TOWARDS A THEORY FOR MULTIPARTY PROACTIVE COMMUNICATION IN AGENT TEAMS

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Helping behavior in effective teams is achieved via some overlapping "shared mental models" that are developed and maintained by members of the team. In this paper, we take the perspective that multiparty "proactive" communication is critical for establishing and maintaining such a shared mental model among teammates, which is the basis for agents to offer proactive help and to achieve coherent teamwork. We first provide formal semantics for multiparty proactive performatives within a team setting. We then examine how such performatives result in updates to mental model of teammates, and how such updates can trigger helpful behaviors from other teammates. We also provide conversation policies for multiparty proactive performatives.

1. Introduction

Shared mental model (SMM) is a hypothetical construct that has been put forward to explain certain coordinated behaviors of human teams [17,28]. Basically, a shared mental model represents each team member's model of the global team state. This representation produces a mutual awareness, with which team members can reason not only about their own situation, but also about the status and activities of teammates and progress of the team toward its goal.

A computational shared mental model enables a team of software agents to engage in effective teamwork behaviors. The scope of such a shared mental model is rather broad and includes common knowledge (beliefs) [24], joint goals/intentions [5], shared team structure [33], shared plans [13], etc.

Multiparty communication (or multiparty dialogues) are conversations that involve more than two parties [6,29,21,16,27,26,25], and play a major role in establishing and maintaining a shared mental model [18]. For example, the Joint Intentions Theory (JIT) introduces a notion of *joint intention* and requires a team of agents with a joint intention to not only commit to their part in achieving a shared goal, but also to commit to informing others when the goal has been accomplished, becomes impossible to achieve, or irrelevant.

Human society is replete with examples of multiparty dialogues: posting messages to mailing lists or newsgroups, publishing web pages, and having a teleconference or videoconference. Furthermore, human teams such as a firefighter squad or a military unit often engage in multiparty dialogues via a shared communication channel to achieve a better situation awareness. Parties involved in a multiparty dialogue can assume roles other than the speaker/addressee roles in traditional two-party communication. One of the most important roles is the *overhearer*, which can be used to organize agent societies [2].

Software agents can assume some of the responsibilities of humans in performing multiparty dialogues; Hence, agents need to be able to communicate with groups and reason about multiparty communications [21]. Such capabilities are required when agents need to cooperate and solve a complex problem, especially when the knowledge to solve the problem is distributed among agents [6].

Agent communication languages like FIPA [9] and KQML [22] mostly focus on two-party communication. KQML has a *broadcast* performative which is defined in terms of several simultaneous *forward* performatives. In broadcast the speaker requests the addressees to forward a message to all the agents that addressees know of. Hence, the speaker is not aware of all the final recipients of the message. Furthermore, not all of the recipients of the message know about each other because broadcast has no designated addressee. Kumar *et. al.* consider two-party dialogues as a special case of multiparty dialogues and formally define a *Request* performative that handles both two-party and multiparty conversations [21]. The *Request* performative has a designated addressee and has the property that the designated addressee(s) may be unknown to the speaker.

Multiparty communication, in general, can be considered as a strong form of broadcast: a multiparty performative is a broadcast with designated receivers taking various roles that are evident to everyone involved. From this perspective, broadcast as defined in KQML is limited in its support for effective group communication because receivers of a broadcast message, not knowing whoever else is involved, cannot update their mental models about others' information awareness. Consequently, they cannot take full advantage of the broadcast message in ensuing team activities. It is thus important to formally characterize the semantics of multiparty communication performatives to better support the development of shared situation awareness in a team.

In this research, we formally define the semantics of several multiparty performatives in a team setting, where the designated addressee and overhearers are mutually known to everyone involved. The overhearers can thus monitor the interaction between the speaker and addressee and reason about their beliefs, desires, and intentions. More importantly, the overhearers can also reason about the beliefs, desires, and intentions of *other* overhearers. Such reasoning will result in updates to the team's shared mental model, which triggers further helpful behaviors from overhearers. In our research, we focus on multiparty *proactive* communication; proactive communication is complementary to passive communication and alleviates several limitations of passive communications [8].

The rest of this paper is organized as follows: In Section 2 we discuss the motivation for our research; we give a concrete example to illustrate the difference

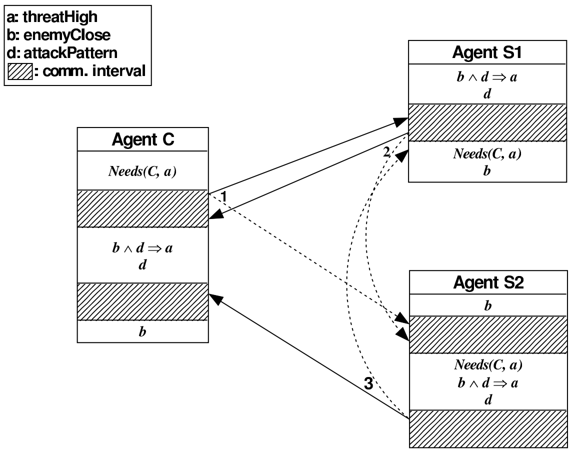

Fig. 1. Motivating example. Upper left box is legend

between broadcast and multiparty communication. Specifically, we illustrate how they entail different updates to shared mental models. Section 3 gives the relevant research background. Section 4 gives the formal definition of three performatives: multiparty inform (*MP-Inform*), multiparty proactive inform (*MP-ProInform*), and multiparty indirect proactive inform (*MP-IndProInform*). We then prove some properties of *MP-IndProInform* and propose a conversation policy for *MP-IndProInform*. Section 5 gives the formal definition of a multiparty proactive subscription performative, multiparty proactive third-party subscribe (*MP-3PTSubscribe*), along with proofs for its properties and a conversation policy. MP-3PTSubscribe is different from Section 4 performatives in that the speaker is not the information provider; the speaker subscribes the information needer to a provider. Section 6 discusses related work and Section 7 concludes the paper.

2. Motivation

Broadcast is a useful communicative action which does not require an agent to know all of the parties that can receive the broadcast message. However, it is limited for describing multi-party agent communication within a team in several ways. Broadcast is limited in maintaining a team's evolving shared mental model. More specifically, it cannot be used to describe an agent communication with a designated addressee while allowing other agents to overhear the conversation. Not having a designated addressee may result in redundant replies, as multiple agents may reply to the original speaker of the broadcast. Moreover, if no agent knows the answer to the query, none of them are responsible for finding an answer to the query.

As an example, consider the agent team shown in Figure 1. Each rectangle represents an agent. The top box in each rectangle (below agent's name) represents each agent's initial beliefs. Shaded boxes represent periods of communication after which agent's beliefs are updated. The boxes further down display an agent's new beliefs established after receiving messages from other agents. Solid arrows represent communication between the speaker and the addressee; dashed arrows represent overhearing of the communicated message by an overhearer. The numbers next to the arrows represent the order in which the communications happened. A commander agent, C, needs to know *threatHigh*, yet C does not know the truth value for *threatHigh*. A scout agent, S_1, knows that *enemyClose* and *attackPattern* together can derive *threatHigh* (i.e. *enemyClose* $\wedge$ *attackPattern* $\Rightarrow$ *threatHigh*). S_1 also knows *enemyClose*, but does not know *attackPattern*. On the other hand, another scout agent, S_2, knows *attackPattern*. One desirable agent communication behavior in this case is for C to request *threatHigh* from S_1, while allowing S_2 to overhear the conversation. S_1 can respond with the knowledge to infer *threatHigh* as well as partial information needed for *threatHigh* (i.e. *enemyClose*), allowing others to overhear. Subsequently, agent S_2 realizes that the information it has (i.e. *attackPattern*) is relevant to what C needs. Hence, it can choose to proactively inform C about *attackPattern* while allowing others to overhear. This kind of communication enables agents to effectively share knowledge and information relevant to their needs by maintaining a stronger evolving shared mental model among them; for example, S_2 knows about C_s need as well as S_1's knowledge and information relevant to these needs. It is difficult to use broadcast to achieve the kind of desirable agent communication described above. This motivates us to introduce multi-party agent communicative actions and formally define their semantics.

3. Background

Fan, Yen, and Volz [8] have developed a formal framework for proactive communications by introducing the notion of information need as an extension to the SharedPlans theory [13]. The SharedPlans theory provides axioms for helpful behavior. Since proactive information delivery is a specific helpful behavior, we have also based our formalism on the SharedPlans theory. Before discussing the semantics of multiparty proactive performatives, we first briefly summarize the main concepts in this framework that we will use in this paper.

3.1. *Proactive vs. Passive Communication*

Proactive information delivery means providing relevant information to a teammate based on the anticipated needs of the teammate. Such anticipation can be derived from a shared mental model about the team structure and the teamwork process [33]. One motivation of our study of proactive communication in the context of teamwork is that passive communication approach (ask/reply), although useful and even necessary in many cases, does have limitations. Proactive communication may provide a complementary solution [8]. For instance, an information consumer in a team may not realize that certain information it has is already out of date. If this agent had to verify the validity of every piece of information before using it, the team could be easily overwhelmed by the amount of communication entailed by these verification messages. Proactive information delivery offers an alternative, as it shifts the burden of updating information from the information consumer to the information provider, who typically has direct knowledge about any changes. In addition, an agent, due to its limited knowledge, may not realize that it needs certain information. For instance, a piece of information may be obtained only through a chain of inferences (e.g., being fused according to certain domain-related rules). If the agent does not have all the knowledge needed to make such a chain of inferences, it simply cannot realize that it needs the information, and thus does not know enough to request it. Proactive information delivery allows teammates to assist the agent in such a circumstance.

