Rare Event Detection and Propagation in Wireless Sensor Networks

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Rarely occurring events present unique challenges to energy constrained systems designed for long term sensing of their occurrence or effect. Unlike periodic sampling or query based sensing systems, longevity can not be achieved simply by adjusting the sensing nodes' duty cycle until an equitable balance between data density and network lifetime is established. The low probability of occurrence and random nature of rare events makes it difficult to guarantee duty cycled battery powered sensing nodes will be energised when events occur. Equally, it is usually considered impractical to leave the sensing nodes energised at all times if the network is to have an acceptably long operational life. In the past decade and a half, wireless sensor network research has addressed this aspect of rare event sensing by investigating techniques including synchronised duty-cycling of redundant nodes, passive sensing, duplicate message suppression and energy efficient network protocols. Researchers have also demonstrated the efficacy of harvesting energy from the environment to extend operational life. Here we survey existing rare event detection and propagation techniques, and suggest areas suitable for continued research.

Categories and Subject Descriptors: C.2.2 [**Computer-Communication Networks**]: Network Protocols

General Terms: Design, Algorithms, Performance, Reliability

Additional Key Words and Phrases: Wireless sensor networks, rare events, duty cycling, energy harvesting

ACM Reference Format:
David C. Harrison, Winston Seah and Ramesh Rayudu, 2014, Rare Event Detection and Propagation in Wireless Sensor Networks. *ACM Comput. Surv.* 0, 0, Article 12 (0000), 23 pages.
DOI:http://dx.doi.org/10.1145/0000000.0000000

1. INTRODUCTION

Traditional wireless sensor network (WSN) nodes are small battery powered devices typically consisting of a micro controller, a modest quantity of random access memory, some non-volatile storage capacity, one or more sensors, and a low power radio transceiver. The finite charge storage capacity of batteries shapes WSN research to the extent that minimising energy consumption becomes a preoccupation; the less energy consumed, the longer the network will continue to operate.

The simplest way for a sensing node to conserve energy, and in doing so maximise its operational life, is to power down for extended periods. For star topology networks where sensing nodes are connected to a permanently powered base station, each node can adopt an independent duty cycle and a media access control (MAC) protocol based on un-slotted carrier sense multiple access with collision avoidance (CSMA/CA). Nodes deployed to periodically sample data for multi-hop transmission to a base station can synchronise their activity [Ye *et al*. 2004] to ensure network connectivity and employ algorithms that minimise overuse of individual routing nodes [Schurgers and Srivastava 2001]. Similar techniques can be adopted for networks where data collection is initiated by a request from the base station [Yao and Gehrke 2003]. Sensing rare events, however, introduces additional complexity.

Rare events are axiomatically situations that occur infrequently; they may also be short-lived, present themselves unpredictably and leave no trace of their presence when complete. For the purposes of this work, rare events are considered random as those following a predictable schedule can easily be sensed assuming accurate time synchronisation [Elson 2003]. Successfully sensing a rare event requires consideration of the extent to which it is ephemeral and transitory. A scheme proved effective for sensing forest fires in progress may not be as successful detecting the instantaneous start of the same fires. Similarly, a scheme for detecting perimeter intrusion on a battle field where events last fractions of a second and leave no discernible trace may prove inappropriate for sensing landslides that last for comparatively extended periods and leave significant physical evidence in their wake, yet occur less frequently.

A study of rare event simulation using Monte Carlo Methods [Rubino and Tuffin 2009] compliments an earlier work on estimating rare event probabilities [Glasserman *et al.* 1999] and defines a rare event as:

> *"an event occurring with a very small probability, the definition of 'small' depending on the application domain"*

Examples given include a civil aircraft failing during a typical eight hour flight and a high speed network node experiencing a buffer overflow. Another introductory text on rare event simulation [Bucklew 2013] does not propose a definition, concentrating instead on the randomness and uncertainty of rare events.

It should be noted that the term 'rare event' is uncommon in WSN research, the literature containing only a handful of papers with the words 'rare' and 'event' in their title [Misra *et al.* 2015; Harrison *et al.* 2015; Xu *et al.* 2012; Cheon *et al.* 2009; Asur and Parthasarathy 2007; Dutta *et al.* 2005; Cao *et al.* 2005a], of which only four have been cited by others[1] [Cheon *et al.* 2009; Asur and Parthasarathy 2007; Dutta *et al.* 2005; Cao *et al.* 2005a]. However, we include in this survey research relating to event sensing in a more general sense that contains techniques, algorithms and analysis suitable for WSNs deployed to detect rarely occurring events.

Rare event WSNs are found in a variety of situations including the battlefield [Arora *et al.* 2004] where low unit costs allow high density, short time-frame, disposable deployments. In industrial settings [Low *et al.* 2005] WSNs are cost efficient when compared to fixed wiring, where robust self-organizing characteristics make them suitable for monitoring hazardous machinery and protecting high value assets. It is entirely practical to perform periodic data collection and rare event detection in one WSN, but quality of service (QoS) aware routing protocols [Gelenbe and Ngai 2008] should be implemented to prevent unacceptable delays when urgent message relating to rare events have to queue up behind more mundane traffic. Whatever the deployment scenario, two metrics emerge as fundamental to rare event sensing [Liu *et al.* 2006; Cao *et al.* 2005a; Cao *et al.* 2005b]:

Detection Probability. Likelihood of an event being detected.
Detection Delay. Time taken for notification to reach a network sink.

WSNs can be considered part of the Internet of Things (IoT) [Atzori *et al.* 2010] and continue to benefit from active research projects and regular publication of surveys targeting specific topics. Recently, statistical, probabilistic, artificial intelligence, and machine learning methods for event detection have been briefly surveyed [Nasridinov *et al.* 2014] yet the majority of WSN surveys in the last five years have focused on areas unrelated to rare events. One exception [Pantazis *et al.* 2013] does consider event sensing as it relates to energy efficient routing with an emphasis on how the criticality of an event informs protocol design. Table I lists ten of the most frequently cited WSN survey papers published since January 1, 2010 with their area of interest.

