

Trust and Cooperation in a Trading Society of Objective-Trust Based Agents

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ABSTRACT

In this paper we develop a notion of “objective trust” for Software Agents, that is trust of, or between, Agents based on actual experiences between those Agents. Experiential objective trust allows Agents to make decisions about how to select other Agents when a choice has to be made. We define a mechanism for such an “objective Trust-Based Agent” (oTB-Agent), and present experimental results in a simulated trading environment based on an Intelligent Networks (IN) scenario. The trust one Agent places in another is dynamic, updated on the basis of each experience. We use this to investigate three questions related to trust in Multi-Agent Systems (MAS), first how trust affects the formation of trading partnerships, second, whether trust developed over a period can equate to “loyalty” and third whether a less than scrupulous Agent can exploit the individual nature of trust to its advantage.

Keywords

Trust Based Agent Interaction, Teamwork and Co-operation, Organisation and Social Structure.

1. INTRODUCTION

Software Agents are increasingly being required to make decisions and act locally, but also operate in the context of a “global” Multi-Agent Society (MAS). As these Agents become fully autonomous they become forced to make decisions about when and when not to engage (for instance to request information, to delegate important tasks or to trade) with other Agents. They must rely on internalised beliefs and knowledge about those other

Agents in the society. This reliance on beliefs forms the basis of a *trust relationship* between intentional entities.

The trust relationship, in its broadest sense, has proved difficult to define [3], [4], [6], [9], [10], [11], [20]. We synthesise the following as a working definition, suited to the purposes of this paper. “*Trust is the assessment by which one individual, A, expects that another individual, B, will perform (or not perform) a given action on which its (A’s) welfare depends, but over which it has restricted control*”. Trust therefore implies a degree of dependency of A on B. This dependency may be reciprocal. Where the dependency relationship is asymmetric and one individual gains control over the other the relevance of the trust relationship is weakened for both A and B [10]. Equally, as the element of imposed compulsion in the relationship between the individuals increases, the role of trust recedes. Similarly, the role of trust is reduced as the protagonists A and B acquire more complete information about each other (when they may accurately assess the future outcome of each transaction) [11]. Williams [20] summarises the trust relationship: “*agents co-operate when they engage in a joint venture for the outcome of which the actions of each are necessary, and where the necessary action by at least one of them is not under the immediate control of the other*”. The trust relationship may further be subject to exogenous events under the control of neither party, which may or may not affect the relationship [10].

Autonomous software Agents face all these issues, dependency on others, restricted control, incomplete information and the effects of exogenous events. It is little wonder, then, that the issues of trust between Agents should attract attention. Until an adequate system of compunction is widely adopted (through legislation, or by mutual agreement, for instance) this situation is likely to remain. Griffiths and Luck [7] emphasise the notion of trust as a reciprocal of risk, in the context of co-operative planning between Agents. Marsh [11] considers the risk/benefit relationship for Agents in a Distributed AI context. Castelfranchi and Falcone [3] divide the notion of subjective trust into component belief types that one Agent might hold with regard to another. They argue that such beliefs may be combined to form a *Degree of Trust* ($\mathbf{DoT}_{XY\tau}$) measure, which may in turn be used to decide whether a task of type (τ) should, or should not, be preferentially delegated by

Agent X to another Agent, Y. Jonker and Treur [9] present a formalised framework for the description of trust based on sequences of experiences between Agents.

We recognise that the definition of trust both as a function of subjective beliefs and as a function of experience will be important to the construction of Agents in the future. As with real life, “reputation is important, but no substitute for experience” [10]. Such direct experiences can form an *objective trust measure* - the trustworthiness of another Agent put to the test and recorded as the basis of selecting that individual for future dealings. Trust should be based, whenever possible, on direct experience rather than on accumulated social attitude. As in real life, there is a limit to what can be achieved by wondering about what another entity might, or might not, do in any particular circumstance.

In this paper we consider *objective Trust-Based Agents* (oTB-Agents), Agents which select who they will trade with primarily on the basis of a trust measure built on past experiences of trading with those individuals. The purpose of this work is to be able to investigate some important questions that arise when Agents are given a “free choice” as to whom they will co-operate with. This paper will consider three questions:

- 1) What happens when Agents who rank experiential trust and trustworthiness highly form into trading societies?
- 2) Does a trust relationship established between Agents over a period of time equate to loyalty between those Agents when trading becomes difficult?
- 3) Trust, although not always subjective, is personal; is it in an Agent’s interest to appear trustworthy in some cases, and not care in others?

We take a practical and experimental approach in our investigations. To this end we adopt a concrete example within which to discuss and evaluate oTB-Agents. Section two provides an overview of that test domain. Section three details the oTB-Agent mechanism and introduces some terminology. By describing the mechanism within this concrete example, we do not intend to convey any presumption that its application should be restricted to this or any particular application area, as we do not consider this to be the case. Section four defines the main functional components of an oTB-Agent. Section five briefly describes our Agent simulator. Section six describes some experiments that shed light on the questions just posed. Finally, we discuss related and future work and draw some conclusions.

2. THE TRADING SCENARIO

Increasingly Agent technology is seen as offering an important contribution to the problems faced by the telecommunications industry. Figure one shows a simplified model for an *Intelligent Network* (IN). The IN provides an infrastructure in which different types of Agent may form a trading community, as well as acting as an interface layer between end-user consumers of a communications service and the underlying telecommunications network which will transport voice and data information between geographically distinct points.

