Cooperative Content Retrieval in Nomadic Sensor Networks

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***Abstract*—A nomadic sensor network consists of: a) sensor nodes, that are fixed at some points and collect information about states or variables of the environment, and b) mobile nodes that collect and disseminate this information. Mobile nodes usually belong to different classes, and are thus interested in different subsets of sensor node information. In such networks, dissemination of information content at smaller costs can be achieved if mobile nodes are cooperative and collect and carry information not only in their own interest, but also in the interest of other mobile nodes. A specific modeling scenario is considered in this paper where the network has the form of a graph; sensor nodes are located on the vertices of the graph and U-nodes move along the edges according to a random waypoint model. We present a game-theoretic analysis to find conditions under which a cooperative equilibrium can be sustained.**

I. Introduction

A *nomadic sensor network* is a recently introduced networking paradigm [1]. It consists of: a) simple, tiny sensor devices (T-nodes) fixed at some points, whose purpose is to collect information about states or variables of the environment and b) more complex mobile devices that are carried by users (U-nodes), that collect and disseminate this information. Compared to traditional sensor networks where communication to end-users is realized in a multi-hop fashion, this paradigm exploits user mobility to conserve limited sensor energy, prolonging the lifetime of the network and making it more cost-efficient.

A U-node can collect sensor data either from the source T-node or from an encountered U-node who has previously acquired the data. Collecting data from other U-nodes may incur a smaller access cost (in time or energy), especially if the source T-node is far-away. Exploiting mobility in this way to reduce content retrieval costs requires each U-node to show some kind of cooperative behavior. However, U-nodes are highly autonomous and intelligent devices; different U-nodes may belong to different classes, and thus be interested in different sensor node information. Acquiring unwanted information incurs a cost in time or energy, thus a U-node would be cooperative and collect information of potential interest to other U-nodes only in anticipation of the same behavior by other U-nodes. The purpose of this paper is to identify requirements and conditions under which cooperative behavior may emerge in such a network. We present a game-theoretic analysis to find conditions under which a cooperative equilibrium exists.

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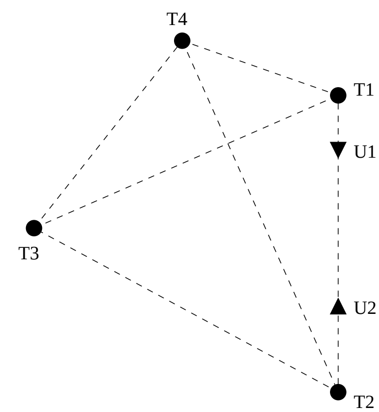


Fig. 1. Network graph

The general modeling scenario that we study is as follows. We consider a graph model of the network (see Fig. 1). T-nodes are located at the vertices of the graph and U-nodes move randomly along the edges of the graph collecting information when they reach a T-node or upon meeting another U-node somewhere on the graph. Nodes move according to a Markovian waypoint model on the graph, with a constant speed v. Waypoints are set to be the vertices of the graph (T-nodes). No pause times at waypoints are considered. Transitions from one waypoint to the next are governed by a Markov chain, i.e. a U-node moves from waypoint T_i to waypoint T_j with probability $p(T_i, T_j)$. This is a special case of the so-called "space graph" model in [2].

In order to simplify the analysis, instead of studying the network as a whole, we decompose the problem by studying possibilities of cooperation on each leg (edge) of the graph. We say that two U-nodes coming from opposite directions and meeting somewhere on a leg (T_i, T_j) are cooperative on (T_i, T_j), if and only if each one copies the content of its origin T-node (e.g., in Fig. 1, U_1 would copy T_1 and U_2 would copy T_2), even if they are not interested in it. We shall find conditions under which the following strategy of each U-node results in an equilibrium. This strategy is made up of two actions: *Initially, a U-node is cooperative and copies unwanted content. However, if it meets a selfish U-node somewhere on a leg, it will only transmit its acquired content with a certain probability.* This strategy may easily be applied, provided that upon meeting each other, U-nodes exchange messages that contain the list of information objects stored in their memory.