This paper is, to the best of our knowledge, the first to survey WSN research that either specifically targets rare event sensing, considers work on rare events to be related, or documents ways the presented work could be applied to rare event sensing. Issues generic to all WSNs, including but not limited to security [Walters *et al.* 2007],

[1]As reported by Google Scholar, August 19, 2015

Table I: Most cited WSN Surveys since January 2010

Survey	Area of Interest
[Cheng *et al.* 2012]	Localisation
[Sundani *et al.* 2011]	Simulators
[Zhang and Varadharajan 2010]	Key management
[Katiyar *et al.* 2011]	Heterogeneous clustering algorithms
[Sen 2010]	Security
[Rodrigues and Neves 2010]	IP based WSNs
[Fan and Jin 2010]	Sensing coverage
[Christin *et al.* 2010]	Industrial automation
[Martins and Guyennet 2010]	Security
[Mohanty *et al.* 2010]	Security

software distribution [Han *et al.* 2005], and radio interference [Zhou *et al.* 2005] are deemed out of scope. Similarly, this survey does not consider event sensing techniques unrelated to the rarity of the event in question. Table II illustrates the relative volume of surveyed work for the following event sensing strategies:

Collaboration. In large multi-hop sensing networks, the energy cost of long-distance communication is significant. If sensing nodes work locally to collaboratively remove false positive event detections, network lifetime can be extended without adversely impacting detection probability. Collaboration can also take the form of nodes with discrete capabilities working together to more reliably detect rare events.

Component Deactivation. It is not always necessary for all WSN node components need to be constantly energised. Deactivating power hungry devices, particularly radio transceivers, saves energy and leads to longer network life-spans, extending the period in which a high detection probability can be maintained.

Duty Cycling. Shutting the entire sensing node down periodically is the ultimate energy saving technique. When nodes synchronise their sleep schedules, predictable levels of detection probability and delay can be maintained whilst extending the life of the network.

Over Population. Densely deploying sensing nodes such that they introduce redundancy in the network enables local collaboration and synchronised duty cycling in addition to an increased tolerance to individual node failure.

Message Suppression. When a number of sensing nodes detect the same rare event, their detection messages may be regarded as duplicates of each other. Suppressing these duplicates reduces network traffic and saves energy in doing so.

Burst Aware Protocols. When a rare event is detected by multiple sensors, a burst of network traffic is generated calling for protocols designed to handle the resulting media contention without introducing unnecessary detection delay.

Always On. Whilst not suitable for all deployment scenarios, the simplest strategy for maximising detection probability and minimising detection delay is to permanently energise all nodes in the network.

Energy Harvesting. The challenge of maximising network longevity and detection probability, and minimising detection delay can be moderated by harvesting environmental energy to augment or replace batteries in sensing nodes.

Table II: Volume of Surveyed WSN Research on Rare Events

Sensing Strategy	Papers Surveyed
Collaboration	17
Duty Cycling	15
Component Deactivation	14
Over Population	8
Message Suppression	7
Burst Aware Protocols	7
Always On	7
Energy Harvesting	6

The body of this paper is organised as follows: Section 2 details commonly used strategies for rare event sensing and surveys existing research, Section 3 discusses issues arising from this survey and Section 4 briefly considers work in associated fields. Conclusions are drawn and open issues are highlighted in Section 5.

2. EVENT SENSING STRATEGIES

Diversity in the characteristics of rare events prevents any one sensing strategy from becoming a panacea. Further, even given a well defined event classification, utilizing a single strategy may be insufficient to minimise occurrences of undetected events whilst maximizing the operational life of the sensing network. This section introduces event sensing strategies with examples of existing work examining them and surveys to what extent each strategy is represented in the literature. Table III summarises surveyed event sensing strategies, indicating their typical impact on detection probability and detection delay. The following sub-sections describe each strategy in more detail.

2.1. Collaboration

In large multi-hop networks, the cost of propagating event detection messages from originating nodes to the base station can be significant. If adjacent nodes collaborate prior to initiating the expensive long distance communication, a group decision is made on whether or not sufficient collective sensing evidence exists to support publication of an event detection message. A survey of cooperative event detection algorithms [Wittenburg *et al*. 2012] claims distributed evaluation exhibits the best energy efficiency and highest detection accuracy when compared to local and centralised approaches.

In a recently proposed probabilistic event monitoring scheme (PEMS) for sparse networks [Das and Misra 2015], sensing nodes detecting an event collaborate to select those whose observations are probabilistically significant. Nodes collaboratively selected for event monitoring then adjust the network topology for improved energy efficiency by assigning responsibility for data forwarding to a single clusterhead.

A system capable of being trained to recognise application specific event types [Wittenburg *et al*. 2010] has been field-tested for construction site intrusion detection with 100 nodes. Transmitting sensed data to a base station for analysis is eschewed in favour of collaboration between sensing nodes to determine if an event has occurred. Each node has multiple sensors and extracts feature vectors from raw data. Adjacent nodes share their feature vectors; if and only if they aggregate to match trained or statistically defined event vectors will a detection message be published.

