EFFICIENT PROPAGATION OF UNCERTAIN INFORMATION
(A RUMOR-BASED APPROACH)

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Abstract

This paper discusses the problem of efficient propagation of uncertain information. When a number of (distributed) agents have only partial access to information, the explanation(s) and conclusion(s) they can draw from their observations are inevitably uncertain. In this context, the efficient propagation of information is concerned with two interrelated aspects: spreading the information as quickly as possible, and refining the hypothesis at the same time. Using the metaphor of rumour-based communication, we describe a formal framework designed to investigate this class of problem, and we report on preliminary experiments using the described theory.

1 Introduction

Consider the following situation: witness of a threatening and unexpected event, say a fire in a building, Jeanne has to act promptly to both escape the danger and warn other people who might get caught in the same situation. However, there are no official signs or alarms indicating where the fire actually started: Jeanne may build some hypothesis, but the conclusions she may reach would be uncertain. In addition, there is no way for Jeanne to trigger an alarm. In other words, Jeanne will try to both circulate the information in order to spread the information to colleagues, and refine the hypothesis at the same time. Typically, Jeanne faces two questions:

- What information should I transmit?
- To whom should I transmit this information?

Clearly, these two questions are interrelated. Depending on the person Jeanne selected to communicates with, she may decide to transmit different messages: the objectives being to ensure that the transmitted information can be used efficiently in the next transmission. This defines, we believe, a problem of efficient propagation of uncertain information. The purpose of this paper is to put forward a formal framework expliciting both the reasoning and communicational aspects involved in these situations. We report on preliminary experiments using the described theory.

The remainder of this paper is as follows. Section 2 offers a background overview of rumor process. While it is usually taken for granted that rumor is essentially a phenomenon that should be avoided if possible, a closer inspection of the literature in this field revealed a more positive interpretation. This proved to be an important inspiration for us. Section 3 presents the formal machinery that we shall use in the framework, focusing on reasoning and communication mechanisms. Section 4 describes our case study example, instantiating the proposed framework. The situation involves a number of agents trying to escape from a burning building. We give the detail of a simple example, showing how critical, in this crisis context, can be the decisions taken by agents as to whether/what communicate. Section 5 draw connections to related works, and Section 6 concludes.
2 Background: Rumouring Processes

Rumor is a complex phenomenon that has been the object of numerous studies in social science but is often seen as something that can only bring lies or defamation. Studies of rumor in social science show, however, that there is more to rumor than just a routing or perception sharing system. Whereas the first studies, done during and after the World War II, seem to consider rumor as something dangerous which should be avoided, more recent stances are somewhat more neutral or positive about it.

During war, rumors could lead to moral loss or information leak. As such, it was something to be fought. The definition of rumor given by [2] reflects this stance. According to them rumor is “a proposition linked to the day’s event, intended to be believed, transmitted from person to person, usually by gossip, without any serious data to ensure its exactitude.” The focus is set on the uncertainty or rumor, or more exactly, its absence of official approval (which of course explains the defiance against rumors during war times). But these definitions also show two other key aspects: rumor concerns recent events and is intended to be believed. J.N Kapferer [12] defines rumor as “the emergence and circulation in the social body of information that either are not yet publicly confirmed by official sources or are denied by them.” As an unofficial information, it must use alternative way to be distributed, individual communication (gossip) or tract distribution. He precisates that a rumor spread very quickly because it has value, and because this value decrease over time. Moreover the rightness of the content has no importance. A true rumor spread exactly like a false rumor. The exactitude of the content is not a criteria to define rumor.

However, one can choose to take a slightly different perspective on the rumouring process. Shibutani [17] defines rumor as improvised news resulting from a collective discussion process, usually originating from an important and ambiguous event. In his own words, rumour is “common use of the group individual resources to get a satisfying interpretation of an event”. In this case, the rumor is seen as being both an (i) information routing process and (ii) an interpretation and comment adding process. Crucially, the distortion of information that is often seen as characteristic of rumor is seen as an evolution of the content due to continual interpretation by the group.

