provide a complete preference order to an agent, clients/owners might need to rank all available choices, which might be very complicated, and then tell it to their agents. Do clients really care if their agent buys a book for $42 instead of $41.99? Therefore, it is not necessary for an agent in e-commerce to get her client's complete preference order and solve the bargaining problem in such a strict way. Instead, an agent needs to be *bounded rational*: able to rank some important choices and seek the best one [20].
- All agents know the payoffs of each action and can predict their opponents' actions perfectly (perfect foresight).
  Objection: This assumption is implausible in an open MAS. Even where each agent can learn from past experience, by detecting and memorizing all attributes of his/her opponents, there is no guarantee that his/her opponents will be consistent with their actions over time.
- All agents can search for the solution in exhaustive fashion. For instance, they are able to consider all possible states of a game. In other words, they are computationally unlimited.
  Objection: Computationally limited agents are characteristic of MAS.

2 Some people use a melting (ice cream) cake rather than a pie to illustrate the waiting cost. Longer bargaining time causes a smaller final cake, thus forcing all bargainers to act fast.

- If there are game theoretic equilibrium strategies, such as the Nash equilibrium strategy or the dominant strategy, then all agents will choose one of them.
  Objection: This is a controversial issue in social science, especially in the Prisoner's Dilemma game where the dominant strategy for both players is to confess. However, "confess" is not the pareto solution while "not confess" is. But from the MAS perspective, only pareto solutions are favorable.
- Agents do not recall past experiences, and therefore no learning mechanism is involved.
  Objection: One of the advantages of agents is their ability to memorize important things, which in turn can reduce computation. (e.g. case-based reasoning).

Considering the limitations of computational power and the existence of imperfect information in the real world, many heuristic techniques from AI have been adopted to develop new models called heuristic-based negotiation models. Most of them are characterized by learning mechanisms such as Bayesian learning, influence diagrams, genetic programming, etc. [9, 18, 23, 25]. Using this model, the negotiators can make decisions faster to find a good solution instead of the best one. However, game theory is still used as a benchmark (comparison) in the evaluation process; for instance, we could measure the effectiveness of a heuristic method by comparing its result to the theoretical result derived from game theory. In addition to these two approaches, some researchers have proposed another model namely an argumentation-based model that focuses more on natural language-like negotiation [6, 7, 19, 22]. The spirit of this work is to provide more flexibility in the negotiation process, such as to allow a negotiator to persuade their opponents to change their perceptions about them or the world states.

In general, in order to produce a bargaining solution, the valuations of seller and buyer should intercept or overlap (create a feasible set). Figure 1 shows a feasible set in the bargaining of two continuous attributes: unit price and quality. In figure 1, the seller's private valuation is a straight line representing the minimum selling price at different quality. An upward sloping of that line means the minimum acceptable price increases as the quality increases. The "seller's acceptable set" is all acceptable bargaining points from the seller's view, in which higher point (higher price for the same quality) is strictly preferred. Conversely, the buyer's private valuation is the buyer's maximum buying price at different qualities. And the buyer's acceptable set is all acceptable bargaining points from the buyer's view, in which a lower point is strictly preferred. Conclusively, any point in the acceptable set farther from private valuation line is strictly preferred. The intersection between two acceptable sets is a feasible set. Intuitively, the result of bargaining will fall in the feasible set, where both buyer and seller make a surplus.

Formally, assume there are only two agents $i \in \{1, 2\}$ bargaining over $\boldsymbol{N}$-attributes. An alternative region $\boldsymbol{A}$ is defined as all possible points in the bargaining space of $\boldsymbol{N}$-dimensional attributes. And both agents have their own preference order $\succsim_i$ over $\boldsymbol{A}$ ($\succsim_i$

is complete, reflexive and transitive in the bounded rationality sense)[3] and private valuation set $\boldsymbol{V}_i \subseteq \boldsymbol{A}$, where $\forall \boldsymbol{v}_m, \boldsymbol{v}_n \in \boldsymbol{V}_i \Rightarrow \boldsymbol{v}_m \sim_i \boldsymbol{v}_n$ (agent *i* is indifferent over all her valuations). Then, for any agent *i*, if an alternative $\boldsymbol{a} \succ_i \boldsymbol{V}_i$, then $\boldsymbol{a}$ generates a positive surplus for her, denoted by $Sur_i(\boldsymbol{a}) \geq 0$ or $Sur_i(\boldsymbol{a})^+$. In figure 1, $\boldsymbol{N}$ equals to 2, $\boldsymbol{A}$ is the rectangle area, $\boldsymbol{V}$ is the straight line representing seller's or buyer's private valuation, $\boldsymbol{v}$ is a point in the straight line, $\boldsymbol{a}$ is a point in $\boldsymbol{A}$, and $Sur_i(\boldsymbol{a})^+$ occurs if point $\boldsymbol{a}$ falls in the *i*'s acceptable set. Now we are ready with some definitions,

