Supporting Impromptu Coordination using Automated Negotiation

Iyad Rahwan, Connor Graham, and Liz Sonenberg

Department of Information Systems, University of Melbourne
Parkville, VIC 3010, Australia
i.rahwan@pgrad.unimelb.edu.au
cgraham@unimelb.edu.au
l.sonenberg@unimelb.edu.au

Abstract. We are concerned with forms of interaction in which multiple users, with differing agendas and interests, may realise opportunities for useful synchronisation of their activities. We present a framework in which intelligent software agents act as semi-autonomous intermediaries among nomadic users. Agents capture and process information about situations (specifically about the environment, users and their activities) in order to jointly find and negotiate opportunities for coordinating the activities of their respective users. The interaction is structured using a negotiation protocol that exploits a hierarchical representation of tasks and goals.

1 Introduction

The use of mobile computing devices and services in everyday life is increasing largely due to the advancement of enabling technologies [13] as well as increasing efforts to make the technology more usable [16]. One of the challenges presented to the developer of such technologies is dealing with the complexity imposed by situations involving users who are mobile. Scenarios involving mobile technology usage often do not involve single, well-modeled users operating within a stable environment and interacting with stationary technologies. Part of the challenge for the developers of mobile technologies is to respond to a user's embeddedness in such situations in a sensible way. Opportunities exist to utilise new technologies to augment and alleviate the complexity of user situations, including the reconciliation of different interests and agendas among multiple parties. This might involve, for example, coordinating a meeting at a particular time in a particular place among many busy individuals.

An additional challenge for developing context-aware mobile systems is responding to actions and interactions that are neither planned nor routine [14] but evolving from interaction with an ever-changing environment. These actions and interactions are aligned to those well documented in computer-supported cooperative work that often form the cement that binds 'core' actions and interactions together: *spontaneous*, *lightweight interactions* [15, 17]. They are described as "impromptu," "quick and easy to initiate," "short and informal," "brief," "unplanned," and "intermittent" [ibid]. These interactions often manifest themselves as accidental, corridor conversations among work colleagues [4]. Thus they are not routine, as some reflection on work practice is often involved. Nor are they planned in a deterministic sense as they are often accidental. However, they are related to individual actors' ongoing courses of action, or generic goals and they often involve negotiating multiple courses of action to achieve a shared goal. We dub these interactions *impromptu coordination*.

Impromptu coordination poses a challenge for technology support not only because of its unpredictability but due to the very nature of the mobile situations that form their backdrop: these situations involve physical movement or traversal through environments possessing multifarious agents (such as people and computational agents) and resources (such as digital displays and mobile phones). In addition, due to the nature of interaction investigated here (impromptu coordination) the demand on the effective exchange of information among agents is high and as a result there is a very high computational load for both the user and the supporting context-aware device. Here we suggest there is an opportunity to utilize specific agent technology to assist with these kind of interactions through the effective use of available resources by involved agents.

Research into computational multi-agent systems [18] has produced a variety of techniques for facilitating and controlling interaction among computational agents. In particular, a wide range of frameworks for automated negotiation have been presented [5].

In this paper, we explore the use of a novel automated negotiation technique, dubbed *interest-based negotiation* [11], to support impromptu coordination among mobile users. By doing so, the paper advances the state of the art in two ways. First, it is the first attempt at using negotiation techniques to support non-routine coordination of mobile users. Most existing work on agents for mobile devices focuses on supporting single users [12] or collaborative teams executing routine tasks [1]. Second, the paper introduces a novel coordination architecture, which integrates context-aware networked devices, agent-based reasoning, and automated negotiation. This approach may be used for building a variety of mobile coordination-support systems, that suit domains beyond that of the simple narrative used here for illustration.

Our argument for the possibility of using interest-based negotiation to support impromptu coordination proceeds as follows. In the next section, we outline key characteristics of mobile user coordination and how they require some form of negotiation. In section 3, we present our conceptual and technical framework for supporting mobile coordination through automated negotiation, and illustrate the use of the framework through an example. We conclude in section 4.

