A Survey of Wireless Sensor Networks Technology

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***Abstract*-Wireless Sensor Networks were first used in military missions. They are currently deployed in a wide range of civil applications as a sensor is becoming smaller and production costs are smaller. The main drawback is the energy constraint as it seems impractical to change or recharge the battery. Several applications require an end-to-end reliable data transport with congestion control to achieve an intended performance, especially during heavy traffic. This paper provides a survey of wireless sensor networks technology. Several research works including sensor network applications, components, reliable transport protocols, and congestion control schemes are summarised and compared in different sections.**

I. Introduction

Sensor networks are one of the most interesting research areas with a profound effect on technological developments [1]. With the significant breakthrough in technology called "Microelectromechanical Systems (MEMS)" technology [2], sensors are becoming smaller. It is possible to fit them into a smaller volume with more power and with less production costs. Many sensors can be deployed in harsh environments to sense and periodically transmit data to the sink or base station.

The main driving force behind research in sensor networks is the military application. However, there is a diversification towards the development of civilian applications such as environmental monitoring [4,5], habitat monitoring [7,8], classroom/home [9,11], structural monitoring [12,13] and health monitoring [14,15]. According to their application-specific characteristic, each application has its own design concept and implementation to suit specific requirements. For several applications such as re-tasking or re-programming of sensors, reliability of data transmission is required. Applying TCP will generate high overheads with more energy consumption [28,29,30]. Different deployment strategies and data sending rate lead to different types of congestion [31]. Moreover, the behaviours of radio signals and concurrent data transmission are also likely to contribute to the congestion problem [32].

Previous surveys have addressed sensor components, technological background, protocols development and research challenges [37-40]. This paper aims to provide a survey in terms of applications and components, reliable transport protocol and congestion control research in wireless sensor networks. Each paper will be briefly described and then compared to each other. Sensor networks history, reliable transport protocol and congestion control are outlined in Section II, III and IV, respectively. Finally, the conclusion is stated in Section V.

II. Sensor Networks History

Starting from specific research objectives contributing to military applications, sensor components have evolved to build more powerful applications with less cost. The main purpose under any development is to minimise the size of a sensor node for it to be easily scattered across a target area. Unlike a laptop or PDA, the power supply unit of each node is unlikely to be changed or recharged over its operational lifetime. Energy is then the biggest concern issue in today's sensor development. MEMS technology makes sensors smaller and cheaper. As a result, more civilian applications have been observed. This section provides information about sensor networks applications and components.

A. Sensor Network Applications

Application Development – From Battlefield to Human Body

Placing sensors in various areas to collect physical data for later analysis allows ubiquitous computing to become realistic. Several military-specific applications have changed into tracking tools to detect natural data. Advanced relevant technologies are evolving, and as a result, sensors could be implanted in the human body.

Sound Surveillance System (SOSUS) [3] is the first obvious sensor networks application [40]. It had been used during the Cold War in the early 1950s to detect and track Soviet submarines with the help of acoustic sensors or hydrophones. The Distributed Sensor Networks (DSN) program was then initiated by the Defense Advanced Research Projects Agency (DARPA) around 1980. The possibility to extend the Apranet to sensor networks was considered together with some research on supporting components such as operating system and knowledge-based signal processing techniques [40].

Sensor nodes are currently becoming smaller with more powerful capabilities and cheaper production costs. An ability to place sensors in remote or dangerous environments without any communication lines plays a key role over traditional wired networks. Various environmental data can be collected, analysed to forecast the upcoming phenomenon, and send prompt warnings. Sensors may be placed, for example, in the soil, across the rain forests [4], or even a glacial area [6] to track global warming and climate change. The industrial sector can also benefit from the usefulness of sensor networks, especially in inventory systems [16].