Definition 1. An *acceptable set* $\boldsymbol{Acc}_i \subseteq \boldsymbol{A}$ for agent *i* is a set such that $\forall \boldsymbol{a} \in \boldsymbol{Acc}_i \Rightarrow Sur_i(\boldsymbol{a})^+$.

Definition 2. A *feasible set* $\boldsymbol{S} \subseteq \boldsymbol{A}$ is a compact set (closed and bounded) such that $\forall \boldsymbol{s} \in \boldsymbol{S} \Rightarrow Sur_1(\boldsymbol{s})^+ \wedge Sur_2(\boldsymbol{s})^+$.

Definition 3. A *disagreement set* is $\boldsymbol{D} = \boldsymbol{A} \backslash \boldsymbol{S}$.

In figure 1, the disagreement set is all points outside the feasible set.

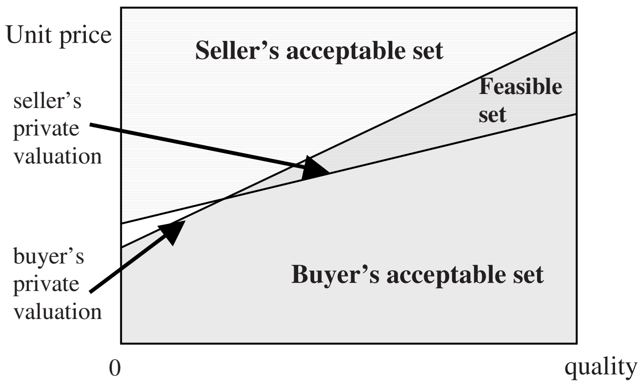

Fig. 1. Bargaining solution

In the alternating-offers bargaining between two bounded rational agents[4], the bargaining process can be illustrated (see figure 2) as picking some initial pairs of alternative points (e.g. four points in the buyer's acceptable set and four other points in the seller's acceptable set) and then repeatedly changing those points such that they become closer until one or more of them reaches a solution, as shown by the direction of the arrows. In the bargaining of multiple-attribute items, a proposal may consist of a set of alternatives (e.g., four in figure 2) and the bargained variable could be one

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[3] Throughout this paper, the binary operator $\geq$ refers to weak preference "at least as good as", and $\prec$ refers to strict preference "strictly preferred than", and ~ refers to indifference relation "as preferred as".

[4] In the rest of this paper, we will use the term *rational* instead of *bounded rational* and use *agent* and *bargainer* interchangeably.

dimensional or multi-dimensional. Figure 2 shows multi-attribute-one-dimensional bargaining, and figure 3 shows multi-attribute-multi-dimensional bargaining.

