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InterSensorNet: Strategic Routing and Aggregation

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Abstract—[1] **Sensor networks are expected to find widespread use in a variety of applications. In the near future, more and more sensor networks will be deployed for multiple services in a surrounding area. Different sensor networks may overlap or partially overlap with each other, and may interfere with each other. However, it also provides an opportunity to construct a low energy, high connectivity, and more robust sensor network. We propose an *InterSensorNet* scheme which is a federation of multiple sensor networks. The success of the InterSensorNet depends on whether a node is willing to cooperate with nodes in a foreign network. What will be the incentive to do so? With concepts from economics and game theory, we propose a *Mechanism Design (MD)* approach to handle the *strategic* agents that respond to incentives. We apply MD to two practical setting of multiple sensor networks and study applications of InterSensorNet Mechanism Design.**

I. INTRODUCTION

Over the last few years, the design of wireless sensor systems has gained increasing importance for a variety of civil and military applications. Wireless sensor networks provide an attractive means to bridge the gap between the physical and virtual world.

The widespread use of sensor networks will make them ubiquitous. New issues will arise due to deployment of multiple sensor networks. Only recently, people start to consider the scenario of multiple sensor networks deployed in the same area. As an example in a battlefield, Air Force, Army and Marine deploy their own sensor networks. Each of them may also deploy different networks for various sensing purposes such as moving targets, radiation, temperature, light, and pressure. Thus, tens of sensor networks, each of different sensor types, on the battlefield may interfere with each other, decreasing the signal-to-noise ratio (SNR). It is possible to turn this drawback into an advantage by utilizing multiple deploying sensor networks. Here we assume multiple sensor networks with different types and under the control of different administrators. We suggest interoperatability between sensor networks to enable an *InterSensorNet*. Many techniques that were not possible before can be enabled with multiple sensor networks. We advocate that an InterSensorNet scheme can model the situation and bring many new research issues, some of them are listed below:

- **Localization and location service.** A node in the local sensornet can determine its location more accurately with the help of nodes in foreign networks. It can also obtain the location service from other networks.
- **Synchronization.** Synchronization could be more accurate with the help from foreign networks, and sometimes a node can get synchronization that is impossible without the help of other networks as a foreign anchor node is close by.
- **Topology control.** With the help from foreign networks, the topology of a sensornet can be made more efficient. Sometime a better topology can be formed with a few nodes from foreign networks; sometime a less number of nodes can be used for certain topology with the help from foreign networks, minimizing the power consumption.
- **In-network processing.** A foreign network can help the in-network processing because it is in a better position to process the data, holds necessary information, or has abundant power to do so.

With cooperation of multiple sensor networks, connectivity and robustness can be improved, and energy dissipation reduced. Interference can be reduced or eliminated too. To promote methodology of the InterSensorNet, two major components are necessary: an internetworking protocol and a mechanism for incentives. The protocol enables communication between different sensor networks and the mechanism for incentives enables cooperation. In this paper, we deal with a subtopic of the topology control and in-network processing, that is, data collection and aggregation. The success of InterSensorNet depends on whether a node is willing to route data for a foreign network. Nodes may attempt to "freeload" from their neighbors, taking advantage of their forwarding services without offering anything in return. Why should one forward someone else's packets, depleting its own battery power and possibly restricting its use of the network in the future? When a suitable incentive scheme is available, nodes that serve as "good citizens" could be rewarded. We will study the mechanism design method for the InterSensorNet, such that the global optimization can be achieved when each strategic agent acts to maximize its own benefit. We present the preliminary work with a few applications to demonstrate the potential advantages of the method.

II. MECHANISM FOR INTERSENSORNET

A. Background

Multi-agent systems have been extensively studied in both computer science and economics, but the two communities have different approaches [1], [2]. In computer science, agents

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are typically assumed either to be *obedient* or to be *adversaries*. An agent is obedient if it follows the prescribed algorithm, such as a routing algorithm. An agent is adversaries if it plays against each other, such as in the mutual exclusion problem. On the other hand, the *strategic* agents in game theory are neither obedient nor adversarial; they will respond to incentives [2], [3]. With the *Mechanism Design (MD)* approach, each agent in the network determines whether it will route data for others so it will be beneficial. At the same time, the global optimal goal also can be achieved.

