Autonomous Mobile Mailbox Model for Communication Cost Reduction

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This paper presents a cost-reductive communication schema for distributed multi-agent environments containing mobile agents. Communication cost reduction is achieved by employing autonomous mobile mailbox as a message-relay system component. Beneficial modes of mobile mailbox behavior are identified under various operational conditions. A mobile mailbox model is proposed and simulation conducted in order to verify its usability.

Keywords: mobile agents, communication, mailbox.

1. Introduction

Collaboration among participating agents presents the key concept in most multi-agent systems [1]. High level inter-agent communication utilizes standardized message formats, interaction protocols and ontologies [10], but still relies on low-level network communication mechanisms. Message passing in distributed environments, where communicating entities do not change their positions over time, is a well-studied issue. On the other hand, effective and efficient communication in an agent society containing mobile entities [2][3] requires a different approach as difficulties may be encountered both in tracking target agent's location and in reliable message delivery.

Various schemas have been proposed in order to tackle described problems, involving trade-offs with respect to desirable communication properties [7]. Proposed location-tracking mechanisms vary from *Broadcast/Multicast* schemes efficient in local networks, *Hierarchical schemes* suitable for special-purpose networks, more general centralized *Central-server* and *Home-object* schemes involving the risk of becoming a performance bottleneck, and *Forwarding-pointer* scheme, where central location registry was avoided at the cost of possible multiple message forwarding [5]. Other schemes were also proposed and analyzed, including Blackboard and Email, where messages are temporarily stored in a mailbox or blackboard, and relayed to/collected by the receiving agent [4].

In [6][7], a mobile mailbox-based message delivery scheme was proposed, where mailbox, detached from its owner agent, temporarily stores incoming messages. The agent pulls its mailbox to retrieve messages and controls its current location. Message delivery cost reduction can be achieved, compared to direct communication, as a consequence of mailbox message-to-mobility (MMR) ratios higher than agent's MMR. The proposed solution presumes a non-autonomous mailbox, where mailbox migration decisions are made by the owning agent.

In this paper, we introduce an autonomous mobile mailbox-based scheme for communication cost reduction in agent societies containing mobile agents. Schema's cost reduction relies not only on lower mailbox message-to-mobility rates, but also on autonomous discovery of (near-) optimal message relay locations. We also analyze performances of different communication schemas and propose their adaptive usage according to different communication environment operational conditions.

2. Communication Model

We observe a scenario in which there are several "static" sender agents and a single mobile "receiver" agent in the system. This scenario can easily be scaled to cases with more than one mobile receiver present in the system. A simplifying assumption is employed that all content messages are of the same size and control messages $1/q$ of the content message size. In order to ensure message delivery among system components, only reliable communication schemes are employed [8]. Performances of three distinct mailbox migration strategies are analyzed under different operational conditions and their results are compared. *Collocated mailbox* migration strategy presumes a mailbox traveling simultaneously with the owner agent, implying direct sender-receiver agent communication. *Fixed-location* mailbox strategy considers a mailbox with initially assigned location, without the ability to migrate. *Mobile mailbox* mediated communication involves an autonomous mobile mailbox with the goal of relaying messages, while reducing overall communication cost.

A system model was built in MATLAB in order to evaluate system execution behavior given various environment parameter values. The result of each calculation is the average price of delivering a single data message from sender (static agent) to receiver (mobile agent). The following model parameters were used:

- c_{msg} – average message delivery cost between sender and receiver
- q – ratio between single content and control message delivery costs ($q < 1$)
- s – number of message sources in the system
- τ – average time period between two adjacent message pulls from mailbox
- μ_A – mobile agent migration ratio
- μ_{MB} – mailbox migration ratio
- λ – average number of messages sent in the system per unit time period
- η_A – agent message to migration ratio
- η_{MB} – mailbox message to migration ratio

The following atomic communication costs were identified in the schemas used, assuming that messages are pulled from mailbox more frequently than mailbox is migrating ($\tau \geq 1/\mu_{MB}$):

Cost of transferring one data message from sender to mailbox or agent:

$$c_{send} = c_{msg} \tag{1}$$

Cost of an agent pulling all of currently available messages in the mailbox:

$$c_{pull} = c_{msg} + \frac{q \cdot c_{msg} \cdot (1 + e^{-\lambda \tau})}{\lambda \tau} \tag{2}$$