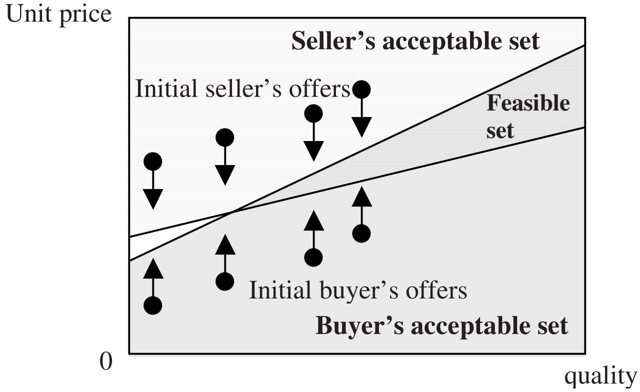

Fig. 2. Two-attribute bargaining process

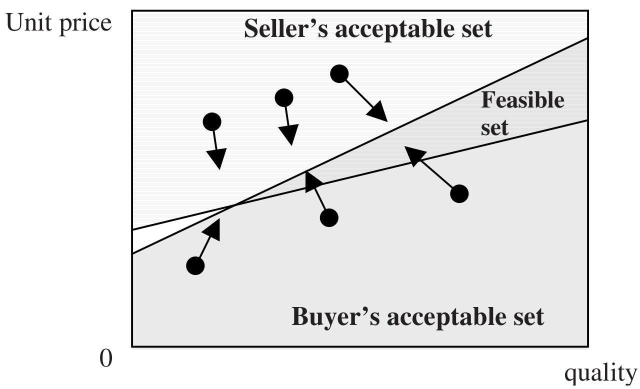

Fig. 3. Multi-dimensional bargaining

In figure 2, the bargained variable is the unit price (one-dimension vertical arrows). For example, in a bargaining of chemical goods a seller might say "Ok, I will give you more discounts; a 5% discount for goods with purity 90%, and a 10% discount for goods with purity 85%. But no discount for goods with purity 95%." In other words, the seller only changes the price of each different good (different quality). In figure 3, the dimension of the bargaining is both the unit price and the quality (two-dimension arrows). For example, a buyer may say "I am willing to increase my offer by $1 if you could increase the purity to 99.5%." Where the new offer is both increasing the price and the quality. Or in the foods industry, a seller might say, "Ok, I will give you 0.5% more discount but half of them will expire by March 2003 and the rest will expire by December 2003." Where the new offer is both decreasing the price and the quality.

The *convergence direction* (arrows' direction in figures 2 and 3) of the multiple-attribute bargaining informs us of two things:

1. The important of each attribute. For instance, the example in figure 2 tells us that the bargainers prefer to choose a specific quality of goods and bargain around it using price adjustment.
2. The strategic maneuvering of the bargainers. For instance, a bargainer might say \$100 for 85% purity and then say \$95 for 80% where both may be the same for him.

Beside the convergence direction shown in figure 2 and 3, another important factor in bargaining is the *convergence rate*. The *convergence rate* of the bargaining indicates the character of the bargainers. In order to understand the convergence rate of the bargaining, the following assumptions are needed:

Assumption 1. A rational agent will choose an alternative that yields the highest *expected* value, i.e., $\text{Max}_{\boldsymbol{a}}(\text{prob}(\boldsymbol{a}) \times Sur_i(\boldsymbol{a})^+)$, where prob($\boldsymbol{a}$) refers to the subjective probability that alternative $\boldsymbol{a}$ will be accepted by her opponent.

Assumption 2. A learning agent will revise her belief of the subjective value of prob($\boldsymbol{a}$) according to her experiences. If $\boldsymbol{a}$ is rejected, then she will reduce her subjective prob($\boldsymbol{a}$') $\forall \boldsymbol{a}' \in \boldsymbol{Acc}$. However, the reduction may not be the same for all $\boldsymbol{a}'$, i.e., the reduction monotonically increases as the alternative becomes farther from her own private valuation (less likely to be accepted by her opponent).

The following example illustrates our assumptions. Assume that two agents are bargaining for a car, and the buyer's valuation is \$2500 and the seller's valuation is \$2000. The seller opens the bargaining by offering \$3000. After thinking for a while, the buyer makes some predictions: prob(\$1800)=0.2, prob(\$2000)=0.5, prob (\$2200)=0.7 and prob(\$2500) =1. From these predictions the expected surpluses of each alternative are \$140, \$250, \$210 and \$0 respectively (by assumption 1). Therefore, the buyer asks for \$2000, which maximizes her expected surplus. If the seller does not accept the offer after a certain time (either insists on \$3000 or makes a counter offer of x > \$2500), then the learning buyer will conclude that she may not get the car for \$2000. So she will revise her prediction. Assume that her revision follows this rule: reduce all prob(x) by 0.4 if x is less than or equals the current offer, or reduce by 0.1 otherwise. Thus, from the example above: prob(\$1800) = 0.2 - 0.4 = -0.2 = 0, prob(\$2000) = 0.5 – 0.4 = 0.1, prob(\$2200) = 0.7 – 0.1 = 0.6 and prob(\$2500) = 1 – 0.1 = 0.9. Now, the expected surpluses are \$0, \$50, \$180 and \$0 respectively. And the buyer will ask for \$2200 now.

Corollary 1. Due to the asymmetric reductions as stated in *assumption 2*, the offers/asks made by seller/buyer are monotonically decreasing/increasing (closer to their private valuation).