3.2. *Basics of the SharedPlans Theory*

SharedPlans theory (SPT) [12] formalizes collaborative activity where multiple agents, each with solutions to different pieces of a problem, work together to form a global solution. Actions in SPT are either primitive or complex. Complex actions are built from primitive actions using the constructs of dynamic logic: $\alpha;\beta$ for sequential composition, p? for testing, etc. All actions in SPT are intended, committed, and performed in some specific context. By convention C_α refers to context in which α is performed.

Bel and *MB* are the modal operators for belief and mutual belief, respectively. Four types of intentional attitudes are defined in SPT. *Int.To* represents an agent's adopted intention to perform an action, while *Int.Th* represents an agent's adopted intention that a proposition hold. *Pot.Int.To* (or *Pot.Int.Th*) is a potential *Int.To* (or *Int.Th*) that is not yet adopted by the agent, but may be adopted when it is reconciled with the existing intentions.

Intention operator $Int.To(A, \alpha, t, t_\alpha, C_\alpha)$ means that at time t, agent A intends to do action α at time t_α in the context C_α, whereas $Int.Th(A, p, t, t', C_p)$ means agent A at time t intends that p hold at t' under the context C_p.

SPT proposes several axioms for deriving helpful behavior. The following axiom simplifies the axiom in [13].

Axiom 1 $\forall A, p, t, \beta, t_\beta, t' > t_\beta, C_p.\ \neg Bel(A, p, t) \wedge Int.Th(A, p, t, t', C_p) \wedge$
$lead(A, \beta, p, t, t_\beta, \Theta_\beta) \Rightarrow Pot.Int.To(A, \beta, t, t_\beta, \Theta_\beta \wedge C_p)$

Axiom 1 says that if A does not believe p is true at time t, but has an intention (at time t) that p be true in future (at time t'), it will consider doing action β if it believes performance of β leads to p becoming true either directly or indirectly through the performance of another action by another agent. A formal definition of *lead* can be found in [8]. Θ_β denotes the constraints under which the action β is performed.

3.3. *Information Need*

The key issue in proactive communication is the concept of information need, formally defined in [32] via modal operator *InfoNeed*(A, N, t, C_n). Information need consists of an information consumer A, a need expression N, an expiry time t, and a context C_n, under which the need is valid.

An information need may state that an agent needs to know the truth value of a proposition (e.g. *Weather(Cloudy,Today)*) or an agent may want to know the values of some arguments of a predicate that would make the predicate true (e.g. *Weather(?x,Today)*) [8]. Therefore, a need expression may be in one of two forms: a factual proposition or a reference expression [8].

Next, we define some functions (predicates) to be used later [8].

- *info*(A, N) returns the information with respect to N evaluated by A.
- *has.info*(A, N) is true if agent A knows information about N.
- *hasKnow*(N) takes as input a need expression N and returns as output K, the inference knowledge regarding N.
- $Need_{\vdash}(N, K)$ takes as inputs N (a need expression) and K (inference knowledge regarding N) and returns a set consisting of the indirect need expressions, i.e. the need expressions from which N can be inferred.
- *pos*(N) is true if N is a proposition.
- *post*(ϵ) takes as input action ϵ and returns ϵ's effects.

We also use some abbreviations, such as awareness (*Bif*), unawareness (*UBif*), and belief contradiction (*CBel*); their definitions can be found in [8].

The following axiom states that when an agent A knows that another agent B needs N (with both agents being part of team TA), it will adopt an attitude of potential intention-that towards B's belief about the needed information.

Axiom 2 (ProAssist) $\forall A, B \in TA, N, C_n, t, t' > t.\ Bel(A, InfoNeed(B, N, t', C_n), t) \Rightarrow [has.info(A, N)) \Rightarrow Pot.Int.Th(A, Bel(B, info(A, N), t'), t, t', C_n)]$

3.4. *Performative as attempt*

Following the idea of *performative-as-attempt* [4], the semantics of performatives is modeled as attempts to establish certain mutual beliefs between the speaker and the addressee. $Attempt(A, \epsilon, P, Q, t, t_1)$ is an attempt by agent A at time t to achieve P by time t_1 by doing ϵ while being committed to Q. Here P represents the ultimate goal that may or may not be achieved, whereas Q represents what it takes to make an honest effort (to which the agent is committed). If the attempt does not achieve P, the agent may retry the attempt, try another strategy, or even drop P. However, if the attempt does not achieve Q, the agent is committed to retrying until Q is achieved, becomes irrelevant, or becomes impossible.

The following example clarifies the concept of *Attempt*. Suppose a basketball player at time t attempts to score at time t_1. Here, the ultimate goal P is scoring (which may or may not be achieved). P can be achieved by shooting the basketball (which represents ϵ). While the player is not committed to achieving P (the player may not score), he/she is committed to performing a successful shot (which represents Q). For instance, if the ball drops out of the player's hands right before taking the shot, the player is committed to picking up the ball and trying the shot again.

A formal definition of *Attempt* [8] is given in Definition 1.

Definition 1 $\mathit{Attempt}(A, \epsilon, P, Q, t, t_1) \equiv \phi?; \epsilon$, where
$\phi = [\neg \mathit{Bel}(A, P, t) \wedge \mathit{Pot.Int.Th}(A, P, t, t_1, C_n) \wedge$
$\mathit{Int.Th}(A, Q, t, t_1, \neg \mathit{Bel}(A, P, t) \wedge C_n) \wedge \mathit{Int.To}(A, \epsilon, t, t, \psi)]$, where
$\psi = \mathit{Bel}(A, \mathit{post}(\epsilon) \Rightarrow Q, t) \wedge \mathit{Pot.Int.Th}(A, P, t, t_1, C_n)$

The semantics of elementary performatives is given by substituting appropriate formula for P and Q in the definition of *Attempt*.

Proactive information delivery means providing relevant information to a teammate based on the anticipated needs of the teammate. Such anticipation can be derived from a shared mental model about the team structure and the teamwork process [33]. We next briefly discuss two proactive performatives, namely proactive inform and proactive third-party subscribe [8].

Proactive inform(*ProInform*) is a proactive performative in which the speaker not only believes in the information communicated but also believes the addressee needs the information. *ProInform* is different from the existing performatives in two ways. First, *ProInform* is *need driven*, i.e. the speaker is aware of the addressee's information need prior to performing the communicative act. Second, *ProInform* allows for exchange of *information need* as well as the exchange of information.

Proactive third-party subscribe (*3PTSubscribe*) is a proactive performative in which an agent anticipates the information need of a teammate and subscribes the teammates' information need to a provider. *3PTSubscribe* is different from other subscription performatives in two ways. First, unlike other subscription performatives *3PTSubscribe* is not initiated by the information consumer, but by a teammate that anticipates the consumer's information need. Second, unlike other subscription performatives the providers in *3PTSubscribe* are *committed* to providing the information to the consumer for the duration of the subscription.

4. Multiparty Proactive Performatives

In this section, we first define a multiparty inform performative (*MP-Inform*), which extends the *Inform* performative [8] to multiparty settings. We then define two multiparty *proactive* performatives, namely multiparty proactive inform (*MP-ProInform*) and multiparty indirect proactive inform (*MP-IndProInform*), which deal with situations that the provider agent has *full* or *partial* knowledge regarding the consumer's information need. We then prove some properties of *MP-IndProInform* and formally derive desirable helpful behaviors for the overhearers. Finally, we propose a conversation policy for *MP-IndProInform*.

In defining the performatives we assume:

- Agents in a team are *sincere*, i.e. whenever some agent A intends another agent B to believe p, A itself believes in p.
- Agents in a team are helpful.
- The speaker is aware of the overhearers, which monitor its conversation.
- The overhearers of a conversation do not ignore the overheard messages.

Formal definition for agent sincerity can be found in [8] and is not discussed. Later in this paper, we use sincerity as a premise to prove certain theorems regarding agent beliefs and behavior.

4.1. *Multiparty Inform*

Multiparty inform (*MP-Inform*) is an extension of the *Inform* performative to multiparty settings. Since *MP-Inform* is a multiparty performative, the agents involved in *MP-Inform* can assume different roles such as speaker, addressee, and overhearer. The speaker of *MP-Inform* intends to inform the addressee (a single agent) while the overhearers (possibly multiple agents) monitor the conversation. Hence, unlike *Inform* in which only the addressee will know about the speaker's intention, in *MP-Inform* the *overhearers* will also know about the speaker's intention. *MP-Inform* is defined as an attempt by the speaker to establish a mutual belief with the addressee and the *overhearers* about the speaker's intention to let the addressee know the speaker knows the information communicated. Formally,

Definition 2 $\mathit{MP\text{-}Inform}(A, B, \{O_1, \ldots, O_n\}, \epsilon, p, t, t_\alpha) \equiv$
$(t < t_\alpha)?;\mathit{Attempt}(A, \epsilon, P, Q, C_p, t, t_\alpha)$, where
$P = \mathit{MB}(\{A, B, O_1, \ldots, O_n\}, p, t_\alpha)$, and
$Q = \exists t''.(t \leq t'' < t_\alpha) \wedge \mathit{MB}(\{A, B, O_1, \ldots, O_n\}, \psi, t'')$, where
$\psi = \exists t_b(t'' \leq t_b < t_\alpha) \wedge \mathit{Int.Th}(A, \mathit{Bel}(B, \mathit{Bel}(A, p, t), t_b), t, t_b, C_p)$

In Definition2, A is the speaker, B is the addressee, and O_1 to O_n are the overhearers. Based on our assumptions, it is easy to establish the mutual belief about ψ; agent B (each agent O_i) believes in ψ upon receiving (overhearing) a message with content ψ from A. The addressee can either accept the communicated information (reply *MP-Accept*), or reject it (reply *MP-Reject*). Formal definitions for *MP-Accept* and *MP-Reject* are given next.