We consider two distinct Agent types in this paper. *Service Control Point (SCP) Agents* are associated with *Service Control Points*, access portals to the telecommunications network. *Service Switching Point (SSP) Agents* serve *Service Switching Points*, providing access points for consumers of telecommunications

services. There may be a large number of SCP and SSP Agents forming a single IN. Each SCP acts as an agent or broker for the suppliers of telecommunications bandwidth and is tasked with ensuring that the available bandwidth is sold. Conversely, each SSP acts as agent or broker for end-consumers of telecommunications services, tasked with ensuring that sufficient bandwidth is reserved to meet the needs of those consumers.

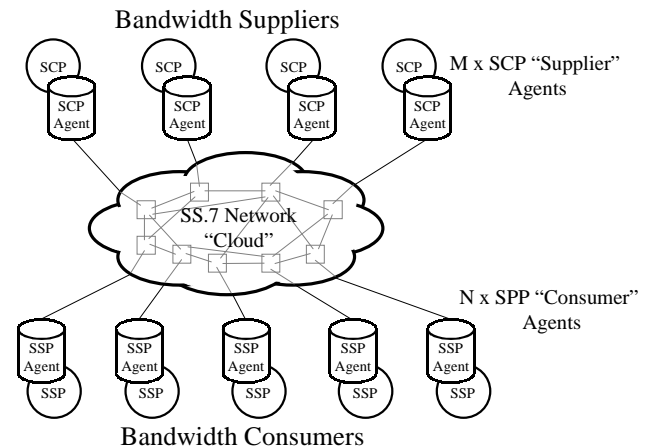


Figure One: Intelligent Networks

In this model message passing between SCP and SSP Agents is assumed to take place over an SS.7 network and to use a contemporary Agent Communication Language and Protocol, such as FIPA-ACL [5], [8]). Beyond requiring that the transmission of messages between Agents is timely and reliable, we will not consider related issues of inter-Agent communication further in this paper.

Agent Architecture models for IN management have proved to be rich ones for investigating issues directly related to resource allocation and load control in the context of current telecommunications systems ([8], [13], [14], [17]). Rather than concerning ourselves with issues relating to overall performance of the network, we will concentrate on the effects of trading decisions based on “objective Trust Based” (oTB) principles. We will focus on the performance of individual Agents from the perspective of the degree to which they trust, and are trusted by, other Agents in the society. In maintaining this focus on issues relating to trust we have developed a “trading scenario”, which gives both SCP and SSP Agents the opportunity to behave in a trustworthy or untrustworthy way in their dealings with fellow Agents. This then forms a basis on which individual Agents select the Agents they will trade with in future.

3. AGENT BASED TRADING

Figure two illustrates the (IN derived) trading scenario used to test and evaluate oTB-Agent based trading. Trading is divided into equal time slots, called a *trading cycle*. At the beginning of each trading cycle each SSP (customer) Agent receives a demand for resource (bandwidth in the scenario) and makes bids to SCP (supplier) Agents to cover that demand. SSP Agents must select SCPs they trust to offer them the resource they require. If the SCP does not offer to cover an SSP’s bid for bandwidth resource, then

the SSP has reason to regard that SCP as untrustworthy. While demand may vary between trading cycles, the total amount of resource available is taken as fixed. Each SCP Agent must attempt to distribute its supply of resource to SSP Agents that it trusts to pass that resource on to its end-users. Any resource not taken up by SSP Agents is deemed lost, to the detriment of the SCP Agent. SSP Agents that fail to use resource offered to them are considered untrustworthy.

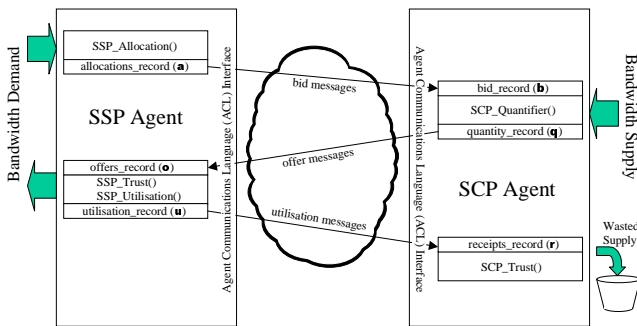


Figure two: The IN Trading Scenario

All SSP and SCP Agents each maintain a *trust vector*, recording the opinion the Agent holds about the trustworthiness of each of the other Agents with which it can trade. The trust vector forms the primary source for selecting trading partners, and is itself updated after each transaction.

Each trading cycle involves three transaction steps (each corresponding to an ACL performative between individual Agents). First, the *bid step*, in which SSP Agents receive their demand load and issue bids to SCP Agents to meet that load. Second, the *offer step*, in which SCP Agents make offers of resource in response to bids they receive. Third, the *utilisation step*, in which SSP Agents distribute the resource units they have been offered to their customers, and notify the SCP that offered the resource whether or not they utilised all the allocation they were offered.

The Bid Step: At each trading cycle every SSP Agent receives a quantity of demand from its customer base, which is the sum of their (the customer's) estimate of the resource they require for the next trading cycle. Each SSP must then select one or more SCP Agents it trusts using an *allocator function*, and issue a *bid message* performative to them indicating the number of units of resource it requires. An SSP Agent may dishonestly (or perhaps prudently) *overbid* its requirement, thereby ensuring it will receive at least as much resource as it requires. In doing so it risks having to return unused units, and be seen as untrustworthy by the SCP Agent that reserved resource for it.