Proof. If agent *i* is rational, then by *assumption 1*, $\boldsymbol{a}_x \succsim_i \boldsymbol{a}_y$ *iff* $\text{prob}(\boldsymbol{a}_x) \times Sur_i(\boldsymbol{a}_x)^+ \geq \text{prob}(\boldsymbol{a}_y) \times Sur_i(\boldsymbol{a}_y)^+$. Assume $\boldsymbol{a}_x$ is chosen, that is the expected surplus of $\boldsymbol{a}_x$ (= $\text{prob}(\boldsymbol{a}_x) \times Sur_i(\boldsymbol{a}_x)^+$) is the highest. Assume $\boldsymbol{a}_x$ is rejected, then all prob($\boldsymbol{a}$) will be reduced by y, where y monotonically increases as $\boldsymbol{a}$ goes farther from the agent's private valuation. Thus the reduction of corresponding expected surplus also monotonically increases as $\boldsymbol{a}$ goes farther from the private valuation. Consequently, if after the reduction the expected surplus of $\boldsymbol{a}_x$ is still the highest one, then $\boldsymbol{a}_x$ is retained, but if there exists $\boldsymbol{a}_y$ such that its expected surplus is greater than the expected surplus of $\boldsymbol{a}_x$, then $\boldsymbol{a}_y$ is closer to the private valuation. Q.E.D.

Proposition 1. If both agents are rational and able to learn, then their proposals converge as bargaining time $t\rightarrow \infty$, unless a solution is found or both proposals equal their private valuation (thus generating zero surplus).

Proof. In the initial bargaining t=0, both agent 1 and 2 will propose their favorite proposal, $\boldsymbol{a}^1$ and $\boldsymbol{a}^2$ respectively. If $\boldsymbol{a}^1 = \boldsymbol{a}^2$ then the solution is found and the bargaining ends. Otherwise, after waiting for Δt both agents will realize that prob($\boldsymbol{a}^1$) and prob($\boldsymbol{a}^2$) are lower than what they believed, thus $\boldsymbol{a}^1$ and $\boldsymbol{a}^2$ are no longer their favorite proposals. Following the corollary above, a new $\boldsymbol{a}$ closer to $\boldsymbol{a}^2$ will be chosen by agent 1, unless $\boldsymbol{a}^1 \in \boldsymbol{V}_1$. And a similar thing applies to agent 2, thus the bargaining converges. Q.E.D.

In static bargaining for a single-attribute item, where the feasible set $\boldsymbol{S}$ does not change over time, if the feasible set $\boldsymbol{S} \neq \varnothing$ and agents are rational, then the existence of a bargaining solution is guaranteed. However, in static bargaining for a multiple-attribute item, rationality and non-emptiness of the feasible set do not guarantee the existence of a bargaining solution. The following two propositions state these intuitions.

Proposition 2. In the static framework when the feasible set $\boldsymbol{S}$ does not change over time, the bargaining solution of single-attribute item is guaranteed *if* agents are rational and the feasible set $\boldsymbol{S} \neq \varnothing$.

Proof. Assume that both agents start the bargaining with two proposals not belonging to the feasible set. Then by *proposition 1* both proposals will move closer until a solution is found or both agents will be stuck in their own valuation set. Assume that both agents are stuck in their own valuation set. Then any agent will have incentive to accept the other's proposal because it generates positive surplus, which is better than not to accept (surplus = 0). Thus the bargaining solution is guaranteed. Q.E.D.

Proposition 3. In the static framework when the feasible set $\boldsymbol{S}$ does not change over time, the rationality and non-emptiness of the feasible set do not guarantee the existence of the bargaining solution over a multiple-attribute item.

Proof (sketch). Assume that both agents start the bargaining with two proposals not belonging to the feasible set, and each proposal only consists one alternative as shown in the left-most pair of alternatives in figure 2. Then by *proposition 1*, both alternatives will converge and get stuck on the private valuation set. Thus, no bargaining solution will be found. Q.E.D.

Corollary 2. In the static framework when the feasible set $\boldsymbol{S}$ does not change over time, the bargaining solution of a multi-attribute item is guaranteed *if* agents are rational and their private valuation set $\boldsymbol{V}_1 \subseteq \boldsymbol{Acc}_2$ and $\boldsymbol{V}_2 \subseteq \boldsymbol{Acc}_1$.