The equilibrium conditions depend mainly on the probability of meeting other U-nodes on the leg. Under the setting we discuss in this paper, satisfying equilibrium conditions for each leg and between each pair of U-nodes means that a cooperative equilibrium is achieved for the whole network. Note that in making this decomposition, we are implicitly assuming that U-nodes base their decision only on their interest for content that is in distance of one leg. The analysis becomes more complicated when this "decision horizon" is more than one, and is not attempted here. (For example in Fig. 1, if node U_1 that starts from T_1 is interested in both T_2 and T_3 and is about to follow the path $\{T_1, T_2, T_3\}$, it should consider the probability of meeting U-nodes that previously acquired data from T_2 or T_3, on all segments of this path.)

On what concerns the knowledge each U-node has, the following assumptions are made. Each U-node knows the topology of the network, the number of other U-nodes and the distances between each pair of T-nodes. They are also aware of the information content at each T-node. Furthermore, U-nodes know that other U-nodes move also according to the random waypoint model on the graph. On the other hand, the (instantaneous) rate at which the information content on each T-node is updated is a function of time unknown to the U-nodes. (Thus a U-node may return to an already visited T-node to get updated information.) In addition, each U-node does not know the interests of other U-nodes for sensor data and has no memory of previous encounters with them.

Several hypotheses that facilitate the analysis are also made. First it is assumed that U-nodes are homogeneous devices, have the same processing and communication costs and have the same movement parameters. Secondly, U-nodes have infinite (in practice this means sufficiently large) storage space. Thus they do not have to consider possible replacement policies (for example, throwing away their less valuable content) and respective costs. Thirdly, that each T-node generates a single type of information content, and information content is not depreciated in time or space. If it was depreciated, a U-node should have to include in its decision the (possibly subjective) value of each information object at the moment of its acquisition. Examples of non-depreciated content include statistical samples (e.g., measurements of physical quantities). On the other hand, information with limited temporal or spatial scope, or software modules that are subject to updates are considered to be depreciating in time or space. We also consider that U-nodes make decisions for their best interest, but are not malicious, i.e., they don't perform actions from which they have no material gain, only to hurt others. Finally, we assume that data exchanged between U-nodes or between a U and T-node consist only of a few bits; thus they are transmitted within an infinitesimal time interval, which is not considered in the analysis.

II. Analytical Model

In the analysis that follows, we consider a number N of U-nodes, and calculate the expected cost for a U-node to follow a certain strategy on an arbitrary leg (T_i, T_j). Because of the symmetry of our model, the cost is the same for all U-nodes. A strategy consists of a sequence of actions, concerning the decisions to collect, carry and transmit information that is not of interest to a U-node. Actions are either of a cooperative or selfish nature. A strategy is itself called cooperative if all the actions it is composed of are cooperative.

We consider that the game is played between a U-node starting from the origin sensor T_i and $N-1$ other U-nodes it may meet before reaching the destination sensor T_j. Our working hypothesis is that a U-node is not interested in the content of the origin sensor, but only in that of the destination. A priori, it assumes the same for the other U-nodes. This will produce conditions for cooperation in a worst-case scenario, since otherwise if a U-node is also interested in the content of the origin sensor, it has greater incentive to cooperate. The analogous assumption for the other U-nodes can be partially justified by the lack of any information about the identities of the encountered nodes and their interests for sensor information.

Costs can be expressed in time or energy units. Here we interpret this cost as the delay to retrieve information content. The length of a leg (T_i, T_j) is denoted by $d(T_i, T_j)$. The communication and processing cost of a U-node to acquire content from a T-node and then transmit it to a U-node is a constant c, translated in time units. Consistently with our assumption of infinite storage, we do not consider any cost for carrying the information. Finally, not to complicate the analysis, the transmission ranges of both U-nodes and T-nodes are set to be zero.