2 The Problem of Impromptu Coordination

We begin in section 2.1 by defining impromptu coordination. Then, in section 2.2, we describe some informal observations on the role of technology in facilitating interactions through which multiple users, with differing agendas and interests, may realise opportunities for useful coordination of their activities. To better understand the opportunities for technology intervention, we take Luff and Heath's [7] advice and "examine activities in which people engage with others when they are 'mobile' and how various tools and artefacts feature in those activities." To this end, we analyse an informal narrative in section 2.3 to distill essential characteristics of mobile use.

2.1 Impromptu Coordination

For mobile users, opportunities for collaboration arise more frequently than with static users due to the more diverse forms of context change, such as change in the user's location or the proximity of multiple users. Such opportunities usually cannot be anticipated a priori. Negotiation is a way of dynamically realising and taking advantage of such opportunities.[1] This also relates to the findings of Perry et al [8], who build on the Luff and Heath [7] study through the examination of 17 mobile workers in the United Kingdom. Specifically, they recommend that technologies supporting mobile workers should "allow more effective planning of activities and flexible allocation of resources" and "allow the location, use of, and access to locally available resources."

2.2 Supporting Impromptu Coordination

In the settings of interest, the user is mobile, connected, and engaged in complex interactions. This creates an opportunity for technology to support the user. In Table 1, we list different levels of support that technology could provide, and compare the extent to which different technologies go. The most basic approach would be to provide connectivity, for example, using mobile telephones. However, when support only takes the form of communication facilitation, users would, 'in their heads,' need to keep track of all changes to their context, manage the complexity of identifying opportunities as events unfold, deal with multiple interaction partners, and so on. This places great cognitive load on mobile users, and it is precisely for this reason that support software such as calendar applications are appropriate tools.

When a mobile phone is endowed with a calendar functionality, the user can 'outsource' the storage of large amounts of information about activities (meetings, special occasions, etc.) to their device. This representation of *individual* activities can then be used to help a user coordinate with others. Applications allowing for group task representation, such as Microsoft Outlook with the Exchange Sever, go a step further by providing stationary users with representations of multiple users activities in a globally accessible manner.

One could envisage device support not only through *representation* of individual and group activities, but also *automation* to support the cognitive processes that exploit and manipulate those representations. Such automatic processes would use the available information about the user's situation as well as information available about other users in order to automatically negotiate agreements over collaboration and coordination of activities. Through more elaborate examples, in the following section we demonstrate that making explicit and available a representation of users' goals and task structures and some ability to view and configure these, through communication or automatically, can better support impromptu coordination.

2.3 Characteristics of Impromptu Coordination

We now discuss particular *characteristics of impromptu coordination* and how they require some form of negotiation. These characteristics emerged from discussions in a

[1] This characteristic stresses the contrast between the focus of this paper and the objectives of intelligent scheduling applications.

Table 1. Levels of support for impromptu coordination

Feature / Technology	Connected while mobile	Represent tasks	Manual task manipulation		Auto task manipulation	
			Individual tasks	Group tasks	Individual tasks	Group tasks
Phone	✓					
Ph/Calendar	✓	✓	✓			
MS Outlook		✓	✓	✓		
All above + automated negotiation	✓	✓	✓	✓	✓	✓

multi-disciplinary focus group and among the authors of a narrative based on a diary of an actual PhD student renamed Omar, generated over a period of three days. The narrative approach has been used in order to understand individual mobile activities in other projects, such as ActiveCampus [3]. An approach grounded in broader and more systematic data collection would be desirable in the future, c.f. [4].

Narrative 1 *I realized I had not set up a lift home so I called my wife. I couldn't get through, so I left her a message and asked her to call me when she was close. While waiting for her to reply, I continued work. Then I called Jack to discuss our Wednesday meeting. Jack happened to be in his car on his way in a direction not too far from my home. He was short on time because he needed to pick up a book from the city first. I managed to get myself a lift by offering to borrow a copy for him from the University library.*

In the narrative above, Omar being connected to Jack was critical to him being able to capitalise on the opportunity presented by Jack's proximity. The phone did not allow him to predict the possible chances of the success of this opportunistic interaction through a representation of Jack's goals or tasks.

