This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the WCNC 2009 proceedings.

VStore: Towards Cooperative Storage in Vehicular Sensor Networks for Mobile Surveillance

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Abstract—**Currently, vehicles are equipped with forward facing cameras to assist the forensic investigations of events by proactive image capturing from streets and roads. With content redundancy and storage imbalance in this in-network distributed storage system, how to maximize its storage capacity is a challenge. In other words, how to maximize the average lifetime of sensory data (i.e. images generated by cameras) in network is a fundamental problem need to be solved. This paper presents, *VStore*, a cooperative storage solution for mobile surveillance in vehicular sensor networks (*VSN*). The mechanisms in VStore are designed for redundancy elimination by exchanging information between vehicles and storage balancing. Compared with previous work, we deal with new challenges in mobile scenario. Field testing was carried out on a real-trace driven simulator, which utilizes about 500 taxies in Shanghai city. The testing results show that VStore can largely prolong the average lifetime of sensory data by cooperative storage.**

Keywords-Vehicular sensor networks; cooperative storage; mobile surveillance; data redundancy; storage balancing;

I. INTRODUCTION

Conventional infrastructures have involved using static sensors for surveillance in city urban areas, which are limited in spatial coverage. An exciting new infrastructure for mobile surveillance, named *Vehicular **S**ensor Network* (***VSN***) [10], is a network of mobile sensors equipped on vehicles, such as taxies and buses. VSNs facilitate collection of surveillance data over a wider area than the fixed infrastructure. Meanwhile, unlike traditional wireless sensor networks, vehicular sensors are typically not affected by strict energy constraints and vehicles can be equipped with powerful processing units and wireless transmitters.

Currently, with the inclusion of forward facing cameras mounted on vehicles, there is an increasing interest in proactive urban sensing where vehicles continuously capture images from streets and maintain the sensory data (i.e. images generated by cameras) in their local storage. It can assist the reconstruction of crimes and, more generally, the forensic investigations of events monitored by VSN, such as traffic accidents [12]. Actually, this architecture can be also regarded as an in-network distributed storage system [7]. Different from conventional sensor networks, it is unfeasible to deliver all the image data to sink because of sheer volume. Moreover, input filtering is impossible because nobody knows which data will be of use for future investigations in advance. In this system, when vehicle has no storage, the fresh image data will replace the oldest data in time series by FIFO strategy. With content redundancy and storage imbalance by repeated sensing between vehicles, a primary concern of VSN for mobile surveillance becomes that of maximizing storage capacity of network. In other words, how to maximize the average lifetime of sensory data in network is a fundamental problem because also no knowledge tells us when data will be useful for possible investigations in advance. In addition, despite non-volatile storage prices will no doubt reduce, we still need to optimize for storage management in VSN. For example, a camera operating at 768x288 (2CIF) resolution and five frames per second can generate approximately 8.6Gb data per day, which will run out of 40GB storage in five days [11].

In this paper, we present ***VStore***, a cooperative storage system in vehicular sensor networks for mobile surveillance. VStore is designed to maximize the average lifetime of image data in network against data redundancy and storage imbalance between vehicles. The main challenges of VStore are enumerated below. First, multiple vehicles running on the same road incurs data redundancy because of repeated image capturing. Meanwhile, high speed of vehicle and dynamic topology make task assignment and negotiation between vehicles difficult. Second, in previous work, the forward facing cameras are always set with fixed sampling rate, inevitably implying ineffective storage utilization. For example, if a vehicle stops for traffic light or runs at very low speed in traffic jam, it should reduce the sampling rate to avoid unnecessary sensing. VStore needs to design an adaptive sampling strategy based on current status of vehicles, such as speed, direction, etc. Finally, discrepancy of driving behaviors between vehicles may cause some vehicles to overflow their storages while others still have available storage spaces. Hence, VStore must balance image data across vehicles to make most use of storage.

The rest of the paper is organized as follows. Section II discusses related work. In Section III, we present the VStore in details. The performance evaluation is presented in Section IV. Section V concludes the paper.

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II. RELATED WORK

Recent years, many techniques have been proposed for disseminating sensing data [1], such as Data-Centric Storage (DCS) that related detections are stored at predefined locations in the network. Geared for application of mobile surveillance in our work, VStore has a completely different focus. That is, the sensory image data is always stored in local storage because whether it will be of use is unknown in advance. VStore mainly focuses on maximizing the storage capacity by cooperative storage. Thus, traditional DCS incurs considerable and unnecessary communication overhead by transferring data from source to storing node.