The Offer Step: Each SCP Agent receives a quantity of units bid from SSPs willing to trade with it. SCP Agents select which SSP bids it wishes to honour using a *quantifier function*, the choice being derived from the Agent's trust vector. The SCP Agents then communicate the offers of resource they are prepared to make back to the SSPs that made the original bids, the *offer message* performative. An SCP may not offer, in total, more resource units than it has access to. To do so would, in this scenario, introduce another round of transactions.

The Utilisation Step: Once an SSP Agent has received all the offer messages from SCP Agents, it will attempt to satisfy the customer demand for the current trading cycle from the offers of resource allocation that it has obtained. If it has received more resource than it requires it returns the excess to one or more SCP Agents on the basis of a *utilisation function*. Returns are notified to SCP Agents in a *utilisation message* performative. Also at this step the SSP Agent updates its trust vector using its *SSP trust function*, on the basis of the difference between the quantity the SSP Agent bid for against the quantity it received from SCP Agents. We assume accountability, in that an SCP Agent can meter units actually consumed at the request of an SSP Agent, so that an SSP cannot just request an unlimited number of units and just discard the excess (thereby appearing trustworthy to the SCP). On the other hand, each SSP is free to return unused units to any SCP, thereby managing its trust relationships.

Finally, on receipt of the utilisation messages, each SCP Agent can update its own trust vector according to its *SCP trust function* by comparing the quantity of resource requested against that actually utilised.

We treat the resource (bandwidth) as a true commodity. Any SSP may request resource from any SCP. We further treat the resource to be a fixed price item. Agents may not "spend more" to secure extra supplies in times of shortage, or reduce their prices in times of oversupply. When supply and demand are mismatched individual Agents must decide which Agents they will favour over others, this is at the heart of the "does trust beget loyalty?" question posed earlier.

There is no overall control or centralised mediation in this system model (as, for instance, in the auction model of Patel, *et al.*, [12]). Each Agent makes its trading decisions based on its past experiences of trading with other Agents in the IN, updating its trust vector, and so affecting its future decisions, based on each new transaction. In the model, Agents that do not adhere to the communications and transaction protocols are excluded from the trading arrangement. Messages sent inappropriately, such as an SCP offer where no bid was made, can be discarded and the sender considered "untrustworthy" for attempting to supply an unsolicited service.

4. THE ALLOCATOR, QUANTIFIER, UTILISATION AND TRUST FUNCTIONS

This section describes the SSP-Allocator, SCP-Quantifier, SSP-Utilisation and the Trust functions used by SCP and SSP Agents in detail. Together these five functions encapsulate the key components of oTB-Agents. In a society of N SCP Agents trading with M SSP Agents, the trust vector owned by the n^{th} SCP Agent will be represented by ${}_n\mathbf{t}$, its trust rating of the m^{th} SSP, a scalar value, by ${}_n\mathbf{t}_m$. Conversely, the m^{th} SSP's (${}_m\mathbf{t}$) trust rating of the n^{th} SCP Agent by ${}_m\mathbf{t}_n$. Individual trust ratings are scaled from 0 (complete distrust) to 1.0 (complete trust). The use and management of these trust values is central to the operation of an oTB-Agent, they are the principal way in which other Agents are selected to trade with. The manner in which it is used, and the mechanism by which it is updated, define important aspects of an Agents apparent "personality" (the way it appears to other Agents) within the society. The *allocations record (a)*, *offer record (o)* and *utilisation record (u)* are message buffers used by SSP

Agents to prepare messages for sending (\mathbf{a} and \mathbf{u}), or receiving (\mathbf{o}) messages from SCP Agents. The *bid record* (\mathbf{b} , receive), *quantity record* (\mathbf{q} , send) and *receipts record* (\mathbf{r} , receive) are used by SCP Agents to buffer messages to and from SSP Agents. They employ the same indexing notation as \mathbf{t} .

4.1 SSP Allocator Function

The SSP allocator function divides the total demand (*actual_demand*) received by an SSP Agent for the current trading cycle into smaller units and populates an *allocations record*, ${}_m\mathbf{a}_n$, which holds the number of units of resource the SSP Agent m will be requesting from SCP Agent n .

The allocator function is controlled by three parameters. (1) The *overbid rate*, *obrate*, which determines how much extra resource the Agent will bid for above its actual demand. Overbid is expressed as a percentage. (2) The *split rate*, *srate*, which determines how many SCP Agents will receive bids from this SSP Agent. This effectively ameliorates the risk for the SSP Agent that any particular SCP Agent will refuse it supply. Split is expressed as an integer ≥ 1 , but \leq number of SCP Agents. (3) The *exploration rate*, *erate*, which determines the probability with which the Agent will ignore its trust ratings and send a bid to a random SCP Agent. This is expressed as a percentage, where 0% refers to no exploration of the market and 100% causes the SSP Agent to always make bids to suppliers at random. The exploration rate parameter addresses a practical problem familiar in the reinforcement learning paradigm, that of balancing the advantages to be gained from trading with known and already trusted partners with the opportunity to discover better partners from the larger pool ([15]).

