A Wireless Biosensor Network Using Autonomously Controlled Animals

Yihan Li and Shivendra S. Panwar, Polytechnic University
Shiwen Mao, Virginia Tech

Abstract

Recent research shows that animals can be guided remotely by stimulating regions of the brain. Therefore, it is possible to set up an animal wireless sensor network for search and rescue operations, which is of great importance to society with a broad spectrum of applications, including natural disaster recovery, homeland security, and military operations. In a wireless biosensor network, each animal carries a backpack for data capture, processing, and network communications, and collaborates in routing and forwarding packets for each other. In this article the system architecture and operation of the biosensor network are introduced. A simple but efficient routing scheme tailored for this special sensor network is presented, as well as our implementation of a backpack prototype used to capture and transfer video data. Other major technical challenges and interrelated issues for this biosensor network are also addressed.

Recent research by Dr. Chapin's group [1, 2] has demonstrated that rats fitted with microelectronics can be guided through inaccessible, difficult, dangerous, and dark environments, and can be trained to perform tasks as cued by a tele-operator, including searching for odor targets such as explosives or contraband. This is done by stimulating multiple brain regions to produce stimulus cues for various commanded movements, as well as rewards to reinforce these movements. The brain stimulation is delivered by wireless communication. Rats may carry video cameras and transmitters in backpacks, which allows the human controller to remotely guide them through different spaces.

Remotely guided rats (or other animals) are ideal for search and rescue operations. Rats perform as well as dogs in finding and discriminating odors of various chemicals, and even finding individual people. When searching for people or distinctive objects, they tend to combine their olfactory, visual, auditory, and tactile senses. In addition, rats are highly adept at negotiating difficult 3D terrain in both light and dark. Since these are natural functions, and rats can move and travel in ways robots cannot, they are more effective than mechanical robots in search and rescue applications. They can also be trained to detect and home in on specific sensory targets, allowing them to be used as biosensors.

Clearly, a system with a few rats will have very limited capability in supporting mission-critical applications over a large search space. Furthermore, for the current system, a human operator must be within radio transmission range of a rat to manually guide its movement. Recent advances in neurophysiology have made it possible to train a large number of rats that are remotely guidable at moderate cost, while advances in low-power very large-scale integration (VLSI) and micro-electromechanical systems (MEMS) also make it possible to design wireless communication and networking devices that could fit into a backpack carried by a rat. For search and rescue missions as well as other applications, it would be highly desirable to deploy a group of rats, and autonomously guide and coordinate them. Such rats will carry backpacks and form a cooperative multihop wireless sensor network in order to jointly complete a critical mission [3].

Applications of this biosensor network have great importance to society, including natural disaster recovery (finding trapped people and hazards), homeland security (search for explosives, bio-agents, etc., in containers or cargo ships), military operations (e.g., reconnaissance and minesweeping), and law enforcement (e.g., collecting evidence from inaccessible regions). For such applications, it is important to develop the wireless communication and networking technologies that enable the setup and operation of such a mobile sensor network consisting of a coordinated set of trained animals and possibly mechanical robots, remotely guided by a command center. Although current experiments are with guided rats, similar training and control methodologies can be developed to guide other types of animals. The networking technology and data processing algorithms will also be applicable to sensor networks using robots.

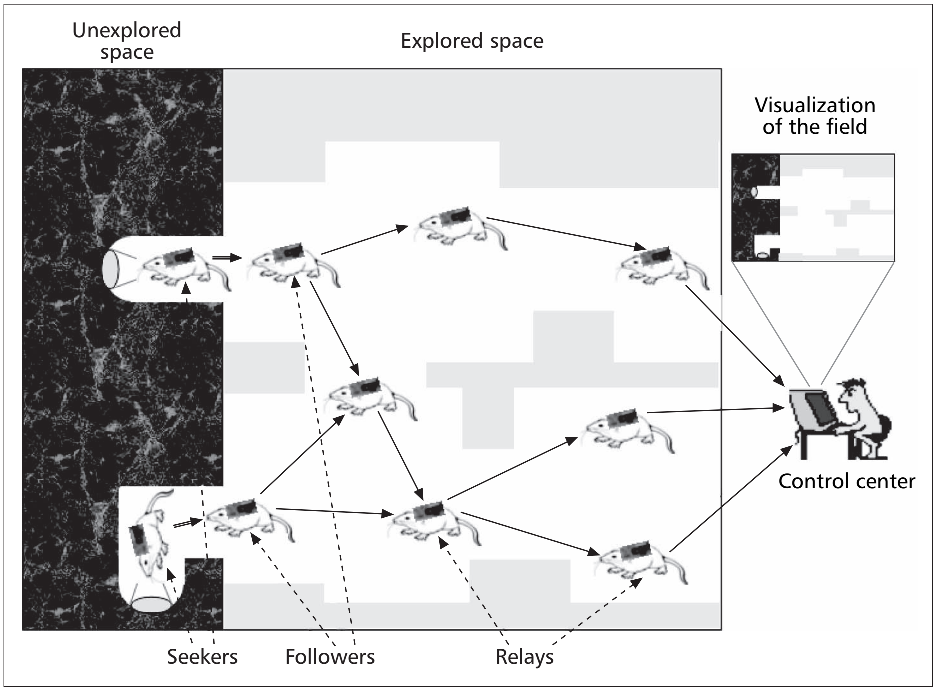
Unique Challenges in Biosensor Network Design