Consider the process $X(t)$ of the position of the U-node on the graph at each time instant t. We find its stationary distribution as follows. First consider the embedded Markov chain of waypoints visited sequentially by a U-node. Under the stationary distribution of this chain, the fraction of transitions to waypoint T_i is denoted by π_i. Then if we have constant velocity, the probability that the U-node is on any segment of length x on leg (T_i, T_j) in direction from T_i to T_j is

$$\frac{\pi_i p(T_i, T_j) x}{\sum_{T_i} \sum_{T_j \neq T_i} \pi_i p(T_i, T_j) d(T_i, T_j)} . \tag{1}$$

That is, it is the fraction of time the U-node spends on the segment of length x while moving from T_i to T_j.

Suppose that the U-node, hereafter called U_i, is at waypoint T_i at $t=0$ and decides to go towards waypoint T_j. Confine the strategy of each player to take values in the set $\mathcal{S} = \{C, S\}$ (C: cooperative, S: selfish). By choosing strategy C, U_i copies, carries and transmits the content of T_i to an encountered U-node that is interested in it, whereas by following strategy S

it ignores it. In order to calculate the expected cost by following a certain strategy, U_i should estimate the probability of meeting another cooperative U-node coming from T_j towards T_i, at a certain distance x from T_i. Suppose there are k other ($k < N$) cooperative U-nodes. To meet another U-node within a distance x, the latter must be at a distance of at most $2x$ at $t = 0$ and be headed towards T_i. Since the move processes of the U-nodes are mutually independent as well as jointly stationary, the instant $t = 0$ is an arbitrary instant at which U_i at T_i observes the position of the other U-nodes. Therefore it observes the other U-nodes in their stationary distribution. Consequently, if $d(T_i, T_j) \geq 2x$ the probability of a meeting with at least one cooperative U-node within a distance x is

$$F_k(x) = 1 - (1 - \frac{\pi_j p(T_j, T_i) 2x}{\sum_{T_i} \sum_{T_j \neq T_i} \pi_i p(T_i, T_j) d(T_i, T_j)})^k . \tag{2}$$

If $d(T_i, T_j) < 2x$, we must also include the event that another U-node is on a leg or direction different from (T_j, T_i) at $t = 0$ but can meet with U_i in time less than x/v. Consider all such legs m and the starting points T_m of the U-nodes on these legs. Let $\{T_m, \ldots, T_j\}$ denote all the paths that may be followed to reach T_j before the meeting, and for which $p(T_m, \cdot) \cdots p(\cdot, T_j) > 0$, where $\cdot$ denote intermediate states. Then this meeting probability equals

$$1 - (1 - \frac{\sum_m \pi_m p(T_m, \cdot) \cdots p(\cdot, T_j) p(T_j, T_i) 2x}{\sum_{T_i} \sum_{T_j \neq T_i} \pi_i p(T_i, T_j) d(T_i, T_j)})^k .$$

The summation in the numerator is over all possible paths that can be followed. This probability again equals (2), since $\sum_k \pi_k p(T_k, \cdot) \cdots p(\cdot, T_j) = \pi_j$ from the balance equations in the embedded Markov chain.

Hence the distribution function $F_k(x)$ gives the probability that a meeting with another cooperative U-node takes place at distance $\leq x$, for any x such that $0 < x < d(T_i, T_j)$.

Suppose that there are only two nodes in the network, U_i and U_j, and that U_i meets with U_j at distance x from T_i ($x < d(T_i, T_j)$). If they follow strategies s_i, s_j respectively ($s_i, s_j \in \mathcal{S}$), then the cost of U_i, denoted as a function $\mathcal{C}_i^{(T_i,T_j)}(s_i, s_j, x)$ of U_i, where $\mathcal{C}_i^{(T_i,T_j)} : \mathcal{S} \times \mathcal{S} \times [0, d(T_i, T_j)] \to R$, is

$$\begin{aligned}
\mathcal{C}_i^{(T_i,T_j)}(C, C, x) &= c + x/v \\
\mathcal{C}_i^{(T_i,T_j)}(S, C, x) &= x/v \\
\mathcal{C}_i^{(T_i,T_j)}(C, S, x) &= c + d(T_i, T_j)/v \\
\mathcal{C}_i^{(T_i,T_j)}(S, S, x) &= d(T_i, T_j)/v .
\end{aligned} \tag{3}$$