Accurate data collection gathered directly from an area of interest could better support understanding in a specific subject such as habitat monitoring to study bird behaviour [7], smart classrooms to evaluate children's learning environments [9] or the exploration of Mars [10]. Nowadays, sensors may be found in some electrical equipment to make daily life more comfortable [11], in buildings to inspect the excitation effects of wind or earthquake [12,13], or in the human body to monitor symptoms as an outpatient [15].

Fig. 1 provides an overview of sensor network applications development. It is not based on the development timeline but on human interaction.

Application Categorisation

There have been several attempts to categorise sensor network applications [20,42]. All of them traditionally focus on the field of the application being used such as health or environmental monitoring. In this report, two categorisations have been provided as follows:

- Traditional Categorisation – Eight types of application are listed in Table 1. This type reflects the utilisation of sensor networks for each specific purpose.
- Objective-Oriented Categorisation – Five groups of application; Military, Public Security/Warning, Education, Business Competitiveness (BC) Improvement, and Quality-of-Life (QoL) Improvement are also provided. Some traditional applications can be placed into more than one category.

TABLE 1
SENSOR NETWORK APLLICATIONS CATEGORISATION

Sensor Network Applications	
Objective-Oriented Categorisation	**Traditional Categorisation**
1. Military	- Military
2. Public Security/Warning	- Environmental Observation and Forecasting - Health Monitoring - Structural Monitoring
3. Education	- Environmental Observation and Forecasting - Health Monitoring - Structural Monitoring - Habitat Monitoring - Smart Classroom
4. Business Competitiveness Improvement	- Tracking (Inventory System) - Smart Office
5. Quality-of-Life Improvement	- Environmental Observation and Forecasting - Health Monitoring - Tracking (Traffic Monitoring) - Smart Home/Office

Discussion

The two main strengths of sensor networks are wireless tracking and collecting physical data from an area of interest for further analysis. A large amount of sensors tend to be scattered over a large area to collect data for different applications as described in [4]. However, this requirement is still challenging and needs more experimental work as sensor networks are application-specific [41]. With the objective-oriented categorisation, we believe that some common requirements can be drawn to develop more general-purpose sensor network applications.

B. *Sensor Network Components*

The main components of sensors consist of a sensing unit, a processing unit, a transceiver, and a power unit as shown in Fig. 2, adapted from [37]. Each component will be described in the next sections.

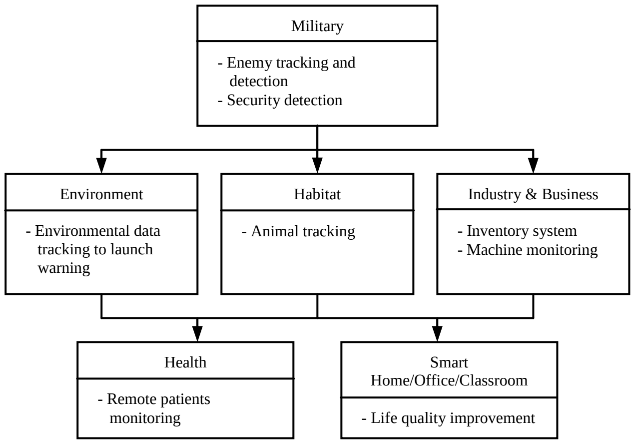

Fig. 1. Sensor Network Applications Development

Sensing Unit

The main functionality of the sensing unit is to sense or measure physical data from the target area. The analog voltage or signal is generated by the sensor corresponding to the observed phenomenon. The continual wavefrom is digitised by an analog-to-digital converter (ADC) and then delivered to the processing unit for further analysis [20,39]. The sensing unit is a current technology bottleneck because the sensing technologies are much slower than those of the semi-conductors [21].

Processing Unit

The processing unit plays a major role in managing collaboration with other sensors to achieve the predefined tasks. There are currently several families of this unit including microcontrollers, microprocessors, and field-programmable gate arrays (FPGAs) [19]. FPGAs consume more energy and were not compatible with traditional programming methodologies. However, they can be reprogrammable and reconfigurable to eliminate deployment costs [22].