Stating that any communication can be defined by six parameters: (1) its source, (2) its content, (3) its diffusion process, (4) the media of its diffusion, (5) the object of the communication and (6) the nature of its effects, J. N. Kapferer proposes another definition of rumor. Rumor can this way be defined by its source (unofficial), its diffusion process (chain diffusion) and its content (something new, or concerning a recent fact). If the media is only gossip, the rumor is considered to be a pure rumor.

- **The source** (1) must be specified by stating which agents can initiate a communication, and in what circumstances. For rumors, any agent should be able to initiate a communication (that is a way of translating the unofficial nature of rumor), but trigerring conditions may vary.
- **The content** (2) to be exchanged must then be defined. An important point is whether the agents will communicate informations, hypothesis or both. To stick with J.N.Kapferer’s definition of rumor, the content should be related to some recent change in the system.
- **The diffusion process** (3) should specify the general form of the exchanges, and the recipients of communication. Rumors should have a chain diffusion process, an agent transmitting the rumor to some others one which in turn transmit it to others. The choice of the recipients can be modelised by a connection graph limiting the possible communication and a recipient choice algorithm.
- **The media** of multi agent communication processes is usually the same, so it is more useful to specify the protocols (4). For rumors, a propagation protocol, defining the form of the interaction and the message formatting is to be designed. Our approach also propose to include a content enhancement and refinement protocol.
- **The object of the communication** (5) should be dependent of the application and not of the multi agent process, and the nature of the effects (6) of communication might belong to agent architecture design more than communication process. It could however be important to
specify how the agent will stock received informations, and the effects of communication on
the system as a whole (does the system gain more consistency, for example).

A crucial aspect of rumor, of course, on which most work are focused, is that it is an uncentralised
process. The information propagates without any official control. It is deeply linked with spatial
or communication constraint, and can be an efficient way to convey information in spite of these.
It is also to be expected that this process can be quite robust to agent error or disparition. For
our approach, the focus will be put on the protocols (information refinement protocols), and the
nature of the content (hypothesis).

3 Agents Reasoning and Communication

This section introduces the formal machinery involved in the agents reasoning and communication
processes. The described situation suggests agents able to deal with uncertain information (in an
inherently nonmonotonic way), to build hypothesis from observations they make, to draw conclusions
from a set of explanations, and to communicate with each other in order to exchange pieces of
information. We first focus on agents reasoning abilities, then describe how interaction takes place
between these agents.

3.1 Agent’s reasoning

Agents reasoning process builds on Poole’s framework [14], which allows to elegantly combine both
the explanation and the prediction processes, using a single axiomatization. Each agent is (slightly
simplified version) of an instance of a Theorist system, as described in [14]

$$\langle \mathcal{F}, C, H, O, \xi \rangle$$

where

- $\mathcal{F}$ a set of facts, taken as being true in the domain
- $H$ a set of formulae which act as possible hypotheses
- $C$ a set of closed formulae taken as constraints
- $O$ is a set of observations
- $\xi$ is the set of preferred explanations of the observations $O$

We first recall a number of basic definitions.

**Definition 3.1 (Scenario [14])** A scenario of $(\mathcal{F}, H)$ is a set $D \cup \mathcal{F}$ where $D$ is a set of ground
instances of elements of $H$ such that $D \cup \mathcal{F} \cup C$ is consistent.

In the following, we shall also refer to $D$ as the hypothesis associated to the scenario.

**Definition 3.2 (Explanation [14])** If $g$ is a closed formula, then an explanation of $g$ from $(\mathcal{F}, H)$
is a scenario of $(\mathcal{F}, H)$ that implies $g$.

