CERIAS Tech Report 2006-56

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by David K. Y. Yau, Jennifer C. Hou, Shankar Mallikarjun

Center for Education and Research in
Information Assurance and Security,
Purdue University, West Lafayette, IN 47907-2086

Systems Support for Radiational Plume Detection, Identification, and Tracking Sensor-cyber Networks

David K. Y. Yau†, Jennifer C. Hou‡, Shankar Mallikarjun*, and Nageswara S. Rao*
† Dept. of Computer Science, Purdue University, yau@cs.purdue.edu
‡ Dept. of Computer Science, University of Illinois at Urbana Champaign, jhou@cs.uiuc.edu
∗ Oak Ridge National Laboratories, {shankarm,raons}@ornl.gov

1 Introduction

Oak Ridge National Lab (ORNL), University of Illinois at Urbana Champaign (UIUC), and Purdue University are collaborative partners in a sensor-cyber network project (http://www.sensornet.org) supported under the national SensorNet Initiative. The project aims to design, realize, evaluate, and deploy a detection, identification, and tracking sensor cyber network (DITSCN) for chemical and radiational plumes. The current focus is on building a system of radiation sensors inter-connected by wireless links for detecting the presence of radioactive materials, identifying the radiation source, and tracking their propagation over time. The resulting networked system of sensors, if proven to be effective, will be deployed in important facilities and along highways to detect low level radioactivity corresponding to, for example, dirty bombs being carried in moving vehicles.

The working system consists of the following major components:

- **Sensors for detecting radioactive materials.** We have mainly used the RAD-7001 radiation sensors by Yankee Environmental System Inc., because of their good sensing ranges and sensitivities, and their ability to detect alpha, beta, and gamma radiation. The RAD-7001 sensor will be supplemented by lower-cost GE-10 and GE-45 sensors in certain situations to provide fine-granularity sensing capabilities.
- **Wireless networks for data communication.** We are in the process of testing a variety of network configurations, from wireline connections, to single hop wireless communication under the control of a concentrator device, to multihop wireless communication that can extend network coverage in a clutter-free manner. Various communication technologies will be used depending on the testbed scenarios. For example, Crossbow motes attached to the GE-10 or GE-45 can provide a radio frequency (RF) or bluetooth interface. The TMS-7200 device, also from Yankee Environmental, can provide an FM interface for an adjoining RAD-7001. Wi-fi equipped laptops or palmtops can provide an 802.11x interface for a connected RAD-7001.
- **Cyber control center for data analysis and sensor tasking.** Collected sensor data are communicated to a cyber control center under given quality of monitoring (QoM) constraints. The cyber center then analyzes and infers, based on realistic dispersion models of plumes with respect to physical phenomena (e.g., terrain and weather effects), where the radiation source was, the trajectory of its movement (speed and direction), and the prediction on its future movement. The center also makes decisions on where to task and activate radiational sensors for their future sensing and communication activities. One important issue we will consider is whether or not, and to what extent, mote-based, palmtop-based, and/or laptop-based communication devices should participate in in-network processing of sensor data fusion/aggregation, taking into consideration of the tradeoff between the detection/predication accuracies and the computation/communication efficiencies.
- **Intelligence in the networked system of sensors.** Central to the notion of convergence of physical and cyber spaces is how intelligence in the networked system of sensors supports tasks such as spatio-temporal formation of ad-hoc communication groups, well-balanced data dissemination/reporting/fusion, and robust and temporally constrained communication over a multihop, un-reliable, best-effort wireless network. We are in the process of determining common denominator functions that should be available in the protocol stack to facilitate the above tasks, and will

(1) design, for each network configuration, light-weight network/MAC protocols, and (2) evaluate their performance in real environments.

2 Grand Challenges of Physical-Cyber Systems

To realize the envisioned DITSCN system, we have identified three grand challenges. Although the three challenges are discussed in the context of DITSCN, we believe that they are universal to the design, implementation, and eventual deployment of physical-cyber systems.