Fluidity Kakihara and Sorenson [6] describe how the interaction experienced by mobile individuals is 'fluid'. Thus "human interaction is becoming ambiguous and transitory. The patterns of social interaction are dynamically reshaped and renegotiated through our everyday activities significantly freed from spatial, temporal and contextual constraints" [ibid]. Fluidity is apparent in the narrative above, describing Omar's activity.

Fluidity in the narrative above suggests that interaction can be rather occasional during impromptu coordination among mobile individuals, since the environment in which these portable devices operate changes more frequently than with stationary computers.

Thus, for the agents involved, well-established, long-term relationships, in which task structures are well-defined and agreed upon, are less likely. In addition, the dynamism in the presence of resources within the immediate environment (such as a car) as a result of mobile situations involving impromptu coordination makes it even more difficult for the agents involved to reduce uncertainty. Negotiation is one way of reaching temporary agreement in such dynamic situations.

Heterogeneity When the modelling of situations involving impromptu coordination among mobile individuals is to take into account varying location, time, user profiles, tasks, interaction history, etc., we are confronted with a much greater variety of agent (and user) types. Each individual agent may achieve tasks in a different way. It is unlikely that information about this heterogeneity will be available a priori. Negotiation is a natural way to exchange information and reach useful agreement or compromise with collaborators (or in collaboration settings) not known before.

In the above narrative, Omar's coordination could have been made easier by a representation of Jack's and, at the very least, his availability. Given the complexity of these representations, some automation of the process of reconciling goals and availability among the multiple parties involved would also have been desirable.

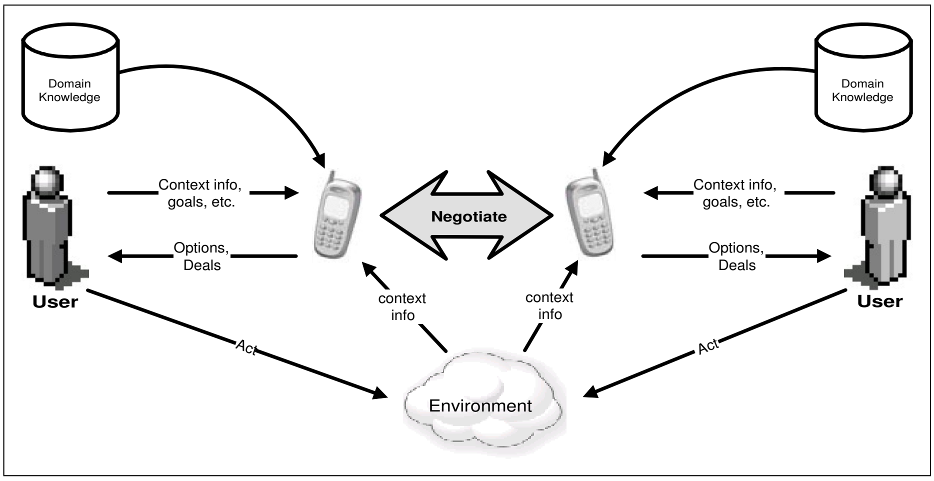

Fig. 1. Conceptual framework for mobile coordination through automated negotiation

Privacy and Connectivity Mobile users who are involved in impromptu coordination are constantly confronted with different interaction partners that want to obtain information about them. Users may be unwilling to disclose all the information required to run a centralised algorithm for coordinating joint activity. They may be willing to do so only when interacting with particular partners, or when the they realise the potential benefit of exchanging such information. Negotiation is a natural way to reconcile one's own wish to protect private information with the potential benefit of interacting with others.

3 Negotiation for Impromptu Coordination

In the previous section, we argued that impromptu mobile coordination requires the ability to represent information about the tasks of different users, and the ability to interactively process this information. The situations in which these users are involved, as already discussed, are complex. In this section, we present how an automated negotiation framework can fulfill these requirements, and hence may be used in order to support interacting mobile users.