We denote by $\alpha(T_j, T_i)$ the probability that U_i meets with a *specific* other U-node before meeting T_j, i.e.:

$$\alpha(T_j, T_i) \triangleq \frac{2\pi_j p(T_j, T_i) d(T_i, T_j)}{\sum_{T_i} \sum_{T_j \neq T_i} \pi_i p(T_i, T_j) d(T_i, T_j)} . \tag{4}$$

As it can be seen, this meeting probability increases with the length of a leg. Additionally, U_i has a higher meeting probability for greater $\pi_j p(T_j, T_i)$, that is if the destination node T_j is more frequently visited, or if U-nodes at T_j have an increased probability of heading towards T_i.

We will derive the expected cost of U_i to take action s_i, when k other U-nodes are cooperative ($0 \leq k \leq N - 1$). We denote this as $\mathcal{C}_i^{(T_i,T_j)}(s_i|k)$. For $1 \leq k \leq N - 1$, we have that

$$\begin{aligned}
\mathcal{C}_i^{(T_i,T_j)}(s_i|k) = &\int_0^{d(T_i,T_j)} \mathcal{C}_i^{(T_i,T_j)}(s_i, C, x) dF_k(x) \\
&+ (1 - \alpha(T_j, T_i))^k \mathcal{C}_i^{(T_i,T_j)}(s_i, C, d(T_i, T_j)) .
\end{aligned} \tag{5}$$

We arrive at the following expressions for different combinations of followed strategies:

$$\begin{aligned}
\mathcal{C}_i^{(T_i,T_j)}(C|k) &= c + \frac{d(T_i, T_j)}{v} \frac{1 - (1 - \alpha(T_j, T_i))^k}{(k+1)\alpha(T_j, T_i)} \\
\mathcal{C}_i^{(T_i,T_j)}(S|k) &= \frac{d(T_i, T_j)}{v} \frac{1 - (1 - \alpha(T_j, T_i))^k}{(k+1)\alpha(T_j, T_i)} \\
\mathcal{C}_i^{(T_i,T_j)}(C|0) &= c + d(T_i, T_j)/v \\
\mathcal{C}_i^{(T_i,T_j)}(S|0) &= d(T_i, T_j)/v .
\end{aligned} \tag{6}$$

III. Game-Theoretic Analysis

We observe from (6) that $\mathcal{C}_i^{(T_i,T_j)}(C|k) > \mathcal{C}_i^{(T_i,T_j)}(S|k) \quad \forall i, k$. Furthermore it can be shown that $\mathcal{C}_i^{(T_i,T_j)}(C|k)$, $\mathcal{C}_i^{(T_i,T_j)}(S|k)$ are decreasing functions of k. The game is a Bayesian analog of the N-person prisoner's dilemma (see [3]). (Since U_i does not know the number or identity of other U-nodes it may meet on (T_i, T_j).) When seen as a noncooperative game, it is evident from the above expressions that there exists only one equilibrium, in which every node is selfish. (Since S strongly dominates C for every player.) However, it may not be the best solution; player U_i can have a benefit by cooperating on (T_i, T_j), when k other U-nodes are cooperative, if

$$\mathcal{C}_i^{(T_i,T_j)}(C|k) < \mathcal{C}_i^{(T_i,T_j)}(S|0) . \tag{7}$$

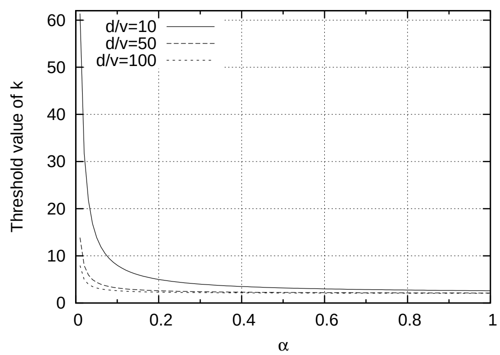
That is, if the cost for U_i when k other U-nodes are cooperative is smaller than its cost when all U-nodes are selfish. This condition also complies with individual rationality of U_i, since $\mathcal{C}_i^{(T_i,T_j)}(S|0)$ is the minimax value U_i can guarantee for itself.