Table III: Typical Effects of Sensing Strategies

Strategy	Detection Probability	Detection Delay	Observations
Collaboration	Increases	Increases	Collaborative sensing can lead to a more accurate understanding of when rare events have occurred and what does and does not constitute a false positive detection. However, the time taken for nodes to exchange collaboration information inevitably delays transmission of event notification messages.
Component Deactivation	-	Increases	The lack of effect on detection probability assumes primary sensors are not the components being deactivated. Powering off the transceiver inevitably leads to transmission delays and in some circumstances may also increase overall energy consumption as powering up the transceiver can consume as much energy as transmitting one packet [Olds and Seah 2012].
Duty Cycling	Reduces	Increases	When combined with an over population of nodes, negative impact on detection probability can be reduced, yet control messages for synchronised schemes introduce network overhead.
Over Population	Increases	May Increase	Whilst a higher density of sensing nodes is beneficial to event detection, the additional network complexity can lead to delays in getting the message out.
Message Suppression	-	Decreases	Removal of duplicate messages removes congestion from the network allowing urgent event notifications to reach their destination more rapidly.
Burst Aware Protocols	-	Decreases	Protocols specifically designed to handle a flurry of network activity are primarily aimed at reducing detection delay. Such protocols typically have a component deactivation element which needs to be carefully configured to minimise the increase in detection delay whilst waiting for deactivated components to warm up again.
Always On	Maximises	Minimises	Stored energy is rapidly exhausted making long term deployments problematic. Combination with energy harvesting promises extension of network life.
Energy Harvesting	Increases	-	Networks powered by energy harvesting have the potential to stay active for longer than those relying on batteries. However, energy availability may be unpredictable leading to temporary reductions in detection probability caused by unexpected node outages.

Rather than a simple threshold breach, more sophisticated event signatures can be used for distributed detection of transient complex events. In [Martincic and Schwiebert 2006] nodes are assumed to be stationary, location aware and uniformly distributed, with a path existing between each pair of nodes. The sensor network is partitioned into equal size cells. Nodes within a cell rotate leadership responsibilities including intra-cell communication where a time stamped weighted average value for the cell is shared with adjacent cells. For a network represented by $p \times q$ cells, an event signature is an $r \times s$ matrix where $r < p$ and $s < q$. To detect an event, leadership nodes “overlay” the event signature on the nodes in their cell; if a match is found, the event is considered to have been detected and an appropriate message is forwarded to the base station.

Distributed Bayesian algorithms for detection of sensing faults in WSNs tasked with the binary detection of environmental events [Krishnamachari and Iyengar 2004] have been shown through theoretical analysis and simulation to correct 85-96 percent of faults even when as many as 10 percent of the nodes are faulty. [Luo *et al*. 2006] present related simulation work whilst also evaluating Neyman-Pearson approaches and more closely considering the energy efficiency of their algorithms.

[Bandyopadhyay and Coyle 2003] identify that clustering nodes and assigning a clusterhead that takes responsibility for forwarding detection messages from the cluster to a base station may save energy. The authors propose a distributed, randomised clustering algorithm and extend it to generate a hierarchy of clusterheads. Energy efficiency is observed to improve as the number of levels in the hierarchy increase.

Real-time event detection services are provided in Data Service Middleware (DSWare) [Li *et al*. 2003] by collaborative correlation of sensing observations based on event characteristics enabling in-network differentiation between event occurrences and false alarms. Data semantic based confidence functions are supported to determine the relative importance of sub-events and capture historical patterns. If detection rates are low, partial detections of critical events are reported.

Military field tests of a distributed target classification system based on collaborative signal processing [Brooks *et al*. 2003] proved successful. Objects in the sensor field generate time varying spatial signatures from multiple sensors, and a moving object is a peak in the signature field that moves over time. Tracking the object is equivalent to tracking the peak. Distributed tracking is achieved by dividing the sensor field into cells within which a node is designated the manager, responsible for inter-cell coordination and intra-cell communication. In collaborative detection, classification, and tracking of moving targets: (1) cells near potential target trajectories are alerted and nodes in these cells collaborate to sense a target; (2) when a target is detected, the cell becomes active and tracking is initiated if the target is of the required type; (3) estimates of the target's current location and velocity are used to estimate potential future locations of the target; (4) as the target approaches the cell boundary, cells on the estimated trajectory are alerted and the process repeats.

The Role Alternating Coverage Preserving Coordinated Sleep Algorithm (RACP) [Hsin and Liu 2004] and the Equitable Sleep Coverage Algorithm for Rare Geospatial Occurrences (ESCARGO) [Harrison *et al*. 2015] collaboratively modify the duty-cycle (Section 2.2) of an over population (Section 2.4) of sensing nodes to reduce network-wide energy consumption whilst maintaining sensing coverage.

Energy efficiency through energy awareness of cooperating sensor nodes is the focus of another surveillance system [He *et al*. 2004] aimed at military deployments. Trade offs between energy and surveillance efficiency are made by adjusting the sensitivity of the system. On initialization, nodes discover their neighbours and elect sentry nodes who monitor the environment for intruders, while the remaining nodes enter a low power mode. If an intrusion is detected by a sentry, it wakes up the other nodes and they collaborate to track the intruder. When the intruder leaves the sensing area, the system resets, alternate sentries are selected, and the process continues.

Collaborative fuzzy logic schemes for event detection have been proposed [Kapitanova *et al*. 2012; Thuc and Insoo 2011; Liang and Wang 2005] and surveyed [Sharma and Singh 2014] though specific applications to rare events have yet to be documented. One challenge fuzzy logic algorithms face is that they typically require large rule-bases, the storage and distribution of which can prove problematic for the limited resource devices typically used in WSNs. Less specific machine learning techniques have recently been proposed for collaborative detection of definitively rare events, namely leaks in water distribution pipelines [Rashid *et al*. 2014].

Works detailed in other sections of this survey that also feature collaborative event sensing are: [Mekikis *et al*. 2013; Alam *et al*. 2012; Milic 2012; Arora *et al*. 2004; Ye *et al*. 2004].

2.2. Duty Cycling

In many event sensing scenarios, an *always on* strategy (Section 2.7) fails to meet longevity requirements beyond a few days or weeks. For extended use, regularly powering nodes down (putting them into sleep mode) improves operational life, potentially at the expense of guaranteed event detection.

Maximizing the detection probability for transient events and minimizing the detection delay for persistent events are fundamental to acceptance of duty cycling as an appropriate strategy for event-driven WSNs. [Zhu *et al*. 2012] characterise the trade-off between system lifetime and detection performance; an algorithm to collaboratively determine when nodes should wake up is proposed and a favourable comparison is made to random sleep scheduling.