In the targeted search and rescue application, teams of animals would be sent into a disaster site, looking for human survivors or other targets, and sending the captured information (e.g., audio and video) back to the command center. Each animal will carry a backpack, containing a microprocessor, a wireless transceiver, possibly a video camera, other positioning sensors (e.g., compass and GPS), and a battery. The wireless transceiver will enable the delivery of captured data to the command center and downloading guidance commands to the animals. The microprocessor will execute autonomous control algorithms to steer the animals to follow desired search paths and generate appropriate *reward* signals, based on animal motion trajectories deduced from the video and other cap-

0890-8044/06/$20.00 © 2006 IEEE

tured data. The captured data will be analyzed at the command center to visualize the disaster site, conduct path planning for the animals, and initiate rescue efforts when necessary.

Small animals such as rats can only carry limited weight (about 100 g) and have limited running time (2 h with periodic rest). Therefore, only lightweight and low-power devices can be installed in the backpack. As discussed in the rest of this article, many operations, including animal control, real-time sensor data processing, medium access control, routing, and transport techniques, have to be implemented in the backpack. Because of the critical constraints of the backpack, all these locally executed computation algorithms need to be extremely simple but efficient. These are unique challenges in the design of such systems compared to a general wireless sensor network.



■ Figure 1. *Illustration of a biosensor network.*

Network Architecture and Task Allocation

Given the absence of fixed network infrastructure and the very short wireless transmission range typical in such applications (i.e., in a pile of rubble), communications between the animals and the command center will be conducted using an ad hoc network infrastructure, in which mobile nodes will collaborate in routing and forwarding packets for each other. In order to reduce the battery consumption on each animal backpack and the complexity of guiding many animals simultaneously, we assign different tasks to different animal sensors:

- *Seekers* are trained to use olfactory and other senses to find a particular kind of target (e.g., survivors in rubble, explosives, and drugs). A seeker carries a video camera and a low-power wireless communication system. It will transmit the visual and other captured data (e.g., audio or temperature) at low power to nearby followers who will retransmit this data at a higher power level through the network.
- *Followers* are trained to closely follow a seeker everywhere. They receive low-power high-bandwidth (e.g., uncompressed) signals from the corresponding seeker, process them, and then transmit them through the network at higher power. The followers' purpose is to reduce the burden in power consumption and backpack weight of the seekers.
- *Relays* form a chain or mesh of repeaters to ensure connectivity between the seeker/follower and the command center. Their sole purpose is to help relay captured information from the seekers back to the command center, rather than to search for the desired targets.

In addition to animal relays, stationary mechanical relays can be jettisoned by animals or put in place by other means. From the networking perspective, we do not distinguish between a seeker and its follower, and rather consider the pair as one node. Figure 1 illustrates typical operation of the proposed network system.

With task allocation among animals, regular teleoperation is necessary only for the seekers, thus greatly simplifying the task of guiding and coordinating a large number of rats. Seeker animals will be guided to search through a treacherous field and possibly go into holes. This will be done mostly through the autonomous control algorithm running on their backpacks (which will generate both motion commands and reward stimuli), but external teleoperation will be invoked when necessary. In the latter case, the human operator at the command center could send control signals (forwarded by relay rats) to the seekers to direct their motion.