Non-volatile memory and interfaces such as ADCs can be integrated onto a single integrated circuit [20,22]. The processing unit needs storage for tasking and to minimise the size of transmitted messages by local processing and data aggregation [21]. Flash memory is widely used due to its cost and storage capacity.

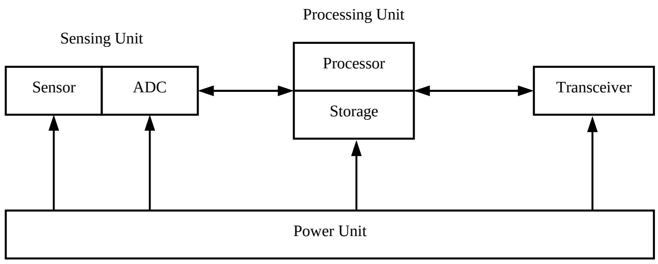

Fig. 2. Sensor Network Components

Transceiver

There are three deploying communication schemes in sensors including optical communication (laser), infrared, and radio-frequency (RF). Laser consumes less energy than radio and provides high security, but requires line of sight and is sensitive to atmospheric conditions. Infrared, like laser, needs no antenna but is limited in its broadcasting capacity. RF is the most easy to use but requires antenna.

Various energy consumption reduction strategies have been developed such as modulation, filtering, and demodulation. Amplitude and frequency modulation are standard mechanisms. Amplitude modulation is simple but susceptible to noise [20]. The RF Monolithics TR1000 and Chipcon 1000 are commercial radios and widely used in various applications [20,22]. Chipcon 1000 is more easily programmed for operation at frequencies between 300 and 1000 MHz [22].

Power Unit

Power consumption is a major weakness of sensor networks. Any energy preservation schemes can help to extend sensor's lifetime. Batteries used in sensors can be categorised into two groups; rechargeable and non-rechargeable. Often in harsh environments, it is impossible to recharge or change a battery. Current sensors are developed to be able to renew their energy from solar or vibration energy [20,21]. Alkaline batteries have a wide voltage range and large physical size whilst lithium provides a constant voltage supply but with very low nominal discharge currents. Nickel Metal Hydride can be recharged but with a significant decrease in energy density [20].

Two major power saving policies can be found in [22]. Unused devices can be shut down and activated when required. This is called "Dynamic Power Management (DPM)" which requires support from the operating system and stochastic analysis to predict future events. In another approach, Dynamic Voltage Scheduling (DVS), power can be varied to allow for a non-deterministic workload.

C. Discussion

In order to develop an efficient application, high performance hardware components are required. The current research aim is to build the smallest sensor with the least energy consumption. The Smart Dust project [23] was established to develop a very small sensor, a few millimetres in volume, which can remain suspended in the air. However, a sensor consists of various components, all of which must combine to achieve the predefined goal. Sensing technologies are developing slowly.

III. Transport Layer Protocol

Wireless sensor networks require several attributes such as fault tolerance and scalability. The relatively short lifetime of a sensor is an additional factor when deploying sensors in a target area. Message loss may be not a serious problem because of the sheer amount of sensors. However, reliable data transport is important for some data [12,28]. This section provides some details of reliable transport protocol for wireless sensor networks researches including PSFQ, ESRT, and RMST.

A. Protocol Development

Motivation

Developing a reliable transport protocol for wireless sensor networks to support more applications deployment is an important issue. Depending on the type of application, each sensor node may be required to perform some local computations [24,25] and data aggregation [26]. Applying TCP to wireless sensor networks is expensive because of its three-way handshake mechanisms and packet header size. UDP is considered to be more suitable for sensors although it was designed to provide unreliable data transport.

There are two possible ways to develop a protocol, the first scheme is to build it independently [28,29] or to run the protocol in conjunction with an existing network or routing protocol [30] such as Directed Diffusion [35].