Typically, different explanations will exist for a given formula. What should be the set of
preferred explanations? Clearly there can be many different ways to classify preferred explanations.
In [14], different comparators are introduced. In our framework, we shall use variants of two of
them:

1. **minimal explanation** prefer the explanations that make the fewest (in terms of set inclusion)
   assumptions. In other words, no strict subset of a minimal explanation should also be an
   explanation.

2. **least presumptive explanation** an explanation is less presumptive than another explanation if
   it makes fewer assumptions (in terms of what can be implied from this explanation together
   with the facts)
By extension, we also use the term *favored (or current) hypothesis* to refer to the hypothesis associated to the preferred explanation.

In our context, agents evolve in a dynamic environment, and we classically assume the following *system cycle*:

1. **Environment dynamics**: the environment evolves according to the defined rules of the system dynamics
2. **Perception step**: agents get perceptions from the environment. These perceptions are typically partial (e.g. the agent can only see a portion of the map), but we assume that they are *certain*, in the sense that the captors are assumed perfect.
3. **Reasoning step**: agents compare perception with predictions, seek explanations for (potential) difference(s), refine their hypothesis, draw new conclusions. More precisely, during this step, if the agent perception prove its hypothesis false, the agent computes the possible explanations for these new perception, given its previous perception. It makes use of Theorist for this task.
4. **Action step**: agents modify the environment by executing the action selected by the previous deliberation steps.

### 3.2 Agent’s Communication

In our system however, observations are not only made directly by agents (by perceiving the environment), but they can also result from communication between agents. The cycle is then augmented with an explicit communication step, which directly follows the reasoning step. During the Communication step, agents engage communication with other agents to warn of their observation and tune up their hypothesis. In a given round, a given agent can only communicate with one agent. If that agent is occupied talking to another agent, it must wait or choose a different agent to communicate with. We shall assume in the following that an argument supporting (resp. rebutting) an hypothesis takes the form of an observation implied (resp. not implied) by this hypothesis. Let us call the initiator of this communication \(a_1\), and the receiver \(a_2\). \(a_1\) sends it its favored hypothesis \(h_1\). \(a_2\) checks it according to its perception and hypothesis list. It may then give 4 possible answers:

- If \(h_1\) is also its current hypothesis, \(a_2\) will validate it, ending the communication.
- If \(h_1\) belongs to its possible hypothesis list, \(a_2\) will send its current hypothesis for checking by \(a_1\). The roles are inverted.
- If its perception invalidates \(h_1\), \(a_2\) answers with an argument against the hypothesis. On reception of this argument \(a_1\) will compute a new hypothesis using its hypothesis list and Theorist. Then \(a_1\) sends it again for confirmation.
- If \(h_1\) does not belong to its hypothesis list and is not invalidated by its perception, \(a_2\) will ask \(a_1\) to give it arguments proving \(h_1\). On reception on such argument, \(a_2\) will compute a new hypothesis and ask \(a_1\) to check it. The roles are inverted. If the hypothesis remains valid, the agent will just trim its hypothesis list of invalidated explanations.

### 4 A Case Study: Crisis Management

This section presents an instance of the general framework introduced earlier. We first describe the different parameters used to instantiate the framework. A complete example is then detailed.

#### 4.1 Description of the situation

This experiment involves agents trying to escape from a burning building. The environment is described as a spatial grid with a set of walls and (thankfully) some exits. Time and space are considered discrete. Time is divided in rounds.

Agents are localised by their position on the spatial grid. These agents can move and communicate with other agents. In a round, an agent can move of one case in any of the four cardinal
directions, provided it is not blocked by a wall. In this application, agents communicate with any other agent (but, recall, a single one) given that this agent is in view, and that it has not yet given it its current favored hypothesis. Note that this spatial constraint on agents’ communication could be relaxed in other contexts (which would require, in turn, to apply a more elaborated recipient choice algorithm).

At time \( t_0 \), a fire erupts in these premises. From this moment, the fire propagates. Each round, for each cases where there is fire, the fire propagates in the four directions. However, the fire cannot propagate through a wall. If the fire propagates in a case where an agent is positioned, that agents burns and is considered dead. It can of course no longer move nor communicate. If an agent gets to an exit, it is considered saved, and can no longer be burned. It still can communicate, but need not move.