Definition 3 Responses to *MP-Inform*
MP-Accept $\equiv \mathit{MP\text{-}Inform}(B, A, \{O_1, \ldots, O_n\}, \epsilon, q, t, t_\alpha)$, where $q = \mathit{Bel}(B, p, t)$, and
MP-Reject $\equiv \mathit{MP\text{-}Inform}(B, A, \{O_1, \ldots, O_n\}, \epsilon, q, t, t_\alpha)$, where $q = \neg\mathit{Bel}(B, p, t)$.

MP-Accept and *MP-Reject* are defined as a *MP-Inform*. Therefore, even though the replies are addressed to the speaker, they can also be overheard by the overhearers.

If the communicated information is inconsistent with an overhearer's beliefs, the overhearer will respond with a *MP-Reject*. If the information is consistent with an overhearer's beliefs, the overhearer will respond with a *MP-Accept or* it may choose to implicitly accept the information by not responding; i.e. no explicit accept message is communicated – reducing the number of communicated messages. The details of implicit accept (e.g. the wait time before concluding that the overhearer has implicitly accepted the information) can be handled by the conversation policy.

Following the communication between the speaker and the addressee (*MP-Inform* followed by addressee's reply), all the team members can update their beliefs regarding the speaker and addressee's beliefs about the information communicated. Furthermore, following each overhearer's possible reply to *MP-Inform* (implicit accept by not responding, or *MP-Reject*), other teammates can update their beliefs regarding the overhearer's beliefs about the information communicated, resulting in an increased awareness about teammates' mental states.

In the following, we use $Done(A, \alpha, t, \Theta)$ to denote the successful performance of performative α by agent A at time t under constraints Θ. By successful performance of a performative we mean the honest goal of the performative has been achieved.

Theorem 4.1. Successful performance of *MP-Inform* act establishes a mutual belief between the speaker, the addressee, and the overhearers, that the speaker believes the informed proposition. Formally,
$\exists\Theta, t_\alpha > t.Done(A, MP\text{-}Inform(A, B, \{O_1, \ldots, O_n\}, \epsilon, p, t, t_\alpha), t, \Theta) \Rightarrow$
$MB(\{A, B, O_1, \ldots, O_n\}, Bel(A, p, t), t_\alpha)$

4.2. *Multiparty Proactive Inform*

Multiparty proactive inform (*MP-ProInform*) is an extension of the *ProInform* to multiparty settings. Unlike *ProInform*, in which only the addressee will know about the speaker's intention, in *MP-ProInform* the *overhearers* will also know about the speaker's intention. *MP-ProInform* is defined as an attempt by the speaker to establish a mutual belief with the addressee and the *overhearers* about the speaker's intention to let the addressee know (1) the speaker knows the information communicated (2) the speaker knows the addressee *needs* the information. Formally,

Definition 4 $MP\text{-}ProInform(A, B, \{O_1, \ldots, O_n\}, \epsilon, I, N, t, t_\alpha, t', C_n) \equiv$
$(t < t_\alpha < t')?; Attempt(A, \epsilon, p_1, p_2, t, t_\alpha)$, where
$p_1 = Bel(B, I, t')$, and
$p_2 = \exists t''.(t \leq t'' < t_a) \wedge \ MB(\{A, B, O_1, \ldots, O_n\}, Q, t'')$, where
$Q = \exists C_p, t_b.(t'' \leq t_b < t_\alpha) \wedge Int.Th(A, Bel(B, \psi, t_b), t, t_b, C_p)$, and
$\psi = Bel(A, InfoNeed(B, N, t', C_n), t) \wedge \ Bel(A, I = info(A, N), t)$

The addressee can reply in four ways: (1) Accept both the information and the information need (*multiparty strong accept* or *MP-SAccept*), (2) Accept the information and reject the information need (*multiparty weak accept* or *MP-WAccept*), (3) Reject the information and accept the information need (*multiparty weak reject* or *MP-WReject*), and (4) Reject both the information and the information need (*mul-*

tiparty strong reject or *MP-SReject*). Formal definitions for replies to *MP-ProInform* are given next.

Definition 3 Responses to *MP-ProInform*
$\textit{MP-SAccept} \equiv \textit{MP-Inform}(B, A, \{O_1, \ldots, O_n\}, \epsilon, q, t, t_\alpha)$, where $q = \textit{Bel}(B, p, t) \wedge \textit{Bel}(B, \textit{InfoNeed}(B, N, t', C_n), t)$
$\textit{MP-WAccept} \equiv \textit{MP-Inform}(B, A, \{O_1, \ldots, O_n\}, \epsilon, q, t, t_\alpha)$, where $q = \neg\textit{Bel}(B, p, t) \wedge \neg\textit{Bel}(B, \textit{InfoNeed}(B, N, t', C_n), t)$
$\textit{MP-WReject} \equiv \textit{MP-Inform}(B, A, \{O_1, \ldots, O_n\}, \epsilon, q, t, t_\alpha)$, where $q = \neg\textit{Bel}(B, p, t) \wedge \textit{Bel}(B, \textit{InfoNeed}(B, N, t', C_n), t)$
$\textit{MP-SReject} \equiv \textit{MP-Inform}(B, A, \{O_1, \ldots, O_n\}, \epsilon, q, t, t_\alpha)$, where $q = \neg\textit{Bel}(B, p, t) \wedge \neg\textit{Bel}(B, \textit{InfoNeed}(B, N, t', C_n), t)$.

The replies are defined as a *MP-Inform*. Therefore, even though the replies are addressed to the speaker, they can be overheard by the overhearers.

Following the communication between the speaker and the addressee (*MP-ProInform* followed by addressee's reply), all the team members can update their beliefs regarding the speaker and addressee's beliefs about the information communicated and the addressee's information need. Furthermore, following each overhearer's possible reply to *MP-Inform* (implicit accept by not responding, or either of *MP-WAccept*, *MP-WReject*, or *MP-SReject*), other teammates can update their beliefs regarding the overhearer's beliefs about the information communicated and the addressee's information need, resulting in an increased awareness about teammates' mental states.

MP-ProInform, unlike *MP-Inform*, is *need driven*, i.e. the speaker is aware of the addressee's information need prior to performing the communicative act. Furthermore, like *ProInform*, *MP-ProInform* allows for exchange of *information need* as well as the exchange of information between the speaker, the addressee and the *overhearers*.

4.3. *Multiparty Indirect Proactive Inform*

Often times the provider agent is aware of the consumer's information need, yet the provider cannot fully satisfy the information need. Given that the provider has the information need's inference knowledge, the provider can infer the *indirect information needs* of the consumer. Indirect information needs are the relevant information necessary to derive the needed information using certain inference knowledge.

For instance, in case 2 of the Illustrated Example section, *enemyClose* and *attackPattern* are required for inferring *threatHigh*; therefore *enemyClose* and *attackPattern* are indirect information needs of S_2. If the provider is aware of any indirect information need, the provider can proactively inform the consumer about (1) the consumer's information need, (2) the information need's inference knowledge, and (3) the consumer's indirect information need. The consumer needs the inference knowledge for synthesizing its information need from the relevant information received from different agents. We will next discuss an example.

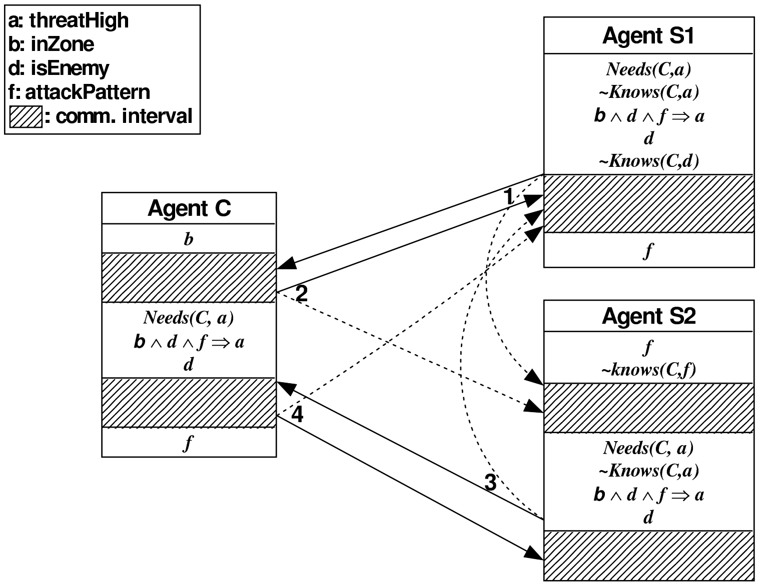

Fig. 2. Multiparty proactive communication. Upper left box is legend

Example problem 1: Suppose a commander agent C and two scouts S_1 and S_2 are members of a team (Figure 2). The information need of C is *threatHigh*. Initially, C neither knows *threatHigh*, nor that it *needs threatHigh* (C only knows *inZone*). Agent S_1 knows that C needs *threatHigh* and C does not know *threatHigh*. Agent S_1 does not know *threatHigh* but it knows *isEnemy*. Furthermore, S_1 has the inference knowledge regarding *threatHigh*, i.e. $inZone \wedge isEnemy \wedge attackPattern \Rightarrow threatHigh$ – no other agent has this inference knowledge. Agent S_2 neither knows *threatHigh*, nor that C needs *threatHigh*; S_2 only knows *attackPattern* (and that C does not know *attackPattern*).