Recent research [Misra *et al*. 2015] specifically targeting rare events proposes a probabilistic duty cycle in sensor medium access control (PDC-SMAC) algorithm for infrequent events in a military scenario intended to reduce the energy cost of 'ineffective sensing' - periods where a node is energised but there is nothing to sense. Sleep scheduling [Kavitha and Lalitha 2014] promises bounded detection delay while maximizing network lifetime. [Cao *et al*. 2005a] introduce a scheme where nodes enter and exit sleep mode in a coordinated fashion ensuring sensing coverage rotates over the network, each node being energised at regular intervals. For persistent events, this scheme introduces an increase in detection delay, with a reduction in detection probability being inevitable for transient events. In scenarios where network longevity takes priority, schemes of this nature may be acceptable.

For situations where the WSN is responsible for alerting humans in the sensing area, such as forestry workers when a fire breaks out or miners when a gas leak is detected, *detection delay* is considered the critical factor as the complex multi-hop nature of disseminating information through a large network can be adversely impacted by intermediary nodes adopting sub-optimal duty cycles. A level-by-level offset schedule based duty cycle pattern [Guo *et al*. 2012] has been proposed that restricts the upper bound of *detection delay* to be $3D + 2L$ where D is the hop count to a central node and L is the duty cycle sleep time. The scheme proposed in [Guo *et al*. 2012] adopts a two phase alarm broadcast following detection of the rare (the authors use the term 'critical') event. In the initial phase an event event notification is sent to a central node which initiates the second phase where the alarm is broadcast to all other nodes.

Adaptive control of the duty cycle [Vigorito *et al*. 2007] for energy harvesting WSNs (Section 2.8) allows sensing nodes to respond to changes in the environment. Such schemes have been shown to perform better than techniques that require a priori knowledge of available energy. This combination of techniques typifies successful rare event sensing research where two or more approaches compliment each other. Duty cycling and energy harvesting are individually advantageous techniques that when combined provide even greater benefit.

Full node duty cycling is also considered in the following papers detailed in other sections of this survey: [Kang *et al*. 2012; He *et al*. 2006; Keshavarzian *et al*. 2006; He *et al*. 2004; Hsin and Liu 2004; Kumar *et al*. 2004; Tian and Georganas 2002]

2.3. Component Deactivation

An alternative to full node duty cycling (Section 2.2) is powering down components when they are not required. The component of WSN nodes that uses the most energy is the wireless transceiver (Table IV). Transmit and receive costs are inevitable, but energy is wasted by media collisions and associated retries. Idle listening, where the transceiver is powered up but receives no packets, is another significant waste of energy. Deactivation of components can be application controlled or initiated by other layers, most notably MAC where the transceiver is often allowed to sleep when there is nothing for it to listen for or receive.

AIMRP, an Address-light Integrated MAC and Routing Protocol [Kulkarni *et al.* 2006] is specifically aimed at rare event detection scenarios. A randomised power saving mode allows nodes to de-activate their transceivers independently of one another. Using simulations, AIMRP has been shown to compare favourably to the more generic sensor MAC (S-MAC) [Ye *et al.* 2002] for event detection applications. S-MAC also supports transceiver deactivation, virtual clusters of nodes perform localised sleep synchronization. Energy consumed by AIMRP and S-MAC are compared for selected values of τ, the maximum permissible end-to-end latency for event reports, τ being equivalent to the maximum allowable *detection delay*; Simulation and analysis of AIMRP shows it consumes less energy than an analysis of S-MAC suggests it would for values of τ between 0.015s and 0.05s.

At the application level, a military intrusion system "Line in the sand" (LITS) [Arora *et al.* 2004] makes the distinction between passive and active sensing. Passive sensors are ones that measure analogue properties of the intruder such as magnetic, thermal and acoustic characteristics, while active sensors are those that determine the intruders' range, velocity and direction of travel by how the target modifies, reflects or scatters a signal transmitted by the sensor. The active sensor in LITS is pulse Doppler, while a magnetometer is used as a passive sensor. Detection of an intruder by the cooperatively low powered passive sensor triggers initialization of the active sensors. In LITS the active and passive sensors are on different nodes which collaborate, with the passive nodes detecting the intrusion and the active nodes tracking it.

A source-initiated or sink-initiate wakeup radio (WUR) based medium access control (GWR-MAC) [Karvonen *et al.* 2014] aims to reduce idle listening and by doing so improve energy efficiency in short range communication networks such as wireless sensor and body area networks. Favourable analytical comparisons are made against conventional duty-cycled (Section 2.2) MAC Protocols suggesting GWR-MAC would be useful and energy efficient for sensing low frequency events requiring a reasonably low detection delay.

The TRafficAadaptive Medium Access protocol (TRAMA) [Rajendran *et al.* 2006] is a time slotted MAC protocol with a distributed election scheme. TRAMA guarantees collision free transmission and allows nodes to power down their transceivers when they are not transmitting or required to receive. Additional MAC protocols that deactivate the transceiver for short periods are described in Section 2.6.

Messages used to control a sensing network are typically modestly sized and sent in small batches at high frequency; those sent in response to event detection tend to be much larger, sent in higher volumes but far less frequently. Deploying two radios on each sensing node [Feng and Potkonjak 2002], a low power device for control traffic and a higher power component for event data, allows the more energy hungry device to be powered down almost all the time.

