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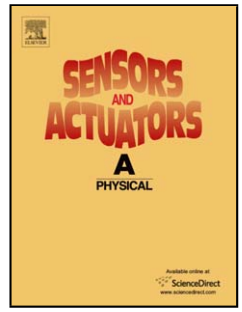

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Energy Managed Reporting for Wireless Sensor Networks

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Abstract–In this paper, we propose a technique to extend the network lifetime of a wireless sensor network, whereby each sensor node decides its individual network involvement based on its own energy resources and the information contained in each packet. The information content is ascertained through a system of rules describing prospective events in the sensed environment, and how important such events are. While the packets deemed most important are propagated by all sensor nodes, low importance packets are handled by only the nodes with high energy reserves. Results obtained from simulations depicting a wireless sensor network used to monitor pump temperature in an industrial environment have shown that a considerable increase in the network lifetime and network connectivity can be obtained. The results also show that when coupled with a form of energy harvesting, our technique can enable perpetual network operation.

Keywords-Wireless Sensor Networks, Industrial Monitoring, Energy-Aware, Energy Harvesting

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I. Introduction

A Wireless Sensor Network (WSN) typically consists of a number of small, inexpensive, locally powered sensor nodes that communicate detected events wirelessly through multi-hop routing [1]. WSNs are continuing to receive escalating research interest due, in part, to the considerable range of applications to which they are suited. Applications include environmental monitoring [2], healthcare [3], and defence [4]. The cost of installing wiring for a single sensor in a building is estimated to average $200 (as much as 90% of the total installation cost), and so it can be seen that WSNs have huge commercial possibilities [5]. A key research area is concerned with overcoming the limited network lifetime inherent in the small, locally powered sensor nodes [1]. Many of the WSN algorithms designed to extend the network lifetime are modified routing algorithms (deciding which route a packet should take through the network) [6], and/or distributed processes [7].

In this paper, we propose a localised technique to extend the lifetime of a wireless sensor network, referred to as IDEALS/RMR (Information manageD Energy aware ALgorithm for Sensor networks with Rule Managed Reporting). The extension in the network lifetime is achieved at the possible sacrifice of low importance packets, as a result of a union between:

- Information control, quantified by a system of rules, referred to as Rule Managed Reporting (RMR)
- Energy management, supplemented by energy harvesting, for example mechanical vibrations [8]

This union results in the nodes' behaviour and operation being determined by their local energy state, and the importance of events happening in their sensed environment. As the nodes harvest energy from vibrations, the network does not have a lifetime limited by the capacity of the onboard batteries. Therefore we can escape the assumption that a WSN has a fixed lifetime after which it becomes useless [9, 10].

II. Related Work

The routing algorithm PRIMP [6] provides a form of energy management, where nodes that have a 'high' energy reserve are chosen to forward packets over those with a 'low' energy reserve. PRIMP is a negotiation based routing algorithm providing only one threshold (the energy level is either high or low). IDEALS provides an arbitrary number of priorities and thresholds, and operates locally upon independent decisions (that do not only apply to routing). Additionally, IDEALS also uses nodes with lower energy reserves to forward packets of high importance (quantified by RMR) – thus increasing the connectivity and packet success.

ReInForM [11] uses knowledge about the channel error, number of hops, and data importance to send packets along multiple routes. The number of different routes used depends on the importance of the packet (implemented elsewhere), thus linking packet reliability with information content. ReInForM is concerned with channel error and successful data transfer as opposed to the energy resources of the nodes.

In Hull et al [12], a bandwidth management method is described, using a rule system to prioritise outgoing data packets depending on their derived importance. This is however only concerned with managing bandwidth, and does not take energy management into consideration. In Jain et al [13], a Dual Kalman Filter architecture is used to reduce the bandwidth by only communicating data that cannot be predicted by the sink node. This however requires a pre-selected, powerful sink node, and also instigates an increased computational load at each sensor node. IDEALS/RMR can operate without a fixed sink node, and operates using simpler mathematical operations such as comparisons and increments, as opposed to matrix multiplications and inversions.