B. Problem Formulation

We first present a model of sensor networks. All of the M sensor networks, $\mathcal{E}_1, ..., \mathcal{E}_M$, are represented by a directed graph G, consisting of a set of $N+1$ nodes $\{n_0, n_1, n_2, ..., n_N\}$. Each node n_i belongs to a network j, $n_i \in \mathcal{E}_j$, where $1 \leq j \leq M$ and $1 \leq i \leq N$. Node n_0 is a basestation. Each node have two types of weight, w_i^R/bit and $w_{i,j}^T$/bit, where w_i^R/bit is the energy dissipation of receiving and processing a bit at n_i independent of where the bit comes from, and $w_{i,j}^T$/bit is the energy dissipation of transmitting a bit from n_i to n_j, which depends on how far away the destination n_j is. Assume $d(i,j)$ is the distance between the two nodes, n_i and n_j, and α is the path loss index. Weight $w_{i,j}^T$/bit is $\upsilon_i + \omega_i \cdot d(i,j)^\alpha$ [4], [5], [6]. For a node n_i to route a bit to destination n_j, two steps are needed, one for receiving and the other for transmitting, with its power dissipation being expressed as $w_i^R + w_{i,j}^T$. A cost coefficient can be $c^i = \frac{\beta}{\eta_i}$, where β is a constant and η_i stands for the energy level at n_i. During a short time period when the energy level does not change significantly, therefore, c^i can remain as a constant. However, the cost coefficient will increase when the energy level is getting scarce. In general, a node n_i is a strategic agent that is rational and selfish, and responds only to the payoff to be received. A node has an energy level, and presumably the basestation has an unlimited energy level.

Now, we briefly describe the mechanism design. Each agent has a type t^i known by agent i only. In fact, type t^i is the marginal cost c^i. What agent i reveals is its strategy a^i. In the system, there are a set of possible outcomes $O(a^1, ..., a^N)$, indicating which nodes participate in the service activity. Each agent has a utility function u, where $u^i \in U$ that expresses its preferences over these outcomes. Agent i chooses a strategy a^i to maximize its utility u^i. The utility function of an agent is known by itself. The desired systemwide goal is specified by a *social choice function* $F : U^N \to O$ that maps each particular instantiation of agents, completely described by their utility functions, into a particular outcome. A social choice function is *strategyproof* if $u^i(F(u)) \geq u^i(F(u|^i z))$, for all i and all $z \in U$. What this formula means is that if the agent reveals its real cost t^i in a^i, the utilization will be maximized. If F is strategyproof, then no agent has incentive to lie about its real cost, and the desired social goal can be achieved. A goal of the mechanism design is to find a social function that is strategyproof. In this paper, for each application we will design a strategyproof mechanism so that a global optimal can be achieved. A mechanism is to generate an outcome set O including a set of *payments* $P = (p^1., ..., p^N)$. Valuation v^i of agent i can be computed as $v^i = v^i(t^i, O)$. According to its valuation and payment function, each agent computes its utility function. An agent does not have an incentive to provide service if its utility is less than zero. Combining these decisions, a global optimal solution can be obtained. Here, we apply this methodology to two sensor-network applications: data collection and data aggregation.

III. MECHANISM DESIGN FOR DATA COLLECTION

We will present a model of data collection in a sensor network. For example, data from the radiation sensors are sent back to the basestation so a radiation map can be constructed. All raw data will be processed in the basestation. There is a default routing path, if existing, via nodes in its local network from every sensor to the basestation. If a sensor node cannot be reached by its local network, nodes in a foreign network can offer assistance in routing. Nodes in a foreign network could also assist routing traffic via a less expensive path. Given a set of traffic, the goal is to design a set of output and payment so that the total cost for data transmission is minimized.