From (6), this inequality is satisfied if

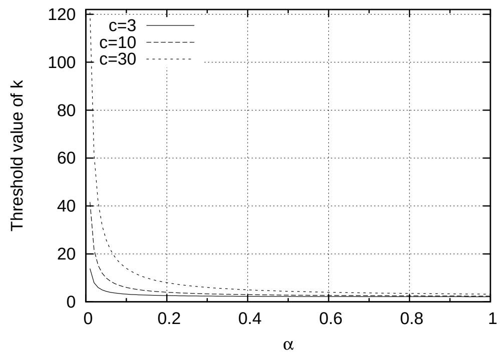
$$1 - \frac{1 - (1 - \alpha(T_j, T_i))^k}{(k+1)\alpha(T_j, T_i)} > \frac{cv}{d(T_i, T_j)} . \tag{8}$$

It must always hold that $c < \frac{d(T_i,T_j)}{v}$; that is, our initial assumption must be that the cost (expressed in time units) for a U-node to acquire and transmit unwanted content must be smaller than the time to reach T_j starting from T_i.

We find an approximate condition for the above inequality to be satisfied. The Taylor polynomial of $(1-\alpha)^k$ at $\alpha = 0$ is, up to a second order approximation, $1 - k\alpha + \frac{k(k-1)\alpha^2}{2}$ ($k > 1$). Substituting this approximate expression in inequality (8), we



(a) $c = 3$



(b) $d/v = 50$

Fig. 2. Approximate threshold values of the number of other cooperative nodes k above which cooperation on a directed leg is better for U_i than full selfishness, for different values of α and d/v, c.

get the condition

$$k > \frac{2cv}{d(T_i,T_j)\alpha(T_j,T_i)} - \frac{2(1+\alpha(T_j,T_i))}{\alpha(T_j,T_i)(k+1)} + 2 \ ,$$

which is satisfied when

$$k > \frac{2cv}{d(T_i,T_j)\alpha(T_j,T_i)} + 2 \ . \tag{9}$$

Based on (9), in Fig. 2 we show approximate threshold values of the number of other cooperative nodes k above which cooperation for U_i on (T_i, T_j) is more beneficial than the case when all U-nodes are selfish.

These confirm that from the point of view of U_i, a smaller number of cooperative nodes is required on long-distance routes or when the destination node T_j is visited more often. On the other hand, a higher number is required when U-nodes are moving at a high speed or if the cost c is higher.

The situation in which each U-node is cooperative on both directions of a leg (T_i, T_j) will be identified as "full cooperation" on (T_i, T_j). The inverse situation in which each U-node is selfish, will be called "full selfishness". When full cooperation is achieved as a strategic equilibrium in a leg of the graph, then we will say that a cooperative equilibrium exists on this leg. If this can be achieved on all legs, then a cooperative equilibrium exists in the whole network. We next proceed to find a strategy of each U-node and conditions under which a cooperative equilibrium can be achieved.

First pay attention to the fact that even is full cooperation is beneficial for U-nodes in the network, this is not enough to sustain an equilibrium. For an equilibrium to exist, there must either be some punishment to selfish nodes or some form of contract, in which all U-nodes would agree to be cooperative, threatening to be selfish if such contract is not signed by everyone [4]. Given that the arrival to such an agreement is difficult in an unstructured network with autonomous nodes, we consider the following scheme that is easily applicable.

A requirement of the scheme is that U-nodes, upon meeting each other, first exchange the lists of information objects in their memory. These lists contain metadata regarding the type of information and the source T-node. Then each U-node executes this strategy: initially it is generous and collects and carries unwanted content; however if on a certain leg of the network it meets a selfish U-node, it will only transmit this content with a probability p, called the cooperation probability ($p < 1$). (If a U-node does not communicate its list of objects, it can be considered selfish and the same strategy applies.)

