Millennial Net

Commercial- and Industrial-Class Wireless Sensor Networks

Maximizing Data Reliability in Wireless Sensor Networks

A Millennial Net White Paper

Introduction

There is an exciting new wave in sensor applications—wireless sensor networking—which enables numerous sensors and actuators to be deployed independent of the costs and physical constraints of wiring, opening up a new world of sensing application possibilities. The ad hoc nature of wireless mesh networks enables the sensor nodes form a network automatically with minimal human intervention. The network is maintained autonomously, healing itself if any damage occurs to the network. The wireless mesh network is reliable and robust because the network "learns" from the problens and changes in the topology, and adapting itself tvery quickly, even at the individual packet-transmission level. There are, however, some challenges that still need to be overcome. There are certain characteristics of wireless sensor networking applications that have complex inter-relationships. In order to develop a network to support real-world applications, all of the characteristics must be taken into account and systematically optimized to work together in harmony.

Wireless Sensor Networking Requirements and Challenges

For a wireless sensor network to deliver real-world benefits, it must support the following requirements in deployment: scalability, reliability, responsiveness, mobility, and power efficiency. Each of requirements is described in Table 1.

Table 1: Essential Requirements of Wireless Sensor Networks

Requirements	Description
Reliability	The ability of the network to ensure reliable data transmission in a state of continuous change of network structure.
Scalability	The ability of the network to grow, in terms of the number of nodes, without excessive overhead.
Responsiveness	The ability of the network to quickly adapt itself to changes in topology.
Mobility	The ability of the network to handle mobile nodes and changeable data paths.
Power efficiency	The ability of the network to operate at extremely low power levels.

The complex inter-relationships between these characteristics is a balance; if they are not managed well, the network can suffer from overhead that negates its applicability in the real world. In order to ensure that the network supports the application's requirements, It is important to understand how each of the wireless sensor networking characteristics affects reliability.

Scalability and Reliability

In typical wireless ad hoc networks, reliability and scalability are always inversely coupled. In other words, it becomes more difficult to build a reliable ad hoc network as the number of nodes increases. This is due to the network overhead that comes with the increased size of the network. In ad hoc networks, the network is formed without any predetermined topology or shape. Therefore, any node wishing to communicate with other nodes should generate more packets than its data packets. These extra packets are generally called "control packets" or "network overhead." Route discovery packets and route response packets in typical ad hoc network routing protocols are a few examples of the overhead. As the size of the network grows, more control packets will be needed to find and keep the routing paths. Moreover, as the network size increases, there is higher chance that communication links get broken in communication paths, which will end up with creating more control packets. In summary, more overhead is unavoidable in a larger scale wireless sensor network to keep the communication paths intact. In typical ad hoc networks, the overhead increases exponentially as the network size grows. In a small network, the amount of control packets is almost negligible. But when the network size starts increasing, the overhead increases rapidly. Since the available overall bandwidth is limited, the increase of overhead results in the decrease of usable bandwidth for data transmission. As the network size grows further, there will be very small amount of bandwidth left for application data transmission.

This characteristic of ad hoc networks imposes an interesting question on the reliability of the network. Since an ad hoc network is designed to automatically adapt itself to a changing environment or interference, it will issue more control packets when it faces environmental dynamics. More dynamics in the environment will increase the number of control packets and, at some point, the network cannot sustain the amount of overhead caused by the dynamics, which will result in less reliability of data transmission. This breaking point will show up earlier in a large-sized network. So, network scalability and reliability are closely coupled and typically they act against each other.

Responsiveness and Reliability

Responsiveness is the ability of the network to quickly adapt itself to changes in topology. To achieve high responsiveness, an ad hoc network should issue and exchange more control packets, which will naturally result in less scalability and less reliability.

Mobility and Reliability

Generally, a wireless sensor network that includes a number of mobile nodes should have high responsiveness to deal with the mobility. So, it is not easy to design a large scale and highly mobile wireless sensor network. The mobility effect on responsiveness will compound the reliability challenge.

Power Efficiency and Reliability

Power efficiency also plays another important role in this complex equation. A typical method for designing a low-power wireless sensor network is to reduce the duty cycle of each node. The drawback is that as the wireless sensor node stays longer in sleep mode to save power, there is less chance that the node can communicate with its neighbors. In addition to creating scalability challenges due to the need for a more complicated synchronization technique to keep more nodes in low duty cycle, this will decrease the network responsiveness and may also lower reliability due to the lack of the exchange of control packets and delays in packet delivery.