Mechanism for Data Collection (MDC) — The cost of a path is the sum of the transmitting cost from the source plus the routing cost of all the intermediary nodes. Here, all data will be transmitted back to the basestation, whose receiving cost is omitted from the calculation. For a path x from source n_s to basestation n_0, $P_{(x,s)}$ is defined as an ordered list of k nodes along the path, $(q_1, q_2, ..., q_k)$, where $q_1 = n_s$ and $q_k = n_0$. The total cost of path x is computed as:

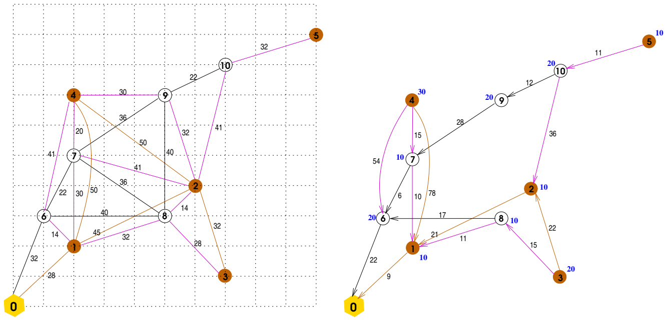
$$\phi_{(x,s)} = a^s \cdot w_{s,q_2}^T + \sum_{2 \leq i < k} a^i \cdot (w_{q_i}^R + w_{q_i,q_{i+1}}^T)$$

The least cost is defined as $\rho_s = \phi_{(z,s)}$ such that path $P_{(z,s)}$ is the least cost path LCP_s from n_s to n_0. Assume $n_s \in \mathcal{E}_k$, the payment to node n_i is defined as:

$$p_s^i = \begin{cases} \rho_s\{a^i = \infty\} - \rho_s\{a^i = 0\} & \text{if } n_i \in P_{LCP_s} \text{ and } n_i \notin \mathcal{E}_k \\ 0 & \text{otherwise} \end{cases}$$

where $\rho_s\{a^i = \infty\}$ and $\rho_s\{a^i = 0\}$ are the modified cost of LCP_s when node n_i claims an infinite charge and a free charge, respectively. When $a^i = \infty$, the modified least-cost path is denoted as $SLCP_s^i$, the *Second Least-Cost Path (SLCP)* with respect to node i. Assume every node reveals its true type, that is, $a^i = t^i = c^i$. Thereafter, the LCP can be calculated by a simple shortest-path algorithm and output $O(a^1, ..., a^n)$ can be obtained accordingly. Node i's valuation is 0 if it does not provide a routing service to the chosen LCP as a foreign node, and $-t^i$ if it is. The utility is $u^i = v^i + p^i$. This mechanism is a form of VGC mechanism [7], [8], [9]. Since the VGC mechanism has been proven to be strategyproof, all nodes will reveal their real types. Thus, mechanism MDC is a strategyproof mechanism.

Note that when there exists only a single path from n_s to n_0 and there is a foreign node $n_i \in \text{LCP}_s$, if $a^i = \infty$, $SLCP_s^i = \infty$, thus the payment becomes infinite. To solve this problem, we



(a) A sensor network map **(b)** A sensor network graph

Fig. 1. Scenario 1 illustrating data collection.

propose to define a *Willing-to-Pay (WTP)* value for n_s, standing for the maximum payment n_s is willing to pay a foreign node for assistance of routing a bit. In fact, it is a perfectly elastic demand function. In such a case, if the foreign agent accepts WTP as the payment, the service will be provided. Otherwise, the service will be denied and the data is simply lost. It is easy to see that it is a dominant strategy for an agent to reveal its real WTP value. If it claims a lower value, it may unnecessarily lose its data; whereas if it claims a higher value, it may end up paying more than its WTP.

Scenario 1: A sample sensor map is shown in Fig 1(a), in which two sensor networks, $\mathcal{E}_1$ and $\mathcal{E}_2$, have been deployed on a $100m \times 100m$ map and share a basestation at (0,0). It is assumed that the sensors can communicate when they are within the radius of 50 meters. The number inside a circle represents the node number, and the number on each edge represents the physical distence $d_{i,j}$ between nodes n_i and n_j. Network $\mathcal{E}_1$ includes nodes $\{n_1, n_2, n_3, n_4, n_5\}$ and network $\mathcal{E}_2$ includes nodes $\{n_6, n_7, n_8, n_9, n_{10}\}$. Two types of weights, the cost coefficient function, and the cost function for path x are:

$$w_i^R = 10; \;\; w_{i,j}^T = \begin{cases} (1 + 0.01 \cdot d_{i,j}^2) & \text{if } d_{i,j} \leq 50 \\ \infty & \text{otherwise} \end{cases} \;\; ;$$

$$\phi_x = c^s \cdot w_{s,q_2}^T + \sum_{2 \leq i < k} c^i \cdot (w_{q_i}^R + w_{q_i,q_{i+1}}^T)$$

Assume that c^i can retain the same value for a certain period of time, as long as η_i has not significantly changed.