TinyDB [10] is an acquisitioned query processing system for sensor networks, designed primarily for TinyOS. The system allows a sink node to extract relevant data from the network of sensors by interrogating it with SQL-like queries. Priorities can be added to outgoing packets (a large change in a sensed value relates to high importance) to overcome congestion problems. Power management exists by optimising queries and adjust reporting rates to minimise consumption. Power management and packet importance are not linked to the original query. TinyDB is designed to provide a general solution for a wide range of scenarios, and as such the overheads are reasonably high - requiring 58K of the 128K memory available on a current generation mote for the code. In contrary, we propose an embedded, localised approach, where a minimal set of rules (requiring minimal overheads) are stored on the node.

The Dust Networks SmartMesh platform [23] is particularly suited to industrial automation (and hence relevant to the industrial monitoring scenario presented in this paper). The platform claims >99.9% end-to-end reliability, and can operate for 5-10 years from an off-the-shelf battery (though this battery life applies only to the nodes that do not perform routing). This system reports data periodically (every minute), and so adding the system of information control and energy management proposed in this paper to such a system could enable significant energy savings (and so either extend the network lifetime, or reduce the capacity and so size of the on-board battery).

We believe that the form of information control (discriminating between packets based on the locally determined information content), coupled with energy management (a node will only participate in communications if it decides the packet is more important than its limited energy reserve) used in the proposed localised IDEALS/RMR system has not been considered before.

III. The Proposed IDEALS/RMR System

The basic principles of IDEALS (Information manageD Energy aware Algorithm for Sensor networks) were introduced in [14] as a system providing an increase in the lifetime of a network through the discrimination of certain packets. IDEALS was simulated under static conditions, and shown to provide a considerable increase in the network lifetime. The aim of this paper is to extend this work by:

- Showing how IDEALS can be coupled with a system for determining the packet information content – in this paper we propose RMR (Rule Managed Reporting)
- Performing a detailed analysis through simulation of the IDEALS/RMR system in a realistic scenario utilising intermittent energy harvesting

The concept of IDEALS/RMR is that a node with a high energy reserve acts for the good of the network by participating in routing all packets that come to it, and by generating its own packets from all locally detected events. However, a node with a near-depleted energy reserve acts selfishly, by only generating or forwarding packets that have a high information content. By doing this, IDEALS is able to extend the network lifetime for important data, through the possible loss of more trivial data.

For the sake of completeness, an overview of the operation of IDEALS is provided in this paper. In a traditional wireless sensor node, events occurring in the surrounding environment are detected by various sensors. These data are passed to the controller for processing, following which they are embedded into a packet and transmitted wirelessly in accordance with the communications protocol [15]. In addition, sensor nodes between the source node and the sink node perform packet routing. Therefore, packets received by a sensor node that are destined for a different node should be retransmitted to neighbouring nodes in accordance with the communications protocol. IDEALS/RMR functions alongside this traditional framework.

The IDEALS/RMR system diagram is shown in Fig. 1. Upon sensing data, the sensors pass the information to the controller, which supplies the data to RMR. RMR is a reporting technique used to decide if an event worth reporting has occurred, and how important such an event is. The concept and functionality of RMR is given in greater detail in section IIIa. Data from RMR is then passed to IDEALS which uses priority balancing to ascertain whether or not transmitting the packet is worth the energy cost incurred. IDEALS' priority balancing is also used by nodes performing packet routing. If a received packet is not important enough to warrant the energy cost, the packet will not be forwarded. The concept and functionality of IDEALS is given in greater detail in section IIIb. The computational costs introduced by IDEALS/RMR are low, as the mathematical operations required are simple comparisons and increments. We believe that the IDEALS/RMR system could be implemented on a wide range of WSN platforms, for example the TI/Chipcon CC2430EM SoC module [24].