The allocator function is best described procedurally:

For each SSP Agent m do:

- 1) Clear ${}_m\mathbf{a}$
- 2) Set $\text{demand} \leftarrow \text{actual_demand} * \text{obrate}$
- 3) Set $\text{bid_packet_size} \leftarrow \text{demand} / \text{srate}$
- 4) If ($\text{rand} < \text{erate}$) Set ${}_m\mathbf{a}_r \leftarrow \text{bid_packet_size}$
where r is a randomly selected SCP Agent and
 rand is a randomly generated number, 0 .. 100
- 5) Else for SCP Agent x , where x is $\max({}_m\mathbf{t}_x)$ and ${}_m\mathbf{a}_x = 0$
Set ${}_m\mathbf{a}_x \leftarrow \text{bid_packet_size}$
- 6) Repeat from step 4 until all bid packets allocated

Step 5 successively selects the most trusted, then the next most trusted until all the bid packets have been allocated. Once the allocator procedure is completed the SSP Agent issues a bid message to every SCP Agent where ${}_m\mathbf{a}_n > 0$ (i.e. a bid has been allocated). Apart from the random selections, bids have been sent to the most trusted trading partners.

4.2 SCP Quantifier Function

The SCP quantifier function distributes the SCP Agent's limited supply amongst all those SSP Agents that made bids, it does so on

the basis of trust, as recorded in its trust vector. The function is unparameterised. Received bids are recorded in the *bid record* ${}_n\mathbf{b}$, the SCP quantifier function populates the *quantity record* ${}_n\mathbf{q}$, which records the offers to be made. If the total of bids (*total_bid_value*) received by the Agent total less than the available supply, the value of each bid is simply transferred to the quantity record, as all SSP Agent bids can be satisfied. When bids exceed supply the following procedure is invoked to distribute the available supply on the basis of trust:

For each SCP Agent n do:

While $\text{total_bid_value} > 0$

For SCP Agent x , where x is $\max({}_n\mathbf{t}_x)$ and ${}_n\mathbf{q}_x = 0$

Set ${}_n\mathbf{q}_x \leftarrow {}_n\mathbf{b}_x$ if $\text{total_bid_value} \geq {}_n\mathbf{b}_x$

else ${}_n\mathbf{q}_x \leftarrow \text{total_bid_value}$

$\text{total_bid_value} \leftarrow \text{total_bid_value} - {}_n\mathbf{q}_x$

Offer messages are issued from ${}_n\mathbf{q}$ notifying the bidding SSP Agents whether their bid has been successful or not, SSP Agents note these offers in their *offers record*, ${}_m\mathbf{o}$. This procedure effectively assigns to the SSP Agents that an SCP Agent trusts the most all the supply they want, giving priority to the most trusted Agents first, until all the supply is used up. The remaining Agents are rejected. Other quantification strategies can be implemented, for example equable distribution where each bidder receives a fair share of the supply, but these are not considered here further.

4.3 SSP Utilisation Function

When an SSP Agent has bid for, and received, more units than it actually requires it may return these excess units to unfortunate SCP Agents, who have lost the opportunity to use them and the units are wasted. If demand exceeds offers, the SSP Agent satisfies its customers as best it can, and transfers all the used offers from ${}_m\mathbf{o}$ to the its *utilisation record*, ${}_m\mathbf{u}$ (full utilisation).

When offers exceed demand, ${}_m\mathbf{u}$ is populated thus:

For each SSP Agent m do:

While $\text{total_offer_value} > 0$

For SCP Agent x , where x is $\max({}_m\mathbf{t}_x)$ and ${}_m\mathbf{u}_x = 0$

Set ${}_m\mathbf{u}_x \leftarrow {}_m\mathbf{o}_x$ if $\text{total_offer_value} \geq {}_m\mathbf{o}_x$

else ${}_m\mathbf{u}_x \leftarrow \text{total_offer_value}$

$\text{total_offer_value} \leftarrow \text{total_offer_value} - {}_m\mathbf{u}_x$

The SSP Agents utilises offers from SCP Agents with which it has the best trust relationships preferentially, and risks damaging relationships that are already weaker. Entries in ${}_m\mathbf{u}$ are transmitted to SCP Agents who made offers as *utilisation messages*, and recorded by the receiving SCP Agent in its *receipts record*, ${}_n\mathbf{r}$. The SSP Agent suffers no actual penalty, except the loss of credibility with its supplier, for returning offers unused.

4.4 SSP Trust Function

An SSP Agent's trust vector is updated on the basis of the perceived reliability of SCP Agents. This is determined on the basis of whether, or not, an SCP Agent honoured individual bids,

${}_m a_n$, with corresponding offers, ${}_m o_n$. A trust function takes two parameters, α ($0 \leq \alpha \leq 1$), the degree to which a positive experience enhances a trust vector element, and β ($0 \leq \beta \leq 1$), the degree to which a negative experience damages the relationship. An individual SSP Agent trust vector element, ${}_m t_n$, is updated thus:

${}_m t_n \leftarrow {}_m t_n - (\beta * {}_m t_n)$, if a bid ${}_m a_n$ was issued, but no offer ${}_m o_n$ received, or

${}_m t_n \leftarrow {}_m t_n + (\alpha * (1 - {}_m t_n))$, if offer ${}_m o_n \geq \text{bid } {}_m a_n$ was issued, or

${}_m t_n \leftarrow {}_m t_n + ((\alpha * ({}_m a_n - {}_m o_n)) * (1 - {}_m t_n))$, if ${}_m o_n < {}_m a_n$, or

${}_m t_n$ is left unchanged otherwise.

These formulations are normalised such that a string of positive experiences asymptotically moves ${}_m t_n$ towards 1.0, and a string of negative experiences moves it towards 0.0. The function matches our intuition that trust is most enhanced by getting exactly what we requested, partially enhanced by getting some of our request and damaged by being excluded. The formulation also conforms to our expectation that recent experiences are given greater weight than earlier ones, the effect of past events are discounted with each new experience. Agents that adopt high values for α are generally more susceptible to single positive experiences, those that adopt a high β value more influenced by negative experiences.