Component deactivation is also considered in the following papers detailed elsewhere in this survey: [Yoo *et al.* 2012; Sun *et al.* 2008a; Sun *et al.* 2008b; Dutta *et al.* 2005; He *et al.* 2004; Polastre *et al.* 2004; Ye *et al.* 2004; Van Dam and Langendoen 2003]

2.4. Over Population / Node Redundancy

In a network with sufficient sensing coverage when all nodes are energised, duty cycling (Section 2.2) increases network longevity, but reduces coverage. Over populating

Table IV: Current Draw for WSN Components

	Active	Sleep
Texas Instruments CC2420 Transceiver[1]	18.8 mA	1 μA
Texas Instruments MSP430 Microcontroller[1]	1.8 mA	5.1 μA
Analog Devices ADXL345 3-Axis Accelerometer[2]	40 μA	0.1 μA
Panasonic EKMB123112 Passive Infrared Sensor[3]	2 μA	-

[1] From www.memsic.com
[2] From www.analog.com
[3] From pewa.panasonic.com

the sensing area allows nodes to synchronise their duty cycle so sensing coverage is maintained when some subset of nodes are powered down. Installing redundant nodes where each primary sensing node has a partner in close proximity allows optimal coverage to be maintained and can provide some tolerance to faults.

SenSlide [Sheth *et al.* 2005], a landslide prediction system, is a WSN hybrid of event detection and data capture. Energy-aware routing protocols are utilised to avoid individual nodes becoming drained of power prematurely but a level of fault tolerance is principally achieved by deploying redundant nodes.

For ephemeral events where a less than perfect detection probability is unacceptable, duty cycling algorithms can preserve coverage when an over population of nodes is deployed. A coverage preserving role alternating algorithm [Hsin and Liu 2004] enables such a deployment to extend the period during which initial sensing coverage is preserved by allowing nodes to enter sleep state if a minimal subset of neighbouring nodes have agreed to collaboratively take responsibility for the sleeping node's sensing area. When the sleeping node wakes up, sponsoring neighbours are now free to enter sleep mode if they can agree on a sponsoring contract with a group of their own neighbours.

Other works surveyed that rely on, or consider an over population of sensing nodes are: [Harrison *et al.* 2015; Zhu *et al.* 2012; He *et al.* 2006; Cao *et al.* 2005a; Kumar *et al.* 2004; Arora *et al.* 2004; Tian and Georganas 2002]

2.5. Message Suppression & Data Aggregation

When a rare event is sensed by multiple nodes in close physical proximity, they generate messages that can be considered duplicates of one another; delivery of a subset of these messages may be sufficient to confirm event occurrence [Heinzelman *et al.* 2002; Yang *et al.* 2013].

CC-MAC [Vuran and Akyildiz 2006], composed of an event MAC (E-MAC) and a network MAC (N-MAC), exploits the spatial correlation of messages generated by sensing nodes to suppress duplicates from nodes in close physical proximity. In a given correlation region, a single node is chosen as being representative of its correlation neighbours; only messages originating at the representative node are transmitted to the network sink, all other messages are suppressed.

Sift [Jamieson *et al.* 2006] is a slotted MAC protocol designed to deal with both the bursty nature of a large number of nodes wishing to transmit at the same time (Section 2.6) and de-duplication of the message queue. In removing some percentage of duplicate messages, Sift aims for the collision free delivery of R messages from N nodes where $R < N$. On successful delivery of R messages, the remaining $N - R$ messages are suppressed.

Message aggregation techniques for data-centric routing [Krishnamachari *et al.* 2002] include suppression of duplicates to reduce energy usage by minimising transmission volumes. In dense networks, greedy aggregation has been shown [Intanagonwiwat *et al.* 2002] to be more efficient than opportunistic aggregation schemes. Sliding window skylines [Borzsony *et al.* 2001] have been also proposed as a suitable technique for message suppression in a system for forest fire detection [Pripužić *et al.* 2008] .

2.6. Burst Aware Protocols

Rare events can trigger a tsunami of messages in the sensor network, all of which would like to be transmitted at the same time leading to channel contention, an increased probability of packet collision and the potential for data loss and delay.

The MAC layer defined by the IEEE 802.15.4 standard [Gutierrez *et al.* 2001] and used extensively in WSN devices has two modes of operation. In beaconed mode, at least one device acts as a personal area network (PAN) coordinator and non-coordinator devices must wait to transmit in contention free time slots. If beaconing is not employed, an un-slotted carrier sense multiple access with collision avoidance (CSMA/CA) algorithm based on listening to the physical medium is used, collisions being avoided by invoking a random exponential back-off algorithm. Beaconed or not, IEEE 802.15.4 MAC is designed to minimise energy usage in the nodes, not maximise delivery rates. In extremely bursty conditions, an alternate MAC may be required.

A geographical cross-layer asynchronous sender-oriented MAC protocol [Zayani *et al.* 2014] has recently been proposed to facilitate opportunistic routing in low duty-cycle wireless sensor networks (Section 2.2) that may experience bursty traffic patterns and unpredictable changes in network topology. This protocols objective is to maximize network lifespan while guaranteeing packet delivery with acceptable end-to-end delays.

Reliable Bursty Convergecast (RBC) [Zhang *et al.* 2007] is a MAC protocol designed specifically to handle bursts of data in multi-hop networks that converge on a limited number of sinks. Using data traces taken from [Arora *et al.* 2004] an implementation of RBC based on B-MAC [Polastre *et al.* 2004] is shown experimentally to perform better than the default TinyOS [Levis *et al.* 2005] radio stack where 100% packet delivery is not required.

S-MAC [Ye *et al.* 2004] is an earlier MAC protocol for ad-hoc deployments of battery operated sensor nodes that remain inactive for extended periods but become suddenly active when an event is detected. S-MAC values energy conservation and self configuration over per-node fairness and latency. Virtual clusters of nodes adopting common sleep schedules reduce control overhead and message passing techniques can reduce contention latency for applications undertaking in-network data processing.

A Receiver-Initiated asynchronous duty cycle MAC protocol for dynamic traffic loads (RI-MAC) [Sun *et al.* 2008b] is a transceiver deactivation (Section 2.3) protocol shown to outperform contemporaries when faced with bursty message flows. Duty-cycle Scheduling based on Residual energy (DSP) and Duty-cycle Scheduling based on Prospective increase in residual energy (DSR) [Yoo *et al.* 2012] are protocols derived from RI-MAC that determine their deactivation schedules based on residual or prospective increases in harvested energy (Section 2.8).

