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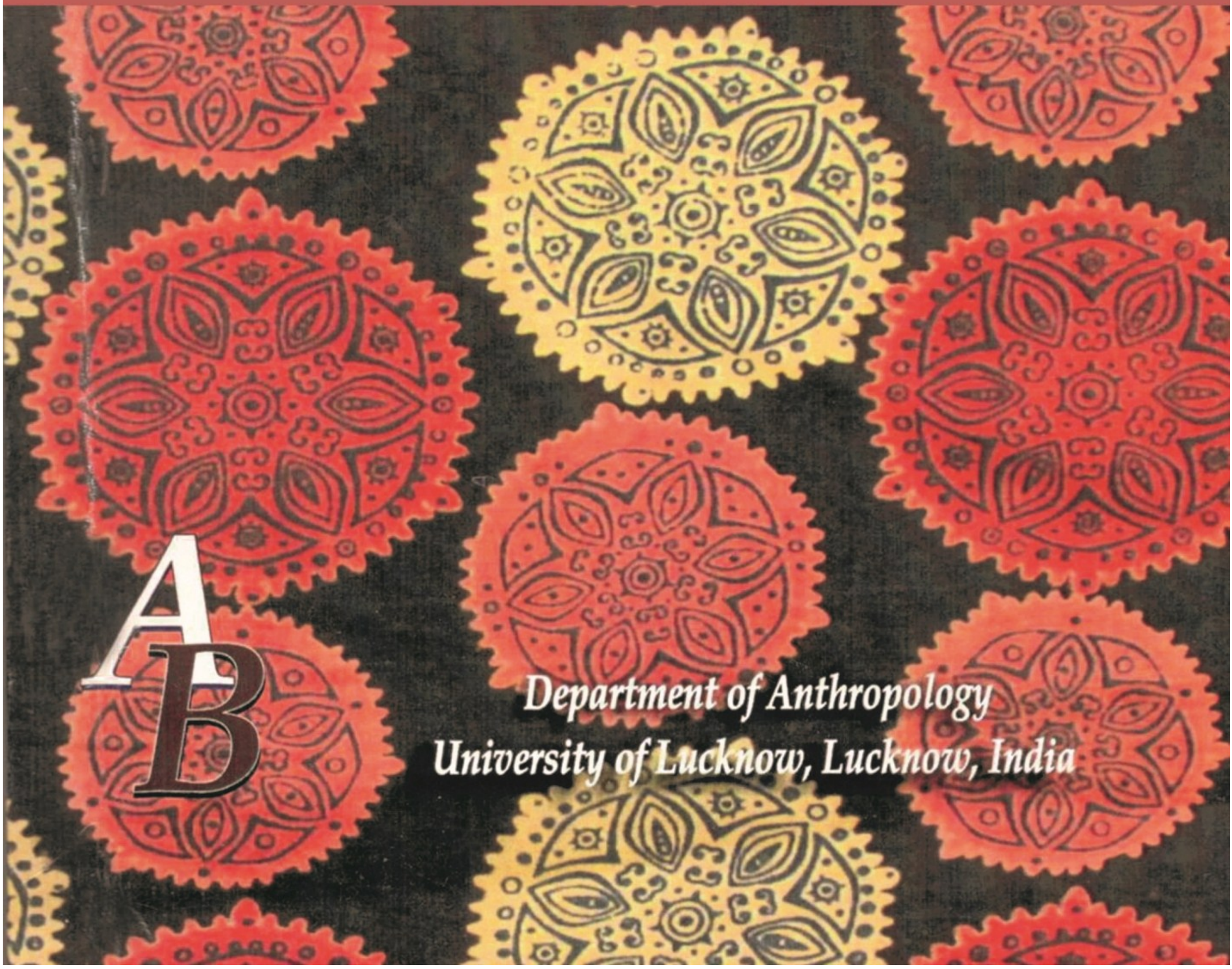

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Routing Challenges in Wireless Ad-Hoc Sensor Networks

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ABSTRACT

Wireless Ad hoc Sensor Network is an autonomous network with no fixed infrastructure. It is a collection of tiny sensor nodes that can communicate wirelessly. Sensor nodes are equipped with low power batteries, small memory, and a short radio range. These limitations set routing in wireless ad hoc sensor networks apart from fixed networks. Routing protocols must handle these issues to ensure multi-hop communication reliable. This paper presents an in-depth exploration of challenges in routing in wireless ad hoc sensor networks.