Several other storage services also have been paid much attention for wireless sensor networks. Work in [2] introduced a two-tier data-centric storage and retrieval service using distributed hash table and double-ruling. PRESTO [3] and TSAR [4] proposed a two-tier data storage architecture comprising sensor nodes and proxies for data acquisition and query processing. DIMENSION [5] is designed to store long-term information by constructing summaries at different spatial resolutions using various compression techniques. TinyDB [6] organizes sensor networks and their collected data as a distributed database and focus on query processing techniques to acquire data from such databases. EnviroStore [7] is a new cooperative storage system for sensor networks geared for disconnected operation. The goal of the system is to maximize its data storage capacity by appropriately distributing storage utilization and opportunistically offloading data to external devices when possible. EnviroMic [8] is a novel distributed acoustic monitoring, storage, and trace retrieval system. It is also designed for disconnected operation, where the luxury of having a base station cannot be assumed. Different from previous work, our study is carried out in vehicular sensor networks. How to achieve cooperative storage in mobile scenario are largely untapped in previous work.

In addition, a number of works have studied vehicular sensor networks [9][10][11][12]. A survey on wireless multimedia sensor networks can be found in [9]. MobEyes is an effective middleware specifically designed for proactive urban monitoring, that exploits node mobility to opportunistically diffuse sensed data summaries among neighbor vehicles and to create a low-cost index to query monitoring data [10]. Compared with MobEyes, VStore in our work contributes to maximizing the average lifetime of sensory image data whereas MobEyes is dedicated to the query processing. S.Greenhill et.al proposed mobile surveillance system by employing the cameras on buses [11][12]. They first introduced a distributed query processing method by utilizing GPS track as index to upload on-demand data to the sink when buses return to depot [11]. In another work, they paid more attention on the multimedia information processing of video stream data [12].

III. COOPERATIVE STORAGE IN VSTORE

A. Network model

In this paper, a vehicular sensor network for mobile surveillance is modeled as a set of $\boldsymbol{n}$ mobile vehicular nodes, denoted as a set $\boldsymbol{V} = \{v_1, v_2, \ldots v_n\}$ and every vehicle node has an individual id *v_id*. Meanwhile, it is assumed that every node was equipped with GPS device, digital map of city, 54Mbps 802.11g wireless transmitter, one forward facing camera and storage device. Similar assumption can be found in related work [10][11][12]. The wireless transmitter has a communication range *cr* such that two nodes *u* and *v* can communicate directly if $|u\text{-}v| \le cr$ and there is no other interference. Here $|u\text{-}v|$ is the Euclidean distance between *u* and *v*. Moreover, the available bandwidth and storage space on every node are limited but not energy because it is practical to assume infinite energy provided by vehicle. Node-meeting is assumed to be short-lived because of the high speed of node. Formally, a VSN consists of a node-meeting schedule, which is a directed multi-graph G=(V,E), where V and E represent the set of nodes and edges respectively. Each directed edge e between two nodes represents a node-meeting between them. In addition, every node can obtain the locations of other nodes at any time from a centralized location service by using GPS device, which is a common assumption in the position-based routing protocols [14] [15] [16].

The road network of Shanghai is large-scale and of high complexity, with thousands of links and intersections. A road network consists of a set of roads embedded in a predefined geographical region, such as metropolitan of Shanghai. A ***link*** with a link id (denoted as *l_id*) is a road section between two intersections (called ***point,*** also with a node id *p_id*). More specially, for a particular link, one intersection point connected with it is named *fpoint* of this link, the other is named *tpoint*, and this information is already stored in the digital map. Note that, for a particular intersection point, it can be the fpoint of a link and simultaneously the tpoint of another link. A ***road*** consists of several ordered links, but all of them share the same symbolic road name [17].

B. Problem definition

In this section we introduce some definitions in VStore.