Techniques for Addressing the Reliability Challenges

Two sets of techniques address the real-world design challenges outlined above. The first - Persistent Dynamic Routing (PDR) - is a breakthrough set of techniques that address all of these requirements to support production-grade wireless sensor network implementations. The second - High-Capacity Wireless Sensor Networks (HC_WSN) - presents emerging research on the issue. These techniques are not mutually exclusive and can be used together to manage the design trade-offs of wireless sensor networks.

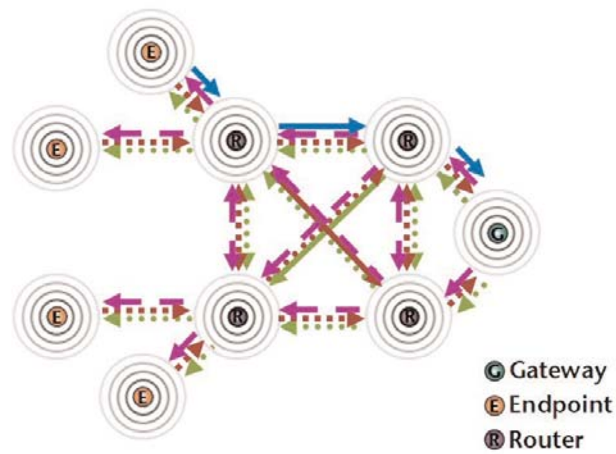
Persistent Dynamic Routing (PDR)

Persistent Dynamic Routing provides a mechanism for the network to ensure reliable data transmission without dropping data packets. Combined with the technique of dynamic route discovery that discovers the best route for packet delivery on the fly, PDR enables a level of scalability and power efficiency that other networking systems cannot achieve.

Almost every existing ad hoc network protocol assumes some level of static status of the network. For example, the route discovery process of AODV assumes there is at least a short duration during which a "snapshot" of the complete route to the destination is possible. The data packet of DSR carries the full route information in itself, which assumes the existence of a "full" route at that moment.

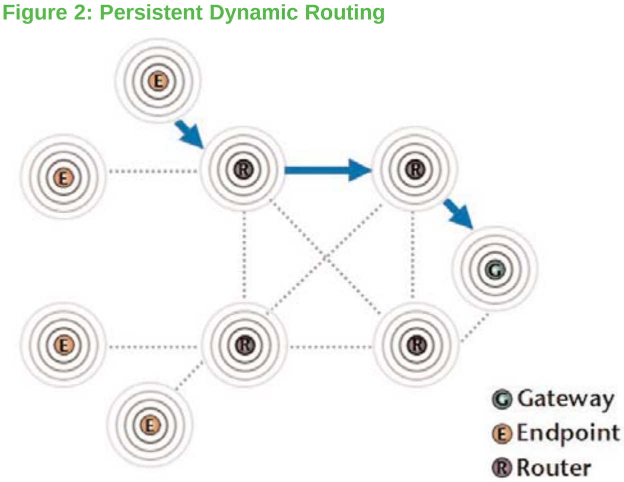
In the case of relatively static network with low fluctuation and interference, this assumption can hold with reasonable level of success. But in a highly dynamic environment, the assumption of this kind of "quasi-static" status does not hold. In other words, the network may be continuously changing so that it is impossible to establish a full route from the source to the destination at a point in time. In this case, traditional routing algorithms such as AODV or DSR can present difficulties. For example, in an AODV system, the source will keep sending the route discovery packet but will not get a definite route response from the destination, which will result in continuous flooding of network with route discovery packets. As a result, the data packet will not be even sent into the network since route discovery process is incomplete. More route discovery packets translate into more overhead. This problem will be even more serious in a large-sized network; since the route discovery is essentially a flooding process, the efficiency of the network will drop significantly.

Figure 1: Flooding Approaches



With PDR, the data packet does not need to wait until the route discovery process grabs a "full" route at a moment in time. A data packet is released and navigates through the network with the best knowledge it has collected from its neighbors at that moment. It works in a manner similar to the mechanism of navigating a maze without any prior knowledge of the maze. The data packet does not wait until the full route is confirmed; rather, it starts navigating the network with whatever information it has about the destination.