Cost of an agent finding a new mailbox location:

$$c_{MBLoc} = \frac{4 \cdot q \cdot c_{msg}}{\lambda \tau} \tag{3}$$

Cost of mailbox or agent resynchronization with sender(s) on each location change:

$$c_{resync} = \frac{3 \cdot q \cdot c_{msg} \cdot s}{\eta_{MB/A}} \tag{4}$$

Cost of mailbox migration:

$$\begin{aligned} c_{MBMove} = c_{msg} \cdot \Bigg(\frac{1}{2 \cdot \tau} \cdot \left(\tau - \frac{n}{\mu_{MB}}\right) \\ \cdot (n+1) + \frac{n \cdot (1+n)}{2 \cdot \mu_{MB} \cdot \tau}\Bigg) \\ n = \text{floor}\,(\tau \cdot \mu_{MB}) \end{aligned} \tag{5}$$

Cost of updating current mailbox or agent position at the corresponding home object:

$$c_{locupdate} = \frac{q \cdot c_{msg}}{\eta_{MB/A}} \tag{6}$$

Collocated mailbox communication costs consist of agent-sender resynchronization on each agent location change (4), cost of transferring a message from sender to agent (1) and the cost of updating home object with current agent location (6). *Fixed-location mailbox costs* consist of the cost required to send a message from sender to mailbox (1) and the cost of agent pulling messages from the mailbox (2). *Mobile mailbox location costs* include all six listed types of costs.

Figure 1 and 2 depict the message transfer costs for systems with 10 and 100 sources, μ_A/μ_{MB} ratio of 10 and average effective message transfer cost for mobile mailbox schema lowered to $3/4$ of the standard average cost. In Figure 1 it can be observed that the range of η_A values, for which mobile mailbox schema is the best communication option, is bounded both from below and above. This value range is fairly short, but does extend much further than the value range covered by fixed-position mailbox schema. With the increased number of message sources (Figure 2) both lower and upper bound are moved to higher η_A values and the value range are extended, still bounded from above. The lower bound of the effective mobile mailbox schema is controlled by adjusting the μ_A/μ_{MB} ratio and the upper bound is controlled by the parameter k value $(c_{eff} = k \cdot c_{msg}, 0 < k < 1)$. As an independent and resource-bounded entity, mobile mailbox has only a restricted means of influencing its environment. Of all the mentioned model parameters, only μ_{MB} can be explicitly controlled by the mobile mailbox. The value of μ_{MB} parameter is nec-

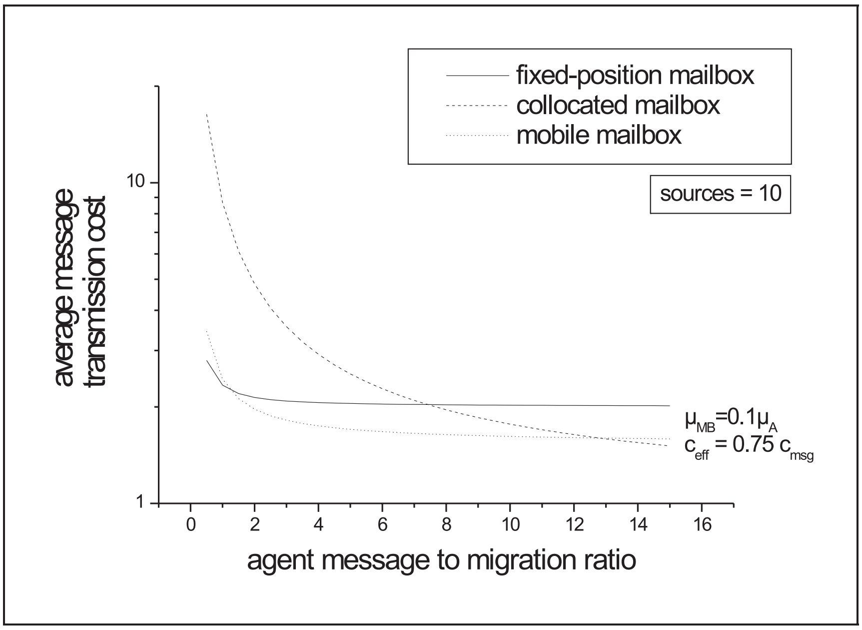

Fig. 1. Schema communication costs, 10 message sources.