Definition 1 (*Maximum photographic distance*):

With the forward facing camera, a node could proactively capture images from links. The camera, however, often has a limited field of vision. That is, it only can generate a high quality image for limited distance in front of the vehicle. This parameter is named as *maximum photographic distance*, denoted as *mpd*, as shown in Figure 1. How to regulate the orientation of camera for capturing image and how to deal with the multimedia information processing are another issues, related work can be found in [11][12]. In addition, we mainly focus on mobile surveillance for links. For the intersection regions, we consider that the traditional fixed cameras could assist for this purpose.

For a particular *mpd*, at every recording point the node will capture an image with generates an image file. For example, as shown in Figure 1, if a node enters into the link l_i by fpoint, it will capture images at points *a*, *b*, *c*, *d* and *e*. Conversely, if it enters by tpoint, the images will be captured at points *f*, *e*, *d*, *c* and *b* in sequence. For every segment between two recording points, we assign a segment id in increasing order from fpoint to tpoint, denoted as *s_id* (e.g., *s_id* from 1 to 5 in Figure 1). Normally, every segment is *mpd* meters long, except for the last segment of the link because the length of link is not always integral times of *mpd* (e.g., Segment 5 in Figure 1). By combining with GPS device and digital map, vehicles can conveniently calculate the locations of recording points according to its current running route.

Definition 2 (*Attributes of image file*):

In general, we define a term of attributes for every image file by a 5-tuple:

Attrib(*l_id*, *s_id*, *timestamp*, *ti*, *v_id*)

where (*l_id*, *s_id*) indicates the source of a image, *timestamp* and *v_id* show when and which node captured this image. *ti* is a counter and defined as:

$$ti = t / \tau \quad \textbf{(1)}$$

where t is the time duration from time 0 (the start time of our simulation) to current time. τ is the predefined configurable parameter, named *valid time*, that for a particular segment, two images are regarded as same if the difference of their *timestamps* is smaller than τ. With time synchronization by utilizing GPS device, we calculate *ti* by the following criterion. Two images im_i and im_j are same when their attributes $Attrib_i$ and $Attrib_j$ satisfy:

$$Attrib_i.l\_id = Attrib_j.l\_id \wedge Attrib_i.s\_id = Attrib_j.s\_id \wedge Attrib_i.ti = Attrib_j.ti \quad \textbf{(2)}$$

In addition, for different surveillance purposes, we can regulate τ with different values. As an example, when we want to monitor the traffic condition, it is reasonable to set τ with 10 minutes because traffic flow always does not have a considerable change in a short time.

Definition 3 (*Metadata of node*): For every node, it holds a metadata table for all nodes in the network, one item in the metadata table is represented as follows:

Metadata(*v_id*, *rs*, *updatedTime*),

It shows the remaining storage space of node *v_id* is *rs* and this item is updated at time *updatedTime*. When two nodes meet, they always exchange their metadata tables and update corresponding items with latest *updatedTime*.

Definition 4 (*Redundancy ratio*): For a given VSN with *n* nodes, by using Equation (2), we define the redundancy ratio *rr* of the network at time *t* as:

$$rr(t) = \frac{\sum_{i=1}^{n} |S_i(t)| - |\bigcup_{i=1}^{n} O_i(t)|}{\sum_{i=1}^{n} |S_i(t)|} \quad \textbf{(3)}$$

where $S_i(t)$ is the multi-set of image files generated by node v_i during [0, *t*] and $|S_i(t)|$ is the size of this multi-set. $O_i(t)$ is the set of different image files generated by node v_i during [0, *t*] and $|O_i(t)|$ is the size of this set. Note that, a multi-set can contain same elements whereas a set only includes individual elements. This metric indicates the redundancy degree of image files in the network, the higher *rr(t)* is, the more storage space will be wasted.

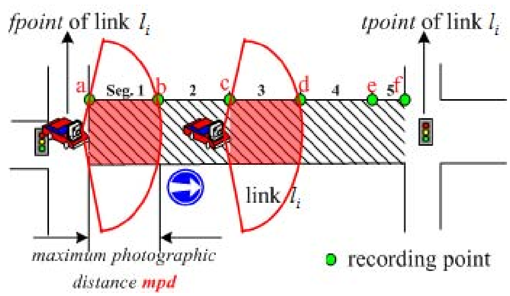


Figure 1. The illustration of maximum photographic distance

Definition 5 (*Average lifetime*): For image files, the average lifetime in the network at time *t*, denoted as Ω(t), is defined as:

$$\Omega(t) = (\sum_{i=1}^{n} f(i)) / n \quad \textbf{(4)}$$

where *f(i)* is a function that calculates the earliest *ti* of image files carried by node v_i. Average lifetime Ω(t) indicates average time duration that an image file can stay in the network. With the limited storage and FIFO replacement strategy, so VStore aims to maximize Ω(t).