In the rest of this article we first focus on the routing solution of this special biosensor network, then introduce our implementation of a backpack prototype for a sensor animal to carry. Other important technical issues related to the biosensor network are then discussed. We present our conclusions at the end of this article.

Routing in the Biosensor Network

In a biosensor network the routing scheme needs to meet some special requirements. As introduced earlier, just like all other locally executed computations, routing has to be simple but efficient.

In addition, it is necessary to provide path redundancy because of the challenging propagation environment in many applications of such networks. In rubble (i.e., in a search and rescue mission) wireless channels are much more unreliable than those in open space. There will be higher packet loss rates (for both control and data packets) and more frequent link failures. If control messages are lost with high probability, guiding the rat movements would suffer.

Current investigation shows that most of the existing routing algorithms do not meet these special requirements. Existing routing protocols for multihop wireless networks can be broadly classified as proactive or reactive. Based on the operation mode, a protocol is proactive if it attempts to maintain a consistent view of the entire network and compute up-to-date routes to all other destinations. On the other hand, a protocol is reactive if it only performs route discovery for a destination when there is data to be sent to that destination.

In a proactive routing algorithm, such as Destination-Sequenced Distance Vector routing (DSDV) [4], each node maintains a routing table to store the next-hop node toward each destination and the cost metric for the path to each destination. To maintain the consistency of the routing tables,

```
When a packet originally sent by the control center is received {
    if ($D>N+1$) $D=N+1$;
    else if (the timer for $D$ expires) $D=N+1$;
    $N=D$;
    forward the packet if it is allowed by flooding;
}
When a data packet is received {
    if (the packet has been received before) {
        discard the packet;
    }
    else {
        if ($D<d+L$)
            $d=D$;
            forward the packet;
        }
        else {
            discard the packet;
        }
    }
}
When an original data packet needs to be sent {
    $d=D$;
    send out the packet;
}
// $D$: the distance (in hops) from the sensor node to the control center
// $N$: the value of the hop count field of a control packet
// $d$: the value of the sender distance field of a data packet
// $L$: a positive integer
```

Figure 2. *The hop-aware flooding algorithm.*

each node needs to periodically send the information on its routing table to all neighbors, and update its routing table based on the information it collects. In a reactive routing algorithm, such as Ad Hoc On-Demand Distance Vector Routing (AODV) [5], routes are discovered on demand in the route discovery phase. Each node on the path needs to set up a reverse path associated with a timer. The computation complexity and memory space requirements of a proactive or reactive algorithm could be too much for a biosensor network. Besides, most of them (e.g., AODV and DSDV) are single path routing protocols and do not provide redundancy for data flows, which is necessary for this type of network.

Given the above observations, we propose a flooding-like routing scheme for wireless biosensor networks, which is simple and provides redundancy [3]. In a biosensor network there are typically two kinds of messages: captured data (e.g., video or pictures captured by the seeker) and control messages. Control messages are short, and may need to be sent frequently from the control center to the animals. The destination of a control message could be any node. Data messages are long, and are sent only from seekers to the control center. Both data and control messages have specific latency and loss constraints. Given these differences, it may be best to use different routing algorithms for control and data messages.

We first consider flooding techniques for control messages. In flooding, when a node receives a packet, it first checks the sequence number of the packet. If the packet has not been received before, the node will broadcast the packet to all its neighbors; otherwise, it will simply discard the packet. Clearly, this mode of routing uses more resources, since each node will forward the packet once in a connected network. However, given the short length and importance of delivering such messages quickly, this cost may be acceptable.

For data messages, using location-aware routing can save network resources as a packet will be forwarded only by a subset of nodes in the network. An example of a location-aware routing protocol is DREAM [6], which assumes that every node knows its geographical coordinates. A node stores the location of all other nodes in its location table and uses the table for packet forwarding. In our application the overhead associated with broadcasting the location information in DREAM could be greatly reduced by exploiting the fact that the direction of data messages is always from sensor nodes to the control center.

In a biosensor network it is not practical to rely on GPS to get the location information of animals, since the animal nodes may be deployed underground where GPS service is unavailable, or in an environment where GPS does not work well. We therefore propose a simple location-aware routing algorithm for data messages. Instead of using the exact location of each node in the system, we use the hop number to approximate the distance from a node to the final destination, typically the control center. We call this routing algorithm *hop-aware flooding*, as described in Fig. 2.