Agents know the environment and the rules governing the dynamics of this environment, that is, they know the map as well as the rules of fire propagation previously described. They also perceive this environment but cannot see further than 3 cases away. Walls also block the line of view, preventing agents from seeing behind them. Within their sight, they can see other agents and whether or not the cases they see are on fire. All these perceptions are memorised.

In our context, an explanation is simply a scenario of \( D \cup F \) which implies \( O \), where \( D \) (set of ground instances of elements of \( H \)) is the associated hypothesis. In order to deliberate, agents maintain a list of such possible explanations (and a list of associated hypothesis) explaining their observations about fire, and a prediction of fire propagation based on their preferred hypothesis. Explanations (and, by extension, hypothesis) are sorted according to the following criterion:

- the agent prefers the minimal explanation, taking into account only fire origins. In other words, an agent will prefer an explanation using an unique fire origin propagating over one using several sources.
- the agent prefer the least presumptive explanation, taking into account propagation and origins. In effect it mean that the agent will favor an explanation considering the fire origin as closer to the observed manifestation.

Based on the deliberations described above, agents also maintain a list of possible escape route, tried by preference (by simply favouring the shortest paths to exits).

### 4.2 Sample of Agents Theories

We now give a snapshot of the declarative representation of agents’ knowledge, illustrating the different kind of rules involved in this example.

- The static elements of the environment description are represented as simple facts in the theory. The following rule states for instance that there is indeed a vertical wall at location \((0,1)\).

\[
\text{fact vwall(at(0,1)).}
\]

- Some explanations are always valid, and are thus represented as factual rules. For instance, the fire can always be assumed to have started at the location it is observed

\[
\text{fact fire(T,at(X,Y)) <- origin(T,at(X,Y)).}
\]

In this example application, hypothesis will always take the form of a conjunction of possible fire origin(s).

- Some explanations are justified in normal circumstances, but may suffer exceptions: they are represented as default rules in the Theorist’s framework. For instance, the fire should propagate in four possible directions. One rule describing this expected behaviour is:

\[
\text{default rule_propagates_L(T2,from(X2,Y)): fire(T,at(X,Y)) <- previous(X,X2), previous(T,T2), fire(T2,at(X2,Y)).}
\]
which should read “if there is a fire, then maybe it comes from”

- Constraints prevents default rules from applying. For example, the landscape has indeed walls and doors which prevent the fire from propagating.

\[
\text{constraint not rule\_propagates\_L(T, from(X,Y)) \leftarrow v\text{wall}(at(X,Y)).} 
\]

### 4.3 Example

We are now in a position to describe the different steps of our illustrative example.

**[Round t=0]** A fire erupts in (6,6), but nobody can initially see it. It will propagate until \(t=3\) before being seen.

**[Round t=3]** 

**Perception step**

- Agent 1 sees fire at (3,6), which was not expected.
- Agent 1 sees Agent 3.
- Agent 2 sees fire at (6,3) and (5,4). They were not expected.
- Agent 3 sees Agent 1.

**Explanation step**

- Agent 1 Having computed an explanation for \(\text{fire}(t=3, \text{at} (3, 6))\), Agent 1 gets 12 possible explanations, each one exhibiting a single origin. One such explanation, as provided by the Theorist system, states that the fire may have started at location (4,5), before propagating to the north (i.e. from south) and to the west.

  \[
  \text{Answer is fire(t3, at(3, 6))} 
  \]

  \[
  \text{Theory is} 
  \]

  \[
  \text{[rule\_propagates\_R(t2, from(4, 6)),} 
  \]

  \[
  \text{rule\_propagates\_D(t1, from(4, 5)),} 
  \]

  \[
  \text{origin(t1, at(4, 5))]} 
  \]

  took 0.539 sec.