Keywords: Wireless Ad hoc Sensor Network, MANET, dynamic topology, routing.

Introduction

Wireless Ad hoc Sensor Network is a group of small sensor devices that **work together** to share data over the network [Hannes Frey, et.al., 2009]. Each sensor node has processing unit (one or more microcontrollers, Central Processing Unit or Digital Signal Processor), storage unit, a transceiver, a power unit, positioning system and holds various sensors and actuators. The nodes have the ability to self-organize after their deployment in an ad hoc manner and there is wireless communication between them. [John A. Stankovic, 2006].

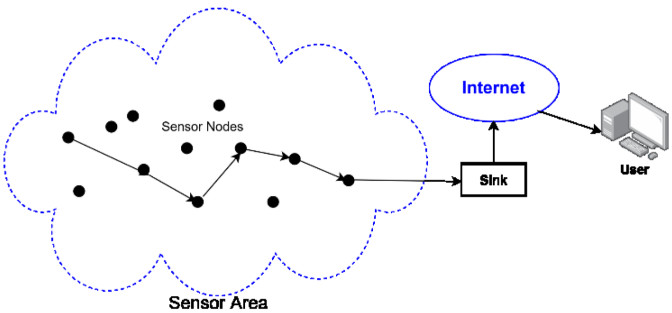

Figure 1. Architecture of Wireless ad hoc sensor network

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A large number of the sensor nodes can be deployed in the network area where they communicate with each other autonomously. A sensor node is a device in WASN that can perform some processing, sense environmental data, and communicate wirelessly with other nodes within the network.

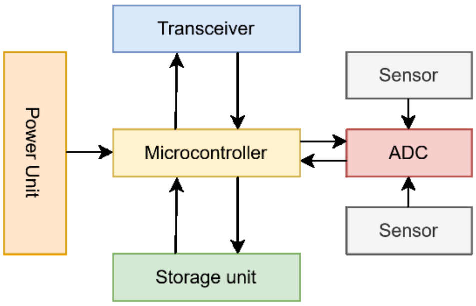

Figure 2. Architecture of a Sensor node

The sensor nodes can communicate either among each other or directly to an external sink. A sink is a fixed or mobile node. It links the sensor network to the Internet or to an existing communications infrastructure. This allows a user to access the collected data. Routing is a process to detect and maintain the best path to forward data packets from source node to destination through intermediate relay nodes. [M. Izuan et.al., 2009].

A mobile wireless ad hoc sensor network (MWSN) is a type of wireless ad hoc sensor network (WASN) where sensor nodes can move inside the boundaries of the network [Peter A. Boncz, et.al., 2007]. Nodes gain mobility by adding wheels or mobilizing units to them. These nodes can couple with transport mediums such as animals, vehicle, robots etc. Movement of these nodes is sometimes induced by the local environmental conditions.

Mobile wireless ad hoc sensor networks (MWSNs) offer significantly more versatility compared to conventional static wireless ad hoc sensor networks. The mobile sensor nodes can be deployed in unpredictable environments and can adapt to fast-changing network topologies [Velmani Ramasamy, 2017].

In MWSNs, sensor nodes can autonomously reposition and self-organize within the network, achieving better network coverage and connectivity compared to static sensor nodes. Therefore, their reliance on dynamic routing makes data delivery challenging and energy intensive.

WASNs have found applications in a wide range of domains. They are used for environmental monitoring to track climate changes, study wildlife behaviour, and detect environmental pollutants. They allow precision farming by monitoring soil conditions and crop health in agriculture. Additionally, these networks have a crucial role in healthcare for patient monitoring and fall detection, and in military applications for surveillance and reconnaissance. These networks can be used in many applications that require unattended operations.

Some of the key advantages of wireless ad hoc sensor networks are lesser catastrophic failures, natural resources conservation, improvement in manufacturing productivity, enhanced emergency response, flexible communication, and upgraded homeland security [F.L. Lewis, 2004].

Ad hoc networks are vital for large-scale ubiquitous computing. They are characterized by the lack of fixed infrastructure and the mobility of nodes. These networks establish direct peer-to-peer connections between nodes within transmission range, and for nodes that are out of transmission range they utilize multi-hop routing through intermediate nodes [Gowrishankar S., et.al., 2010].

Characteristics of Wireless Ad hoc Sensor Networks

Wireless ad hoc sensor networks have the following characteristics.