When the control center sends a control packet, the packet will be forwarded to the nodes (animals) by flooding. A *hop count* field is attached to the packet and set to 0. Each node in the system maintains its *distance* to the control center denoted as D hops. When a node receives a packet originally sent by the control center, it checks the hop count field. We denote the value of the hop count field of the packet by N. If $D > N + 1$, the node will set its distance to $N + 1$ (i.e., $D = N + 1$). The reason to do this is that a node may receive packets originally from the control center by multiple routes with different hop counts, and the distance between the node and the control center should be the minimum number of hops a packet travels. However, the distance D should have a *lifetime* T, since the node may move further away from the control center, and the distance may have to be updated to a larger number of hops. Therefore, when the timer for D expires, the node will simply set $D = N + 1$ for any newly received packet with hop number N. Then, if the packet is forwarded according to the flooding policy, the hop count field of the packet is updated to D. By doing this, each node in the system will have an estimation of how many hops it is from the control center. The selection of T is chosen based on the level of mobility of the nodes. If the topology changes rapidly, T should be small so that D can be updated more frequently.

In the network, each data packet (originally sent by the seeker/follower) includes a *sender distance* field. We denote the value of this field by d. When the seeker/follower sends out a data packet, it sets d to its own distance from the control center. When a relay receives a data packet, it first checks the sequence number as in flooding to see if the packet has been received before. If yes, it simply discards the packet; otherwise, it further compares its own distance D to the sender's distance d carried in the packet. If $D < d + L$, where L is a positive integer, it forwards the packet and replaces d by D; otherwise, it discards the packet. This process continues until the control center is reached. By doing this, a relay only forwards a data packet that is sent by a node *further* away (in hops) (when $L = 0$) or at most $L - 1$ hops *closer* (when $L > 0$) than itself to the control center. With this simple scheme, the number of transmissions for a data packet is effectively reduced, resulting in lower bandwidth requirement and energy consumption.

If each node always maintains its exact distance (in hops) D, $L = 0$ will be sufficient for all data messages to reach the control center when the network is connected. However, a node may move after a recent update of its D, or its distance D is not updated frequently enough by control packets. Thus, it is possible that when a node receives a data packet, there is

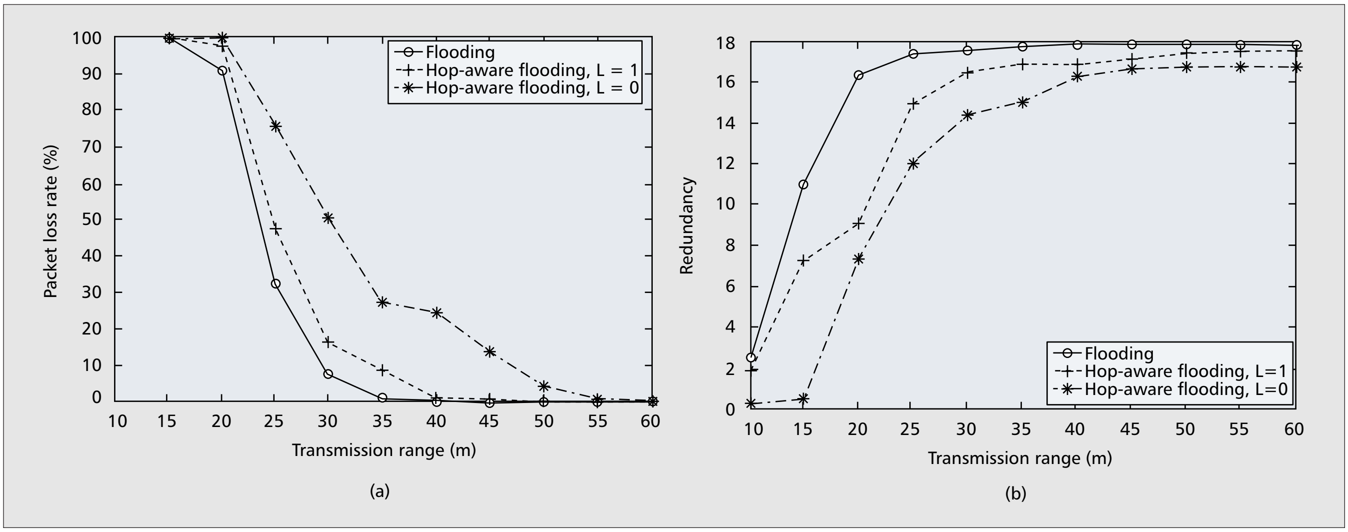


Figure 3. *Simulation results for the routing schemes: a) loss rate for different transmission ranges; b) redundancy for different transmission ranges.*