Figure 2: Persistent Dynamic Routing



PDR can significantly decrease the overhead of packet delivery in a highly dynamic network since it does not send excessive numbers of route discovery packets nor does it use proactive route updates. Also, the route discovery packet in PDR does not go more than one hop in each discovery process, resulting in less flooding of the network. In practice, flooding is used only once at the very beginning of the network formation and, from then on, route discovery is only done in the local area to collect knowledge on the best route to the destination. This "best knowledge" has no guarantee that it is correct, and the data packet does not "ask" for that kind of guarantee. In this sense, PDR is based on the probabilistic rather than deterministic approach. In a relatively static network, the higher probability that the destination matches the actual deterministic route would give PDR the same level of performance as AODV, if not better. In highly dynamic environment, PDR produces significantly less overhead in packet delivery than the AODV flooding approach.

Gateway establishes tree structure for dynamic addressing. Route discovery packet broadcasts through the network establishing mesh routing (AODV) which floods the network. Route response packet broadcasts to validate the route. Data packet sent to the gateway.

With PDR, the endpoint sends the data packet which is dynamically propagated through the network and delivered to the gateway.

High-Capacity Wireless Sensor Networks (HC-WSN)

Lee, et al (1), pointed out that the average number of packets per data delivery increases as the size of the network increases in AODV. The increase of packets per data delivery is not just proportional to the size of the network, rather, it increases exponentially. When the size of the network grows further, almost no data can be delivered since the number of packets needed per data delivery approaches infinite. This phenomenon is largely due to the ad hoc nature of the wireless sensor network. As the size of the network increases, more links are likely to break between the source and the destinations, and more packet exchanges are necessary to heal and reconstruct the delivery paths. Therefore, the issue for managing this scalability/reliability trade-off is how to minimize the number of packets per data delivery in a large-sized wireless sensor network.

One way to increase the scalability of the network without increasing overhead is to increase the capacity of the network, i.e. to increase the volume of data that can be transmitted through the network. Increasing capacity will enable the network to handle more packets in a given network size. One way of achieving this is to increase the network bandwidth; however, higher bandwidth typically consumes more power, negating one of the critical factors (and benefits) of wireless sensor networks. Therefore, alternative approaches are needed. Several available approaches include multiple gateways, simultaneous multiple frequency access, and data aggregation. Each approach can increase capacity, but comes with a trade-off.

Typical wireless sensor networks use a single gateway to aggregate the sensor data and pass it to the host application or system. Adding additional gateways to the network can reduce the number of hops the data must take before reaching the gateway. Since each data packet takes fewer hops, more data packets can be transmitted through the network without adding to the total number of hops. In this scheme, the multiple gateways must be connected via some kind of "fatter pipe" such as Ethernet or 802.11.

Another technique is to use multiple radio frequencies simultaneously. Using multiple channels through channel hopping can increase the robustness of the network by increasing resistance to interference and RF noise. But channel hopping or dynamic channel switching can also be used to send more data through the frequency band. The tradeoff here is that more power will be consumed to use multiple frequencies in a network. For example, a node will require a more complex route-discovery/link-recovery process, which will take longer time and, as a result, burn more power. A longer route-discovery process could also result in a less responsive network. In practice, using multiple frequencies in one network can also require more memory and processing speed in a sensor node.

Data aggregation is another method for increasing network capacity without increasing the use of available communication bandwidth. With this technique, multiple data packets are aggregated into one (e.g. at the routers) packet which is then transmitted through the network. Packet aggregation serves to minimize the number of packets propagating through the network, which minimizes the overhead, thus maximizing the throughput of real sensor data. This technique typically results in a drop in responsiveness and increases delay in packet delivery.

Conclusion

Persistent Dynamic Routing provides supports the high data reliability needed for mission-critical and life-critical networks and does so without sacrificing power and scalability. This approach delivers reliable packet delivery while supporting ultra-efficient topology discovery and re-discovery, extreme power efficiency, and high scalability. High Capacity Wireless Sensor Networks provide techniques for increasing the capacity of networks; this results in much higher scalability and throughput of wireless sensor networks without sacrificing reliability.

References

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About Millennial Net

Millennial Net develops commercial- and industrial-grade wireless sensor networking systems that enable OEMs and systems integrators to quickly and cost-effectively implement wireless sensor networks. These networks enable the remote monitoring and management of critical devices while providing data to enable more informed decision-making, better control and increased revenue opportunities. Millennial Net's patented ad hoc, self-organizing wireless sensor networking MeshScape™ system leads the industry in power efficiency, support for dynamic systems and mobile sensors, reliability, and scalability. Millennial Net also leads the industry in real-world deployments with networks installed across commercial building and industrial environments. Millennial Net is headquartered in Chelmsford, MA.

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