A MAC protocol designed to cope with the burst of traffic that follows detection of a rare event is Demand Wakeup MAC (DW-MAC) [Sun *et al.* 2008a]; sleeping transceivers are woken on demand yet data transmissions are guaranteed not to collide at receiving nodes. DW-MAC is a synchronised duty cycle MAC protocol that assumes accurate clock synchronisation by. Each cycle is divided into three periods: Sync, Data and Sleep. DW-MAC wakes up nodes on demand during the Sleep period of a cycle in order to transmit or receive a packet.

Sift [Jamieson *et al*. 2006] is a MAC specifically for event sensing networks, its principles being similar to those found in rare event WSNs powered by energy harvested from the event itself [Cheng *et al*. 2013] where bursts of data must be dealt with before the limited available energy is consumed.

2.7. Always On

Leaving event sensing nodes powered on at all times may be necessary if missing an event occurrence is unacceptable, notification of the event needs to be as fast as possible or the network deployment timescale is sufficiently short that battery depletion is unlikely. Estimating the longevity of always on sensing networks is problematic. In a study of a large intrusion detection system [Kumar *et al*. 2005] it is suggested that mistakes as large as an order of magnitude are routinely made. Nevertheless, adopting an always on strategy remains an appropriate course of action in certain circumstances.

Structural engineers monitoring vibrations require rich data at high sample rates yet bandwidth limitations in WSNs made up of more than a handful of nodes make reliable delivery of such a data deluge impractical. Wisden [Xu *et al*. 2004] observes that a single triple axis accelerometer generating 16-bit samples at 100Hz requires 4.8Kbps and suggests delivery of data relating to interesting events (rather than a continuous time series) is sufficient for analysis of structural vibration. Even taking this into consideration and allowing for data compression before transmission, in such an environment sensor nodes are busy almost all the time.

Monitoring events on an active volcano with small low-power WSN devices [Werner-Allen *et al*. 2006] was achieved by leaving the sensing nodes energised at all times. The short deployment (three weeks), volume of events detected (230), their ephemerality (less than 60 seconds each) and transient nature made an *always on* strategy acceptable. Similarly, a system for surveillance of temporary museum exhibits [Viani *et al*. 2012] stays energised at all times to maximise detection probability; extending network life is of little concern as batteries can provide sufficient power for an entire exhibition.

Permanently powering all WSN nodes is a technique adopted in a military intrusion detection system [Arora *et al*. 2004] and is referenced when considering coverage maintenance in low duty cycled WSNs [Hsin and Liu 2004].

2.8. Energy Harvesting

WSN research has traditionally focused on minimizing energy consumption in battery powered sensor nodes, balancing longevity against functionality. Increasingly, researchers are evaluating the efficacy of harvesting energy from a variety of environmental sources [Gilbert and Balouchi 2008; Sudevalayam and Kulkarni 2011].

Energy sources such as solar are reliable (the sun always comes out) but unpredictable (it may be obscured by clouds). For rare event sensing where the event may occur at a point where limited environmental energy is available, a *Harvest-Store-Use* architecture [Sudevalayam and Kulkarni 2011] coupled with multiple storage devices as used in Prometheus [Jiang *et al*. 2005] and AmbiMax [Park and Chou 2006] would appear appropriate, yet neither Prometheus nor AmbiMax address rare event sensing directly, Prometheus being specifically aimed at periodic data capture.

A proposed adaptive scheduling scheme for cooperative energy harvesting networks [Ammar and Reynolds 2015] combines cooperative communications (Section 2.1) and energy harvesting in a scheduling scheme intended to maximizes packet delivery ratio with the aim of gaining acceptable detection probability without necessarily minimising detection delay. Cooperating nodes advertise their status as either 'active/on' or 'inactive/off' (a form of duty cycling (Section 2.2) but without component deactivation (Section 2.3)) based on their harvested energy levels. When a node detects an event and wishes to transmit an notification message, if a cooperating node is currently marked as 'active', the source node will forward the message via it's cooperating neighbour; otherwise the source nodes attempts to transmit on its own. Simulation results indicate the scheme would provide similar performance to a state-of-the-art alternative [Li *et al*. 2012], but does not require threshold parameter optimization.

An adaptive scheme for duty cycling (Section 2.2) [Vigorito *et al*. 2007] in energy harvesting WSNs does not attempt to model the energy source allowing usage in situations where a prior knowledge of the source is unavailable. The scheme's computational efficiency and adaptability to near depletion scenarios prevent node outages whilst tunable stability restricts variance in individual node duty cycles. Similarly, ODMAC [Fafoutis and Dragoni 2011], an on-demand MAC specifically aimed at energy harvesting WSNs supports individual duty-cycles for nodes with different energy profiles but does not consider its application to rare event sensing.

DSR and DSP [Yoo *et al*. 2012] (cf: Section 2.6) propose dynamic duty cycle scheduling for energy harvesting WSNs based on RI-MAC [Sun *et al*. 2008b]. DSR allows sensor nodes to adjust their duty cycle based on their remaining energy store. DSP estimates future energy harvesting opportunities and aggressively adjusts duty cycles proportionately. Reductions in end-to-end delay are demonstrated for DSR and DSP over unmodified RI-MAC for $N \times N$ grids, when N is in the range $4m$ to $8m$, with $20m$ between each node and a transmission range of $30m$.

A survey of energy harvesting for structural health monitoring (SHM) sensor networks [Park *et al*. 2008] did not restrict itself to rare events but recent research [Cheng *et al*. 2013; Tomicek *et al*. 2013] addresses SHM via WSNs powered by energy extracted from the rare event itself, namely an earthquake. The focus is on a MAC protocol that is capable of handling both the bursty nature of the messages generated by the event (Section 2.6) and the limited energy extracted from the earthquake via frequency tuned piezoelectric vibration energy harvesters.