A. RMR

The purpose of RMR is to determine if an event worth reporting has occurred, and how important such an event is. A range of methods exist for deciding how event reporting should be managed (when a node should report that an event has occurred). The simplest method is to report periodically, every *t* minutes. However, this means that packets are transmitted (and an energy cost incurred) even when the sensed parameter has not significantly changed since the previous transmission. The second option is a querying approach, where the sink node instigates data transfer by requesting data from a subset of the nodes [10] (for example the sink node querying *"where in the building is the temperature over 25 degrees?"*). The third method is to use an 'intelligent' sensor node, which decides locally when events in the sensed environment should be reported to the sink node. This is this method that RMR uses.

RMR receives data from the sensors via the controller. To ascertain the information content, the *rule database* is inspected. Any number of predefined rules can be entered by the designer, and describe differing events that can be detected in the sensed environment, including but not limited to:

- **Threshold rules** (report when the sensed value crosses a preset value)
- **Differential rules** (report when the change in the sensed value is larger or smaller than a preset value)
- **Feature rules** (report when a preset pattern or feature is noticed in the sensed value)
- **Periodic rules** (report at preset time intervals)
- **Routine rules** (report if a packet of that importance or higher has not been sent for a preset period)

For examples of these rules, see table 1 for the rule set used in the simulation shown in section V. If multiple applications run on the network, then multiple rule sets can be created. To determine if any rules have been fulfilled, *rule compliance testing* checks the sensed data against each rule in the *rule database* (using the *history* for information about previous packets and sensed values). For the majority of rules, only the 'previous value' or 'time since' needs to be stored in memory – requiring very minimal overheads (the exception to this are feature rules, which may require additional storage and computational power to detect features in the sensed parameter). Any rules that are fulfilled are passed to *message priority allocation* to determine the information content of the packet. When the designer originally creates the rules, they assign a message priority (MP) to each rule. In this investigation, five different MPs were used (MP1-MP5). A high message priority (MP1) relates to an important packet (for example car tyre pressure sensor detecting a fast puncture requiring urgent action). Conversely, a low message priority (MP5) relates to a low importance packet (for example a routine 'everything is ok' packet). Intermediate priorities MP2-MP4 are allocated to packets whose information content lies between these two extremes (for example, MP3 may relate to a slow puncture).

B. IDEALS

IDEALS determines whether or not a node should transmit a packet through *priority balancing*. The node's energy resources are characterised by *power priority allocation*, which assigns a power priority (PP) based on the state of the battery and energy harvesting environment. Nodes with high energy reserves are allocated a high power priority (PP5), while near depleted energy resources are allocated a low power priority (PP1). Intermediate priorities PP2–PP4 relate to the power levels which lie between these extremes. *Priority balancing* compares the message priority (MP) obtained from RMR with the power priority (PP) obtained from *power priority allocation* and decides whether or not the packet should be sent.

A packet will be sent if the PP $\geq$ MP. Therefore, as the residual energy drops, packets will be selectively discarded in order of their information content. The priority allocation and balancing process can be seen in fig. 2. For example, if the battery is full (PP5), packets with any information content (MP1–MP5) will be transmitted. However, if the battery is low (PP1), only packets with a high information content (MP1) will be transmitted. It can also be seen in that a fraction of the energy is allocated to PP0. This is reserved to maintain an energy store for power management and control, during which no sensing or communications takes place. Priority balancing also affects the routing process – if a node's residual energy level does not warrant sending a packet of a certain priority, it will not participate in routing.

Data deemed not to be significant enough (considering the state of the network) can be dropped at a number of stages: event generation (if a change in the data does not trigger a rule, an event will not be generated), local priority balancing (if the PP < MP, the packet will not be created from the generated event), and routing (if no route exists across the network where the PP $\geq$ MP, the packet will not reach its destination).

IV. Simulating IDEALS/RMR

The IDEALS/RMR system lends itself to applications where sensor nodes are small, energy constrained (particularly those that feature one or more sources of energy harvesting) embedded devices that are required to report data in an unassisted fashion. Naturally, it must be possible to prioritise different classes of data that are processed by the node – therefore, the system is not suited to an application where all data are equally important (generally systems that have a binary event trigger – for example a system where light switches in a building are replaced by a network of wireless switches). The IDEALS/RMR rules and parameters must be adjusted to suit the exact application and scenario requirements.