- **Convergence of physical and cyber spaces.**

  A DITSCN requires that the physical and cyber spaces be closely coupled, in the sense that (i) all the physical characteristics in the physical space should be transported to the cyber space in a timely fashion for judicious analysis and decision making in the cyber space; and (ii) the decisions made in the cyber space should be used to effect actions in the physical space, again in a timely fashion. These requirements must be made even within operational constraints imposed by the environment and by available resources. To achieve the convergence goal, we must address several technical issues. First, we must consider how sensors effectively gather data that characterize the physical space and deliver the most useful and relevant data to the cyber space, considering the given bandwidth, delay, and signal attenuation constraints. Tackling this technical problem boils down to resolving issues such as (i) spatio-temporal formation of ad hoc communication clusters whose data dissemination/fusion/aggregation actions must be coordinated in a distributed manner; and (ii) reliable and temporally guaranteed wireless communication of high-confidence data over un-reliable, best effort multihop wireless networks.

  Second, the issue of how the intelligence of the cyber space takes advantage of the sensor data to the maximum possible extent must be addressed. To tackle this problem, we must devise computationally efficient models that can accurately characterize the physical characteristics (to be detected/tracked). The necessary input to the models is then collected by tasking and activating sensors in a spatio-temporal optimal manner. The models should be so devised that they can accommodate adequate in-network processing for efficient communication.

  Third, the control center in the cyber space must task and activate sensors to collect high-quality, high-confidence data, taking into account of energy/computation budgets. Radiation sensors can operate at different sensing ranges and sensitivities, with the trade-off of higher capability settings versus higher energy requirements. Sensors that operate in the low-power mode can be activated along predicted pathways of plume propagation to facilitate future detection and predication. Similarly, sensors in areas with weak or ambiguous predicted data can be set at high sensitivities. More generally, sensors may support multiple sensing modalities (e.g., alpha, beta, and gamma detection), and the chosen modality should be the one expected to contribute the maximum information to the analytical problem at hand.

- **Acknowledging and Managing Uncertainty in the Cyber-physical space.**

  The physical space is deemed to behave non-deterministically, either by nature or due to the lack of complete and accurate information that characterizes it. The latter is due to the fact that the data communication process is inherently unreliable and the measurement error inevitably produces noise in data analysis. In addition, computationally-efficient models are very often simplified abstractions of complex physical phenomena. (For example, the detection of radioactive particles by a Geiger-Muller (GM) counter has been modeled as a Poisson process.) If certain physical characteristics that were initially benign and hence uncaptured or inaccurately represented in the model become manifest in a certain period of time, the inference results as dictated by the model may, in the extreme case, lead to singularity points where analytical models completely break down.

  While eliminating uncertainties in the measurement and inference process is intuitively appealing, we argue that acknowledging the existence of uncertainty and enabling the data dissemination/collection mechanisms, inference models, and decision making processes to deal with uncertainty in a robust fashion is perhaps more appropriate. Technical challenges that are yet to be tackled then include (i) How do we quantify uncertainty? (ii) How do we build uncertainty early into protocol designs and inference models and allow the use of possibly incomplete/inaccurate sensor data with measurement errors? For example, the density of sensors deployed in a monitor area affects the redundancy of the information gathered and consequently the system's ability to identify and remove statistical outliers. Positions of the sensors deployed, on the other hand, affect the spatial correlation of the sensor information gathered. Furthermore, the time instants at which sensors are scheduled to report readings affect the temporal correlation of the sensor information. How do we effectively determine the density and placement pattern of sensors and their sensing/communication schedules so as to reduce the susceptibility of inference results to uncertainty? (iii) How do we ensure that with the use of uncertainty management, the adverse effects of uncertainty can be eliminated or confined to an acceptable level?