A detailed survey of power management in energy harvesting WSNs [Kansal *et al*. 2007] considers event monitoring as a deployment example. Particular attention is paid to *detection delay* making a distinction between the delay introduced by the MAC layer and energy aware routing protocols.

2.9. Classification of Existing Work

Table V summarises work discussed in this section highlighting which sensing strategies are featured in deployed applications, MAC protocols and supporting technologies.

Table V: WSN Research on Rare Event Sensing

	Duty Cycling	Component Deactivation	Over Population	Energy Harvesting	Collaboration	Burst Aware Protocols	Message Suppression	Always On
Applications								
[Mekikis *et al*. 2013]					x			
[Cheng *et al*. 2013]				x		x		
[Tomicek *et al*. 2013]				x				
[Viani *et al*. 2012]								x
[Wittenburg *et al*. 2010]					x			
[He *et al*. 2006]	x		x					
[Werner-Allen *et al*. 2006]								x
[Dutta *et al*. 2005]		x						
[Sheth *et al*. 2005]			x					
[Arora *et al*. 2004]		x	x		x			x
[He *et al*. 2004]	x	x			x			
[Xu *et al*. 2004]								x
MAC Protocols								
[Zayani *et al*. 2014]	x	x						
[Karvonen *et al*. 2014]		x						
[Yoo *et al*. 2012]		x		x		x		
[Sun *et al*. 2008b]		x				x		
[Sun *et al*. 2008a]		x				x		
[Rajendran *et al*. 2006]		x						
[Vuran and Akyildiz 2006]				x			x	
[Jamieson *et al*. 2006]						x	x	
[Polastre *et al*. 2004]		x						
[Ye *et al*. 2004]		x			x	x		
[Van Dam and Langendoen 2003]		x						
[Ye *et al*. 2002]		x						
Supporting Technologies								
[Ammar and Reynolds 2015]				x	x			
[Tang *et al*. 2015]				x				
[Misra *et al*. 2015]	x				x			
[Das and Misra 2015]				x				
[Harrison *et al*. 2015]	x		x	x		x		
[Rashid *et al*. 2014]				x				
[Kavitha and Lalitha 2014]	x							
[Yang *et al*. 2013]							x	
[Zhu *et al*. 2012]	x		x					
[Milic 2012]					x			

Continued on next page. . .

Table V – Continued from previous page

	Duty Cycling	Component Deactivation	Over Population	Energy Harvesting	Collaboration	Burst Aware Protocols	Message Suppression	Always On
[Alam *et al*. 2012]					x			
[Guo *et al*. 2012]	x							
[Kang *et al*. 2012]	x							
[Thuc and Insoo 2011]					x			
[Wittenburg *et al*. 2010]					x			
[Pripužić *et al*. 2008]							x	
[Vigorito *et al*. 2007]	x			x				
[Martincic and Schwiebert 2006]					x			
[Keshavarzian *et al*. 2006]	x							
[Luo *et al*. 2006]					x			
[Cao *et al*. 2005a]	x							
[Kumar *et al*. 2005]								x
[Hsin and Liu 2004]	x		x					x
[Krishnamachari and Iyengar 2004]					x			
[Kumar *et al*. 2004]	x		x					
[Bandyopadhyay and Coyle 2003]					x			
[Li *et al*. 2003]					x			
[Brooks *et al*. 2003]					x			
[Feng and Potkonjak 2002]		x						
[Heinzelman *et al*. 2002]							x	
[Intanagonwiwat *et al*. 2002]							x	
[Krishnamachari *et al*. 2002]							x	
[Tian and Georganas 2002]	x		x					

3. DISCUSSION

WSNs can be classified by their data delivery profile as being *continuous*, *event-driven*, *observer-initiated* (query-based) or a *hybrid* [Tilak *et al*. 2002]. Based on the literature, it appears continuous, periodic sensing is the model that has been of most interest to WSN researchers, though event-sensing is increasing in popularity. The most widely cited[1] survey on WSN research [Akyildiz *et al*. 2002] briefly mentions event sensing and query based approaches, but the majority of the technologies and systems it surveys target periodic sensing deployments. A more recent survey [Yick *et al*. 2008] gives more space to event sensing and a survey of the state of the art of WSN programming techniques published within the last three years [Mottola and Picco 2011] features the application of *event-triggered* distributed processing.

[1]Citations as of October 7, 2015 - Google Scholar: 14,097, Microsoft Academic Search: 4,249.

Rare events are characterised by domain specific low occurrence probabilities, but selecting appropriate detection and propagation techniques relies on an understating of a number of other attributes:

Frequency. While the probability of a rare event occurring in a given time period may be low, over an extended time period occurrences may become regarded as frequent. For example, the probability of an earthquake hitting New Zealand in then next given sixty seconds is low, yet the country experiences several hundred earthquakes a year.
Randomness. To what extent do the events occur in a partially predictable fashion? In industrial settings there may be a trigger event such as certain piece of machinery being switched on that makes the rare event possible, but not necessary probable.
Ephemerality. How long a rare event lasts can inform strategies for dealing with it. If it an event typically lasts for n time units, is it acceptable to detect in the nth time unit? To what extent is it better to detect it in the 1st time unit?
Transitory Nature. After an event occurs, is there any evidence it happened? If there is, is it acceptable to detect the effect rather than the event? A fracture in a water main can be sensed either as a physical change at the location of the break (potentially problematic for a long pipe) or as a drop in water pressure beyond the break.
Connectedness. Once an event has occurred, does that imply something about the next occurrence? Can the magnitude or timing of subsequent events be predicted? Measuring the ephemerality of events as they occur could inform a sleep-scheduling algorithm that starts by assuming events are instantaneous but learns that the event always last (i.e. are detectable) for some period of time, hence the sleep cycle can be modified to be slightly less than that period.
Criticality. How important is it that an event be detected? Once detected, how quickly must a notification message be propagated to interested parties? This may be related to event frequency, it may be acceptable to miss frequently occurring less critical events simply because it is a certainty another one will occur in the near future.
Network Lifetime. How long must this network be active? Is the event so rare that once detected the network is permitted to effectively destroy itself by using all its energy to propagate the notification message.