	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9	n_{10}
c^i	1	1	2	3	1	2	1	1	2	2

The network graph is shown in Fig 1(b), where $c^i \cdot w_i^R$ is marked next to node n_i and $c^i \cdot w_{i,j}^T$ is marked on the directed link from n_i to n_j. Only links that are used in communication are shown. Listed below are LCP, P_i, and their corresponding cost, ϕ_i, from each sensor node n_i , without or with assistance of the foreign networks, to the basestation n_0, respectively:

network $\mathcal{E}_1$				
n_i	via $\mathcal{E}_1$ only	cost	via $\mathcal{E}_1$ or $\mathcal{E}_2$	cost
n_1	(n_1, n_0)	9	no change	9
n_2	n_2, n_1, n_0	40	no change	40
n_3	(n_3, n_2, n_1, n_0)	72	(n_3, n_8, n_1, n_0)	55
n_4	(n_4, n_1, n_0)	97	(n_4, n_7, n_1, n_0)	54
n_5	unavailable	∞	$(n_5, n_{10}, n_2, n_1, n_0)$	117
-	total cost excluding n_5	218	total cost excluding n_5	158

network $\mathcal{E}_2$				
n_i	via $\mathcal{E}_2$ only	cost	via $\mathcal{E}_2$ or $\mathcal{E}_1$	cost
n_6	(n_6, n_0)	22	no change	22
n_7	(n_7, n_6, n_0)	48	(n_7, n_1, n_0)	29
n_8	(n_8, n_6, n_0)	59	(n_8, n_1, n_0)	30
n_9	(n_9, n_7, n_6, n_0)	86	(n_9, n_7, n_1, n_0)	67
n_{10}	$(n_{10}, n_9, n_7, n_6, n_0)$	118	(n_{10}, n_2, n_1, n_0)	86
-	total cost	333	total cost	234

For $\mathcal{E}_1$ without counting n_5, the total cost of all paths via $\mathcal{E}_1$ is 218, and is reduced to 158 with routing via both $\mathcal{E}_1$ and $\mathcal{E}_2$. For $\mathcal{E}_2$, the total cost of all paths via $\mathcal{E}_2$ is 333, and is reduced to 234 with routing via both $\mathcal{E}_1$ and $\mathcal{E}_2$. Here, sensor n_5 cannot be routed to n_0 since none of other nodes in $\mathcal{E}_1$ is within 50-meter range. With assistance of n_{10} from network $\mathcal{E}_2$, n_5 can be reached. All together, payments and utilities resulted from routing assistance of foreign networks are listed in Fig 2. For LCP_5 with respect to n_{10}, there is no $SLCP_5^{10}$. Thus the WTP of 70 is used for payment. The computation is based on that every node i will reveal its real cost c^i as its strategy a^i. If a node on the LCP attempts to reveal $a^i > c^i$, e.g., n_1 on the (n_8, n_1, n_0) publishes $a^{1'} = 2.5$ ($c^1 = 1$, actually), it may lose its competition to path (n_8, n_6, n_0) and its utility becomes zero. On the other hand, if a node is eager for competition by revealing $a^i < c^i$, e.g., n_1 publishes $a^{1'} = .5$ ($c^1 = 1$, actually), it may win its competition as the (n_6, n_1, n_0), but its utility turns out to be negative. Therefore, the MDC is incentive compatible and nodes will reveal their true costs.

It is assumed that every agent has incentive to receive the payment as long as its utility is positive. Here, payment is an abstract concept. It does not necessarily imply currency rewarded or a real billing system. A credit scheme could be established. In an InterSensorNet, payment might mean the earned credit that network $\mathcal{E}_1$ can use to request routing services from network $\mathcal{E}_2$ such as in case of n_5. Thus, the credit can be used to exchange service and the service can be mutually profitable.

A network that requests service wants to reduce its cost. This cost including its own cost $\rho_s\{a^F = 0\}$ and the payment p_s^F to other networks should be less than the cost via its local network. However, the existing mechanism design does not guarantee this. It is only true when there is one and only one foreign node $n_F \in \text{LCP}_s$.