Proof (sketch). Since $\boldsymbol{V}_1 \subseteq \boldsymbol{Acc}_2$ and $\boldsymbol{V}_2 \subseteq \boldsymbol{Acc}_1$, then there is at least one dimension where the mapping of any pair of alternatives into that dimension produces a one-dimensional bargaining with guaranteed solution. Then by *proposition 1* if the solution of any pairs is guaranteed, the collective solutions of them are also guaranteed. Q.E.D.

Proposition 4. In a dynamic framework when the feasible set $\boldsymbol{S}$ moves dynamically during the bargaining process (e.g., due to changes of private valuations), then the existence of a single-attribute bargaining solution is guaranteed if agents are rational, $\boldsymbol{S} \neq \varnothing$ and $\Delta\boldsymbol{S}/\Delta t$ < convergence rate.

Proof (sketch). Since the convergence rate > $\Delta\boldsymbol{S}/\Delta t$, then the distances between the alternatives proposed with the feasible set is decreasing over time. Thus, the alternatives proposed eventually enter the feasible set, and the bargaining solution is guaranteed. Q.E.D.

3 Extended Bargaining Protocol

As described before, many modifications of the classical alternating-offer model have been suggested in order to improve the bargaining model. This project is motivated by the same spirit, i.e., relaxing the classical alternating-offer model and then studying the new model's advantages/disadvantages. This approach is adapted directly from the open economy view: create as many bargaining variations as possible and let nature select the best one. In particular this research proposes the following modifications to the classical alternating-offer protocol:

1. Allowing bargaining without revealing the negotiators' preferences to each other. For example in the bargaining between seller S and buyer B, the following negotiations would be allowed:

   S: I offer you $500 per unit.
   B: your price is too high, give me a lower price.

   Or

   S: I will not sell for less than $500.
   B: I cannot afford more than $400.

   In the first case, S sets the upper bound, and B asks for a reduction without revealing its minimum willingness to pay. In the second case, neither side reveals their exact valuations, but a range of them. Therefore, the first step of negotiation is to find an agreement on the range, and then proceed to the exact amount.
2. Allowing negotiation using strategic delay [1, 4]. A strategic delay is especially important at the beginning of the bargaining since it could serve as a signal of the negotiators' valuation. The less expected gain a negotiator anticipated from the bargaining, the more patient he is [4].
3. Allowing any revisions of the proposal before agreement is reached. In almost all the literature, it is assumed that the sequence of proposals monotonically converges to the agreement. For instance, the sequence of seller A and buyer B may look like <A offers $500, B asks $400, A offers $450, B asks $425, A accepts>. It is common that A will not revise its offer to be higher than the last offer. However, this convergence of values is not always true in an open system, because during the negotiation A may revise its valuation dynamically (e.g. the average price increases, or the demand for the same good increases, etc.). Consequently, allowing such properties will increase the complexity of the bargaining strategy (cf. proposition 2 and proposition 4).
4. Allowing negotiators to try to stimulate changes in each other's beliefs. In almost all the literature, it is assumed that the bargaining is only for the price. However, many real bargaining situations do not involve price, and in fact often implicitly or explicitly involve changing attitudes.

3.1 Issues in the Design of New Protocols

Rosenschein and Zlotkin [11] point out some important properties of a negotiation protocol:

1. efficiency: the result should be either pareto optimal or global optimal.
2. stability: there should be no incentive for all agents to deviate from agreed-upon strategies.
3. simplicity: there should be as little computational and communication cost as possible.
4. distribution: there should be no central decision-maker (a potential point of failure).
5. symmetry: the protocol should be the same for all similar agents. For instance, none of the agents is treated differently by the protocol.

Sandholm [17] extends this list by adding other possible properties such as guaranteed success and individual rationality. However, none of the properties above guarantee that the system will attract users' participation, especially in an open electronic marketplace. Therefore, we may add another property to be considered: attractiveness, i.e., the protocol should be able to attract users' (agents or human) participation. Due to the nature of the problem raised, the design of the protocol in this project only considers efficiency, simplicity, distribution, symmetry, and attractiveness. A proposed protocol should encourage agents to use various strategies. And some agents may deviate from the best strategy due to internal factors (such as not knowing the best strategy or making an error in computation) or external factors (such as being interrupted by other agents/owner or finding a better deal). Thus, individual rationality is excluded.