3.1 Conceptual Overview

Our conceptual framework for mobile coordination through automated negotiation is illustrated in figure 1. An agent running on a user's mobile device acts as an intermediary between the user and other potential collaborators. The agent gathers information from the environment (e.g., lecture times, location of user and colleagues) and from the user (e.g., availability, goals). The agent then uses this information, as well as domain-specific knowledge (e.g., procedures for borrowing books from the library) in order to negotiate with agents representing other users. Negotiations are motivated by the user's goals and aim at achieving 'deals' with other users and present the opportunity to alleviate the difficulties presented to mobile users involved in impromptu coordination. Negotiation may result in useful potential deals (e.g., appointment, lunch, lift home), these are proposed to the respective users, who might accept, reject, or modify these deals as they see suitable. To enable this kind of automated support, we need to encode information about users goals and use this information in the negotiation process. In order to address this issue, the automated negotiation framework we adopt enables agents to exchange information about their respective users' goals. As a result, agents are more likely to improve the likelihood and quality of a deal.

3.2 The Negotiation Framework

Since we require a negotiation mechanism that exploits representations of users' tasks and goals, we base our framework on the recently proposed *interest-based negotiation* framework [11]. We now give a brief overview of the framework.

Each computational agent has explicit representations of its *desires*. In order to achieve its desires, an agent decomposes these desires into less abstract *goals*, which may themselves be decomposable into other (sub-)goals, until concrete *actions* are reached (i.e., physical actions agents may execute directly in the world). This results in a hierarchical structure in which the top-level root nodes represent desires, intermediate nodes represent abstract goals, and leaf nodes represent concrete actions to be executed.

The framework involves a set $AGENTS$ of agents, a set $PROPS$ of belief propositions representing the agent's view of the world, and a set $ACTIONS$ of *actions*.

The framework makes use of planning rules of the form $\varphi_1 \ \& \ \dots \ \& \ \varphi_n \rightarrow h$, where $\varphi_1, \dots, \varphi_n \in PROPS \cup ACTIONS$ and $h \in PROPS$. Intuitively, a planning rule means that the agent believes that if actions or sub-goals $\varphi_1, \dots, \varphi_n$ were realised, then h will be realised. We denote by $PRULES$ the set of all possible planning rules.

Definition 1. ***(Plan)*** *A* plan *for desire $d \in PROPS$ is a finite tree such that:*

- *d is the root of the tree.*
- *A non-leaf node is a proposition $p \in PROPS$ and has exactly n children $\varphi_1, \dots, \varphi_n$ where $\varphi_1 \ \& \ \dots \ \& \ \varphi_n \rightarrow p \in PRULES$.*
- *The leaves of the tree are actions.*

An agent i may have more than one desire, defined in a desire set $\mathcal{D}_i$. Given a set of initial desires, the agent selects a consistent (sub-)set of these desires, which can also be achieved using a set of consistent plans.[2] The agent *intends* (i.e., becomes committed to) these desires as well as their corresponding plans. The exact mechanism by which the agent selects its intended desires and plans (e.g., based on desires' relative importance, or plans' relative costs) is outside the scope of our study.[3]

Part (a) in Fig. 2 shows a sketch of (parts of) the plan structures for Omar and Jack from the narrative 1 above. Jack intends to go to the city because it is part of a plan for getting a book, which is, in turn, part of a larger plan for writing a research paper. To get a book, Jack needs to both get the book details and go to the city. To write the paper, Jack also needs to collect data, and possibly achieve other goals and actions. This is encoded in the following rules:[4]

$$\textit{getBookDetails} \ \& \ \textit{goToCity} \rightarrow \textit{getBook}$$
$$\textit{getBook} \ \& \ \textit{collectData} \rightarrow \textit{writePaper}$$

On the other hand, Omar wants to go home, and one way to do so is to get a lift.

Since agents are not always capable of achieving their goals individually, they may choose (or need) to negotiate with other agents in order to obtain their commitments towards achieving certain actions. A contract specifies what actions each agent has to perform.