- **Designing deeply embedded but open systems components.**

  An effective DITSCN must be intimately aware of its deployment environment, including both its physical and population aspects. From the physical aspect, a radiational plume model depends on parameters such as the absorption, propagation, and dispersion coefficients. Absorption is affected by the surveillance landscape and its material composition (e.g., water, foliage, and soil), which can be identified by the spectral properties of the areas under surveillance. Propagation is determined by the prevailing strengths and directions of winds or water flows. Dispersion depends on factors such as temperature and the contour of plume concentrations. Modeling various physical phenomena has been traditionally the tasks of physicists and ignored by systems and network designers. With the convergence of physical and cyber spaces, they now play a central role in the overall performance of a DITSCN, and hence should be considered early in the systems and protocol design.

  The people aspect of DITSCN recognizes the underlying networked system as ultimately a protection mechanism that can positively impact the lives and well being of human users. For example, a radiational DITSCN protects people from harmful plume effects; its utility can reasonably be measured by the sizes and densities of the covered population areas and ultimately those of the evacuated areas. This implies that systems and network designers should also take into account of human population, street layout, and routes for evacuation, early in network and systems design. Availability and accessibility of these physical and population data in national data repositories to authorized personnel, through specific application portals, will also be important.

  Deeply embedded sensors covering vast geographical areas require a large scale deployment in large numbers. Various applications of sensors for different physical phenomena will require that diverse components of different vendors be used for diverse applications. To support such diversity on a large scale, it is beneficial for sensor hardware modules to be available as off-the-shelf components and integrable into the system in a plug-and-play manner. This requires that system components conform to open and well-defined data and communication interfaces. Configuration parameters that define the sensing process, format of captured sensor data, and communication protocol for transporting data between components should be available for use by component manufacturers and software developers. Note that the communication protocol should also support negotiation of security parameters and encryption of data according to these parameters, so that an open data format does not compromise secure access to private information.

David Yau received his Ph.D. from the Univeristy of Texas at Austin, and is now an associate professor of computer science at Purdue University. His research interests are in mobile, wireless, and sensor networks, network security, quality of service, and protocol design and implementation. He received an IBM Fellowship and the NSF CAREER award. He serves as Steering Committee member (2007) and TPC Co-chair (2006) of IEEE IWQoS, and as TPC Co-chair (2007) and Vice General Chair (2006) of IEEE ICNP. He serves on the editorial board of the IEEE/ACM Transactions on Networking.

Jennifer C. Hou received her Ph.D. from University of Michigan, in 1993, and is currently a professor in Computer Science at UIUC. Her research interests are in network modeling and simualtion, cyber-physical systems for healthcare, wireless sensor networks, and wireless mesh networks. She is TPC Co-chair of IEEE INFOCOM 2008, ACM Mobicom 2007, IEEE MASS 2006, 1st WICON 2005, ACM/IEEE IPSN 2004, and IEEE RTAS 2000. She has also served on the editorial board of IEEE Trans. Wireless Communications, IEEE Trans. Parallel and Dist. Sys., IEEE Wireless Communication Magazine, and ACM Trans. Sensor Networks. Hou received an ACM recognition of service award (2004), a Cisco University Research Award (2002), the Lumley Research Award from Ohio State Univ. (2001), and an NSF CAREER award (1996–2000).

Shankar Mallikarjun received his Ph.D. in Computer Science from UIUC in 2000, and is currently a Research Staff member in in the Computational Science and Engineering Division of Oak Ridge National Laboratory (ORNL). He has participated in the Sensor-Cyber Networks (SCN) Research Team as the technical point of contact. His research interests are in the areas of real-time and embedded systems and systems support for wireless sensor networks.

Nagi Rao received his Ph.D. from Louisiana State University in 1998 and is a Corporate Fellow in Computer Science and Mathematics Division in the Computational Science and Engineering Division of Oak Ridge National Laboratory (ORNL). He has formed the Sensor-Cyber Networks (SCN) Research Team in 2005 as part of the ONR-funded SensorNet Project. He has published more than 200 journal and conference papers in the areas of multiple sensor fusion, high-performance networking, fault diagnosis and robot navigation. He received the 2005 IEEE Computer Society Technical Achievement Award for contributions to the information fusion area.