- Dynamic network topology: Links are formed and broken due to node mobility or failure.

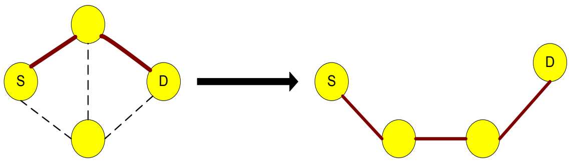

Figure 3. Dynamic network topology

- Constrained resources:
    - Battery power
    - Wireless transmitter range
- Heterogeneity of nodes: Nodes with different processing power, transceivers, energy sources, or sensing capabilities.
- Ability to cope with node failures (fault tolerance).
- Low bandwidth.

Significance of WASNs

The significance of WASNs in contemporary technology and research extends to various aspects:

Data Collection- WASNs enable the collection of high-resolution, real-time data from remote or inaccessible areas. This data is invaluable for scientific research, environmental protection, and decision-making in various industries.

Cost-Efficiency- Compared to deploying fixed infrastructure in remote locations, setting up WASNs is often more cost-effective. This is particularly relevant for applications in developing regions or areas with challenging terrain.

E**nvironmental Impact-** The energy-efficient operation of WASNs minimizes their environmental footprint, making them suitable for applications where environmental impact needs to be minimized, such as wildlife monitoring or conservation efforts.

Innovation Hub- WASNs serve as a fertile ground for innovation. Researchers and engineers continuously develop novel protocols, algorithms, and hardware solutions to address the unique challenges posed by these networks.

Humanitarian Aid and Disaster Response- WASNs play a vital role in disaster management and humanitarian aid by providing real-time data on disaster-affected areas, helping first responders make informed decisions.

National Security- In military and defense applications, WASNs enhance situational awareness, surveillance, and battlefield communication, contributing to national security.

Difference between Traditional Network and Wireless Ad hoc Sensor Network

In traditional network, there are fixed topologies, fixed and known neighbours, fixed relationship between IP address and location. If a router has valid path to a destination, that path stays valid forever until a part of the system breaks down [Andrew S. Tanenbaum, 2018]. In wireless ad hoc sensor network, each node consists of a router and host with sensor on the same computer. The topology may be changing all the time as well as nodes can move in and out or shift to new locations any time, so path quality and validity can change spontaneously, without warning.

Traditional network connects high-power devices such as computers and routers to share general data. A wireless ad hoc sensor network (WASN) uses numerous tiny, battery-operated nodes equipped with physical sensors to collect and send specific environmental data like temperature, pressure, or motion to a central point. In traditional network, application independent network is used but in WASN application-dependent network is used.

WASNs are designed to overcome the limitations of traditional wired networks and infrastructure-based wireless networks in several ways:

- Infrastructure Independence

WASNs do not require a fixed infrastructure like routers or access points. Instead, they self-organize into a network by establishing direct communication links with nearby nodes. This inherent flexibility makes them ideal for scenarios where infrastructure deployment is impractical or costly, such as disaster-stricken areas, remote wildlife habitats, or battlefields.

-Diverse Applications

WASNs have found applications in a wide range of domains. They are used for environmental monitoring to track climate changes, study wildlife behaviour, and detect environmental pollutants. In agriculture, they enable precision farming by monitoring soil conditions and crop health. Additionally, they play a crucial role in healthcare for patient monitoring and fall detection, and in military applications for surveillance and reconnaissance.

- Dynamic Topology

The network topology in WASNs is highly dynamic due to factors like node mobility, environmental changes, and energy fluctuations. Traditional routing protocols designed for static networks are often ineffective in handling such dynamic conditions.

Similarities between Wireless Ad hoc Sensor Network and Mobile Ad hoc Network

A wireless ad hoc sensor network (WASN) comprises spatially distributed, autonomous sensor devices that collaborate to monitor environmental and physical parameters such as temperature, pressure, sound, vibration, motion, or pollutants across various locations. Nowadays, wireless ad hoc sensor networks support diverse civilian domains, including habitat monitoring, healthcare, smart homes, and traffic management and also in military application areas. A mobile ad-hoc network (MANET) connects mobile devices like phones or laptops for general peer-to-peer data communication [M. Devi and N. S. Gill, 2019]. This self-configuring wireless ad-hoc network consists of dynamic, wirelessly linked nodes acting as mobile routers. These routers move independently which causes the network topology to change rapidly and unpredictably. The main reason that WASNs immediately resemble mobile ad hoc networks is that both are distributed wireless networks without a significant network infrastructure in place, and routing between two nodes often relies on intermediate relays via multi-hop paths, while both ad hoc and sensor nodes typically depend on battery power [JA Garcia-Macias and Javier Gomez, 2007]. Therefore, minimizing power consumption is a primary concern. Since both network paradigms utilize unlicensed wireless bands, they remain vulnerable to cross-technology interference. Ultimately, their distributed nature necessitates robust self-management capabilities.