Definition 2. ***(Contract)*** *A* contract *is an expression of the form*

$$Do(x_1, \alpha_1) \wedge \dots \wedge Do(x_n, \alpha_n)$$

where $x_i \in AGENTS \mid 1 \leq i \leq n$ and where $Do(x_i, \alpha)$ denotes that agent x_i will execute action α.

Negotiation aims at achieving a *deal*: a contract that is acceptable by all agents required to perform actions within that contract.

Participants in the negotiation dialogue may exchange information about each others' plan structures according to a specific interaction protocol. They can then exploit

[2] More details on the formal model can be found in [9].

[3] This may be operationalised, for example, using a hierarchical planner [2].

[4] Note that for the time being, we use a simple notation for describing rules. More realistically, one would need to express and reason about the temporal aspects of actions.

and/or influence each others' plan structures in order to enable or improve agreement(s). Agents interact using a set of locutions (or primitive message types), which can be exchanged by agents according to a protocol. Due to space limitations, we only present the locutions along with an informal explanation.

L1 PROPOSE(i, j, Ω): Agent i proposes a contract Ω to agent j.
L2 ACCEPT(i, j, Ω): Agent i accepts contract Ω previously proposed by j.
L3 REJECT(i, j, Ω): Agent i states that contract Ω is not acceptable to it.
L4 ASSERT(i, j, X): Agent i states that it believes statement X.
L5 QUESTION(i, j, X): Agent i asks agent j whether it believes statement X.
L6 CHALLENGE(i, j, X): Agent i asks agent j to provide a justification for formula X.
L7 RETRACT(i, j, X): Agent i retracts formula X that it previously asserted.
L8 REQ-PURPOSE(i, j, x): Agent i asks agent j to assert one of the super-goals of the action or goal denoted by x.
L9 REQ-ACHIEVE(i, j, x): Agent i asks agent j to explain how it intends to achieve the goal or desire denoted by x.
L10 QUIT(i): Agent i announces its withdrawal from the negotiation dialogue.
L11 PASS(i): Allows agent i to pass its turn in the dialogue.

Using locutions **L5**, **L8**, **L9** and **L4**, agents can exchange information about each others' plans. Then, they could influence each others' plans by doing one of the following:

– Argue that some of the beliefs or rules used in constructing a plan is incorrect. This may be achieved through a combination of challenges and counter assertions (using **L6** and **L4**);
– Introduce new beliefs or planning rules, by making new assertions;

These forms of influence may cause a variety of changes in the receiving agent's adopted plans and selected desires. Based on this, agents may be endowed with a variety of *strategies* that guide the way they influence each other. We do not further explore these issues here, but the reader may refer to [10, 11] for a more elaborate discussion.

3.3 Illustrative Example

Let us revisit the narrative introduced in section 2.3. Recall the situation where Omar fails to get in contact with his wife to secure a lift home. A device equipped with negotiation abilities could automatically attempt to find alternative ways to get a lift home by searching for nearby friends and checking (with their devices) for potential coordination. As soon as Omar's device detects that Jack is in a nearby area, it requests a lift from Jack's device. Upon inspection of the request, Jack's device discovers there is not enough time to drop by the university if Jack was to pick the book from the city on time; i.e., that there is some form of conflict between the two actions (in this case, the conflict is temporal). Omar's device could attempt to find out the reason behind the rejection, and suggest an alternative plan for getting the book (by Omar lending his copy of the book to Jack), in exchange for getting a lift.

Table 2 shows the dialogue sequence just described, using the locutions defined in the previous section, between Omar's and Jack's negotiation-enabled mobile devices.

Table 2. Example negotiation dialogue

Omar:	PROPOSE$(omar, jack, Do(jack, giveLift)$
Jack:	REJECT$(jack, omar, Do(jack, giveLift)$
Omar:	PASS
Jack:	ASSERT$(jack, omar,$ conflict$(goToCity, giveLift))$
Omar:	REQ-PURPOSE$(omar, jack, goToCity)$
Jack:	ASSERT$(jack, omar,$ prule$(getBookDetails\ \&\ goToCity \rightarrow getBook))$
Omar:	ASSERT$(omar, jack,$ prule$(lendBook \rightarrow getBook))$
Jack:	PASS
Omar:	PROPOSE$(omar, jack, Do(omar, lendBook)\ \&\ Do(jack, giveLift))$
Jack:	ACCEPT$(jack, omar, Do(omar, lendBook)\ \&\ Do(jack, giveLift))$

Part (b) in Fig. 2 shows Jack's modified plan, which now help achieve the desires of both himself and Omar.