  To classify these hypothesis, he first selects the minimal hypothesis considering only the origin. In this case, all the hypothesis suppose only one origin for the observed fire. Among those, he then selects the less presumptive hypothesis. In this case, the selected hypothesis is:

  \[
  \text{[origin(t3, at(3, 6))]} 
  \]

- Agent 2 Searching explanations for fire at (6,3) and (5,4), Agent \(a_2\) gets 6*6 possible explanations, such as:

  \[
  \text{Answer is fire(t3, at(6, 3)) and fire(t3, at(5, 4))} 
  \]

  \[
  \text{Theory is} 
  \]

  \[
  \text{[rule\_propagates\_R(t2, from(6, 4)),} 
  \]

  \[
  \text{origin(t2, at(6, 4)),} 
  \]

  \[
  \text{origin(t3, at(6, 3)),} 
  \]

  \[
  ] 
  \]

  Among those theories, 4 propose a common origin, and as such are minimal according to the origin criteria. Among those 4 the less preemptive one is eventually:

  \[
  \text{[rule\_propagates\_R(t2, from(6, 4)),} 
  \]

  \[
  \text{rule\_propagates\_D(t2, from(6, 4)),} 
  \]

  \[
  \text{origin(t2, at(6, 4))].} 
  \]
Communication step  Agent 1 and 3 are the only agent seeing each other. Agent 3 has no reason to initiate a communication, but Agent 1 has one: it has just changed its hypothesis and will try propagating and validating it. Agent 3 asks for arguments and Agent 1 sends it fire(t=3,at(3,6)). With this fact, Agent 3 recomputes its hypothesis and get the same favoured hypothesis. The hypothesis is confirmed and the communication stopped.

[Round t=4]

Movement step  Agent 3 moves towards the west exit, which is the closest exit. Agent 1 moves towards the east exit, for the same reason. Although it is closer to the east exit, Agent 2 moves towards the west exit because it predicts that fire will arrive at the east exit before it can go out this way.

Perception step  Agent 1 sees Agent 2 and conversely. All the fire seen by agents are predicted during this step.

Explanation step  No agents has been confronted to unpredicted events. They have no need for explanation and just trim their hypothesis list.

Communication step  Agent 1 and Agent 2 will communicate together. Agent 1 send its hypothesis (origin(t=3,at(3.6))). As this hypothesis is not invalidated by its perception but does not belong to its hypothesis list, Agent 2 ask for arguments. Agent 1 send argument (fire(t=3,at (3.6))). Agent 2 then computes possible explanations for this and its perception, and gets 6*6*12 possible explanations. Among those, only one contains a common origin for the three observed fires:

\[
\text{[rule\_propagates\_R(t2, from(6, 4)), rule\_propagates\_D(t2, from(6, 4)), rule\_propagates\_D(t1, from(6, 5)), rule\_propagates\_D(t0, from(6, 6)), rule\_propagates\_R(t3, from(4, 6)), rule\_propagates\_R(t1, from(5, 6)), rule\_propagates\_R(t0, from(6, 6)), origin(t0, at(6, 6))].}
\]

Agent 2 then proposes this hypothesis to Agent 1, which in turn ask for arguments. Finally both agreed upon this hypothesis.

Movement step

- Agent 3 continues its escape towards the west exit.
- Agent 2 confirms its chosen path with its new hypothesis, and keeps going towards the west door.
• Agent 1, however, using its new hypothesis, discovers that its escape route is bad. It changes its course to go towards the west exit.

[Round t=5 to 10] From time t=5 to time t=10, Agents 1, 2 and 3 exit the building. Agent 1 and 2 are closely followed by the fire. One false move would have been fatal. If Agent 1 did not communicate with agent 2 or agent 3 it would not have been able to determine whether the fire was coming from left or right and would have chosen the east exit, and would have been trapped by the fire.