C. Cooperative storage in VStore

In this section, we present ***VStore***, a cooperative storage system in vehicular sensor networks for mobile surveillance. Two sub-mechanisms aiming to maximize storage capacity of VSN are introduced in details.

1) Cooperative recording and redundancy elimination: Cooperative recording refers to capturing images from links and keeping unique image files in the network based on Equation (2). Here, an inherent assumption is that the same link segment can be recorded by more than one node during a same time interval *ti*. To attain cooperative recording in mobile scenario, first we review the related work in static wireless sensor work, where energy-efficiency is a critical issue. In static wireless sensor networks, when multiple nodes are sensing the same event simultaneously, they always form a group. Then the group members coordinate to elect a leader, who finally assigns the task to one of the members[8]. In our work, however, it is infeasible to carry out this negotiation process because of high speed of nodes and dynamic topology. Meanwhile, it is impossible to allocate tasks in advance because we do not know the routes of vehicles. Based on such characteristics of vehicular sensor networks for mobile surveillance, we propose a new approach for cooperative recording. That is, for every node, it first captures images from links, and then whether it should delete these image files for redundancy elimination depending on exchanging information with other nodes. To be more precise, when a node generates one image files, it also creats a tag for this file including the attributes as in Definition 2. When two nodes meets, they first exchange their tags of images and metadata of nodes (as in Definition 3) in terms of *metadata packet* and retain a copy for new tags, then they execute the redundancy elimination by the following principle: for a image file im_i and a tag Tg_j carried by node v, v will delete im_i when:

$$Attrib_i.l\_id = Tg_j.l\_id \wedge Attrib_i.s\_id = Tg_j.s\_id \wedge Attrib_i.ti = Tg_j.ti \wedge Attrib_i.\ timestamp < Tg_j.\ timestamp \quad \textbf{(5)}$$

To avoid the tag storm due to flooding, every tag has its own *TTL* (*Time-To-Live*). When the tag runs out of its TTL, it will be eliminated from the network, including all the copies of this tag.

2) Distributed storage balancing:

In our work, several reasons account for the storage imbalance. As mentioned above, node generates image files from links at every recording point. Compared with previous work [10] [11] [12], which always assume that sensors are set with fixed sampling rate, the sampling scheme in VStore can largely reduce the excessive and unnecessary sensing. In fact, by utilizing GPS, the forward facing camera can adapt its sampling rate based on current driving status. The adaptive sampling rate ¢ can be defined as:

$$¢ = 1/(mpd/spd) = spd/mpd \quad \textbf{(6)}$$

where *spd* is the current speed of vehicle. That is, *spd* will impact the sampling rate of the camera, which also leads to storage imbalance because of various driving behaviors between vehicles.

VStore needs to migrate data from highly utilized to less utilized storage space between nodes in order to improve overall storage capacity. In traditional static sensor works [7], researcher always adopt the lazy-offload scheme in order to save energy by postponing data balancing until the latest possible time. This is not applicable in proactive sensing in vehicular sensor work because the image files are generated continuously in the network. Thus, infrequent storage balancing implies potential networks congestion because of data transferring of sharp volume. On the other hand, in previous work, node first decides whether it needs to offload, and then chooses a neighbor with large remaining storage space to migrate data. This approach is also not applicable in our work because vehicles often keep running, the highly dynamic topology makes neighbor selection useless. Even if choosing an appropriate neighbor with large remaining storage, however, limited connection time and bandwidth still cannot guarantee the data transferring. Based on this discussion, we propose that the node in VSN should offload data as soon as it needs. More precise, in VStore, when node v encounters node u with establish a connection, v decides to migrate image data to u in terms of *image packet* when its remaining storage space satisfies the following condition.