There are two difficulties in the example discussed: (1) C (or S_2) is not aware of C's information need, and (2) even though S_2 (or C) knows *attackPattern* (or *inZone*), which can be used to infer *threatHigh*, S_2 (or C) do not have the knowledge to relate *attackPattern* (or *inZone*) to C's needs.

The proposed solution is illustrated in Figure 2. The box immediately under each agent's name displays an agent's initial beliefs (beliefs before communicating with others). Shaded boxes represent periods of communication, which result in belief updates. The boxes further down display an agent's new beliefs established after receiving messages from other agents. Solid arrows represent communication between the speaker and the addressee; dashed arrows represent overhearing of the communicated message by an overhearer. The numbers next to the arrows represent the order in which the communications happened.

- First, agent S_1 proactively informs C about C's information need (i.e.

threatHigh), the inference knowledge regarding *threatHigh* (i.e. $inZone \wedge isEnemy \wedge attackPattern \Rightarrow threatHigh$), and *isEnemy* (message 1).

- Second, upon receiving message 1, agent C accepts the information communicated (message 2). Agent S_2 overhears the messages and learns about the C's information need (i.e. *threatHigh*), the inference knowledge regarding *threatHigh*, and the relevant information (i.e. *isEnemy*).
- Third, since S_2 now knows that *attackPattern* is necessary to infer *threatHigh*, it will proactively inform C about *attackPattern* (message 3).
- Fourth, upon receiving message 3, agent C accepts the information communicated (message 4). Agent S_1 will overhear messages 3 and 4 and updates its beliefs accordingly.

To capture the semantics of such situations we formally define a new performative, multiparty indirect proactive inform (*MP-IndProInform*). *MP-IndProInform* is defined as an attempt by the speaker to establish a mutual belief with the addressee and the *overhearers* about the speaker's intention to let the addressee know (1) the speaker knows the addressee's information need, (2) the speaker knows the information need's inference knowledge, and (3) the speaker knows the indirect information need of the addressee. Formally,

Definition 5 $\mathit{MP\text{-}IndProInform}(A, B, \{O_1, \ldots, O_n\}, \epsilon, I, IN, K, N, t, t_\alpha, t', C_n) \equiv$
$(t < t_a < t')?;\mathit{Attempt}(A, \epsilon, p_1, p_2, t, t_\alpha)$,where
$p_1 = \mathit{Bel}(B, I, t')$, and
$p_2 = \exists t''.(t \leq t'' < t_a) \wedge \ MB(\{A, B, O_1, \ldots, O_n\}, Q, t'')$, where
$Q = \exists C_p, t_b.(t'' \leq t_b < t_\alpha) \wedge \mathit{Int.Th}(A, \mathit{Bel}(B, \psi, t_b), t, t_b, C_p)$, and
$\psi = \mathit{Bel}(A, \phi, t)$, where
$\phi = \mathit{InfoNeed}(B, N, t', C_n) \ \wedge \ K = \mathit{hasKnow}(N) \ \wedge \ IN \in \mathit{Need}_{\vdash}(N, K) \ \wedge \ I = \mathit{info}(A, IN)$

The addressee can accept or reject any combination of the speaker's beliefs regarding the information need, information need's inference knowledge, and the indirect information need. Therefore, the addressee can reply in eight possible ways (Table 1). Each row in Table 1 specifies the beliefs communicated via the corresponding performative. The rightmost column of the table specifies agent's belief on the inference knowledge. The agent either believes in the inference knowledge specified by the speaker (K), or a in a different inference knowledge (K'). The replies are defined as a *MP-Inform* and are addressed to the speaker, but since they are defined as a *MP-Inform*, they can also be overheard by the overhearers.

Following the communication between the speaker and the addressee (*MP-IndProInform* followed by addressee's reply), all the team members can update their beliefs regarding the speaker and addressee's beliefs about the information need of the addressee, the information need's *inference knowledge*, and the addressee's indirect information need. Furthermore, following each overhearer's possible reply to *MP-Inform* (implicit accept by not responding, or either of other 7 replies defined in Table 1), other teammates can update their beliefs regarding the overhearer's be-

Performative	Bel. on I	Bel. on Info Need	Bel. on Knowledge
MP-SReject-K	$\neg$*Bel(B,I,t)*	*Bel(B,*$\neg$*InfoNeed(B,N,t',*C_n*),t)*	*Bel(B,K=hasKnow(N),t)*
MP-SReject-K'	$\neg$*Bel(B,I,t)*	*Bel(B,*$\neg$*InfoNeed(B,N,t',*C_n*),t)*	*Bel(B,K'=hasKnow(N),t)*
MP-WReject-K	$\neg$*Bel(B,I,t)*	*Bel(B,InfoNeed(B,N,t',*C_n*),t)*	*Bel(B,K=hasKnow(N),t)*
MP-WReject-K'	$\neg$*Bel(B,I,t)*	*Bel(B,InfoNeed(B,N,t',*C_n*),t)*	*Bel(B,K'=hasKnow(N),t)*
MP-SAccept-K	*Bel(B,I,t)*	*Bel(B,InfoNeed(B,N,t',*C_n*),t)*	*Bel(B,K=hasKnow(N),t)*
MP-SAccept-K'	*Bel(B,I,t)*	*Bel(B,InfoNeed(B,N,t',*C_n*),t)*	*Bel(B,K'=hasKnow(N),t)*
MP-WAccept-K	*Bel(B,I,t)*	*Bel(B,*$\neg$*InfoNeed(B,N,t',*C_n*),t)*	*Bel(B,K=hasKnow(N),t)*
MP-WAccept-K'	*Bel(B,I,t)*	*Bel(B,*$\neg$*InfoNeed(B,N,t',*C_n*),t)*	*Bel(B,K'=hasKnow(N),t)*

Table 1. Possible replies for *MP-IndProInform*

liefs about the information need of the addressee, the information need's *inference knowledge*, and the addressee's indirect information need, resulting in an increased awareness about teammates' mental states.

MP-IndProInform not only allows for the exchange of information and information need, but also allows for the exchange of *inference knowledge* regarding the information need. Having such inference knowledge enables the overhearers to provide different pieces of information necessary to satisfy the information need and can trigger further helpful behaviors from the overhearers.

4.4. *Properties of Multiparty Indirect Proactive Inform*

Next we formally derive a desired agent behavior regarding multiparty proactive communication. The first two theorems show the mental states of the overhearers, whereas the last theorem shows how the mental state of an overhearer can lead the overhearer to helping other teammates.

Theorem 4.2. Successful performance of the *MP-IndProInform* act with respect to I, N, and K establishes a mutual belief between the speaker, the addressee, and the overhearers that the speaker believes (1) N is the information need of the addressee, (2) K is the inference knowledge regarding N, and (3) I is the indirect information need of the addressee regarding N. Formally

$\mathit{Done}(A, \mathit{MP\text{-}IndProInform}(A, B, \{O_1, \ldots, O_n\}, \epsilon, I, IN, K, N, t, t_\alpha, t', C_n), t, \Theta) \Rightarrow$
$\mathit{MB}(\{A, B, O_1, \ldots, O_n\}, \psi, t_\alpha)$, where
$\psi = \mathit{Bel}(A, \phi, t)$, where
$\phi = \mathit{InfoNeed}(B, N, t', C_n) \ \wedge \ K = \mathit{hasKnow}(N) \ \wedge \ IN \in \mathit{Need}_{\vdash}(N, K) \ \wedge \ I = \mathit{info}(A, IN)$

Theorem 4.3. Successful performance of a *MP-IndProInform* with respect to I, N, and K followed by a successful *MP-SAccept-K* by the addressee establishes a mutual belief between the speaker, the addressee, and the overhearers that (1) N is the information need of the addressee, (2) K is the inference knowledge for N, and (3) I is an indirect information need regarding N. Formally,

$Done(A, MP\text{-}IndProInform(A, B, O_1, \ldots, O_n, \epsilon, I, IN, K, N, t_0, t_1, t', C_n), t_0, \Theta) \wedge$
$Done(B, MP\text{-}SAccept\text{-}K(B, A, O_1, \ldots, O_n, \epsilon, I, IN, K, N, t_2, t_3, t', C_n), t_2, \Theta) \Rightarrow$
$MB(\{A, B, O_1, \ldots, O_n\}, \eta, t_3)$, where
$\eta = Bel(A, \rho, t_3) \wedge Bel(B, \rho, t_3)$, where
$\rho = InfoNeed(B, N, t', C_n) \ \wedge \ K = hasKnow(N) \ \wedge \ IN \in Need_{\vdash}(N, K) \ \wedge \ I = info(A, IN)$

Similar theorems can be proved for other replies to *MP-IndProInform* and are omitted for lack of space.

Theorem 4.4. If after overhearing a *MP-IndProInform* followed by a *MP-SAccept-K* between agents D and B, an overhearer agent, A, believes IN is an indirect information need of agent B, A will consider helping B with *MP-IndProInform*. Formally,
$Bel(A, InfoNeed(B, N, t', C_n), t) \wedge Bel(A, \neg has.info(A, N)), t) \wedge$
$Bel(A, K = hasKnow(N), t) \wedge Bel(A, IN \in Need_{\vdash}(N, K), t) \wedge$
$Bel(A, I = info(A, IN), t) \ \wedge \ \neg Bel(A, Bel(B, I, t), t) \Rightarrow \exists t_1, t_2, C_p.$
$Pot.Int.To(A, MP\text{-}IndProInform(A, B, \{O_1, \ldots, O_n\}, \epsilon, I, IN, K, N, t_1, t_2, t', C_n), t, t_1, C_p)$

4.5. *A Proposed Conversation Policy*

Defining the semantics of performatives is desirable as it allows reasoning about beliefs, intentions, and capabilities of other agents. However, reliable reasoning about other agents is difficult. Conversation policies make it easier for the agents involved in a conversation to reason about each other.