4.5 SCP Trust Function

The SCP trust function is analogous to the SSP trust function, except that it is driven from a comparison of the resource offered, ${}_n q_m$, against that utilized, ${}_n r_m$.

${}_n t_m \leftarrow {}_n t_m - (\beta * {}_n t_m)$, if an offer ${}_n q_m$ was made, but no utilisation ${}_n r_m$ was made, or

${}_n t_m \leftarrow {}_n t_m + (\alpha * (1 - {}_n t_m))$, if utilisation ${}_n r_m = \text{offer } {}_n q_m$, or

${}_n t_m \leftarrow {}_n t_m + ((\alpha * ({}_n q_m - {}_n r_m)) * (1 - {}_n t_m))$, if ${}_n r_m < {}_n q_m$, or

${}_n t_m$ is left unchanged otherwise.

5. The Simulator

We have prepared a simulator in order to investigate the properties of oTB-Agents in the IN like trading situation. The simulation is detailed in that it performs each step in the oTB-Agent algorithm for every Agent at each trading cycle, and emulates every communication message between Agents. The simulator allows the investigator to specify the number of SCP and SSP Agents that will participate, and to set the important parameters for both types of Agent, the α and β trust modification rates; and the overbid rate, the split rate and exploration rate (for SSP Agents). The investigator may single step the simulation, or run it for a pre-determined number of trading cycles, modify parameters and continue. The simulation provides a graphical indication of messages between Agents, and indicates the utilisation of bandwidth resource due to that Agent (as a percentage of the total possible). The investigator may also inspect the trust relationships between any single Agent and its trading partners. At the end of a simulation session logging files

may be produced giving a complete record of the development of the trust vectors.

6. EXPERIMENTS IN oTB-AGENT BASED TRADING

Experiment one will investigate the effects of load on the relationship between SSP and SCP Agents. We establish trading communities of 10 Suppliers (SCP) and 20 Consumer (SSP) Agents. All SCP Agents are the same ($\alpha = \beta = 0.25$), as are all SSP Agents ($\alpha = \beta = 0.25$, $srate = 4$, $erate = 20\%$, $obrate = 0\%$ (i.e. no overbid)). In these experiments all suppliers receive an identical allocation of bandwidth, and all consumers have an equal demand placed on them. All SCP and SSP Agents are identical and treated identically to ensure that the effects of the oTB-Agent procedure are placed in a “fair” trading situation (our first question from section 1).

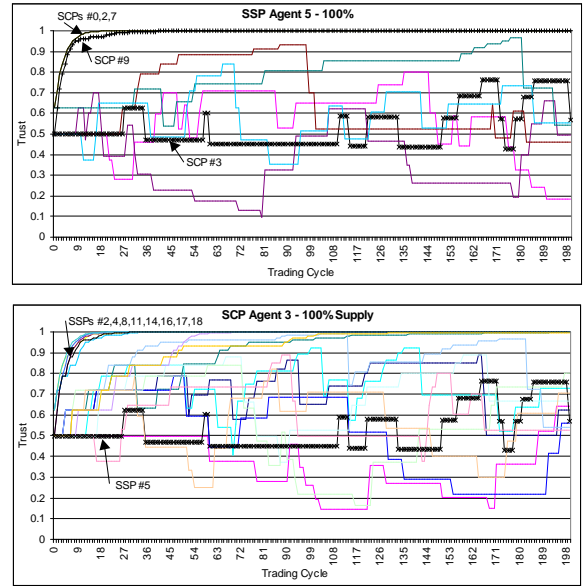


Fig 3: Trust Relationships Between Agents at 100% Load

This experimental investigation is in three parts, and the results are summarised in figures 3, 4 and 5. In each part the supply of bandwidth resource is successively restricted in relation to demand. Under these circumstances SSPs must develop strong relationships in order to ensure supply (in the converse situation, SCPs are under pressure). Three separate runs are made, one where supply exactly matches demand (100% supply, figure 3), one where supply is 75% of demand (figure 4) and one where supply is only 50% of demand (figure 5). Each graph in these figures indicates the changing trust relationships of a single Agent (SSP above, SCP below) to all its trading partners. In each case, the SSP graph (top) is one of 20, and the SCP graph (below) one of ten.

Each figure also highlights the relationship between specific pairs of Agents (figure 3 between SSP #5 and SCP #3, figure 4 SSP #5 and SCP #8, figure 5 SSP #9 and SCP #3). Note that each run is completely separate, starting with a new random initialisation. Agent numbering for each figure is independent. At the start of each experimental run of 200 trading cycles every trust vector element in all Agents is seeded with an initial value random value

in the range 0.499999 and 0.500001. In general, oTB-Agents do not have any “opinion” about the trustworthiness of other Agents (i.e. a trust value of 0.5) at the start of a trading session. This small random perturbation pre-disposes them to start trading with some Agents in preference to others. oTB-Agents are therefore initially *trust neutral*, [9], prior to gaining experience through trading.