Lemma 1: Given a sensor node n_s and its least cost path LCP_s, if there is one and only one foreign node $n_F \in LCP_s$, assume ϕ_z is the cost of the LCP z for n_s via its local network only, $\phi_v = \rho_s\{a^F = 0\}$ is the cost of LCP_s without counting the routing cost of n_F, and p_s^F is the payment to n_F, then, $\phi_v + p_s^F \leq \phi_z$.

Proof: When a path routes data via n_F in a foreign network, since $\phi_v = \rho_s\{a^F = 0\}$ and $p_s^F = \rho_s\{a^F = \infty\} - \rho_s\{a^F = 0\}$, $\phi_v + p_s^F = \rho_s\{a^F = \infty\}$, which is the cost of $SLCP_s^F$. If the $SLCP_s^F$ contains no foreign node, $\rho_s\{a^F = \infty\} = \phi_z$; otherwise,

n_s	LCP_s	ρ_s	Payment and Utility						
			$i \in P_{LCP_s}$	$SLCP_s^i$	$\rho_s\{a^i = \infty\}$	$\rho_s\{a^i = 0\}$	p_s^i	v_s^i	u_s^i
n_1	(n_1, n_0)	9	-	-	-	-	—	-	-
n_2	(n_2, n_1, n_0)	40	-	-	-	-	—	-	-
n_3	(n_3, n_8, n_1, n_0)	55	n_8	(n_3, n_2, n_1, n_0)	72	34	38	-21	17
n_4	(n_4, n_7, n_1, n_0)	54	n_7	(n_4, n_6, n_0)	96	34	62	-20	42
n_5	$(n_5, n_{10}, n_2, n_1, n_0)$	117	n_{10}	unavailable	∞	85	70 (WTP)	-56	14
n_6	(n_6, n_0)	22	-	-	-	-	—	-	-
n_7	(n_7, n_1, n_0)	29	n_1	(n_7, n_6, n_0)	48	10	38	-19	19
n_8	(n_8, n_1, n_0)	30	n_1	(n_8, n_6, n_0)	59	11	48	-19	29
n_9	(n_9, n_7, n_1, n_0)	67	n_1	(n_9, n_7, n_6, n_0)	86	48	38	-19	19
n_{10}	(n_{10}, n_2, n_1, n_0)	86	n_1	$(n_{10}, n_9, n_7, n_6, n_0)$	118	67	51	-19	32
			n_2	$(n_{10}, n_9, n_7, n_1, n_0)$	109	55	54	-31	23

Fig. 2. Payment and utility for Scenario 1.

the $SLCP_s^F$ is chosen due to its lower cost, thus $\rho_s\{a^F = \infty\} < \phi_z$. Therefore, $\phi_v + p_s^F = \rho_s\{a^F = \infty\} \leq \phi_z$. $\square$

Shown in this example, the cost of LCP_4 is $\rho_4 = 54$, where $n_7 \in P_{LCP_4}$ is the only foreign node, and $\phi_v = \rho_4\{a^7 = 0\} = 34$. The payment to n_7 is 62, thus $\phi_v + p_4^7 = 34 + 62 < 97$, where $\phi_z = 97$ is the cost of (n_4, n_1, n_0). However, it is different when more than one foreign node is on the path. For example, in path LCP$_{10}$, there are two foreign nodes, n_1 and n_2, with $\rho_{10} = 86$ and $\phi_v = 36$. The total payment is 105, since $p_{10}^1 = 51$ and $p_{10}^2 = 54$. Then the sum $36 + 105 > 118$, the cost of $(n_{10}, n_9, n_7, n_6, n_0)$. Though this *overpayment* problem does not effect the dominant strategy in this mechanism, it is not fair for some networks. It is possible to design a mechanism to eliminate this overpayment. A mechanism, *Recursive Payment Protocol*, could be applied to handle this problem [10].

With this mechanism, the power dissipation adapts to the energy level in each node automatically. The nodes with more energy tend to route more traffic and the others route less traffic. It optimizes the power usage and maximizes the life time of the entire network.