Conversation policies can be specified via different representations. We use a Petri-Net representation [10] for specifying the conversation policy of *MP-IndProInform*. A Petri-Net is a graphical language for modeling distributed system. It is composed of place nodes, transition nodes, and arcs connecting places and transitions. Place nodes hold tokens. There are two types of place nodes: (1) input places, which have an arc to a transition, and (2) output places which have an arc from a transition. A transition that has tokens in all its input places can fire, by which tokens are moved from transition's input places to output places. The conversation policy for *MP-IndProInform* is given in Figure 3. Performatives are represented by transitions and are fired when the performative is executed.

Of all possible replies to *MP-IndProInform*, we consider only the three replies that result in helpful behavior from the overhearers (*MP-SAccept-K, MP-SAccept-K', MP-WReject-K'*). Other replies will just result in belief updates and thus are not included in the conversation policy. Next, we will briefly describe these three replies. *MP-SAccept-K* means the addressee of the initial *MP-IndProInform* believes in the information need, the inference knowledge regarding the information need, and the indirect information need. *MP-SAccept-K'* is similar to MP-SAccept-K; the only difference is that the addressee of the initial *MP-IndProInform* believes in a different inference knowledge regarding the information need, namely K'. *MP-WReject-K'* means that the addressee of the initial *MP-IndProInform* believes in the information need, but does not believe in the indirect information need com-

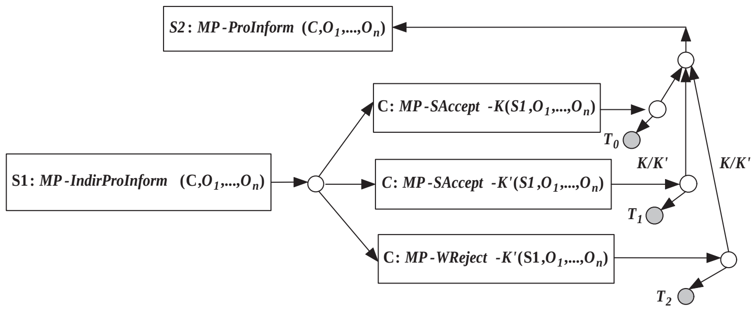

Fig. 3. Petri-Net representation of a conversation policy for *MP-IndProInform*. *MP-IndProInform* is followed by one of the 3 replies shown, after which an overhearer may provide assistance or a terminal state is reached (T_0 to T_2).

municated. Furthermore, the addressee of the initial *MP-IndProInform* believes in a different inference knowledge, K'.

We explain the conversation policy of Figure 3 using the example discussed in Figure 2. Initially, agent S_1, using a *MP-IndProInform*, proactively informs C about $threatHigh$ (C's information need), K (inference knowledge regarding $threatHigh$), and $isEnemy$ (C's indirect information need). Agent C can then reply in three ways:

(1) Agent C accepts all the information communicated and replies with (*MP-SAccept-K*). Agent S_2 (which initially believes in $attackPattern$), overhears the messages and realizes from K (the inference knowledge) that $attackPattern$ is an indirect information need for C. If S_2 is being helpful, it will proactively inform C about $attackPattern$ via a *MP-IndProInform*. Otherwise, it will do nothing (terminal state T_0).
(2) Agent C accepts $threatHigh$ (as its information need) and $isEnemy$, but it believes in K', a different inference knowledge regarding $threatHigh$. In this case, S_2 learns about C's beliefs (e.g. K') by overhearing the reply. S_2 can infer the indirect information need of C using K' and proactively inform C about the indirect information via a *MP-IndProInform*. Alternatively, if S_2 is not helpful it will do nothing (terminal state T_1).
(3) Agent C accepts $threatHigh$ (as its information need), rejects $isEnemy$, and believes in K', a different inference knowledge for $threatHigh$. In this case, S_2 learns about C's beliefs (e.g. K' and $isEnemy$ being rejected) by overhearing the reply. Similarly, S_2 can infer the indirect information need of C using K' and proactively inform C about the indirect information via a *MP-IndProInform*. Alternatively, if S_2 is not helpful it will do nothing (terminal state T_2).

We have assumed that the overhearers by default will accept the overheard messages implicitly and will not reply to the communicated messages. The conversation policy can be extended to accommodate the cases where the overhearer does *not* accept the overheard messages and replies to the communicated message.

5. Multiparty Proactive Subscription Performatives

In this section, we first define a multiparty third-party subscribe(*MP-3PTSubscribe*) performative, which extends the third-party subscribe(*3PTSubscribe*) performative [8] to multiparty settings. We then prove some properties of *MP-3PTSubscribe* and formally derive desirable helpful behaviors for the overhearers. Finally, we propose a conversation policy for *MP-3PTSubscribe*.

5.1. *Multiparty Third-party Subscribe*

Suppose an agent anticipates the information need of a teammate and attempts to subscribe the information need to a potential provider. Many times no single provider can fully satisfy the teammate's information need, whereas a group of providers can collectively satisfy the need. Performing the subscription act as a multiparty dialogue helps the providers to collectively satisfy the teammate's information need. We will next discuss an example.

Example problem 2: Suppose C, S_1, S_2, and S_3 are four agents in a team. The information need of C (a commander) is *ThreatHigh*. Agent S_1 (a scout) knows that C needs *ThreatHigh* and C does not know *ThreatHigh*. Furthermore, since S_1 itself does not know *ThreatHigh*, it intends to subscribe C's information need to either of two potential providers for *ThreatHigh*, namely S_2 or S_3 (two other scouts). Neither S_2 nor S_3 know *ThreatHigh*; however, S_2 knows that *ThreatHigh* can be derived from *IsEnemy* and *IsClose* (i.e., $IsEnemy \wedge IsClose \Rightarrow ThreatHigh$); no other agent has this inference knowledge. Furthermore, S_2 knows *IsEnemy* and S_3 knows *IsClose*; S_2 (or S_3) know that no other agent knows of *IsEnemy* (or *IsClose*).

There are several difficulties in the example discussed: (1) Neither C nor S_2 or S_3 are aware of C's information need, (2) even if S_2 provides C with *IsEnemy*, C does not have the inference knowledge to infer *ThreatHigh* from *IsEnemy*, (3) even though S_3 knows *IsClose*, which can be used to infer *ThreatHigh*, S_3 does not have the knowledge to relate *IsClose* to C's needs.

The proposed solution is illustrated in Figure 4.

- First, agent S_1 proactively subscribes C's information need (i.e. *threatHigh*) to S_2 (We assume it selects S_2 – and not S_1 – due to past experiences).
- Second, S_2 informs S_1 that it accepts C's information need, believes in an inference knowledge regarding C's need (i.e. $IsEnemy \wedge IsClose \Rightarrow ThreatHigh$), and is committed to proactively providing *IsEnemy* to C.
- Third, By overhearing the conversation between S_1 and S_2, agent S_3 learns about C's information need (i.e. *ThreatHigh*), the inference knowledge regarding *ThreatHigh*, and S_2's commitment to providing C with *IsEnemy*. Using the inference knowledge, S_3 can infer the indirect information needs of C. Since S_3 knows *IsClose*, S_3 informs S_1 that it is *committed* to proactively providing *IsClose* to C.

When S_2 (or S_3) informs C about *IsEnemy* (or *IsClose*), it must also provide

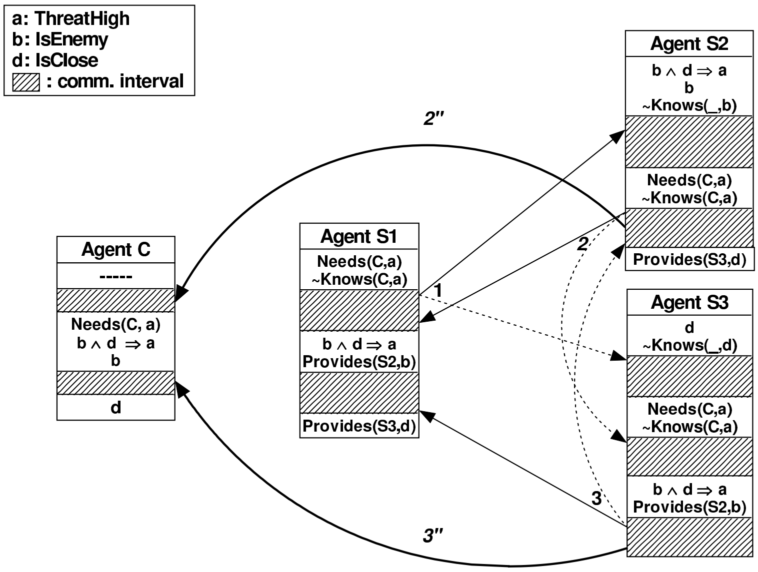

Fig. 4. Multiparty proactive subscription. Upper left box is legend

C with the inference knowledge regarding *ThreatHigh*, so that C can synthesize *ThreatHigh* from the relevant information. Therefore, S_2 (or S_3) uses *IndProInform* – which is the two-party version of *MP-IndProInform* – to inform C (messages 2" and 3"). Since the recipient is known, two-party communication is used lower communication and information processing cost.