We proceed to write a condition under which this strategy is preferable for U_i on (T_i, T_j), and thus can lead to an equilibrium. Given that there are $\binom{N-1}{k}$ different combinations of U-nodes where exactly k other U-nodes are cooperative, this condition is

$$\mathcal{C}_i^{(T_i,T_j)}(C|N{-}1) \leq \sum_{k=0}^{N-1} p^k (1{-}p)^{N-k-1} \binom{N-1}{k} \mathcal{C}_i^{(T_i,T_j)}(S|k) \ . \tag{10}$$

That is, the expected cost for U_i when all U-nodes are cooperative must be smaller or equal to the expected cost when U_i is selfish and k other U-nodes are cooperative with probability p, $k = 0, \ldots, N-1$. It is evident that (7) is a special case of this condition, where $p = 0$ and $k = 0$ (admitting $0^0 = 1$).

Substituting from (6), we have that (in the following we omit the parameters in $d(\cdot)$, $\alpha(\cdot)$ for notational convenience)

$$\begin{aligned} c{+}\frac{d}{v}\frac{1-(1-\alpha)^{N-1}}{N\alpha} &\leq \frac{d}{v}\{(1-p)^{N-1} \\ &+ \sum_{k=1}^{N-1} p^k (1-p)^{N-1-k} \binom{N-1}{k} \frac{1-(1-\alpha)^k}{(k+1)\alpha}\} \end{aligned} \tag{11}$$

The right-hand side (rhs) of this inequality becomes

$$\begin{aligned} &\frac{d}{v}(1-p)^{N-1}\{1 + \frac{1}{a}[\sum_{k=1}^{N-1} (\frac{p}{1-p})^k \binom{N-1}{k} \frac{1}{k+1} \\ &- \sum_{k=1}^{N-1} (\frac{p(1-\alpha)}{1-p})^k \binom{N-1}{k}]\} \ . \end{aligned}$$

It can be derived that $\sum_{k=1}^{N-1} \left(\frac{p}{1-p}\right)^k \binom{N-1}{k} \frac{1}{k+1} = \sum_{k=1}^{N-1} \left(\frac{p}{1-p}\right)^k \frac{1}{N} \binom{N}{k+1} = \frac{1}{Np(1-p)^{N-1}} - \frac{1-p}{Np} - 1$ and $\sum_{k=1}^{N-1} \left(\frac{p(1-\alpha)}{1-p}\right)^k \binom{N-1}{k} = \left(\frac{1-\alpha p}{1-p}\right)^{N-1} - 1$. Therefore (11)