no node in its transmission range that is closer (in hops) to the control center. Therefore, a larger L will be necessary so that the data message can still be forwarded by some node. There is a trade-off between redundant transmissions and the loss rate. In this article we define the redundancy as $R = W/N$, where W is the number of packet copies generated by relays, and N is the number of original packets generated by the seeker. For example, if the seeker has sent out 1000 packets and the redundancy is 20, the relays forward a total of 20,000 packet copies. With a smaller L, the redundancy will be lower, but the loss rate could be higher. When L increases, the loss rate will be reduced while the redundancy will increase. The selection of L is related to the level of mobility and the transmission range of the nodes.

In 802.11 medium access control (MAC), broadcasts do not use request/clear to send (RTS/CTS) to reserve the channel, or acknowledgments (ACKs) to confirm successful delivery. Although the MAC protocol complexity is greatly reduced, its performance may be more susceptible to high node density than the unicast IEEE 802.11 MAC protocol. When multiple nodes sense the channel idle, they may start transmission simultaneously and thus cause collisions. In the proposed protocol we let a sensor delay passing a packet to the MAC layer for a randomly generated period of time in order to avoid such collisions. The backoff delay is uniformly distributed within the interval $[0, \tau_{max}]$. Our simulation result, which is omitted due to lack of space, shows that the collision rate is reduced significantly when τ_{max} is chosen appropriately (e.g., a few milliseconds).

We simulated the hop-aware flooding scheme in a sensor network with 20 nodes in a 100 m × 100 m region and compared its performance to that of a basic flooding scheme. All nodes are randomly placed in the region initially. The *random waypoint* mobility model is used, but with constant speeds [7]. More precisely, each node first chooses a random destination in the region, and then moves toward it at a constant speed. When it reaches the destination, it makes a decision whether it will pause for a constant time interval (1.0 s in our simulation) or start another movement right away. Figures 3a and 3b show the loss rate and redundancy obtained from the 20-node network, respectively, of hop-aware flooding (when $L = 0$ and 1) and basic flooding. We assume that the speed of each node is 0.1 m/s, which is close to the speed of a rat. We can see that when $L = 1$, the loss rate of the hop-aware flooding scheme is higher but close to that of flooding, while its redundancy is lower than that of flooding.

Backpack Prototype Development

We have designed and implemented an early version of the backpack using off-the-shelf commercial products, and set up a simple wireless sensor network. Although the current backpack is still too heavy for a rat to carry, we believe that the weight can be further reduced by current or future integration techniques. The following devices are used in our backpack.

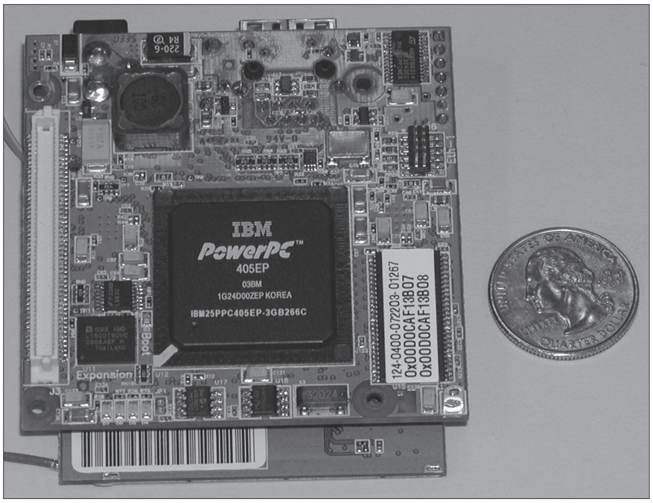
CerfCubes from Intrinsyc Software — Intrinsyc software provides IBM PowerPC-based Cerf boards, which are based on the Linux 2.4 kernel. The CerfCube 405EP is a low-power reference design platform with an IBM 405EP microprocessor at its core. In combination with a Netgate mini PCI card, these devices can communicate using the 802.11b WLAN protocol. The CPU board includes a 32-Mbyte flash memory and 32 Mbytes RAM. The boards also have an external Ethernet interface.