To capture the semantics of such situations we formally define a new performative, multiparty proactive third-party subscribe (*MP-3PTSubscribe*). *MP-3PTSusbcribe* is an extension of third-party subscribe *3PTSusbcribe* to multiparty settings. Unlike *3PTSusbcribe*, in *MP-3PTSusbcribe* the *overhearers* will also know about the speaker's intention. Moreover, unlike *MP-IndProInform* (or *MP-ProInform*), in *MP-3PTSusbcribe* a middle agent anticipates the information need of a teammate; the middle agent then subscribes the information need to a provider. In *MP-IndProInform* (or *MP-ProInform*), the provider and the anticipator are the same.

MP-3PTSusbcribe is defined as an attempt by the speaker to establish a mutual belief with the addressee and the *overhearers* about the speaker's intention that (1) the addressee believe that the speaker knows the teammate's information need, and (2) whenever the addressee acquires new information related to the information need, the addressee intend to send the information to the teammate. Formally,

Definition 6 *MP-3PTSubscribe*$(A, B, D, \{O_1, \ldots, O_n\}, \epsilon, I, N, t_1, t_2, t_3, C_n) \equiv$
$(t_1 < t_2 < t_3)$?;*Attempt*$(A, \epsilon, p_1, p_2, t_1, t_2)$, where
$p_1 =$*Bel*$(B,$*info*$_{t_3}(D, N), t_3)$, and

$p_2 = \exists t''.(t_1 \leq t'' < t_2) \wedge MB(\{A, D, O_1, \ldots, O_n\}, Q, t'')$, where
$Q = \exists C_p, t_b.(t'' \leq t_b < t_2) \wedge \mathit{Int.Th}(A, \psi \wedge \phi, t_1, t_b, C_p)$, and
$\psi = \mathit{Bel}(D, \mathit{Bel}(A, \mathit{InfoNeed}(B, N, t_3, C_n), t_1), t_b)$, and
$\phi = \mathit{Int.Th}(D, [\forall t' \leq t_3[\mathit{BChange}(D, N, t') \wedge \mathit{Bel}(D, I = \mathit{info}_{t'}(D, N), t') \Rightarrow$
$\exists t_a, t_c.\mathit{Int.To}(D, \mathit{IndProInform}(D, B, \epsilon', I, N, t_a, t_c, t_3, C_n), t', t_a, C_n)], t_b, t_b, C_n)$.

The addressee can reply in four different ways:

(1) Accept the information need of the teammate and commit to provide the information to the teammate whenever necessary (*multiparty strong accept subscription* or *MP-SAcceptSub*).
(2) Accept the information need and *not* commit to provide the information (*multiparty weak accept subscription* or *MP-WAcceptSub*).
(3) Reject the information need and *not* commit to provide the information (*multiparty strong reject subscription* or *MP-SRejectSub*).
(4) Accept the information need of the teammate and commit to provide the indirect information need to the teammate whenever necessary (*multiparty indirect strong accept subscription* or *MP-IndirSAcceptSub*).

The replies are defined as a *MP-Inform*; thus they can be overheard by the overhearers.

Following the communication between the speaker and the addressee (*MP-3PTSubscribe* followed by addressee's reply), all the team members can update their beliefs regarding the speaker and addressee's beliefs about the information need of their teammate and the addressee's commitment to providing help to the teammate.

If the addressee's reply is any of the first three replies in the list above, the overhearer can do one of the following:

(1) implicitly accept teammate's information need by not responding
(2) reject the teammate's information need via a *MP-Inform*

If the addressee's reply is *MP-IndirSAcceptSub* (the fourth reply in the list above), the overhearer can do one of the following:

(1) implicitly accept teammate's information need and the inference knowledge regarding the information need by not responding
(2) reject any combination of teammate's information need and the inference knowledge regarding the information need by responding via a *MP-Inform*

5.2. *Properties of Multiparty Third-party Subscribe*

Next we formally derive a desired agent behavior regarding multiparty third-party subscribe performative. The first two theorems show the mental states of the overhearers; the third theorem shows how the mental state of an overhearer can lead the overhearer to helping other teammates.

Theorem 5.1. Successful performance of the *MP-3PTSubscribe* act establishes a mutual belief between the speaker, the addressee, and the overhearers that the sender believes the delivered information-need. Formally,
$Done(A, MP\text{-}3PTSubscribe(A, B, D, \{O_1, \ldots, O_n\}, \epsilon, I, N, t_1, t_2, t_3, C_n), t, \Theta) \Rightarrow$
$MB(\{A, B, D, O_1, \ldots, O_n\}, \psi, t_2)$, where
$\psi = Bel(A, InfoNeed(B, N, t_3, C_n), t_1)$

Theorem 5.2. Successful performance of a *MP-3PTSubscribe* with respect to B and N, followed by a successful *MP-IndirSAcceptSub* by the addressee of *MP-3PTSubscribe* establishes a mutual belief between the speaker, the addressee, and the overhearers that (1) the speaker and the addressee believe B will need N, and (2) the addressee adopts a commitment to helping B. Formally, for $(t_0 < t_1 < t_2 < t_3 < t')$,
$Done(A, MP\text{-}3PTSubscribe(A, B, D, \{O_1, \ldots, O_n\}, \epsilon, I, N, t_0, t_1, t', C_n), t_0, \Theta) \wedge$
$Done(D, MP\text{-}IndirSAcceptSub(D, A, \{O_1, \ldots, O_n, A\}, \epsilon', I, N, t_2, t_3, t', C_n), t_2, \Theta') \Rightarrow$
$MB(\{A, B, O_1, \ldots, O_n\}, p_1 \wedge p_2 \wedge p_3, t_3)$, where
$p_1 = Bel(A, InfoNeed(B, N, t', C_n), t_1)$, and
$p_2 = Bel(D, \varpi, t_2)$, where
$\varpi = InfoNeed(B, N, t', C_n) \wedge \mathrm{K} = hasKnow(N) \wedge IN \in Need_{\vdash}(N, K) \wedge \mathrm{I} = info(D, IN), t_b)$
$p_3 = \forall t_3 \leq t < t'.BChange(D, IN, t) \Rightarrow \exists t_a, t_c, C_p.$
$Int.To(D, IndProInform(D, B, \epsilon'', I, IN, K, N, t_a, t_c, t', C_n), t, t_a, C_p)$

Theorem 5.3. If after overhearing a *MP-3PTSubscribe* followed by a *MP-IndirSAcceptSub* between agents E and D about B's information need, an overhearer agent, A, believes IN is an indirect information need of agent B, A will consider helping B. Formally,
$Bel(A, InfoNeed(B, N, t', C_n), t) \wedge Bel(A, \neg\ has.info(A, N)), t) \wedge$
$Bel(A, K = hasKnow(N), t) \wedge Bel(A, IN \in Need_{\vdash}(N, K), t) \wedge$
$Bel(A, I = info(A, IN), t) \wedge \neg Bel(A, Bel(B, I, t), t) \Rightarrow$
$\exists t_1, t_2, C_p.Pot.Int.To(A, Q, t, t_1, C_p)$, where
$Q = \forall t_1 \leq t'' < t'.BChange(A, IN, t'') \Rightarrow$
$\exists t_d, t_e.Int.To(A, IndProInform(A, B, \epsilon, I, IN, K, N, t_d, t_e, t', C_n), t'', t_d, C_p)$

5.3. *A Proposed Conversation Policy*

We use a Petri-Net representation to specify the conversation policy for *MP-3PTSubscribe* (Figure 5). We will next explain the conversation policy using the example discussed in Figure 4. Initially, agent S_1, using a *MP-3PTSubscribe*, attempts to subscribe information need of C (i.e. *ThreatHigh*) to S_2. Agent S_2 can reply in 4 different ways:

(1) Agent S_2 accepts the information need and commits to helping C with *ThreatHigh* (*MP-SAcceptSub*). This results in the desired terminal state, T_1.
(2) Agent S_2 accepts the information need, but does not commit to helping C (*MP-WAcceptSub*). This results in terminal state T_2 and can happen when more

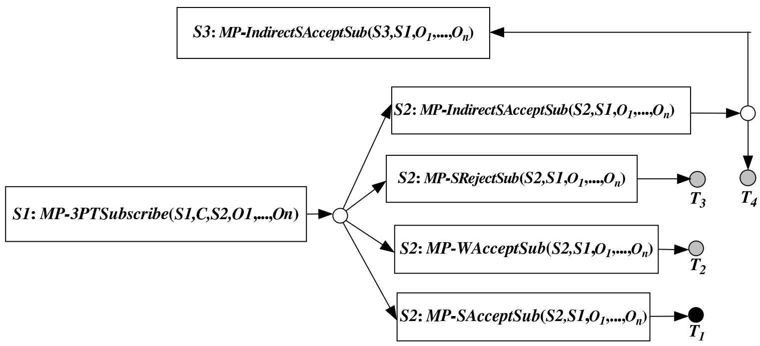

Fig. 5. Petri-Net representation of a proposed conversation policy for *MP-3PTSubscribe*. *MP-3PTSubscribe* is followed by one of the 4 replies shown, after which an overhearer may provide assistance or a terminal state is reached (T_1 to T_4).

urgent things prevent S_2 from making a commitment. In this case, the protocol may be extended such that S_1 will persuade S_2 to make a commitment to C's information need.

(3) Agent S_2 rejects the information need and makes no commitment to helping C (*MP-SRejectSub*) – terminal state T_3.