IV. MECHANISM DESIGN FOR DATA AGGREGATION

Instead of transmitting individual sensor data back to the basestation, data can be aggregated at sensor nodes to reduce the energy dissipation. For example, average radiation of an area can be obtained by aggregation. An aggregation tree is formed as a *Least Cost Aggregation Tree (LCAT)*. Each sensor has a tuple (*Data*,*Operation*). A node receives the tuples from its child nodes, if any, and performs the aggregation operation over these tuples plus its own tuple to produce a new tuple to be sent to its parent node. Finally, the basestation, as a root, receives an aggregated tuple from each of its child nodes. If a sensor node cannot be reached by its own network, nodes in a foreign network can offer assistance in constructing an aggregation tree. Nodes in a foreign network could also assist configuration of a less expensive aggregation tree. It is an active method by including operators in the tuple so a node from foreign networks is able to perform aggregation as well. However, a foreign node will only receive tuples from its child nodes, apply the aggregation, and send to its parent, without contributing its own tuple. This method also can be used in applications such as beamforming [11], [12].

Mechanism for Data Aggregation (MDA) — The goal of the mechanism design is to minimize the total cost by designing a set of output and payment. In this case, the output is construction of a reverse minimum spanning tree. Node n_i's valuation is 0 if it is not part of the tree, and $-t^i$ if it is, where t^i is the cost of node n_i. To construct an aggregation tree T_x^k for network $\mathcal{E}_k$, P_x^k is defined as a set of t nodes, where $P_x^k \supseteq \mathcal{E}_k$ since every sensor node in $\mathcal{E}_k$ must be included by the aggregation tree T_x^k, and n_0 is always the sink of the tree. If there is no foreign node in T_x^k, $P_x^k = \mathcal{E}_k$. Every sensor node n_i is assigned a parent node q_i^x, and maintains a set of child nodes $H_i^x = \{n_j \mid q_j^x = i \text{ and } n_j \in P_x^k\}$. The cost of an aggregation tree T_x^k is defined as follows,

$$\gamma_x^k = \sum_{n_i \in P_x^k} a^i \cdot (w_{i,q_i^x}^T + \theta_i^x \cdot w_i^R)$$

where, $\theta_i^x = |H_i^x|$, representing the number of child nodes n_i has. The least cost is defined as $\Gamma^k = \gamma_z^k$ such that tree T_z^k is the *least cost aggregation tree LCAT$_k$* for $\mathcal{E}_k$. As mentioned previously, a sensor node provides aggregation service for its local network by obligation; whereas, a sensor node provides aggregation service for a foreign network only based on its profits to be obtained. Therefore, for the least cost aggregation tree $LCAT_k$ of network $\mathcal{E}_k$, the payment is calculated as follows for every foreign node $n_i \in LCAT_k$:

$$p_k^i = \begin{cases} \Gamma^k\{a^i = \infty\} - \Gamma^k\{a^i = 0\} & \text{if } n_i \in LCAT_k \text{ and } n_i \notin \mathcal{E}_k \\ 0 & \text{otherwise} \end{cases}$$

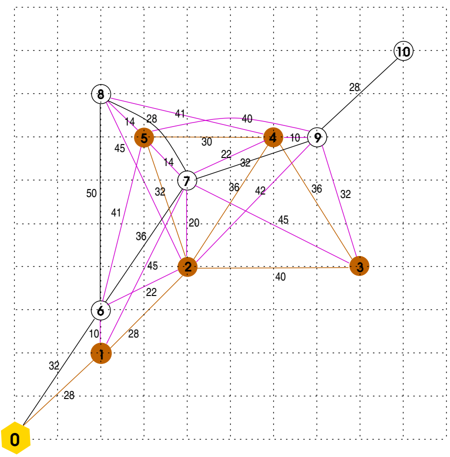
where, $\Gamma^k\{a^i = \infty\}$ and $\Gamma^k\{a^i = 0\}$ are the modified cost of $LCAT_k$ when n_i claims an infinite charge and a free charge, respectively. When $a^i = \infty$, the modified least cost aggregation tree is denoted as $SLCAT_k^i$, the *second least cost aggregation tree* with respect to n_i. The valuation is computed as $v^i = -t^i$ and the utility is $u^i = v^i + p^i$. Similar to MDC, the mechanism MDA is strategyproof. The following example is used to illustrate how an efficient aggregation tree can be built with the mechanism design approach.

Scenario 2: Fig 3 shows a network map for data aggregation, on a $100m \times 100m$ map with a basestation n_0 at (0,0). Two sensor networks have been deployed, network $\mathcal{E}_1$ including nodes $\{n_1, n_2, n_3, n_4, n_5\}$, and network $\mathcal{E}_2$ including nodes $\{n_6, n_7, n_8, n_9, n_{10}\}$. The cost function is the same as in Scenario 1. The current values of c^i are shown in Fig 3 as well.