Consider the realistic, simulated scenario [16]: in an industrial environment, a WSN is used to monitor the temperature of 20 randomly organised pumps (as shown in figure 3). In the simulated scenario, each pump operates once daily for a random period of time, with an ambient temperature of 25°C, and an operating temperature of 50°C [16]. It takes around two hours for the sensed temperature of the pump to change from ambient temperature to within 10% of the normal working temperature. Sensors are duty cycled, inspecting the pump every five minutes. The simulation is run over a period of five days. During pump operation, mechanical vibrations occur locally at a fixed frequency, allowing 0.1mW of harvested power to supplement the nodes' batteries. This is calculated from a pump vibrating at 25 milli '**g**' (where **g** is $9.81 m/s^2$), which equates to a harvestable power of at least 0.1mW [8, 16]. While the pump is inactive, no vibrations occur, and no energy can be harvested. The vibration harvesting device is always functioning and attempting to harvest any energy that is available; this consumes negligible energy.

The energy parameters used in the radio model are described in the appendix. They equate to a situation where the nodes are powered from a 1.2F super-capacitor. The nodes have a power consumption of around 35mW to transmit at a data rate of 40kbps. A packet, including synchronisation and error bits, is taken to be 1000 bits in length (considerably longer than the average packet length of 176 bits for IEEE 802.15.4 [17] to allow for radio synchronisation). A low-power receive radio transceiver has been selected, which helps to limit effects of packet flooding. It is important to note that radio communications are synchronised and duty cycled. In contrary, vibration harvesting occurs continuously (while the pump is operating), and so 30mJ can be harvested over a five minute period.

The network was simulated using an in-house simulator (WSNsim) developed as a part of this research. WSNsim is a top down wireless sensor network simulator created in Microsoft Visual Studio .net 2003, aimed at enabling high level network and performance observations. The use of a custom simulator (as opposed to the numerous freely available network simulators [18, 19]) enabled the structured, unproblematic integration and customisability of IDEALS/RMR into the simulator. Further information on WSNsim can be found in the appendix. When IDEALS/RMR is active, reporting rules are defined as shown in Table 1. These rules were created by inspecting the normal operating conditions of the pump, and anticipating various possible faults of varying importance. The inclusion of routine rules aims to provide a reasonable up-to-date and accurate picture of the network (note that these rules are chosen so that as the PP of the node decreases, the period of the routine rules increases). The differential and threshold rules aim to capture specific events that occur in the environment. We believe that it should be simple to select a set of rules provided the designer has knowledge of the environment being sensed.

Two different sets of data were created and simulated for the pumping station:

- Normal conditions (representing the pumping station operating with no faults) – section Va.
- Fault conditions (numerous faults occur in the pumping station) – section Vb.

In an industrial monitoring scenario such as this, it can be seen that near 100% reliability is of importance. As such, the deliberate discarding of packets may cause concern. No locally powered system is capable of meeting this requirement under all conditions, and However, in selectively discarding low importance packets, IDEALS/RMR is able to increase the reliability for more important packets.

For each set of data, four simulations were conducted:

a) Traditional (no IDEALS/RMR or vibration harvesting)
b) Vibration Harvesting (no IDEALS/RMR)
c) IDEALS/RMR (no vibration harvesting)
d) IDEALS/RMR (with vibration harvesting)

For the node specific simulation results shown in this section, node-08 (attached to pump-08) is monitored. Node-08 was chosen as it is located in a central position (and so plays a critical role in network communications), and also has the average number of neighbouring nodes (four). By looking at an individual sensor node as opposed to the average of all nodes, we are able to inspect how the localised algorithms are operating. Node-08 and the sink node are highlighted in fig. 3. For each simulation, three sets of temporal network statistics are recorded: node energy levels, network connectivity and packet success. These are defined at the relevant points in section V.

V. Simulation Results

A. Operation under Normal Conditions

The normal operation data represent the case where all of the pumps and nodes are operating correctly. The data were generated using random pump on times and durations, with exponential growth and decay. Uniform noise with a maximum amplitude of 0.5°C was added to the sensed temperature to represent temperature fluctuations and sensor error. These data were simulated to investigate the magnitude of the network lifetime extension that is possible through the use of IDEALS/RMR, under normal (no fault) conditions. The data generated for node-08 for the duration of the simulation can be seen in Fig. 4.