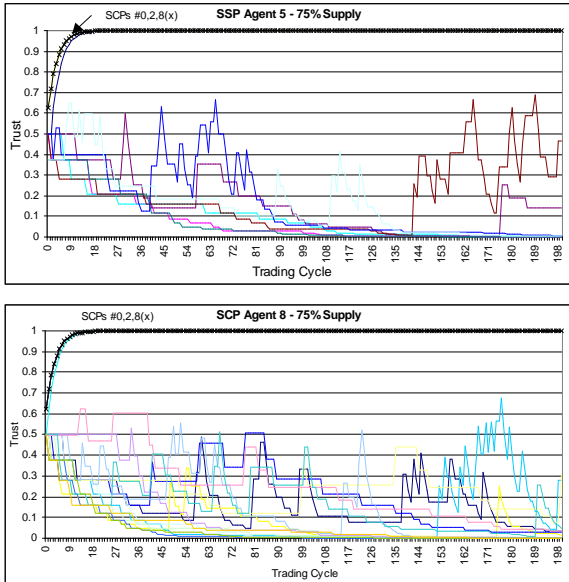


Figure 4: Trust Relationships Between Agents at 75% Load

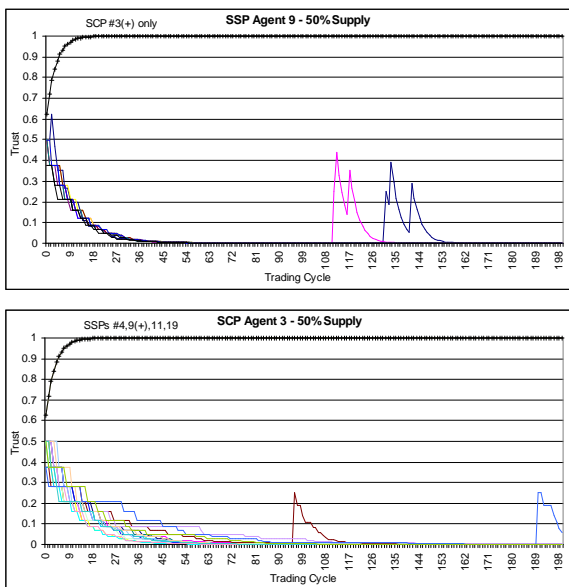


Figure 5: Trust Relationships Between Agents at 50% Load

In all instances we see that SSP and SCP Agents tend to “pair-off” very quickly. In the 100% supply case (figure 3) we can see that SSP Agent builds trust relationships with SCP Agents #0, 2 and 7 quickly, followed by Agent #9 (highlighted with a ‘+’) soon after.

These are its preferential trading partners, but it partially trusts many other SCP Agents and trades with them from time to time (this occasional trading between SSP #5 and SCP #3 is highlighted with an ‘x’ markers).

In the 75% loading case (figure 4) we note that this “pairing-off” is more pronounced. Moreover, the number of preferred trading partners has dropped. This indicates that suppliers (who have the upper hand in this situation) prefer to maintain a smaller number of trusted customers, and serve them fully. In turn the customers must continue to bid to these suppliers regularly in order to safeguard their supply of bandwidth. The preferential trading partnership between SSP Agent #5 and SCP Agent #8 is highlighted in the middle row. This effect becomes ever more pronounced as supply is further restricted. At 50% supply (figure five) the gulf between those Agents that can trade because they succeeded in establishing a trust partnership and those that did not is very clear. SSP Agent #9 only secured one trust relationship (with SCP #3, highlighted ‘+’), and is clearly going to struggle for supply.

Figure six makes explicit the overall relationship between the degree of trading trust an SSP Agent has been able to secure and its ability to deliver bandwidth to its customers. Each marker in the graph shows the average trust rating for each SSP Agent across all the SCP Agents, against its success in meeting demand. When supply equals demand (100% supply, diamond markers), the overall ability of an SSP Agent to deliver is hardly affected by its perceived trust rating (delivery rate is largely unaffected by overall trust rating). As supply is restricted, (75% supply, square markers), there is a clear correlation between trust rating and ability to deliver has developed. When supply is further restricted to 50% of demand (triangle markers) the correlation is pronounced. The performance of each of the three sub-groups shown circled is directly proportional to the number of suppliers with which the SSP Agent has managed to build a trading relationship. The worst performing group (group 3) only established a partnership with one other SCP Agent (SSP Agents #2, 3, 4, 9 and 13, with an average trust rating of 0.1 and a 0.252% delivery record). The higher group (group 1) comprises Agents #5, 11, 14, 16 and 18, with an average delivery record of 0.729%, established relationships with three suppliers. In this instance no SSP Agent formed a group will four partners.

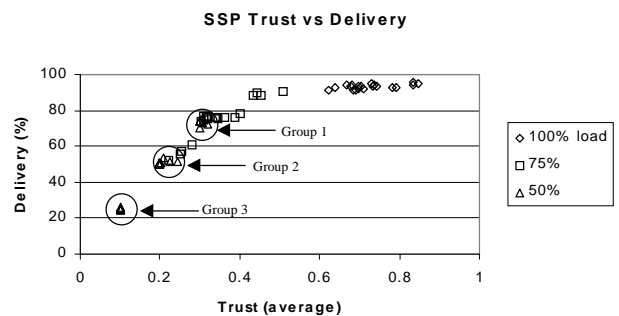


Figure 6: The Effect of Trust Rating on SSP Delivery Performance

Experiment two addresses our second question, as to whether establishing a trust relationship over a period of time will equate

to loyalty when trading becomes difficult. We repeat the conditions of part one of experiment one (supply = demand), except that at trading cycle 100 supply is reduced to 75% of demand. Figure seven shows a pair of trust graphs linking the effect on the trust, and hence trade, relationship between SSP Agent #18 and SCP Agent #9 (highlighted 'x'). It is clear from inspection of these graphs (and the others in the set), that in addition to the loss of weaker trust relationships (as was the case in experiment one), suppliers have a marked tendency to discard their strong partners on a last-in first-out basis. It appears that, at least in this case, trust does beget loyalty.