(4) Agent S_2 does not know *ThreatHigh*, but it has the inference knowledge regarding *ThreatHigh* and can infer the indirect information needs of C (i.e. *IsEnemy* and *IsClose*). Since S_2 knows *IsEnemy*, it informs S_1 that it is committed to helping C with *IsEnemy*. Agent S_3 overhears messages 1 and 2 and learns about the information need of C (i.e. *ThreatHigh*), the inference knowledge regarding *ThreatHigh*, and S_2's commitment to helping C with *IsEnemy*. Having the inference knowledge regarding *ThreatHigh*, S_3 can now infer the indirect information needs of C (i.e. *IsEnemy* and *IsClose*). Since S_3 knows *IsClose*, if it is being helpful, it informs S_1 that it is committed to helping C with *IsClose*. Otherwise, it will do nothing (terminal state T_4).

We have assumed that the overhearers by default will accept the overheard messages implicitly and will not reply to the communicated messages. The conversation policy can be extended to accommodate the cases where the overhearer does *not* accept the overheard messages and replies to the communicated message.

6. Discussion and Related Work

In this section, we briefly discuss the research on multiparty dialogues and overhearing and compare/contrast them with our research.

Agent communication languages, like KQML [22] and FIPA [9], mostly focus on two-party dialogues. Dignum and Vreeswijk discuss the issues that arise when moving from two-party to multiparty dialogues and propose a testbed for multiparty dialogues based on the idea of blackboard systems [6]. Traum further discusses the issues in multiparty dialogues [29]. Kumar *et. al.* consider two-party dialogues as a special case of multiparty dialogues and formally define a *Request* performative that handles both two-party and multiparty conversations [21].

To the best of our knowledge [21] provide the only work in the literature on defining the *semantics* of multiparty performatives. In this paper, we take a further step by providing the semantics of multiparty *proactive* performatives. Moreover, we define the semantics of multiparty proactive *inform*, which has not been defined in previous research. The *Request* performative defined in [21] has the property that the intended recipient may be unknown to the speaker. Our performatives are designed for a team of agents, in which all the recipients known.

Our research is different in that we focus on *proactive* communication [8], which can be complementary to passive communication. Proactive information delivery means providing relevant information to a teammate based on the anticipated needs of the teammate. Such anticipation can be derived from a shared mental model about the team structure and the teamwork process [33]. In general, proactive information delivery can alleviate several limitations of passive communications [8]. For instance, an agent may not know its information need due to its limited knowledge. Proactive information delivery allows teammates to help the information consumer in such situations. Also, the information consumer may not realize the information it has is outdated. Verifying all the information before usage can result in overwhelming amount of communication. Proactive information delivery shifts the burden from the information consumer to the information provider, which has direct knowledge about updates to the information.

Kaminka *et. al.* use overhearing for plan recognition [19]. Gutnik and Kaminka model overhearing and propose algorithms for *conversation recognition* – identifying the conversations that took place within a system, given a set of overheard messages with possible message losses [14]. Novik and Ward employ cooperative overhearing to model interactions between pilots and air traffic controllers [23]. Busetta *et. al.* define an overhearing architecture in which an overhearer agent monitors the conversation between some service agents [2]. Suggester agents subscribe to the overhearer and are informed by the overhearer when certain information is being communicated between the service agents. The suggester agents can then give appropriate information (or service) to the service agents without being explicitly asked. Aiello *et. al.*, further propose an interaction language between the overhearer and the suggester [1]. Rossi *et. al.* attempt to formalize the process of monitoring group conversations and recognizing the social roles via overhearing [26,?]. In [27], they use overhearing for distributive and collective readings in group protocols.

Our research leverages overhearing in providing a specific helpful behavior, namely proactive information delivery in a multiparty setting. Moreover, unlike other approaches our research focuses on the mental states of the participants in a conversation, which can enable the participants in a conversation to infer the information needs of their teammates and provide help.

7. Summary

In this paper, we provide formal semantics for multiparty proactive performatives within a team setting. We then examined the effect of these performatives on the mental model update of teammates, and how these updates can trigger helpful behaviors from other teammates. First, we formally defined the semantics of a multiparty inform performative (*MP-Inform*) that can increase awareness about teammates' mental states via other teammates *overhearing* the conversations. Second, We formally defined the semantics of two multiparty proactive performatives (*MP-ProInform* and *MP-IndProInform*) that deal with situations which the provider agent has *full* or *partial* knowledge regarding the teammate's information need. Third, we defined a multiparty proactive subscription performative, where an agent can subscribe the information need of a teammate to an information provider. Based on these definitions we formally derived desirable helpful behaviors for the overhearers. Furthermore, we provided conversation policies involving multiparty proactive performatives. The conversation policies can be extended to accommodate the cases where the overhearers do not accept the messages communicated between the speaker and the addressee.

Multiparty proactive communication enables a team of agents to share not only relevant information but also relevant knowledge, resulting in a better situation awareness and triggering additional helpful behaviors. The work in this paper not only can serve as a formal specification for designing agent teams that support proactive information exchange, but also can offer opportunities for extending existing agent communication protocols to support multiparty proactive information delivery. Moreover, the work is also useful in other areas such as mobile peer to peer systems (e.g. in distributed query processing) or for achieving multiparty agreement in multiagent systems [30]. Multiparty communication entails some communication cost and information processing cost for the overhearers. For future work, we plan to empirically evaluate the cost vs. benefits of multiparty communication.

Appendix A. Proof of the Theorems

Theorem 4.1.
Successful performance of *MP-Inform* means the honest effort of *MP-Inform* must have been achieved. Therefore, at $t_1 < t_a$ agents $A, B, O_1, \ldots, O_n$ establish the mutual belief that,
(1) $MB(\{A, B, O_1, \ldots, O_n\}, \psi, t_1)$, where $\psi = \exists t_b.(t_1 \leq t_b < t_\alpha) \wedge$
$Int.Th(A, Bel(B, Bel(A, p, t), t_b), t, t_b, C_n)$

A is assumed to be sincere. Therefore, if A intends others believe that it believes in p, A itself must believe in p. Hence,
(2) $Int.Th(A, Bel(B, Bel(A, p, t), t_b), t, t_b, C_n) \Rightarrow Bel(A, p, t)$

From (1), (2) and assuming agents have perfect recall of what was believed, we have:
(3) $MB(\{A, B, O_1, \ldots, On\}, Bel(A, p, t), t_a)$ □

Theorem 4.2.
Successful performance of *MP-IndProInform* results in the honest effort of *MP-IndProInform* being achieved. Thus, at $t_1 < t_a$ agents $A, B, O_1, \ldots, O_n$ establish the mutual belief that,
(1) $MB(\{A, B, O_1, \ldots, O_n\}, \psi, t_1)$, where
$\psi = \exists t_b, C_n.(t_1 \leq t_b < t_\alpha) \wedge Int.Th(A, Bel(B, Bel(A, \phi, t), t_b), t, t_b, C_n)$, where
$\phi = InfoNeed(B, N, t', C_n), t) \wedge K = hasKnow(N) \wedge IN \in Need_{\vdash}(N, K) \wedge$
$I = info(A, IN)$

A is assumed to be sincere. Therefore, if A intends others believe that it believes in ϕ, A itself must believe in ϕ. Hence,
(2) $Int.Th(A, Bel(B, Bel(A, \phi, t), t_b), t, t_b, C_n) \Rightarrow Bel(A, \phi, t)$

Therefore, from (1) and (2), and assuming agents have perfect recall of what was believed, we have:
(3) $MB(\{A, B, O_1, \ldots, O_n\}, Bel(A, \phi, t), t_a)$ □

Theorem 4.3.
By successful performance of *MP-IndProInform* and Theorem 4.2, we get:
(1) $MB(\{A, B, O_1, \ldots, O_n\}, \psi, t_1)$, where
$\psi = Bel(A, InfoNeed(B, N, t', C_n), t_0) \wedge Bel(A, K = hasKnow(N), t_0) \wedge$
$Bel(A, IN \in Need_{\vdash}(N, K)), t_0) \wedge Bel(A, I = info(A, IN), t_0)$

Successful performance of *MP-SAccept-K* results in the honest effort of *MP-SAccept-K* being achieved. Thus, at $t'' < t_3$ agents $A, B, D, O_1, \ldots, O_n$ establish the mutual belief that,
(2) $MB(\{B, A, O_1, \ldots, O_n\}, \phi, t'')$, where
$\phi = Bel(B, InfoNeed(B, N, t', C_n), t_2) \wedge Bel(B, K = hasKnow(N), t_2) \wedge$
$Bel(B, IN \in Need_{\vdash}(N, K), t_2) \wedge Bel(B, I = info(A, IN), t_2)$

A's commitment in *MP-IndProInform* and B's commitment in *MP-SAccept-K* prevent them from changing beliefs about $InfoNeed(B, N, t', C_n), K = hasKnow(N), IN \in Need_{\vdash}(N, K)$, and $I = info(A, IN)$ before t_3. Assuming agents have perfect recall of what was believed, we can conclude:
$MB(\{A, B, O_1, \ldots, O_n\}, \eta, t_3)$, where
$\eta = Bel(A, \rho, t_3) \wedge Bel(B, \rho, t_3)$, where
$\rho = InfoNeed(B, N, t', C_n) \wedge K = hasKnow(N) \wedge IN \in Need_{\vdash}(N, K) \wedge$
$I = info(A, Need_{\vdash}(N, K))$ □

Theorem 4.4.
After overhearing a *MP-IndProInform* followed by a *MP-SAccept-K* between agents D and B, agent A has the following beliefs:
(1) $Bel(A, InfoNeed(B, N, t', C_n), t)$,
(2) $Bel(A, K = hasKnow(N), t)$,