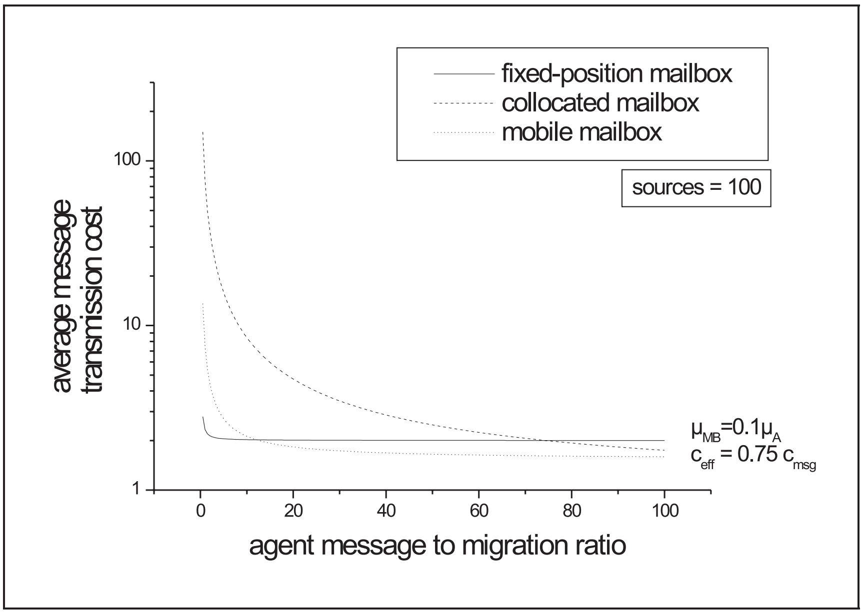

Fig. 2. Schema communication costs, 100 message sources.

essary to be adjusted according to the observed τ values. Parameter k can be controlled implicitly, by choosing the most promising next mailbox position (i.e. reducing average message transfer costs) based on future source activity predictions or, if advantageous, switching to alternative migration schemas (collocated or fixed-location schema).

3. Autonomous Mobile Mailbox

In order to confirm numerical analysis results and test possible approaches to lowering the average message transmission cost (i.e. useful migration strategies), a dedicated simulator was built using the Java programming language.

3.1. Communication Environment

Communication environment was modeled as follows:

- $H = \{h_i \mid i = 1, n\}$ – the set of hosts in the network
- $A = \{a_i \mid i = 1, m\}$ – the set of sender agents
- $T = \{c_{ij} \mid i, j = 1, n\}$ – symmetrical matrix representing associated message-transfer costs between network nodes (fully connected graph)
- $I = \{i_j \mid j = 1, m\}$ – the set of host indices representing the sender agents distribution in the network
- $R = \{r(t)\}$ – the time-based vector set representing the host indices, where the receiver agent is located at certain times
- $\Lambda = \{\vec{\lambda}_i(t) \mid i = 1, m\}$ – the time-based vector set representing the varying message rates of sender agents
- T_e – evaluation time period within which the transfer costs will be calculated and a decision about a mailbox's possible immediate migration will be given, based on the message rate prediction. The message rate within this period is considered constant.
- T_h – horizon time period or "window of opportunity in time" within which the rate predictions can be considered accurate and possible mailbox locations evaluated. It is assumed that $T_h = n \cdot T_e, n \in \mathbf{N}$.

Associated model costs are based on the model given in section 2 of this paper. Model does not make any assumptions on mobile agent behavior.

Message transfer cost from sender to mailbox in time interval $[t_i - T_e, t_i]$,where $c_{i_p b}$ represents cost of transferring one message between host h_{i_p} (agent location) and h_b (mailbox location):

$$C_{trns}(t_i) = \sum_{p=1}^{m} c_{i_p b} \cdot \lambda_p(t_i) \tag{7}$$

Mailbox registration cost in synchronized push model communication (move from $c_{i_p b}$ to $c_{i_p b'}$):

$$C_{reg} = q \cdot \sum_{p=1}^{m} (2 \cdot c_{i_p b} + c_{i_p b^*}) \tag{8}$$

Mailbox migration cost (depending on a number of buffered messages):

$$C_{mig} = c_{bb^*} \sum_{p=1}^{m} \sum_{t=T_1}^{T_2} \lambda_p(t) \tag{9}$$

Mailbox position update cost:

$$C_{hmreg} = q \cdot c_{b^* h} \tag{10}$$

Message transfer cost from mailbox to agent (greedy pull):

$$c_{pull} = c_{br} \cdot \sum_{p=1}^{m} \sum_{t=T_1}^{T_2} \cdot \lambda_p(t) \tag{11}$$