Designing Concept and Methodology

One of the main goals to achieve reliable data transport is to orchestrate data receiving and forwarding processes to lessen the packet loss due to buffer overflow. PSFQ (Pump Slowly, Fetch Quickly) [20] proposes three different operations including pump, fetch and report. Data from the source node will be distributed slowly in order to allow such nodes experiencing data loss, to fetch the missing packets very aggressively. Timing is a core process to avoid operational synchronisation. Hop-by-hop recovery is used to avoid exponential error accumulation as in the end-to-end scheme. Data delivery status information could be sent back to users in a piggyback fashion.

Focusing only on the forward or sensor-to-sink direction, ESRT (Event-to-Sink Reliable Transport Protocol) [29] was designed to provide a reliable data transport by inspecting current network state in terms of reliability and congestion. The state result is categorised and the reporting frequency is then repetitively adjusted to reach an optimal point. ESRT provides both reliable data transport and congestion control. Local buffer level monitoring is used to detect congestion.

Directed Diffusion [35] is a routing protocol which provides multipoint-to-multipoint communication. A sink first indicates an interest and propagates to the nodes. Interest and node information is kept as gradients. The optimised reinforced path is then established to send the attribute-value pairs data. RMST (Reliable Multi-Segment Transport) [30] is implemented as a filter to provide some information about the data fragment such as ID and total number to detect loss. A NACK will be sent via a back-channel to upstream neighbouring nodes in case of data loss.

B. Discussion

In a densely deployed environment, data loss may be accepted. However, this condition may apply only in the case of forward or sensor-to-sink direction. The sink plays a major role in the network by broadcasting several control packets to the sensors. Those packets could not be dropped as it may cause the whole network performance to degrade. Moreover, there are various types of sensing data which need some combination from different nodes to create usable data before forwarding to the sink such as structural displacement due to wind or earthquake.

PSFQ designing concepts seem to be more complicate but can apply to a broader area of application. The data retransmission mechanisms are not mentioned in the ESRT. However, PSFQ does not provide congestion control approaches as ESRT does. The last protocol, RMST, is designed to run over the powerful Directed Diffusion protocol. Although it may take the least effort compared to the other two, it does not seem generic enough. Research on reliable transport protocol tends to be more challenging. It should be generic and lightweight enough to run over any existing network and link protocols without minimal modification. Application and layer independency, congestion control, and energy efficiency are key characteristics of the new protocol.

IV. CONGESTION CONTROL

Like ordinary networks, sensor networks are likely to face congestion problems under heavy traffic. Data delivery in sensor networks may be frequently light but may be very heavy under a specific event, for example, during a disaster or an attack. Each sensor has limited resources including memory. Moreover, radio signals may vary with interference due to concurrent data transmission from different nodes. Some research is focused on this issue. This section describes congestion control research.

A. Development

Motivation

There are many factors in sensor networks which can be varied and become unpredictable. Under normal situations, a periodic sensing may not lead the network to a congestion problem. However, sensor networks are designed to collect physical data from a real area of interest and most of them are naturally occurring. When a special event occurs, for example, a fire forest or flooding, much data would be sent to the base station simultaneously. In these circumstances congestion is likely to happen. Moreover, the widest adopted communication media in sensor networks is radio frequency (RF). The nature of the radio signal itself varies over time. This makes the problem worse. Most research on developing congestion control is based on monitoring communication channels and buffers to adjust data sending rate from the neighbouring nodes.

Designing Concept and Methodology

CODA (Congestion Detection and Avoidance) [31] can address two types of problem including persistent, transient, and both. To deal with transient congestion, open-loop hop-by-hop backpressure scheme is activated. By monitoring channel loading only when receiving and forwarding a packet, if congestion is detected, a receiving node will broadcast a suppression message to its neighbours. Upstream nodes will then throttle their sending rate or drop packets. In case of persistent congestion, a sink operates control over multiple source nodes by sending ACKs to regulate them after detecting some fraction of the throughput limit excess.