There are other types of arguments that Omar could provide in an attempt to entice Jack to drop the goal of going to the library. For example, after acquiring more information about Jack's goal structure, Omar may attempt to disqualify Jack's ultimate goal of writing a paper, say by stating that data collection cannot be done on time anyway. See [11] for more details on arguments and locutions.

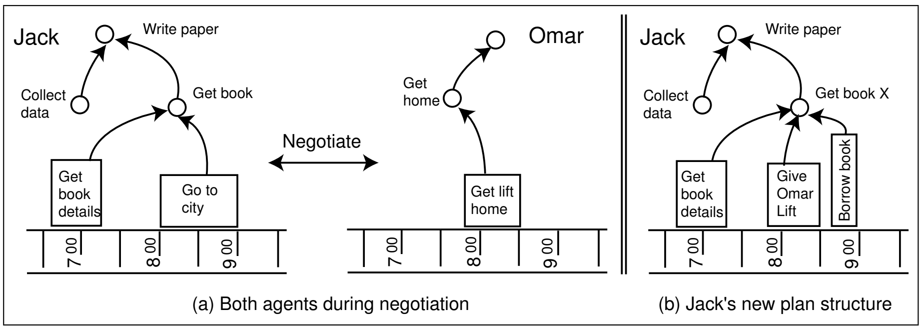

Fig. 2. An abstract view of negotiation

3.4 Characteristics Revisited

The framework we presented offers the features required to deal with the characteristics of impromptu mobile coordination discussed in section 2.3 above. In particular, the framework caters for the fluidity encountered in situations of mobile use involving impromptu coordination, since coordination does not assume predetermined and pre-negotiated task structures. Moreover, the focus on tasks and their underlying goals also enables impromptu realisation of opportunities for coordinating activities. By expressing the resources and objectives explicitly, it becomes possible to build technology that processes this information in order to “allow more effective planning and flexible allocation of resources” [8].

4 Conclusions

In this paper, we have argued that automated negotiation technologies, from the multi-agent systems literature, are valuable for facilitating impromptu coordination among mobile individuals. We have grounded our discussion in current studies of mobile users and, through a narrative, identified key issues of mobile coordination and showed how they may be addressed using negotiation technologies. In particular, we argued for the suitability of negotiation frameworks that represent and manipulate users’ goals. This is because negotiation allows coordination to be task-focused in the context of a user’s current situation, and so no long term coordination structures are required (as is required, for example, in the Electric Elves project [1]). We have presented a framework for automated negotiation that exploits a hierarchical representation of tasks and goals, and demonstrated how it can be used to provide the required support.

In the longer term, future work includes experimenting with, testing, and validating various negotiation strategies within the negotiation framework in real usage situations involving interaction with the environment by users and computational agents. Other future research include detailed consideration of the design and usability issues surrounding the interaction with the user. There is also an opportunity to rationalise the environment in terms of resources and affordances that agents and users alike can interact with and utilise. For example, a GPS service running on the Internet can be seen as a resource-for-computational agent and a city building as an affordance-for-human agent. We hope to explore these notions in future work.

Acknowledgement

Thanks to Michael Rovatsos, Christine Satchell, Greg Wadley, Anton Kattan, and Fernando Koch for useful discussions. We thank Hewlett Packard’s Philanthropy Division for donating equipment. Iyad Rahwan is grateful for the support of a Melbourne University Research Scholarship and a top-up scholarship from CMIS, CSIRO.