Assuming agent A has the following beliefs
(3) $Bel(A, \neg has.info(A, N)), t)$,
(4) $Bel(A, IN \in Need_{\vdash}(N, K), t)$,
(5) $Bel(A, I = info(A, IN), t)$,
(6) $\neg Bel(A, Bel(B, I, t), t)$

Since $I = info(A, IN)$ holds, it follows that $has.info(A, IN)$. By Axiom 2 and $Bel(A, InfoNeed(B, N, t', C_n), t)$ we have:
(7) $Pot.Int.Th(A, Bel(B, I, t'), t, t', C_n), t, t', C_p)$

Assuming agent A is willing to help and there is no conflict with other adopted intentions, this potential intention can reduce to:
(8) $Int.Th(A, Bel(B, I, t'), t, t', C_n), t, t', C_p)$

Agents are assumed to have the capabilities to perform communicative actions. Also, from Theorem 4.3 we know that A's *MP-IndProInform* followed by B's *MP-SAccept-K* can make $Bel(B, I, t')$ true. Thus there exists t_1 and t_2 such that
(9) $Lead(A, MP\text{-}IndProInform(A, B, \{O_1, \ldots, O_n\}, \epsilon, I, IN, K, N, t_1, t_2, t', C_n), Bel(B, I, t'), t, t_1, \Theta)$

From the assumption $\neg Bel(A, Bel(B, I, t), t)$, (8), (9) and Axiom 1, we can derive:
$Pot.Int.To(A, MP\text{-}IndProInform(A, B, \{O_1, \ldots, O_n\}, \epsilon, I, IN, K, N, t_1, t_2, t', C_n), t, t_1, C_p)$ □

Theorem 5.1.
Successful performance of *MP-3PTSubscribe* results in the honest effort of *MP-3PTSubscribe* being achieved. Thus, at $t'' < t_2$ agents $A, B, D, O_1, \ldots, O_n$ establish the mutual belief that,
(1) $MB(\{A, B, D, O_1, \ldots, O_n\}, Q, t'')$, where
$Q = \exists C_p, t_b.(t'' \leq t_b < t_2) \wedge Int.Th(A, \psi \wedge \phi, t_1, t_b, C_p)$, and
$\psi = Bel(D, Bel(A, InfoNeed(B, N, t_3, C_n), t_1), t_b)$, and
$\phi = Int.Th(D, \Omega, t_b, t_b, C_p)$, and
$\Omega = [\forall t_b \leq t' \leq t_3, I.[BChange(D, N, t') \wedge Bel(D, I = info_{t'}(D, N), t') \Rightarrow \exists t_a, t_c.Int.To(D, IndProInform(D, B, \epsilon', I, N, t_a, t_c, t_3, C_n), t', t_a, C_p)]$

Based on the possible world semantics of *Int.Th* and *MB*, we have
(2) $MB(\{A, B, D, O_1, \ldots, O_n\}, Q', t'')$, where

$Q' = \exists C_p, t_b.(t'' \leq t_b < t_2) \wedge Int.Th(A, \psi, t_1, t_b, C_p)$, and
$\psi = Bel(D, Bel(A, InfoNeed(B, N, t_3, C_n), t_1), t_b)$

A is assumed to be sincere. Therefore, if A intends others believe that it believes in $InfoNeed(B, N, t_3, C_n)$, A itself must believe in $InfoNeed(B, N, t_3, C_n)$. Hence,
(3) $MB(\{A, B, D, O_1, \ldots, O_n\}, Q'', t'')$, where
$Q'' = Bel(A, InfoNeed(B, N, t_3, C_n), t_1)$

Since A's commitment in *MP-3PTSubscribe* prevent it from changing beliefs about $InfoNeed(B, N, t_3, C_n)$, and assuming agents have perfect recall of what was believed, we have:
(4) $MB(\{A, B, D, O_1, \ldots, O_n\}, Q''', t_2)$, where
$Q''' = Bel(A, InfoNeed(B, N, t_3, C_n), t_2)$ □

Theorem 5.2.
By applying theorem 5.1, we get:
(1) $MB(\{A, B, D, O_1, \ldots, O_n\}, Q, t_1)$, where
$Q = Bel(A, InfoNeed(B, N, t', C_n), t_0)$

Successful performance of *MP-IndirSAcceptSub* results in the honest effort of *MP-SAcceptSub* being achieved. Thus, at $t'' < t_3$ agents $A, B, D, O_1, \ldots, O_n$ establish the mutual belief that,
(2) $MB(\{A, B, D, O_1, \ldots, O_n\}, Q', t'')$, where
$Q' = \exists t_b, C_p.(t'' \leq t_b < t_3) \wedge Bel(D, \varpi, t_b) \wedge Int.Th(D, \Omega, t_b, t_b, C_p)$, where
$\varpi = InfoNeed(B, N, t', C_n) \wedge \mathrm{K}{=}hasKnow(N) \wedge IN{\in}Need_{\vdash}(N, K) \wedge \mathrm{I}{=}info(D, IN), t_b)$, and
$\Omega = [\forall t_b < t''' \leq t_3.[BChange(D, N, t''') \wedge Bel(D, I = info_{t'''}(D, N), t''') \Rightarrow$
$\exists t_a, t_c.Int.To(D, IndProInform(D, B, \epsilon', I, N, t_a, t_c, t', C_n), t''', t_a, C_p)]$

Since A's commitment in *MP-3PTSubscribe* and D's commitment in *MP-IndirSAcceptSub* prevent them from changing beliefs, and assuming agents have perfect recall of what was believed, from (2), (3) and the properties of *Bel* we can conclude that
$MB(\{A, B, O_1, \ldots, O_n\}, p_1 \wedge p_2 \wedge p_3, t_3)$, where
$p_1 = Bel(D, \varpi, t_3)$, and
$p_2 = Bel(A, InfoNeed(B, N, t', C_n), t_1)$, and
$p_3 = \forall t_3 \leq t < t'.BChange(D, IN, t) \Rightarrow \exists t_a, t_c.$
$Int.To(D, MP\text{-}$
$IndProInform(D, B, O_1, \ldots, O_n, \epsilon'', I, IN, K, N, t_a, t_c, t', C_n), t, t_a, C_p)$ □

Theorem 5.3.
After overhearing a *MP-3PTSubscribe* followed by a *MP-IndirSAcceptSub* between agents E and D, agent A has the following beliefs:
(1) $Bel(A, InfoNeed(B, N, t', C_n), t)$, and

(2) $\mathit{Bel}(D, \varpi, t)$, where
$\varpi = \mathit{InfoNeed}(B, N, t', C_n) \wedge \mathrm{K}{=}\mathit{hasKnow}(N) \ \wedge \ IN' \in \mathit{Need}_{\vdash}(N, K) \wedge$
$\mathrm{I}{=}\mathit{info}(D, IN'), t_b)$

Assuming agent A has the following beliefs
(3) $\mathit{Bel}(A, \neg \mathit{has.info}(A, N)), t)$,
(4) $\mathit{Bel}(A, IN \in \mathit{Need}_{\vdash}(N, K), t)$,
(5) $\mathit{Bel}(A, I = \mathit{info}(A, IN), t)$,
(6) $\neg \mathit{Bel}(A, \mathit{Bel}(B, I, t), t)$

Since $I = \mathit{info}(A, IN)$ holds, it follows that $\mathit{has.info}(A, IN)$. By Axiom 2 and $\mathit{Bel}(A, \mathit{InfoNeed}(B, N, t', C_n), t)$ we have:
(7) $\mathit{Pot.Int.Th}(A, \mathit{Bel}(B, I, t'), t, t', C_n), t, t', C_p)$

Assuming agent A is willing to help and there is no conflict with other adopted intentions, this potential intention can reduce to:
(8) $\mathit{Int.Th}(A, \mathit{Bel}(B, I, t'), t, t', C_n), t, t', C_p)$

Agents are assumed to have the capabilities to perform communicative actions. Also, from Theorem 5.2 we know that E's *MP-3PTSubscribe* followed by A's *MP-IndirSAcceptSub* can make $\mathit{Bel}(B, I, t')$ true. Since *MP-3PTSubscribe* has already been performed (the overheard *MP-3PTSubscribe*), a *MP-IndirSAcceptSub* by A can make $\mathit{Bel}(B, I, t')$. Thus there exists t_1 and t_2 such that

(9) $\mathit{Lead}(A, \mathit{MP\text{-}IndirSAcceptSub}(A, E, O_1, \ldots, O_n, A, \epsilon, I, N, t_1, t_2, t', C_n)$
$\mathit{Bel}(B, I, t'), t, t_1, \Theta)$

From the assumption $\neg \mathit{Bel}(A, \mathit{Bel}(B, I, t), t)$, (8), (9) and Axiom 1, we can derive:
(10)
$\mathit{Pot.Int.To}(A, \mathit{MP\text{-}IndirSAcceptSub}(A, E, O_1, \ldots, O_n, A, \epsilon, I, N, t_1, t_2, t', C_n), t, t_1, C_p)$

From (10) and the definition of *MP-IndirSAcceptSub* we get:
(11) $\mathit{Pot.Int.To}(A, Q, t, t_1, C_p)$, where
$Q = \forall t_1 \leq t'' < t'.\mathit{BChange}(A, IN, t'') \Rightarrow$
$\exists t_d, t_e.\mathit{Int.To}(A, \mathit{IndProInform}(A, B, \epsilon, I_1, IN, K, N, t_d, t_e, t', C_n), t'', t_d, C_p)$ □

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