A similar hop-by-hop flow control scheme is proposed by [32]. Queue occupancy and channel have been monitored to detect congestion. The receiving congestion notification node will throttle its rate, stop forwarding data and then send one packet to inform its children. In another approach, rate limiting, a token is implemented to measure how well a parent of a node can forward an entire packet. One token will be added to a bucket if the parent is able to forward all its packets. A sensor is allowed to send only when its token count is above zero. Further, there are another two schemes to mitigate congestion which are MAC layer mechanisms and application adaptation.

RAP, a real-time communication architecture for large-scale sensor networks is proposed by [33] to minimise a packet deadline miss ratio by providing general service APIs to an application. It consists of five components including query service, connectionless transport layer, location service, distributed packets prioritisation service, and Velocity Monotonic Scheduling (VMS) to prioritise packet urgency based on both deadline and distance-aware. VMS also solves a fairness problem as the more distant packets tend to have higher priority than the closer. Each packet priority is based on a static or dynamic requested velocity.

Phase shifting and queue occupancy monitoring have been proposed by [34]. By comparing a node's rate to that of its parent, the smaller value will be selected to propagate packets. However, some computations are needed to calculate the average rate such as the number of downstream nodes. Moreover, fairness is also determined by choosing a queue proportional to the normalised number of nodes serviced by that queue.

B. Discussion

The congestion control approaches mentioned above focus on channel monitoring to dynamically adjust the data forwarding rate. CODA is designed to cover two types of the problem corresponding to the deployed sensors and their data rate. However, it does not provide any queue occupancy monitoring. Sending ACK in the case of persistent congestion, even if it is small in size, may worsen the traffic status. This mechanism also requires feedback signalling which results in higher cost. Only packet prioritisation could be found in RAP. However, VMS is well-designed to support both static and dynamic computation of the requested velocity and it also solves the fairness problem. Both channel and queue occupancy monitoring are provided in [32] and [34]. A child node can transmit packets only when its parent does not experience congestion problem and some help from the MAC layer to shift the transmitting time to avoid interference are proposed in [32]. A similar concept also exists in [34] by comparing the normalised rate of a node and its parents.

V. Conclusion

Recent advanced hardware technologies result in more powerful sensors as small as a few millimetres volume. The main drawback is still energy constraints. Additional strategies aiming at extending sensor lifetimes have also been studied along with pre-processing or data aggregation prior to transmission [24,25], and the optimal positions to place sensors [27].

Several reliable transport protocols have been developed or proposed. Some of them strongly depend upon a network routing protocol [30]. As a result, portability is not yet achievable. Current channel usage monitoring or network status is used to evaluate and adjust the data rate to minimise packet dropping. Frequent topology changes in sensor networks have an impact on hop-by-hop recovery whilst exponential error accumulation is an obstacle for end-to-end recovery.

Channel loading and queue occupancy are core to congestion occurrence in sensor networks. Waiting for the parent nodes to drain their queue before forwarding the received packets and broadcasting backpressure signals to upstream nodes to reduce the data rate [31] seem very efficient, but more data or signals can occasionally worsen the problem. Alternatively, comparison between the normalised data rate of a node and its parent [32,34], and allowing a node to forward packets only when its parent successfully clears its queue [34] needs much computation. Dynamically calculated packet prioritisation based on deadline and distance-aware can solve fairness problems in frequent topology-changed sensor networks [33].

This report aims to provide some surveys of wireless sensor networks. Some research information about the network applications, components, reliable transport protocols and congestion control approaches are given. Sensor networks are challenging in having to be small, powerful but with less energy consumption, as well as accommodating different application requirements. Further, the transport protocol plays a major role in providing end-to-end communication with congestion control. TCP does not seem able to provide reliable data transport in sensor networks. A reliable transport protocol with congestion control capability for sensor networks is required to be generic, lightweight, and not dependent upon existing lower layer protocols.

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