$$rs_v = rs_{min} \wedge (rs_v < rs_u) \wedge (rs_u - rs_v > \alpha \times rs_v) \quad \textbf{(7)}$$

where rs_v and rs_u are the remaining storages spaces of node v and u, respectively. rs_{min} is minimum remaining storage space in node v's metadata table of nodes and their *updatedTimes* are close to the current time (We set 5 minutes in our work). α is the configurable parameter which determines how sensitive nodes are to storage imbalance. We do not utilize adaptive sampling rate ¢ of the camera in storage balancing because we found that frequent changes of driving status incur the instability of ¢. The amount of data to be transferred from v to u, denoted by D_{vu}, is simply defined as (node chooses data to be transferred from oldest to fresh in time series):

Table I: Default experiment parameters

Focused Area	50 km^2
Simulation Time Duration	3600 s
Number of Taxies (*n*)	500
Communication Range (*cr*)	100 m
Max. Photographic dist.(*mpd*)	30 m
Valid Time (τ)	60 s
TTL of Tag (*TTL*)	60 s
Packet Size	256 KB
Bandwidth	2.5 MB/s
Storage Size on Every Node	250 pkts

$$D_{vu} = (rs_u - rs_v)/2 \quad \textbf{(8)}$$

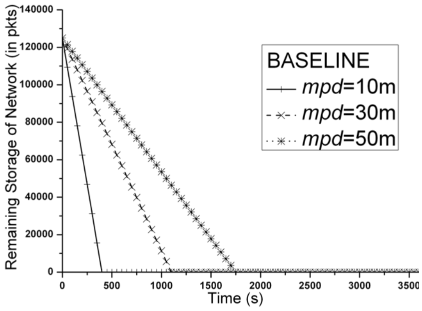
In summary, nodes in VStore first exchange metadata of nodes and tags of image files in terms of metadata packet during a connection. Then, whether they need to offload data depends on their current remaining storage spaces by using Equation (7). In addition, when the storage is full, newest image files will replace the oldest files by FIFO.

IV. PERFORMANCE EVALUATION

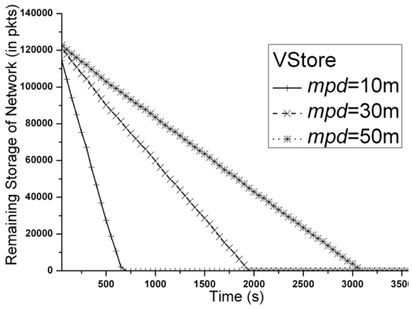
The primary goal of VStore is to maximize the storage capacity. Two mechanisms in VStore are already introduced in Section III. The one is the cooperative recording and redundancy elimination, and the other is the storage balancing. In this section, we present the performance evaluation of VStore.

A. *Experimental setup*

The testing is based on a real-trace driven simulator. We compare VStore with BASELINE, which is without cooperative storage scheme of VStore. In BASELINE, it is assumed that vehicles only do proactive sensing and store image files in their local storages. Table I lists some properties of tested area and the default parameters used for all the experiments in our simulation. We set the values of the experimental parameters based on field testing in Shanghai urban area, such as maximum photographic distance, communication range, etc. For example, in our simulations, the forward facing cameras are set with maximum photographic distance of 30m. Also, we consider that *valid time*=60s is enough for mobile surveillance. We set bandwidth=2.5 MB/s as used in [11], which said a 54Mbps 802.11g wireless link is available but in practice the effective payload throughput is about 20 Mbps. Meanwhile, we predict some real technology will support higher bandwidth and communication range requirement soon. The packet size is assumed constant 256KB for simplicity in our testing including metadata packet and the image packet (we assume every image captured by camera is 800x600, JPEG, less than 256KB, thus one image can be transferred as one image packet). Moreover, compared with the large image file, the tag of image



(a)



(b)

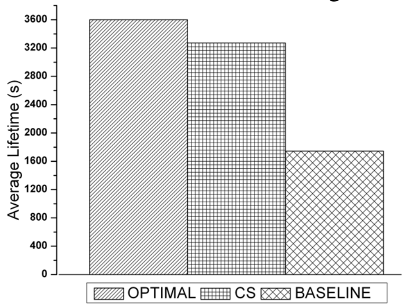
Figure 2. (a) The storage space occupancy in BASELINE. (b) The storage occupancy in VStore

and the metadata of node are much smaller, which can be only tens of bytes. In our work, every tag is 40 bytes including the related attributes of the image file as in Definition 2. Each item in metadata table of nodes is 20 bytes as in Definition 3. Each data point in all figures is averaged over 20 runs. In addition, as mentioned above, we assumed that every node can obtain the location of other nodes at any time from a centralized location service, which is similar with other position-based routing protocols [14][15][16]. Thus, the overhead for calculating the locations can be neglected.