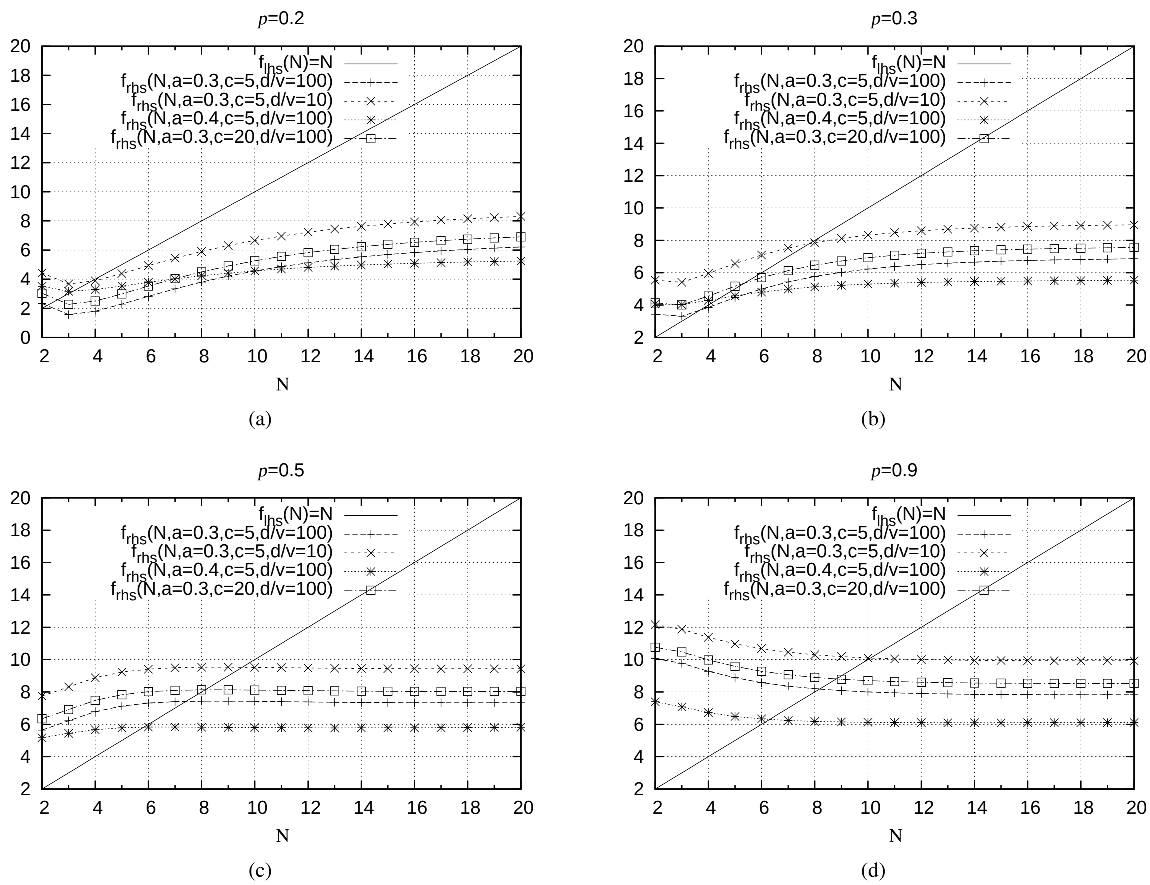


Fig. 3. Graphical illustration of cooperative equilibrium conditions, for different values of the cooperation probability p and model parameters: the crossover points of f_{rhs} with the diagonal N show approximate threshold values of N above which a U-node is cooperative in a directed leg in our model.

becomes

$$c+\frac{d}{v}\frac{1-(1-\alpha)^{N-1}}{N\alpha} \leq \frac{d}{v}(1-p)^{N-1}\{1 + \frac{1}{\alpha}\big[\frac{1}{Np(1-p)^{N-1}} - \frac{1-p}{Np} - \left(\frac{1-\alpha p}{1-p}\right)^{N-1}\big]\} .$$

Applying the second order Taylor polynomial approximation to $(1-\alpha)^N$ at $\alpha = 0$, we finally obtain the condition

$$N \geq 1 + \frac{2}{\alpha} + \frac{2(1-\alpha)}{\alpha}\{\frac{1}{\alpha N} - (1-p)^{N-1} - \frac{1}{aNp}\big[1-(1-p)^N\big] + (1-\alpha p)^{N-1} + \frac{cv}{d}\} . \quad (12)$$

In Fig. 3 we show graphically the required number of nodes in the network that would satisfy this condition, for different values of the meeting probability α and d/v. (We draw the rhs of (12), called f_{rhs} and the diagonal N, called f_{lhs}.) It can be deduced from the graphs that a cooperative equilibrium on a leg is easier to achieve (i.e., we need a smaller number of U-nodes) for smaller values of c and larger values of d/v. The behavior with respect to α is less intuitive: when the cooperation probability of other U-nodes is small, a higher meeting probability leads a U-node actually having less incentive to cooperate and appearing more selfish, whereas if the cooperation probability of other U-nodes is high, it leads a U-node to actually be cooperative. Finally, as the probability of cooperation decreases, a smaller number N of nodes in the network is required for an equilibrium to be achieved. We can expect this result, since a cooperative U-node "punishes" more a selfish U-node by giving its acquired content with a smaller probability. Therefore U-nodes refrain from being selfish.