Two aggregation trees without assistance from the foreign networks are shown in Fig 4(a); The other two trees with

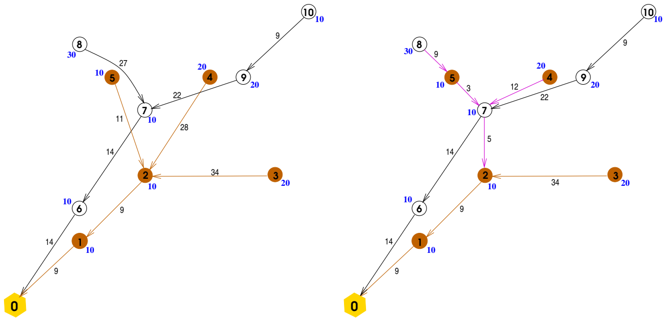
$\mathcal{E}_k$	$LCAT_k$	Γ^k	Payment and Utility						
			$i \in \text{LCAT}_k$	$SLCAT_k^i$	$\Gamma^k\{a^i=\infty\}$	$\Gamma^k\{a^i=0\}$	p_k^i	v_k^i	u_k^i
$\mathcal{E}_1$	$(n_1,n_2,n_3,n_4,n_5,n_7)$	122	n_7	(n_1,n_2,n_3,n_4,n_5)	131	97	34	-25	9
$\mathcal{E}_2$	$(n_5,n_6,n_7,n_8,n_9,n_{10})$	131	n_5	(n_6,n_7,n_8,n_9,n_{10})	136	118	18	-13	5

Fig. 5. Payment and utility for Scenario 2.



	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9	n_{10}
c^i	1	1	3	2	1	1	1	3	2	1

Fig. 3. Scenario 2 illustrating data aggregation.



(a) Via local networks only **(b)** Via local or foreign networks

network $\mathcal{E}_1$							
T_x^1 via $\mathcal{E}_1$ only				LCAT_1 via $\mathcal{E}_1$ and $\mathcal{E}_2$			
n_i	q_i^x	θ_i^x	cost	n_i	$q_i^{LCAT_1}$	$\theta_i^{LCAT_1}$	cost
n_1	n_0	1	19	n_1	n_0	1	19
n_2	n_1	3	39	n_2	n_1	2	29
n_3	n_2	0	34	n_3	n_2	0	34
n_4	n_2	0	28	n_4	n_7	0	12
n_5	n_2	0	11	n_5	n_7	0	3
				n_7	n_2	2	25
γ_x^1			131	Γ^1			122

network $\mathcal{E}_2$							
T_y^2 via $\mathcal{E}_2$ only				LCAT_2 via $\mathcal{E}_2$ and $\mathcal{E}_1$			
n_i	q_i^y	θ_i^y	cost	n_i	$q_i^{LCAT_2}$	$\theta_i^{LCAT_2}$	cost
n_6	n_0	1	24	n_6	n_0	1	24
n_7	n_6	2	34	n_7	n_6	2	34
n_8	n_7	0	27	n_8	n_5	0	9
n_9	n_7	1	42	n_9	n_7	1	42
n_{10}	n_9	0	9	n_{10}	n_9	0	9
				n_5	n_7	1	13
γ_y^2			136	Γ^2			131

(c) The itemized cost of all four aggregation trees

Fig. 4. Aggregation trees of Fig 3.

assistance from the foreign networks are shown in Fig 4(b). The cost of all of the four aggregation trees are itemized in Fig 4(c). The cost of the trees is reduced from 267 to 253. Next, payments and utilities resulted from aggregation assistance of foreign networks are listed in Fig 5.

V. CONCLUSION

The InterSensorNet scheme has been introduced in this paper which provides a framework for future sensor networks. The mechanism design provides incentives for the InterSensorNet. Future works include the analysis of protocol complexity and communication overhead, initial credit, and other practical issues.

Though only the routing and aggregation problems have been considered in this paper, the similar approach can be applied to other problems such as location services and topology controls. Another important issue to be addressed in the InterSensorNet is that different sensornets may have different data formats and semantics. Thus, dynamically generated semantic tags will be useful to retrieval, aggregate, and understand the information generated by the sensors.

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