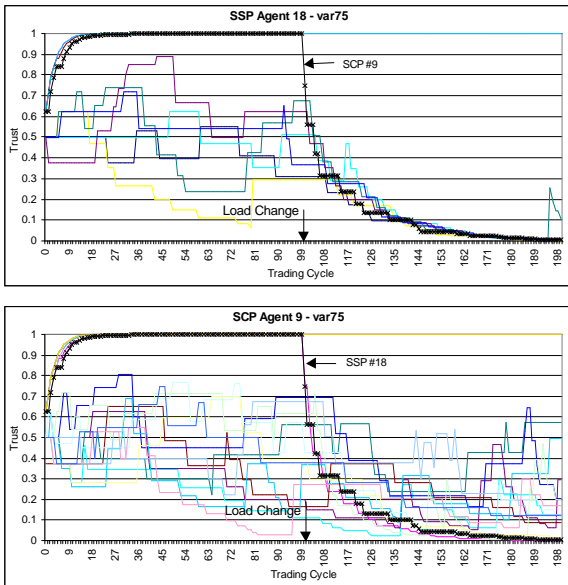


Fig 7: The effect of Increased Load

To address our third question, whether an Agent can exploit the “personal” nature of the trust relationship, we perform an experiment in which the SSP Agents are divided equally into two groups. In one group (the “normal” group) they trade “honestly”, only bidding for the units of bandwidth they actually require. The second group bid “greedily”, bidding for 150% of the units they require ($obrate = +50$). Supply is set to equal demand, and the other conditions are as before. Figure eight summarises the results obtained from running of this experiment.

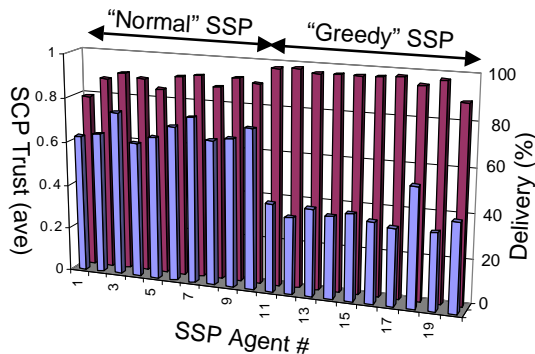


Fig 8: The Effects of Overbidding

The effects of this greedy behaviour are clear. While the average trust rating by all SCP Agents (front rank) of the greedy SSP Agents is far lower than that for the normal ones (0.391 vs. 0.680), their overall delivery performance (rear rank) is somewhat better (96.1% vs. 88.5%). They perform better because they receive more offers of bandwidth due to overbidding. The effect of the oTB-Agent procedure is to always preferentially buy from your preferred suppliers. So where the normal Agents have good relationships with their preferred suppliers, and reasonable relationships with others, greedy Agents have equally good relationships with their preferred suppliers, but very poor relationships with all the others, who they have treated badly. An element of duplicity, it seems, is still effective in a society where trust is otherwise highly valued.

7. Related Work

There exist a number of issues in the research for security and trust in MAS. We consider three in the context of this work:

Cryptography and Classical Network Security Techniques vs Social Approaches. Wong and Sycara, [21] address a number of security and trust issues faced by MAS and provide an infrastructure to deal with such issues. They make use of techniques that are well known in the network security literature, and they apply these techniques to MAS. As these authors mention, there is no measure proposed about trust or honesty. There is no way of ensuring that an Agent will carry out a task as expected, or of guiding an Agent to interact with other Agents that will *probably* be honest. Another approach of dealing with security issues in MAS was made by Thirunavukkarasu, Finin and Mayfield, [18]. They introduced a number of new KQML performatives enabling Agents to interact in a secure manner. These authors use classic network security techniques and do not propose any security or trust models.

It is obvious from this kind of research that network security is not sufficiently considering the requirements of multi-agent systems. Following a social approach for security in MAS, Biswas, Debnath and Sen [2] have proposed a model where Agents have relatively complex behaviours. They use a probabilistic mechanism in which an Agent A will decide whether or not to honour a request for help by Agent B. This mechanism takes under consideration previous observations of Agent B, as well as the additional cost incurred by Agent A from Agent B. The researchers demonstrate that Agents that adapt their trust models over time and use the probabilistic decision mechanism are able to successfully withstand the invasion of selfish and exploitative Agents.

oTB-Agents use similar mechanisms for adaptation and decision making. However, unlike oTB-Agents, the Agents of the model of Biswas, Debnath and Sen consider all of their previous observations equally before delegating a task. oTB-Agents using the trust function of section 4 place extra weight on recent experiences, although they are influenced by all experiences between the two Agents.

Implicit vs Explicit Cognitive Approaches. In implicit approaches, Agents use only a subjective probability to model the trustworthiness of the others. Schillo and Funk [16] conducted a number of simulations where Agents interact with each other using a modification of the prisoner' s dilemma (i.e. the disclosed prisoner' s dilemma with partner selection). Each single Agent

builds a model of trustworthiness of the other Agents by gathering data on past behaviour and evaluating averages. When Agents are asked about their knowledge on other Agents, they are free to lie about their observations. Nevertheless, Schillo and Funk show that by averaging the values of a sufficient number of observations Agents can learn models almost twice as fast as other Agents that use only their own observations, while still reaching the same or better accuracy.