3.2. Mailbox Model

Mailbox model is composed of several functional modules (Figure 3). *Controller* module is responsible for control communication and travel plan execution. *Predictor* module is responsible for tracking history and predicting future message source activities. *Planner* module is responsible for itinerary planning. *Knowledge Base* contains (partial) knowledge of communication environment. *Message Queue* acts as a FIFO storage buffer for incoming messages.

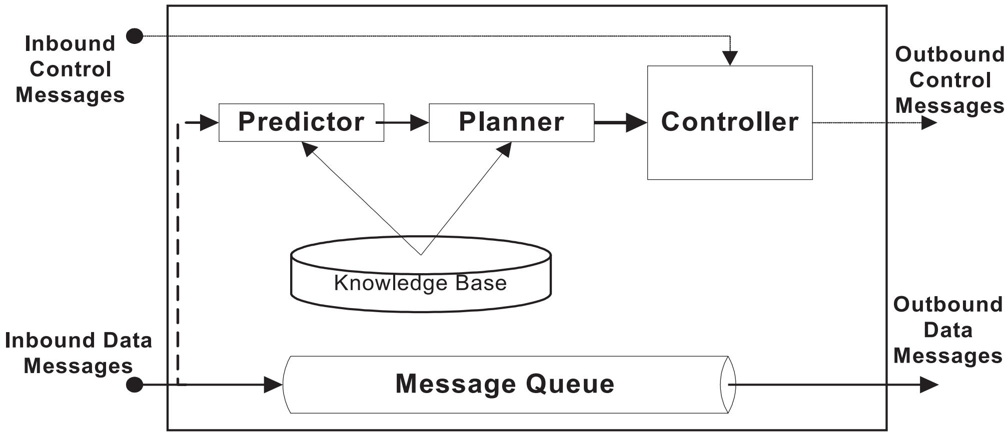

Fig. 3. Mobile mailbox model.

Mailbox bases its predictions of future sender message rates purely on observations of past sender behavior (Predictor) and knowledge of the communication environment provided to the mailbox (Knowledge Base).

Employed prediction methods can be varied from producing only next-time-period source activities to producing long-range predictions for the next T_h time period. In the current model, only the next immediate period is considered ($T_{ep} = T_h$). As the mobile mailbox is intended to present a lightweight, resource-constrained system component, employed planning methods must be simple, but effective enough, trading planning proficiency for lower resource consumption.

We consider a moving window consisting of message rates (per unit time) observed in each of the last n time-units, and compute the value in the next time period. As a trade-off between computationally light methods and satisfying accurate predictions, an Extrapolated straight line fit method was chosen. Value observed in the most recent time unit, Weighted average of the moving window and Random value sampled from Poisson distribution methods were also considered, but they lack ability to handle significant gradients in message rates and the predictions are always “behind” the current value since they summarise what has already occurred. Reducing the cost of communication by planning optimal mailbox positions during the course of system execution is the task of the Planner module. On the basis of the Predictor module output and the knowledge of the communication environment, migration plans are produced. Plan accuracy strongly depends not only on the accuracy of the predictions used, but also on particular planning method(s) employed. Reactive and proactive planning methods were identified. The proactive mailbox is employed to take advantage of possible cost-reduction if message pull happens at an appropriate time (mailbox empty or contains small number of messages). In this case, the mailbox might be in a future better position with a better capability to migrate further, if necessary.

Due to mailbox lightweight nature, no security mechanisms have been envisioned so far. Message source authentication and content protection are the responsibility of both sending and receiving agents. However, future deployment of this communication scheme in untrusted environments may require some kind of authentication mechanism in order to prevent message rate prediction manipulation and unauthorized collection of stored messages.