3.2 Design an Experimental Study

In order to evaluate the performance of the new protocols, we should test them against the classical alternating-offer protocol. The experiments will consist of 2 sessions: experiment with a classical alternating-offer protocol (control) and a modified protocol designed using some or all of the modifications described earlier. There are three criteria used in the measurement of the protocol's efficiency: percentage of failure, length of bargaining, and computational cost. And there are also two metrics to find the protocol's effectiveness: fairness and participation rate.

The measurement of these five criteria is as follows:

- Percentage of failure = number of failures (walkout)/ number of bargaining sessions.
- Length of bargaining = number of alternations until negotiation concluded.
- Computational costs = time needed for each decision.
- Fairness = % difference between buyer and seller surplus.
- Participation rate = proportion of participants in extended alternating-offer bargaining compared to participants in classical alternating-offer bargaining.

In order to measure these five criteria, the agents used in the experiments should be bounded rational and learning agents, as stated in assumptions 1 and 2. Moreover, the bargaining systems chosen are static-single-attribute bargaining and dynamic-single-attribute bargaining. The dynamics appear through changes of agents' perceptions toward their goal. From proposition 4, the existence of the bargaining solution is guaranteed only if the dynamics change slower than the convergence rate. Therefore, a controllable change is introduced into the bargaining system by the change of market price at each period. Basically, each agent has a negotiation deadline.

The computation models of each bargainer are now discussed. The buyer will maximize her utility U_B, as follows:

A buyer has private valuation: v_B, time deadline: τ_B, belief about market price: M_B^T, belief about seller's time deadline: τ_B^S, belief about the probability of seller to walkout: p_B^{Sout}. Let p_B^M be the buyer's perceived probability that there are sellers who are willing to sell at market price M. P^{BO} is the price offered/counter offered by the buyer. P^{SO} is the price offered/counter offered by the seller. P_B^{SAcc} is the buyer's perceived probability that the seller will accept P^{BO}. δ_t is the kroneker delta, equaling 1 if $t \le \tau_B$ or zero otherwise. ω is the weight (importance) assigned to the market price. And the buyer's belief about the trustworthiness of the seller's statement is $trust_B^S$.

Buyer's Expected Utilities:

If the buyer chooses to reject the offer and walkout (WO), then her utility for walk out is:

$$U_B^{WO} = \delta_{t+1} p_B^M \left(v_B - M_B^\tau\right) \tag{1}$$

By choosing walkout, the buyer's expected utility depends on the probability to find a seller who is willing to sell the goods at market price M_B^T such that the buyer could make surplus v_B - M_B^T before the deadline arrives (multiplied by the kroneker delta).

If the buyer chooses to accept (Acc) the offer then her utility is:

$$U_B^{Acc} = \left(v_B - P^{SO}\right) + \omega\left(M_B^\tau - P^{SO}\right) \tag{2}$$

where the first term is the surplus she got at price P^{SO} (the price offered by the seller), and the second term is the surplus she 'feels' will come from the market. However, her feeling about the difference between her bargained price and the market price may not be the same over time. For example, if Pat is driving in a desert and suddenly finds a grocery which sells ice cream for $5, will she consider how much is the market price? If not at all, then assign $\omega = 0$. If she cares a lot, assign it = 1. Note: here we don't need δ_{t+1} because she will get the utility immediately after she accepts.

If the buyer chooses to counter offer/re-offer (CO) then her expected utility is:

$$U_B^{CO} = \delta_{t+1}\left[p_B^{SAcc}\left[\left(v_B - P^{BO}\right) + \omega\left(M_B^\tau - P^{BO}\right)\right] + p_B^{SOut} U_B^{WO}\right] \tag{3}$$

where

$$p_B^{SAcc} = (1 - p_B^{SOut})\, p_B(SAcc \mid \sim SOut) \tag{4}$$

Or P_B^{SAcc} is the buyer's perceived probability that the seller will accept her offer P^{BO}. Thus, the expected utility is the sum of the expected surplus made if seller accepts the buyer's offer and the expected utility if the seller walks out.

The utility of choosing to strategically delay (SD) is:

$$U_B^{SD} = \delta_{t+1}\left[p_B^{SAcc}\left[\left(v_B - P^{CO}\right) + \omega\left(M_B^{\tau} - P^{CO}\right)\right] + p_B^{SOut} U_B^{WO}\right] \tag{5}$$

The utility function above equals the utility of not re-offering or insisting on a previous offer. Generally, the purpose of strategic delay is broader than just calculating utility function. For example, strategic delay by agent *i* could be

- a signal of her unwillingness to accept an offer by her opponent, indirectly telling her opponent to revise his subjective probability prob(a);
- a signal of her insistence to stick to her previous offer;
- a signal of her patience that she can wait for a longer time, which also reveals the importance of the bargained item to her.