NetGate EL-2511 MP Plus 802.11b miniPCI Card — The Intrinsyc CerfCubes are not provided with wireless access. We selected the NetGate EL-2511 MP Plus 802.11b miniPCI card, with the Intersil PRISM 2.5 chipset.

Antennas — Two cubes cannot communicate with each other without antennas when the distance between them is more than 8 cm. When antennas are used, two CerfCubes can hear each other within a distance of 2 m.

Axis 205 Network Camera from Axis Communications — An Axis camera is based on Linux, and has its own IP address and a built-in Web server. Its features, such as three different resolutions (up to 640 × 480) and a frame rate of 30 frames/s in all resolution modes, make it suitable for our application. The system consists of a 32-bit RISC CPU, a motion JPEG compression chip, works on a Linux 2.4 kernel, and has 8 Mbytes of RAM and a 2-Mbyte flash memory. It can be directly connected to the Ethernet port of the Intrinsyc device.

A backpack prototype (without a video camera) is shown in Fig. 4. We have successfully set up a simple network with a video camera, a laptop computer (serving as the control center), and two relay nodes. In the testbed network captured data can be forwarded to the control center by using fixed routing, flooding, and a hop-aware flooding scheme. A received video frame from an experiment is shown in Fig. 5. In future work we plan to expand the network with more relay nodes and test its performance under different conditions.



■ Figure 4. *A backpack prototype to be carried by a sensor animal.*

Other real-time processing, as mentioned earlier, will be incorporated in the backpack as well.

Other Related Technical Issues

Because of tight constraints on backpack size and weight, and the critical importance of conserving battery energy, a cluster of interrelated problems need to be addressed in addition to the routing issue in a wireless biosensor network. We briefly review some of them in this section.

Animal Training

Because of the task allocation in the biosensor network, rats need to be trained to function in three different types of roles: seekers, followers, and relays. Seekers will be trained to use olfactory and other senses to find a particular kind of target, such as people in the rubble, explosives, or drugs. In addition to searching, rats will also be trained to maintain connectivity with other rats, restore lost connectivity, and be semi-autonomously guided into positions by optimizing signal strength from multiple connections. A follower has a preassigned seeker it must follow closely, whereas a relay needs to discover its neighbors and move in a way such that it is always connected with two or more neighboring nodes. All these can be achieved by the reward stimulation generated by the backpack microcontroller carried by rats. The controllers running in their backpacks will help to guide them to stay at a proper distance from their neighbors and regain connectivity once lost, with minimal guidance from the remote command center.

Cooperative Control of Animal Nodes

Cooperative control techniques, which can autonomously guide and reward a large set of animals with different tasks, need to be investigated. The design of the control system depends on the obtainable feedback regarding the past trajectories of individual animals, radio connectivity between neighboring animals, and the location of neighboring animals. It also depends on trainable stimulus responses of the animal (what type of motion commands animal can respond to via stimulus cues) and desirable stimulation profiles (motion guidance precision, reward frequencies, etc.). The control strategy for relay animals also depends on the optimal relay distances and mobility patterns.

Sensor Data Processing

The video and other captured data will be processed locally to deduce motion trajectories of seeker animals, based on which autonomous controller can guide the animal movement. The captured data (together with the estimated trajectory information) will also be sent back to the control center to create a visualization of the explored site, which is necessary for high-level path planning and coordination of different seeker animals. In order to accomplish these goals, signal processing algorithms and simple video compression algorithms need to be developed. Due to the erratic and uncontrollable motion of the camera (mounted on the animal), these schemes will require considerable computation, and hence energy, to reliably determine the motion between successive frames. On the other hand, since these operations must be done in real time at the animal site using the hardware/software installed in the backpack, the designed algorithms must be computationally simple and robust to noise, while meeting the performance objective.

Search Strategy in a Rubble Site

When conducting search and rescue in the rubble site, the animal sensors will start out searching above ground and go into any found holes or openings. Since much of the knowledge of maze searching applies to a single seeker, these techniques need to be generalized to explore algorithms for a team of seekers. The objective of a search could be to minimize the total search time by minimizing the distance traveled by each seeker. However, for purposes of simplifying the control actions people may wish to minimize the total movement of all the animals (seekers and relays), while maintaining a signal path through relays from the seeker to the control center. The accuracy and efficiency of any search depends on the predictability of movements of animals in response to available control commands, as well as the autonomous movement of animals when they receive no commands during network partition.