3.3. Simulation and Results

A simulated system consists of n hosts and m sender agents that are distributed randomly in the network. Network edges are also randomly generated within given margins, bearing in mind that lower (or equal) cost will occurr in direct host connection, compared with the indirect one. Agents’ message rates are simulated by a periodic triangular function with different periods. Dependency between a chosen set of parameters and the competitiveness of a proactive mailbox when compared with the system without mailbox, is the main goal of the simulation. *Competitiveness of the mailbox* is defined as a ratio between total costs incurred when a proactive mailbox is used and total costs in the system without the mailbox.

The following set of parameters is chosen:

- Total number of hosts: 10
- Total number of agents: 30
- Network costs $c_{ij} \in [1, 10]$
- Receiver agent mobility host residence time: 3 (the receiver agent migrates every 3 time units to the randomly chosen location)
- Mailbox messages pulling period: 3 (messages will be pulled every 3 time units)
- Message rate function amplitude: 2 (max. 2 messages can be sent within considered time interval)
- $T_h = T_e$

Figure 4 shows the dependency between competitiveness and the range of network costs for different host residence times of the receiver agent. For the case of infinite residence time, the mailbox is not beneficial, regardless of the range of network costs. Inefficiency of the mailbox is clearly caused by the two-stage communication process, because messages will be propagated via more costly paths and cannot be mitigated by the receiver agent's registration/deregistration costs, due to its static nature. The mailbox is fairly efficient in case of high agent's migration frequency, especially if the network heterogeneity is higher. The receiver agent often changes its location, which generates high message delivery costs.

Figure 5 shows the dependency between competitiveness of the mailbox and the message rate amplitude of sender agents. It is evident that the mailbox is inefficient for the homogeneous network since there are no opportunities to mitigate the extra delivery costs introduced by the two-stage communication effect. The mailbox becomes efficient in case of higher mobility of the receiver agent and lower message rates. Increasing the network heterogeneity, the usability of the mailbox is still feasible, even with increased host residence time of the receiver agent, if the message rate amplitude is low.

Figure 6 shows the dependency between competitiveness of the mailbox and the number of hosts in the network. The mailbox's efficiency

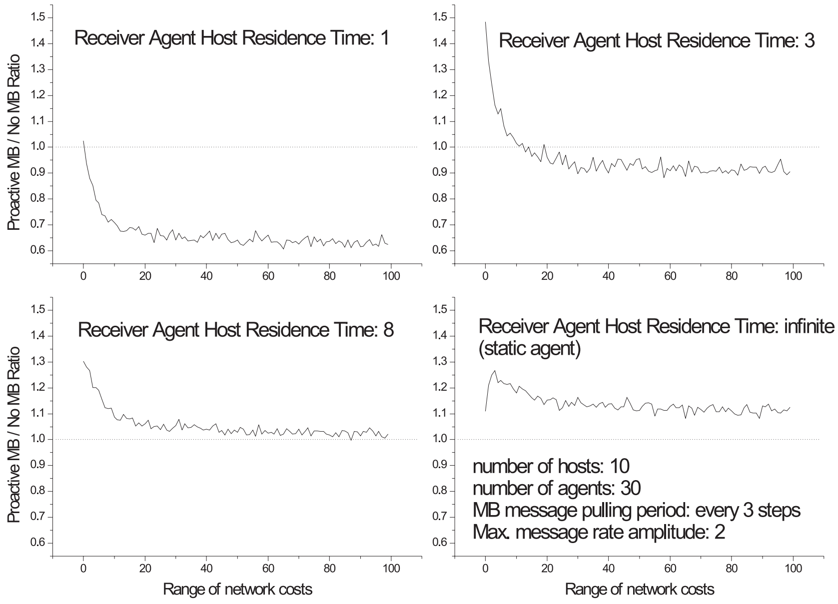

Fig. 4. Competitiveness for different Receiver Agent residence host times.