To detect a rare event at a given location, at least one node within sensing range of that location must be operational when the event occurs. Similarly, once the event has been detected, sufficient nodes must be active such that a low latency route exists for forwarding event notification messages to the network sink. Whether powered by batteries or energy harvested from the environment, WSNs deployed to detect and report rare events are constrained by the twin requirements of maximising detection probability and minimising detection delay whilst working with a limited energy source. The event sensing strategies surveyed in this paper address these constraints, either individually or in complimentary combinations.

Two themes are highlighted in Table V. Firstly, applications deployed for extended use, i.e. ones that do not adopt an *always on* strategy (Section 2.7), rarely rely on just one of the strategies presented here. Secondly, almost all MAC protocols for rare event sensing make use of component deactivation to the extend that they regularly turn off the wireless transceiver.

The predominance of multi-strategy real-world deployments is reflected in the number of citations of the surveyed papers. A the time of writing, the two most widely cited articles[1] included in this survey [Heinzelman *et al*. 2002; Ye *et al*. 2002] focus on single strategies: *message suppression* (Section 2.5) and *component deactivation* (Section 2.3) respectively. If the individual strategies are considered the building blocks of an efficient and successful WSN, which ones to use and how to combine them are fundamental considerations when developing real-world systems.

4. ASSOCIATED WORK

In situations where event occurrence cannot be detected at an individual node or by a collaborative evaluation by neighbouring nodes, sensed data can be transmitted to a base station for consolidated event determination. A simulated mine safety system [Li *et al*. 2008] takes this approach to detect gas leaks, water seepage and areas of high oxygen concentration that could provide refuge for mine workers in an emergency. Whilst the system as a whole detects rare events, the WSN nodes themselves perform periodic data capture only.

In addition to sensing geospatial phenomenon, malicious disruption of the WSN itself can be considered a rare event. [da Silva *et al*. 2005] propose a decentralised three phase rules based algorithm for intrusion detection focusing on multiple attacks strategies including message delay, alteration and repetition. [Sun *et al*. 2007] and [Roman *et al*. 2006] describe the application of intrusion detection mechanisms to WSNs whilst [Czarlinska *et al*. 2007] consider attacks on sensor-actuators in hostile environment to be rare events. Similarly, fault detection and tolerance in WSNs deployed to detect critical rare events [Mahapatro and Khilar 2013; Ould-Ahmed-Vall *et al*. 2012; Jurdak *et al*. 2011] are of significant importance.

Beyond dedicated WSNs, rare geospatial events can be monitored by collaborative use of personal electronic devices. Further, some classes of rare events can be predicted by off-line analysis of data captured from multiple heterogeneous sensor networks not originally deployed in a detection role.

Community Sensing [Krause *et al*. 2008] is an area of research investigating the use of the built-in sensors and communication capabilities of smart phones to detect and monitor rare events. The iShake App [Dashti *et al*. 2011] and others [Faulkner *et al*. 2011] aim to assist in the detection of earthquakes and similar rare events with mobile sensing devices. Feeds from social networking sites have also been evaluated for their real-time "social sensing" potential [Sakaki *et al*. 2010].

5. CONCLUSION AND FUTURE WORK

Energy efficiency has long been the focus of WSN research [Akyildiz *et al*. 2002; Yick *et al*. 2008]. A comparatively recent study [Anastasi *et al*. 2009] specifically surveys energy conservation techniques for WSNs. For a given sensing task, innovative techniques that demonstrably reduce energy consumption while maintaining an appropriate level of sensing functionality and network connectivity will continue to be in demand.

As an increasing number of wireless devices are deployed under the IoT banner, distinctions between network types (sensor, actuator, ad-hoc, body-area) will become blurred and more about deployment scenarios than equipment and protocols. Should IoT drive a convergence of underlying technologies and the standardisation of low cost, energy efficient, programmable wireless devices, multi-purpose networks rather than point solutions may become the norm. Such a convergence of device use and network traffic could cause a significant degradation in rare event detection delay unless the

[1]Citations as of October 7, 2015 - Google Scholar: [Heinzelman *et al*. 2002] 8,864 [Ye *et al*. 2002] 5,544. Microsoft Academic Search: [Heinzelman *et al*. 2002] 1,991 [Ye *et al*. 2002] 2,222.

system as a whole honours QoS rules requiring critical rare event notification messages to be transmitted with high priority.

Regardless of the multi/single purpose nature of future deployments, it appears reasonable to predict the rare event strategise identified in this survey will continue to be used in appropriate circumstances, yet the relative occurrence of each may change over time; some becoming more or less significant based on the rise or fall in ubiquity of others. Collaboration may be more frequently used if energy harvesting techniques improve to the point where significant overpopulation of always-on devices are deployed to provide a more nuanced picture of rare event occurrences. Conversely, component de-activation may become less prevalent if rechargeable battery and charging technology improves significantly in capacity and efficiency; the ability to store more energy, more quickly potentially negating the need to frequently shut down energy hungry components.

Energy harvesting promises to provide extended life to WSNs and has been extensively investigated for data capture applications [Seah *et al*. 2009], but comparatively little research exists on the successful application of this technology to rare event WSNs. An area suitable for further research is the impact unpredictable energy harvesting patterns have on existing energy conservation techniques used to prolong the life of battery powered rare event WSNs. Some schemes will prove unworkable yet others may lend themselves to modifications that allow energy harvesting to further extend the life of the WSN whilst ensuring high detection probability and maintaining low detection delay.

Attention could also be given to the challenges of providing low-latency forwarding of event notification messages where nodes collaboratively duty cycle to conserve energy. Existing opportunistic forwarding algorithms [Füßler *et al*. 2003; Sanchez *et al*. 2007] may prove unsuitable in certain rare event sensing scenarios.

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Received June 2014; revised October 2015; accepted xxxx 201x