Therefore, strategic delay is selected if

- it is effective to let the opponent revise their perceived value of the agent's acceptance;
- it is better not to re-offer any value other than the previous offer;
- it is effective to let the opponent revise their perceived values of the agent's discount rate and valuation;
- simultaneously any combinations of the three situations above are true.

The utility to make an argument (Arg) is:

$$U_B^{Arg} = \delta_{t+1}\left[p_{BNEW}^{SAcc}\left[\left(v_B - P^{CO}\right) + \omega\left(M_B^{\tau} - P^{CO}\right)\right] + p_{BNEW}^{SOut} U_B^{WO}\right] \tag{6}$$

By making an argument, the agent tries to change the opponent's perception about the current world state. At this point, the argument tries to persuade the opponent to revise their perceived market price. For example, by indicating that the market price will be very low in the near future, a buyer can persuade a seller to sell with a lower price today, since if the buyer walks out, the seller will get less from the market.

Seller's Expected Utilities:

The seller's expected utilities are almost the same as the buyer's expected utilities, except that some calculations come from the seller's perspective. For example, the seller's expected surplus (profit) is calculated as the offered price minus valuation, instead of valuation minus the offered price in the buyer's case.

Reject and walkout (WO):

$$U_S^{WO} = \delta_{t+1} p_S^M \left(M_S^{\tau} - v_S\right) \tag{7}$$

Accept (Acc):

$$U_S^{Acc} = \left(P^{BO} - v_S\right) + \omega\left(P^{BO} - M_S^{\tau}\right) \tag{8}$$

Offer/Counter offer/Re-offer (CO):

$$U_S^{CO} = \delta_{t+1}\left[p_S^{BAcc}\left[\left(P^{SO} - v_S\right) + \omega\left(P^{SO} - M_S^{\tau}\right)\right] + P_S^{BOut} U_S^{WO}\right] \tag{9}$$

where

$$p_S^{BAcc} = (1 - p_S^{BOut})\, p_S(BAcc \mid\sim BOut) \tag{10}$$

Strategic Delay (SD):

$$U_S^{SD} = \delta_{t+1}\left[p_S^{BAcc}\left[\left(P^{CO} - v_S\right) + \omega\left(P^{CO} - M_S^{\tau}\right)\right] + p_S^{BOut} U_S^{WO}\right] \tag{11}$$

Argumentation (Arg):

$$U_S^{Arg} = \delta_{t+1}\left[p_{SNEW}^{BAcc}\left[\left(P^{CO} - v_S\right) + \omega\left(P^{CO} - M_S^{\tau}\right)\right] + p_{SNEW}^{BOut} U_S^{WO}\right] \tag{12}$$

Based on the utility functions above, both buyer and seller make their choice consecutively, i.e., they choose the decision that generates highest utility from their point of view.

4 Conclusion

The goal of this paper is to prepare the basic framework in the design of a new alternating-offers bargaining protocol. Up to now, there are three contributions of this paper towards this end:

- The characteristics of the bargaining protocols have been analytically studied to find the answer to some basic questions: such as, can the bargaining always converge? in what conditions do bargaining solutions exist? what happens if two agents use different criteria to update their beliefs? Some of the simple questions have been answered in this paper. Nevertheless, there are many other questions waiting deeper study.
- The paper has explored the usefulness of trying to improve alternating-offers bargaining, in particular to apply it to e-commerce applications. So far, most of the work in negotiation in MAS concentrates on auctions. This paper tries to highlight the importance of bargaining in negotiation. One of the future challenges is to build not only an agent-agent bargaining system, but also a human-agent bargaining system, or human-agent-agent-human bargaining system.
- The paper has set the groundwork for an agent-based simulation, which could serve as a test-bed of the protocol design. Currently, several mechanisms for an agent's decision making have been identified. However, there are still many unsolved problems, such as what kind of learning mechanism is appropriate? should an agent trust the arguments made by her opponent? should every agent maintain the history and a model of other agents?

Our future research aims to implement the design, run experiment and find better protocol, which can accommodate more sophisticated bargaining strategy.

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