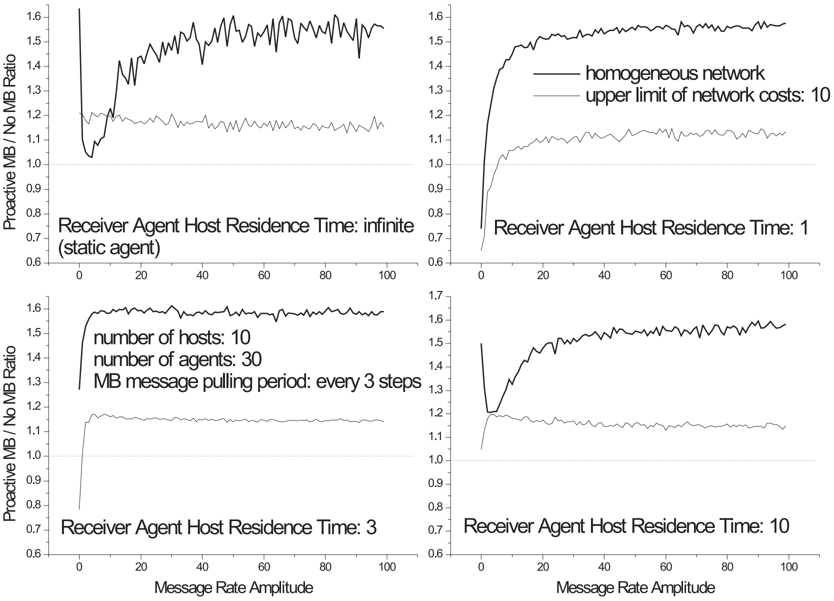

Fig. 5. Competitiveness for different message rate amplitudes.

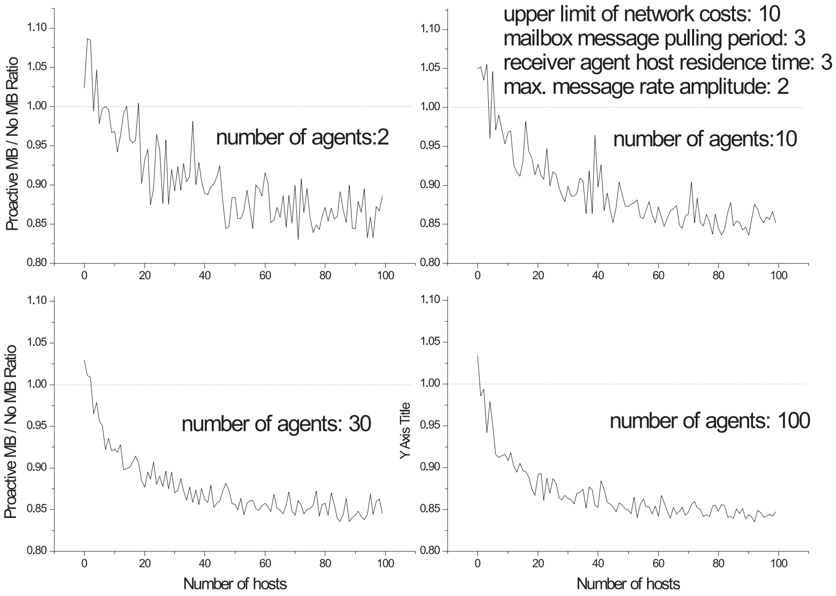

Fig. 6. Competitiveness for different numbers of hosts in the network.

is significantly influenced by the number of hosts. In a network with fewer hosts, the mailbox does not have enough opportunities to mitigate the effect induced by a two-stage communication process. In case of an increased hosts number, the mailbox is offered more possibilities to deliver messages at lower costs. Increased dispersion of message sources, caused by the higher number of sender agents, will decrease the likelihood for the mailbox to be "too far" from agents. This will result in a more even message transfer cost over various positions of the mailbox. Accordingly, efficiency of the mailbox will be less variable as the number of sender agents increases and the graph will be smoother.

4. Conclusion and Future Work

In this paper we analyzed performances of three different communication schemes, based on relayed communication model, for multi-agent systems containing mobile agents. An autonomous mobile mailbox communication schema was introduced as a means of communication cost reduction. Operational parameter spaces were identified, for which each of the schemas yields the lowest communication costs. Cost reduction is a consequence of two important methods a mailbox employs: short-term on-the-fly prediction of future message source activities based on past observations and of finding (near-) optimal network locations for relaying those messages. Based on the defined cost model, simulation results showed the usability of the mobile mailbox schema, especially in networks of more heterogeneous host interconnection costs.

As a future work plan to employ more sophisticated heuristics-based mailbox location planning algorithms ($T_h = n \cdot T_{ep}$) thus yielding possibly higher cost savings, yet preserving the computational requirements low. Also, we plan to integrate such a communication schema as an messaging facility into our mobile agent system [9].

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