5 Related Work

Gossip Problem. Rumors and gossip first appear in Multi Agent System with the problem of gathering distributed information known as the gossip problem. Each agent has a distinct piece of information, called a rumor, in the beginning. The goal is to make every agent know all the rumors [16]. Some variation of it are the rumor-spreading problem, where the communicating agent is determined each round by an adversary [3], and the collect problem. In the last one, each of \( n \) processes in a shared memory system have several pieces of information, and all these processes must learn all the values of all others while making as few as possible primitive read or write operations [15]. It has also been used for reaching consensus [8].

Gossip-based protocols. Let us consider a multi agent system. Each agent has a determined number of neighbours it can communicate with. Each time an agent receives a rumor, it transmits it to a number of agents chosen at random among its neighbours. Then in turn, each of these agents would do the same. This rumor spreading is analogous to the spreading of an epidemic, which have been the object of mathematical studies [4] and can spread exponentially fast. Such an information propagation system has first been used for replicated database consistency management [11]. It has been applied to unstructured peer-to-peer communities. Every time an agent detects a change in the system (that would be the rumor), it sends it to a random neighbour, and repeats
this operation until it has contracted enough neighbour(s). Some anti-entropy mechanisms are sometimes used to ensure that every agent can get to know each change, even if the rumor has already died out [9]. Another application of these protocols is reliable multicast [5]. It aims at propagating an information from an agent to another agent without a centralised source or knowledge of the system topology, and with a lower cost than with a simple flooding. It is robust to agent deficiency, and very scalable. A variation of it uses weight to enhance the reliability in specific topology [13], and its moderate cost makes it an interesting paradigm for networks-on-chip communications [10].

Rumor routing. Another approach of rumor as an alternative to flooding is rumor routing [6]. In the context of sensor networks, there is a need to transmit queries to agents having observed an event. A fast route between an agent making a request and the agents observing the events might be needed. It can be found by flooding event notifications or queries, and creating a network-wide gradient field [1], but it is a costly approach. Braginsky and Estrin instead propose to use a kind of traceable rumor. Each time an agent observes a new event, it sends an event notification rumor to a random neighbour. This neighbour transmits it in turn to another neighbour, keeping trace of whom it received it from, and how many agent(s) have acted as relay(s), creating rumor paths. When an agent needs to make a query, it sends it to one of its neighbours. If it has heard of the event concerned before, it transmits the query to the agent who told it the rumor, else it transmits to a random neighbour. Eventually, the query will cross the rumor path and be led to the right source. Gossip-based protocols and rumor routing propagates pure information, therefore the main studied aspects are the velocity and robustness of these processes.

Reputation Systems. At last, rumor has also been used in AI as second-hand information. Buchegger and Le Boudec use it in a reputation system [7]. Their agent can make decisions about the reliability of others agents according to their previously observed behaviour, but also according to what others agents tell about it.

6 Conclusion

This paper discusses the problem of efficient propagation of uncertain information. When a number of (distributed) agents have only partial access to information, the explanation(s) and conclusion(s) they can draw from their observations are inevitably uncertain. In this context, the efficient propagation of information is concerned with two interrelated aspects: spreading the information as quickly as possible, and refining the hypothesis at the same time. Using the metaphor of rumour-based communication, we describe a formal framework designed to investigate this class of problem, and we report on preliminary experiments using the described theory.

An obvious advantage of this process that we observed on the described example is that agents does not wait to collect all data before providing hypothesis. When temporary hypothesis are good enough to be acted upon is to be be determined, but we can expect that this process enable quicker reaction to events than a static centralised data analysis. The problem is that, of course, it can give incomplete or wrong hypothesis. However situation in which decision need to be done very quickly, without having time to wait for all data to strat acting could probably benefit from such a process. Further studies are required, however, to determine when exactly this kind of communication would be beneficial, but we expect quickly evolving systems will provide interesting applications. Whereas this paper has mainly focused on agents’ reasoning and content selection, we plan to also investigate in future research the related problem of recipient selection.

References