Note that in the model we develop in this paper we do not have to consider a "stricter" condition for a cooperative equilibrium to exist (i.e., a condition that would call for a higher N). This is because we have assumed in the beginning that each U-node thinks, a priori, that all the other U-nodes are interested in the content it collects; thus we have excluded the case where a U-node would not collect unwanted information because it might think that other U-nodes would also not be interested in it (and hence also might not collect data at their respective origin points). Therefore if such cooperative equilibrium conditions are satisfied in all directed legs simultaneously, a cooperative equilibrium exists in the whole network.

IV. Related Works

Previous applications of game-theoretic methods in examining cooperation between mobile nodes have focused mainly on traditional ad-hoc networks, where cooperation consists of each node acting as a relay and forwarding packets of other nodes, at the expense of an increased processing and energy cost. This kind of cooperation is the main subject of the papers in [5]–[8].

A work with a similar subject to ours is [9]. Therein, the authors consider a general delay-tolerant network where information is disseminated in a store-carry-and-forward manner. The considered model is very similar to ours: information generating nodes are static, and mobile nodes are either interested in certain information or not, but may collect it anyway in order to exchange it with information of interest (barter exchange). The authors additionally consider depreciation of information content over time. The objective for each node is to decide which messages to collect from the information-generating nodes, based on their actual value, or the value they could have as a trade object (barter value). The authors find, by the means of simulations, an equilibrium strategy. In contrast to the above-mentioned approach, in this paper we have analytically derived an equilibrium strategy and conditions considering the mobility of nodes in the network.

Finally, it is worth mentioning that game theory has been applied in several other problems in wireless networks, such as multiple access schemes or to model conflicts between transmitters-jammers. A good overview can be found in [10].

V. Ending Note

In this paper, we have studied a simple model of a nomadic sensor network, and derived conditions under which rational U-nodes will exhibit cooperative behavior on legs of the network, given that a cooperative U-node will actually transmit acquired sensor data with a probability p when it meets a selfish U-node. The parameter p may either be a fixed parameter of the system, or have a value everyone agrees to. We think it should be greater than zero, to allow for dissemination of information even if U-nodes make irrational or erroneous decisions. Cooperative equilibria can exist in the whole or parts of the network, i.e., one or more legs in the network. In the continuation of this work, we plan to study such equilibria in various graph topologies.

The model in this paper admits several simplifying assumptions that sacrifice reality for analytical tractability. However, the assumptions regarding the knowledge each U-node may have *are* realistic; furthermore, one should be aware of the fact that mobile devices, advanced as they may be, still have limited computational capabilities, as well as limited interactions with an intelligent human user. Hence such a simple model can indeed be used by U-nodes to decide whether or not they will be cooperative.

One drawback however, is that the equilibria produced by this model are not completely self-enforced. The cooperation probability is the same for all U-nodes, and hence it should be set by another authority or be stipulated by a common agreement between the players. The same analysis can be followed to derive cooperative equilibrium conditions when the cooperation probability is different for each U-node. In a more realistic scenario the cooperation probability would correspond to a reputation value of each U-node to be cooperative. Reputation values can be obtained from interactions between U-nodes (examples of distributed algorithms can be found in [11]).

Further research issues involve relaxing some of the assumptions used in the paper, such as infinite storage capacity, non-depreciation of information in time or space, zero transmission ranges, etc. An unresolved issue is also the behavior of a U-node towards the second, third, etc. U-node it may potentially meet on the same leg, since the proposed strategy only guarantees that U-nodes will exhibit cooperative behavior to the *first* U-node they encounter on the leg. (A U-node may have acquired the content but not transmit it to the remaining U-nodes it will meet.) It would also be interesting to append a value to each sensor node that expresses the average interest of U-nodes in its content, and that would be taken into account for a U-node's decision. Additionally, an open issue is to find cooperation conditions when the number of U-nodes is not known a priori to all players, but is a random variable. Finally, the ultimate goal should be to describe the dynamics of the game, by studying it either as a repeated game or as an evolutionary game. It is anticipated that an equilibrium can also be sustained in a repeated game, where punishments occur for selfish nodes in subsequent rounds of the game. By the evolutionary approach, we can study how the strategies of the players would evolve until a stable situation has been reached.

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