Difference between Wireless Ad hoc Sensor Network and Mobile Ad hoc Network

Even though WASNs and MANETs are very much similar, they also have basic differences. Some of these differences are due to the nature of both types of networks: MANETs are usually close to humans, that means most nodes in the network are devices that are meant to be used by human beings e.g., laptop computers, PDAs, mobile radio terminals, etc., whereas sensor networks focus on interaction with the environment rather than human interaction.

The sensor nodes in wireless ad hoc sensor network are placed in the environment to gather information and act upon it. Therefore, sensor networks have large number of nodes that are more densely deployed than mobile ad hoc networks. This huge increase indicates the need of handling scalability issues. [JA Garcia-Macias and Javier Gomez, 2007].

If a network is going to be deployed in unattended areas where human interaction is not possible, some nodes will ultimately get damaged and die. This makes the topology of the network to change dynamically. Since nodes can fail any time, the design of the wireless ad hoc sensor network must include **reconfiguration tools** to keep the network functional. In some applications nodes can be attached to animals, vehicles, or moving objects, but most applications have static nodes, so some **problems** that are significant in mobile ad hoc networks do not matter much in wireless ad hoc sensor networks. Topology can change not only from node failure, but also from sleep-awake cycles in wireless ad hoc sensor networks. These cycles save energy, which is an important design objective for resource- constrained sensor networks.

This limitation of resources represents a defining characteristic of sensor networks. Nodes are left unattended for months or years and operate on batteries. These nodes typically rely on few kilobytes of memory, processor that operate at speeds of only some megahertz, low-data-rate and short-range communications spanning just a few meters at several kilobits per second.

Ad hoc sensor networks have **strict power limits** and **fixed nodes**, unlike mobile ad hoc networks (MANETs) with moving devices. Their routing needs focus on saving battery, sending data to a sink, and handling large node counts.

The wireless ad hoc sensor networks offer service not simply to move bits from one place to another, but to provide answers also. These answers should be responses to the questions like, what are the areas of the network where the temperature is below the specified threshold? What is the route followed by the enemy? Thus, answering to such types of questions implies considering geographic context- a requirement rarely needed in standard networks. In some applications a node's specific network address or ID is secondary, making its geographic location the primary attribute of interest. [JA Garcia-Macias1 and Javier Gomez, 2007].

Challenges in Routing in Wireless Ad hoc Sensor Networks

There are many ways which make routing in wireless ad hoc sensor networks differ from conventional routing in fixed networks. In WASN, there is no fixed infrastructure, wireless links are unreliable, sensor nodes may fail or die, and routing protocols must comply with stringent energy-efficiency.

Limited computing, storage capacity, transmission range and battery power of sensors make routing in wireless ad hoc sensor networks very challenging.

Node Deployment: In WASN node deployment is randomized, the sensor nodes are randomly spread over large area that creates an ad hoc routing infrastructure. If the placement of nodes is uneven, optimal clustering helps devices to connect and save energy. Energy and bandwidth constraints restrict individual sensor transmissions to short distances. Therefore, data delivery relies primarily on multi-hop wireless routes.

Autonomy: Relying on a central control unit to manage radio and routing operations makes a sensor network vulnerable to attack. To prevent this single point of failure, the nodes themselves manage routing decisions autonomously.

Resource Constraints: Sensor nodes in WASNs are typically resource constrained. They have limited computing power, storage, and battery power. These constraints necessitate the development of efficient routing mechanisms to prolong the network's lifetime and optimize resource utilization.