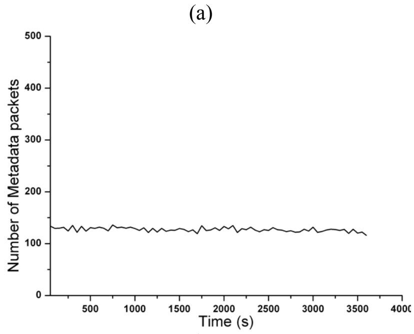
B. *Experiment results*

To illustrate how VStore maximizes storage capacity via redundancy elimination and storage balancing, Figure 2 first plots remaining storage changes over time between BASELINE and VStore (Initially, the network has storage capacity of 250×500=12500 packets, 500 nodes, every one has storage capacity of 250 packets). As can be seen in Figure 2(a) and (b), for all values of *mpd*, VStore significantly delays network storage saturation time. For example, with *mpd*=30m, the time of storage saturation is delayed from time 1089s in BASELINE to 1947s in VStore. Meanwhile, it is shown that as the *mpd* decreases, both BASELINE and VStore have higher storage consumption rate. The underlying reason is that from the Equation (6), for a particular *spd*, the sampling rate becomes higher with *mpd* decreasing, which incurs more image files to be generated in the network.

For the average lifetime of image file in the network, we present the comparison in Figure 3(a). We used VStore with the infinite storage on every node as an OPTIMAL mechanism. Thus, all the image files can be



(a)



(b)

Figure 3. (a) The average lifetime of three mechanisms. (b)

Communication overhead of exchanging metadata packet, including tags and metadata of nodes.

stored in the network without data loss due to the storage overflow. As shown in Figure 3(a), we calculate the average lifetime Ω(3600) by Equation (4). Oblivious, the OPTIMAL can bring average lifetime of packet to 3600s because of infinite storage capacity. Meanwhile, the average lifetime of image file in VStore can be 3272s, about 90.8 % of the ideal average lifetime in OPTIMAL. Note that, such performance is based on the limited storage capacity in VStore. BASELINE, however, performs worst in three mechanisms, the average lifetime of packet is only 1744s. That means, when t=3600, the network can only store images which were generated during [1856s, 3600s]. The images generated during [0s, 1855s] were already deleted because of FIFO replacement. Based on above analysis, we demonstrate the effective cooperative storage capacity of VStore to prolong the average lifetime of image file in the network. We also explore the communication overhead of spreading tags and metadata between nodes in terms of metadata packet. The number of metadata packet sent per second by the sensor nodes is plotted in Figure 3(b). As shown, the total number of metadata packet sent per second is about 125.7 on average, in other words, for one node is 0.25 packet/s, which is acceptable for vehicular sensor networks. The metadata packet only uses a fraction of bandwidth for redundancy elimination and metadata exchanging between nodes.

V. CONCLUSION

In this paper, we proposed *VStore*, a cooperative storage solution for mobile surveillance in vehicular sensor networks (*VSN*). The critical issue is how to maximize storage capacity of the network, i.e., maximize the lifetime of sensory data in the network by cooperative storage. Compared with previous work, we deal with new challenges in mobile scenario. With proactive sensing by forward facing cameras equipped on vehicles, nodes in VStore first capture images from links and then eliminate redundancy by exchanging tags of images. Meanwhile, VStore also includes a storage balancing mechanism to offload data from heavy load nodes to light load nodes. We carried out our testing on a real-trace driven simulator. Our results show that VStore can largely prolong the average lifetime of the image data in the network by redundancy elimination and storage balancing. Nearly 80% reduction of redundancy ratio can be achieved, which enables the average lifetime of image file to increase more than 76 %.

ACKNOWLEDGMENTS

This research was partially supported by Natural Science Foundation of China grant No.60573138 and 60773091, the National Grand Fundamental Research 973 Program of China under Grant No.2006CB303000, the National 863 Program grant No.2006AA01Z247, and National Science Foundation of USA grant CNR-0626380.

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