Schillo and Funk's Agents are characterised along two dimensions; being honest/dishonest and altruistic/egoistic. As with [2] the age of an observation is not taken into account. Furthermore no consideration is given as to the reliability of the sources that provide information about Agents.

Explicit cognitive approaches appear more sophisticated, as they attempt to model the "mind" of the other Agents. Castelfranchi and Falcone, [3] give a number of guidelines that should be taken into consideration when modelling the trustworthiness of other Agents. These authors separate the concept of trust from that of delegation and mention a number of beliefs that should exist before delegating a task to another Agent (i.e. competence, disposition, dependence beliefs etc.). They also assert that a subjective probability includes too many important beliefs and parameters. In the future work section we outline the ways we intend to enhance our trust model in order to include belief revision and analysis.

Centralised vs Decentralised Control Over the Groups of Agents. In organisations where there is a form of centralised control, trust can be viewed as a three party relationship. Agents trust the ability of the authority to assess contract violations and to punish the violators. Agents also trust that other Agents will not violate contracts because they respect/fear the authority. On the other hand, there exist groups of Agents with no form of centralised control. In these groups, Agents need to develop their social skills in order to avoid being exploited by deceitful Agents. The oTB-Agents described here exist in an environment without centralised control.

8. Discussion

The experiments show that oTB-Agents tend to form strong, tight, clusters of trading partners very quickly, and that these partnerships become increasingly important as supply and demand for the traded commodity becomes mismatched. Trust builds trust, but unreliability breeds indifference, "*trust is a peculiar resource which is increased, rather than depleted, through use*" [6]. The Agents modelled here show a clear preference for building strong relationships with trusted partners, sustaining successful partnerships and discarding less trusted partners when conditions turn unfavourable. "Deceitful" Agents, those who generally behave in an untrustworthy manner can still thrive in this community, as long as they maintain good trust relationships with a few key partners.

Reciprocal behaviours in a variety of forms are recognised as effective strategies for forming stable groupings with in larger community [2]. The oTB-Agents defined here appear to adopt an extended "tit-for-tat" attitude, as might be encountered in various game theoretic approaches, such as the Iterated Prisoner's Dilemma ([1], [16], [20]). The scenario presented here differs from the well-understood iterated prisoner's dilemma in that the selection is made on the basis of every transaction between the

Agents. Simple Tit-for-tat strategies are considered to be insufficient for most domains of practical interest [2], these problems are largely overcome when the complete transaction history is considered. In addition, SSP oTB-Agents partially base their partner choice on the basis of exploration.

Variations of the formulation used here to evaluate trust find wide application in some of the more numerically orientated approaches to machine learning (such as reinforcement learning, [19], for example) and is ubiquitous, though by no means universal, in theories of natural learning. Jonker and Treur [9] propose a similar formulation for the "quantitative" component of their formalisation of trust. Despite its apparent simplicity the application of this formulation invariably imparts interesting behaviours to the systems that incorporate it.

It is clear from the experiments that a successful first transaction is central to establishing the inter-Agent trading relationship, and an area where the subjective assessment of possible partners is critically important. Equally, were this trading community to be augmented with a "reputation" mechanism (such as those of [2], [16] and [22]), by which Agents entering the market could consult existing traders, then the "greedy" Agents of experiment three would be put at a disadvantage.

9. Future Work

Our aim will be to produce a formal specification of the trust model of oTB-Agents, that encompasses all three components of a trust based trading relationship, reputation, subjective trust and objective trust. Each, we believe, has an important role to play at different times in the overall life of a trading partnership.

There exist a number of reasonable attempts to formalise the concept of trust in MAS ([4], [9]). The formal specification of trust models should include, among other things, decisions such as the use and formation of a trust evolution or update function as well as the properties that should hold for that function [9].

In order to be able to claim that our model of trust is widely applicable, a number of issues should be addressed in the future. One such issue is the exchanging of observations about other Agents. Although we argue that objective experience is more important than reputation, consulting other Agents has proved to be helpful in many experiments ([2], [16]). Nevertheless, in the case where a kind of reputation mechanism is used, then the reliability of the Agents-information sources should be taken into consideration. In particular, Agents should be able to model the trustworthiness of other Agents and validate the honesty of their sources at the same time.

The behaviour of the Agents can become more complex, i.e. have more opportunities to cheat during interactions. The modelling of the trustworthiness of other Agents can become more complex as well. We intend to integrate our trust modeling with subjective belief analysis and revision ([3]). An Agent should be able to evaluate the competence, the willingness and the trustworthiness of the another Agent before delegating a task. New parameters should be introduced in the trust modeling process, such as the risk threshold of one Agent (i.e. how much is an Agent willing to risk the delegation of a task).

Our oTB-Agents trade and develop trust along a single dimension only. More sophisticated Agents will engage with other Agents for a variety of different reasons, and trust should be, in part a function of the task being performed (Agent X may be reliable

when performing task1, but unreliable on task2). We would expect an Agent to maintain an estimate of trust about each task under these circumstances.

A number of other issues are worth considering in future experiments and simulations of Agent communities, such as silent communication, feelings and affective trust. Having to reply to every request can be costly considering communication overheads. A form of silent communication can be adopted in our trading environment, enabling Agents to either refuse to reply to a request or just indicate that they cannot satisfy that request. Agents can be enhanced in the future so that they can have feelings (i.e. love, friendship) about other Agents, thus making them biased to delegate tasks to them.

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