Energy Efficiency: Wireless ad hoc sensor networks predominantly rely on battery power, and lack of energy is a significant concern, particularly in demanding environments such as battlefields. Since sensor nodes are randomly placed in unattended environments, they are not reachable and battery replacement in the sensor nodes is not feasible. Sensor node performance is severely affected when their batteries fall below a predetermined threshold. Conservation of energy represents a primary challenge for network designers, given the large number of sensor nodes within a wireless ad hoc sensor network, each with restricted energy resources. Therefore, routing protocols should prioritize energy efficiency and should prolong network lifetime while providing a fast, reliable, and uninterrupted communication between the sensor nodes.

Complexity: The complexity of a routing protocol can directly affect the overall performance of the wireless ad hoc sensor network. This challenge arises from the limited hardware capabilities and substantial energy constraints inherent to these networks.

Scalability: With sensors becoming more cost-effective, wireless ad hoc sensor networks can accommodate hundreds or even thousands of sensors with ease. As a result, routing protocols must be designed to support network scalability. They should be capable of accommodating additional nodes without causing network disruptions.

Delay: Certain applications necessitate real-time responses without significant delays, like sensing temperature or monitoring alarm. Therefore, routing protocols should aim to minimize data transmission latency, particularly in applications where prompt data delivery is critical.

Sensor Location: Wireless ad hoc sensor network designers face a significant challenge in accurately determining the locations of sensor nodes. Many routing protocols rely on localization techniques to acquire information about node positions. Some scenarios make use of Global Positioning System (GPS) receivers to achieve this. Properly determining sensor node locations is essential for effective network operation and data routing within the network.

Resilience: Wireless ad hoc sensor networks are often deployed in harsh environments. Sensor nodes may unpredictably stop operating or exit the network due to battery exhaustion or environmental reasons. Routing protocols should exhibit robustness to withstand such challenging conditions so that when a current routing node fails, an alternative route could be found. They must be capable of adapting to various environmental conditions, including severe and loss-prone environments, while maintaining consistent functionality.

Data Transmission: Wireless ad hoc sensor networks employ four distinct modes of data transmission; each tailored to specific application requirements. These modes include event-driven, query-driven, continuous, and hybrid transmission. In the query-driven and event-driven models, data transmission is initiated by a node when a sink node generates a query or when predefined events occur. In contrast, the continuous transmission mode involves periodic data transmission without the need for specific triggers. The performance of routing protocols in these networks is intricately linked to network size and the quality of the transmission medium. Higher-quality transmission media can directly enhance network performance, leading to more efficient and reliable data transmission.

Device Heterogeneity: While most civilian wireless ad hoc sensor networks employ homogeneous nodes, integrating heterogeneous sensors can yield substantial operational benefits. Deploying heterogeneous nodes with different processing power, transceivers, power sources, or sensing capabilities can enhance overall performance of the network. Deploying a heterogeneous set of sensors introduces several technical challenges for data routing. Node heterogeneity can significantly optimize key performance metrics, including network scalability, energy consumption, and bandwidth utilization.

Mobility Adaptability: Sensor networks must often support mobile sensor nodes, mobile sinks, or moving target events. This requires routing protocols to provide dynamic topology support to manage these distinct forms of movement.

Coverage: In WASNs, each sensor node has limited sensing range and accuracy, offering only a localized view of their environment. Because single-node coverage is constrained in both range and accuracy, ensuring optimal area coverage becomes an important design parameter.

Data Aggregation: Because sensor nodes often gather duplicate information, combining similar data packets before sending them helps to reduce total network traffic. This process, known as data aggregation, blends sensed data from multiple nodes using some aggregation functions like duplicate suppression, average, minima, and maxima.

Quality of Service: Certain applications demand strictly bounded delivery latency, as sensor data becomes obsolete if not transmitted within a specific time frame. However, in many operational contexts, energy conservation which is directly related to network lifetime is prioritized over strict real-time data delivery and high data quality [Jamal N. Al-Karaki and Ahmed E. Kamal, 2004].

Conclusion

Wireless Ad-hoc Sensor Networks (WASNs) have witnessed widespread adoption due to their self-organizing nature and the absence of infrastructure requirements. This paper provides the analysis of key routing challenges and issues inherent to Wireless Ad-Hoc Sensor Networks (WASNs). Recent studies show that these networks operate under strict physical and environmental constraints, designers must intentionally sacrifice performance in one area to achieve acceptable results in another. As provided in this paper that wireless ad hoc sensor networks operate under very different conditions, their routing protocols require a completely different approach than MANETs. Although, several critical challenges persist in this field, there is a need for comprehensive research and innovative solutions.

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