Wireless Communications

In such a special sensor network, the radio transmission system has to meet the needs of the sensors, the network management system for routing information, and the control system for status and remote guidance information. Each of these information sources has its own throughput and signal quality requirements. In the physical layer, radio propagation characteristics, both in open fields and under rubble piles, need to be examined. Based on the resulting channel characteristics, it is important to investigate how to position the relays and guide their movement in order to provide good connectivity between seekers and the command center, while minimizing the number of relays and transmission power.

Medium Access Control

Currently, IEEE 802.11 is used as the MAC protocol in our experimental system. In order to save backpack weight and energy, it could be helpful if the MAC scheme is tailored for the biosensor network to reduce the computation and memory complexity. On the other hand, a cooperative MAC protocol might improve the link quality offered by the IEEE 802.11 MAC protocol [8]. In a traditional IEEE 802.11 ad hoc network, transmissions received by nodes other than the receiver node are discarded. These transmissions are a wasted resource, given the inherently cooperative nature of our application. In the IEEE 802.11 standards, a lost packet has to be retransmitted by the source at a later time, perhaps at a low data rate. It is very probable that some other nodes between the transmitter and receiver can overhear the lost packet. Because they are closer to the destination, they can transmit at a higher rate and/or with a lower outage probability, and thus increase the throughput for the system.

■ Figure 5. *A screen shot of the "rat's eye view" video received at the control center.*

Transport Issues

Our previous work [9] showed that multipath routing improves the quality of received video in ad hoc networks. However, the nature of the problem addressed in the biosensor network is quite different from that in our earlier work. For instance, one difference is that multiple paths now occur randomly and may not be known explicitly. Another difference is that while it is desirable to deliver the captured information in a timely manner to the control center, delayed data frames are still useful. This is because such frames could be archived at the control center for later review and backtracking to make sure the search is complete. Caching the sensor data in intermediate nodes could be a solution. If the network is temporarily partitioned, the cached packets can be retransmitted when connectivity is restored [10].

Conclusion

In this article we introduce a wireless sensor network using autonomously controlled animals. In such a network animals are assigned different roles: a seeker/follower pair will capture data (e.g., video or pictures), and relays will help forward the data to the control center. A biosensor network will have great importance to society in situations including natural disaster recovery, homeland security, and military operations. Since a sensor animal (e.g., a rat) can only carry limited weight, all the operations installed in a backpack have to be extremely simple and efficient. The hop-aware flooding scheme, a new routing scheme tailored for this special wireless sensor network, is presented, as well as the implementation of a backpack prototype for rat sensors to carry. Other important technical issues related to the unique challenges of the biosensor network are briefly reviewed and discussed.

Acknowledgments

This work is supported in part by the National Science Foundation (NSF), Defense Advanced Research Projects Agency (DARPA), the New York State Center for Advanced Technology in Telecommunications (CATT), and the NSF sponsored Wireless Internet Center for Advanced Technology (WICAT) at Polytechnic University, Brooklyn, New York.

This work was greatly enriched by discussion with Professor John Chapin, whose DARPA grant funded this work, and his group at SUNY Downstate Medical Center, and Professor Yao Wang, who leads a parallel effort on video coding and video stabilization for the bio-sensor network. We also want to thank Professors Henry Bertoni, David Goodman, Zhongping Jiang, and Joshua Gluckman for their constructive discussions. We thank Srinivas Burugupalli and Jong Ha Lee for obtaining the experimental results presented in this article.