References

1. H. Chalupsky, Y. Gil, C. A. Knoblock, K. Lerman, J. Oh, D. V. Pynadath, T. A. Russ, and M. Tambe. Electric elves: Applying agent technology to support human organizations. In

H. Hirsh and S. Chien, editors, *Proceedings of the 13th International Conference of Innovative Application of Artificial Intelligence (IAAI-2001)*. AAAI Press, 2001.
2. K. Erol, J. Hendler, and D. Nau. Semantics for hierarchical task network planning. Technical Report CS-TR-3239, UMIACS-TR-94-31, Department of Computer Science, University of Maryland, 1994.
3. W. G. Griswold, R. Boyer, S. W. Brown, T. M. Truong, E. Bhasker, G. R. Jay, and R. B. Shapiro. Using mobile technology to create opportunitistic interactions on a university campus. In *UbiComp 2002 Workshop on Supporting Spontaneous Interaction in Ubiquitous Computing Settings*, September 2002.
4. E. A. Isaacs, J. C. Tang, and T. Morris. Piazza: a desktop environment supporting impromptu and planned interactions. In *Proceedings of the 1996 ACM conference on Computer supported cooperative work*, pages 315–324. ACM Press, 1996.
5. N. R. Jennings, P. Faratin, A. R. Lomuscio, S. Parsons, C. Sierra, and M. J. Wooldridge. Automated negotiation: prospects, methods and challenges. *International Journal of Group Decision and Negotiation*, 10(2):199–215, 2001.
6. M. Kakihara and C. Sørensen. Mobility: An extended perspective. In R. S. Jr, editor, *Proceedings of the 35th Hawaii International Conference on Systems Sciences*, Big Island, Hawaii, USA, 2002. IEEE Press.
7. P. Luff and C. Heath. Mobility in collaboration. In *Proceedings of the 1998 ACM conference on Computer Supported Cooperative Work*, pages 305–314. ACM Press, 1998.
8. M. Perry, K. O'Hara, A. Sellen, B. Brown, and R. Harper. Dealing with mobility: understanding access anytime, anywhere. *ACM Transactions on Computer-Human Interaction*, 8(4):323–347, 2001.
9. I. Rahwan. *Interest-based Negotiation in Multi-Agent Systems*. PhD thesis, Department of Information Systems, University of Melbourne, Melbourne, Australia, 2004. (to appear).
10. I. Rahwan, P. McBurney, and L. Sonenberg. Towards a theory of negotiation strategy (a preliminary report). In S. Parsons and P. Gmytrasiewicz, editors, *Proceedings of the 5th Workshop on Game Theoretic and Decision Theoretic Agents (GTDT-2003)*, pages 73–80, 2003.
11. I. Rahwan, L. Sonenberg, and F. Dignum. On interest-based negotiation. In F. Dignum, editor, *Advances in Agent Communication*, volume 2922 of *Lecture Notes in Artificial Intelligence*, pages 383–401. Springer Verlag, Berlin, Germany, 2004.
12. T. Rahwan, T. Rahwan, I. Rahwan, and R. Ashri. Agent-based support for mobile users using AgentSpeak(L). In P. Giorgini, B. Hederson-Sellers, and M. Winikoff, editors, *Agent Oriented Information Systems*, volume 3030 of *Lecture Notes in Artificial Intelligence*, pages 47–62. Springer Verlag, Berlin, Germany, 2004.
13. N. M. Sadeh. *M–Commerce Technologies, Service, and Business Models*. Wiley, Hoboken NJ, USA, 2003.
14. A. Strauss. *The Continual Permutations of Action*. Aldine de Gruyter, New York NY, USA, 1993.
15. J. Tang, , E. Isaacs, and M. Rua. Supporting distributed groups with a montage of lightweight interactions. In *Proceedings of Conference on Computer Supported Co-operative Work, Chapel Hill NC, USA*, pages 23–34, New York NY, USA, 1994. ACM Press.
16. S. Weiss. *Handheld Usability*. Wiley, Hoboken NJ, USA, 2002.
17. S. Whittaker, G. Swanson, J. Kucan, and C. Sidner. Telenotes: Managing lightweight interactions in the desktop. *Transactions on Computer Human Interaction*, 4:137–168, 1997.
18. M. J. Wooldridge. *An Introduction to MultiAgent Systems*. John Wiley & Sons, Chichester, England, 2002.