References

[1] S. K. Talwar *et al.*, "Behavioural Neuroscience: Rat Navigation Guided by Remote Control," *Nature*, vol. 417, May 2002, pp. 37–38.
[2] http://www.rybak-et-al.net/chapin.html
[3] Y. Li *et al.*, "A Mobile Ad Hoc Bio-Sensor Network," *Proc. IEEE ICC 2005*, Seoul, Korea, May 2005.
[4] C. E. Perkins and P. Bhagwat, "Highly Dynamic Destination-Sequenced Distance Vector Routing (DSDV) for Mobile Computers," *ACM SIGCOMM Comp. Commun. Rev.*, vol. 24, no. 4, Oct. 1994, pp. 223–44.
[5] C. Perkins, E. Belding-Royer, and S. Das, "Ad Hoc On-Demand Distance Vector (AODV) Routing," IETF RFC 3561, July 2003.
[6] S. Basagni *et al.*, "A Distance Routing Effect Algorithm for Mobility (DREAM)," *Proc. MobiCom '98*, pp.76-84, 1998.
[7] D. B. Johnson and D. A. Maltz, "Dynamic Source Routing in Ad Hoc Wireless Networks," *Mobile Computing*, T. Imielinski and H. Korth, Eds., vol. 353, Kluwer, 1996, Ch. 5, pp. 153–81.
[8] P. Liu, Z. Tao, and S. Panwar, "A Cooperative MAC Protocol for Wireless Local Area Networks," *Proc. IEEE ICC '05*, Seoul, Korea, May 2005.
[9] S. Mao *et al.*, "Video Transport Over Ad Hoc Networks: Multistream Coding with Multipath Transport," *IEEE JSAC*, vol. 21, no. 10, Dec. 2003, pp. 1721–37.
[10] A. Valera, W. Seah, and S. V. Rao, "Cooperative Packet Caching and Shortest Multipath Routing in Mobile Ad Hoc Networks," *Proc. IEEE INFOCOM '03*, Mar./Apr. 2003, pp. 260–69.

Biographies

YIHAN LI [S'99, M'04] (yli@photon.poly.edu) received an M.S. degree in system engineering and a Ph.D. degree in electrical and computer engineering from Polytechnic University, Brooklyn, New York, in 2000 and 2004, respectively. Before that, she received B.S. and M.S. degrees from Tsinghua University, Beijing, P. R. China, in 1993 and 1997, respectively, both in electrical engineering. She was a networking system engineer at Founder Inc., Beijing, from 1997 to 1998. She is a research scientist in the Department of Electrical and Computer Engineering of Polytechnic University. Her research interests include high-speed switching, wireless networking, and sensor networks. She is a recipient of the 2001 International ACM Student Research Contest Award and the 2000 AT&T Student Research Symposium Award. She co-authored a textbook, *TCP/IP Essentials: A Lab-Based Approach* (Cambridge University Press, 2004).

SHIVENDRA S. PANWAR [S'82, M'85, SM'00] (panwar@catt.poly.edu) is a professor in the Electrical and Computer Engineering Department at Polytechnic University. He received a B.Tech. degree in electrical engineering from the Indian Institute of Technology, Kanpur, in 1981, and M.S. and Ph.D. degrees in electrical and computer engineering from the University of Massachusetts, Amherst, in 1983 and 1986, respectively. He joined the Department of Electrical Engineering at the Polytechnic Institute of New York (now Polytechnic University). He is currently director of the New York State Center for Advanced Technology in Telecommunications (CATT). He spent the summer of 1987 as a visiting scientist at the IBM T.J. Watson Research Center, Yorktown Heights, New York, and has been a consultant to AT&T Bell Laboratories, Holmdel, New Jersey. His research interests include the performance analysis and design of networks. Current work includes video systems over peer-to-peer networks, switch performance, and wireless networks. He has served as Secretary of the Technical Affairs Council of the IEEE Communications Society (1992–1993) and is a member of the Technical Committee on Computer Communications. He is a co-editor of two books, *Network Management and Control*, Volume II, and *Multimedia Communications and Video Coding* (1994 and 1996, Plenum), and co-authored a textbook, *TCP/IP Essentials: A Lab-Based Approach* (Cambridge University Press, 2004). He is a co-recipient of the 2004 IEEE Communications Society Leonard G. Abraham Prize in the Field of Communications Systems.

SHIWEN MAO [S'99, M'04] (smao@vt.edu) received B.S. and M.S. degrees from Tsinghua University, Beijing, P.R. China, in 1994 and 1997, respectively, both in electrical engineering. He received an M.S. degree in system engineering and a Ph.D. degree in electrical and computer engineering from Polytechnic University in 2000 and 2004, respectively. He was a research member at IBM China Research Laboratory, Beijing, from 1997 to 1998. In the summer of 2001 he was a research intern at Avaya Labs-Research, Holmdel, New Jersey. Currently, he is a research scientist in the Bradley Department of Electrical and Computer Engineering, Virginia Tech, Blacksburg. His research interests include multimedia and wireless networking. He is a co-recipient of the 2004 IEEE Communications Society Leonard G. Abraham Prize in the Field of Communications Systems. He is a co-author of *TCP/IP Essentials: A Lab-Based Approach* (Cambridge University Press, 2004).