1) Node Energy Levels: Fig. 5 shows the energy levels of node-08 for the duration of the simulations. In fig. 5, '1' means that the node's energy reserve is full, while '0' means that the energy reserve is depleted. It can be seen that in simulation 'a', node-08 depletes its energy reserve after around nine hours, as it is sending a packet every five minutes, regardless of the information content and energy levels. When energy harvesting is enabled, the node receives sporadic energy increases. However, as shown in fig. 7, these increases do not provide for a reliable and dependable network. In simulation 'c', the energy level of node-08 does not deplete in a linear fashion. This is because of the threshold/priority system that IDEALS introduces, and is explained in greater detail for the controlled simulations of [14]. RMR has provided a significant increase in the lifetime of the node as, when controlling reporting, it has attempted to differentiate between events and redundant data. Finally, in simulation 'd', IDEALS/RMR has been significantly enhanced by vibration harvesting, and at the end of the simulation, the node's energy reserve is 90% full.

2) Network Connectivity: Fig. 6 shows the network connectivity statistics obtained under each simulation. Network connectivity is a measure of the ability of any node in the network to successfully transmit a packet to the sink node. If the network is 100% connected, any node in the network can successfully transmit a packet to the sink node. However, if the network is 50% connected, only half of the nodes can successfully transmit a packet to the sink node.

In the case of simulation 'a', network connectivity is completely lost (0%) after around six hours due to nodes in the network depleting their energy reserves. While node-08 did not deplete its energy reserve for nine hours (see Fig. 5), other nodes in the network (that are in critical positions to provide packet forwarding) have depleted their energy reserves after six hours, and so no packets can reach the sink node (reinforced by Fig. 7). In simulation 'b', the network connectivity initially drops at the same rate as in simulation 'a'. However, vibration harvesting occurring intermittently in all of the sensor nodes maintains a low network connectivity for much of the simulation. In 'c', IDEALS/RMR manages the network, and the extension in network lifetime and connectivity is obvious. In this network, network connectivity for the most trivial packets (with message priority 5 – MP5) is lost after 12 hours. However, the network is still 95% connected for the most important packets (MP1) at the end of the simulation. It is interesting to note that the network is connected for longer than case 'a' for even the most trivial of packets (MP5). This is because RMR is controlling reporting, and not transmitting packets every five minutes, as seen in Fig. 7. In simulation 'd' vibration harvesting has enhanced the benefits of IDEALS/RMR, and the network remains connected for all but the most trivial packets (MP5) for the entire duration of the simulation (with the exception of a brief 5% drop for MP4 packets between 79 and 89 hours).

3) Packet Success: Fig. 7 shows the packet success statistics for node-08. This graph shows the packets (depicted by grey dots) that were transmitted from node-08 and successfully received by the sink node. Packets that were sent by the node, but not received by the sink node (due to a lack of network connectivity) are not shown. In simulation 'a' packets are generated every five minutes for 5 hours 25 minutes, after which no more packets are received by the sink node as network connectivity has been lost (shown in Fig. 6). Simulation 'b' sees packets received sporadically for the duration of the simulation, because the nodes in the network are also harvesting mechanical vibrations. The increase in packet success that simulation 'b' sees over 'a' is not practically useful, as the sporadic nature of the vibration harvesting means that a reliable and dependable network is not presented (for example, the pump turning on and off during days three and four are not reported). At the beginning of the simulation c), node-08 has a full energy reserve, and so any event is reported (this can be seen as many packets are sent during the first 12 hours). However, towards the end of the simulation, the energy in the node's reserve has significantly reduced (as shown in Fig. 5), and the node is operating in power priority 1 (PP1). Because of this, only the most important packets (of MP1) are transmitted and successfully received by the sink node. In simulation 'd', an abundance of packets have been successfully received for the entire duration of the simulation. IDEALS/RMR has balanced the node's energy resources and the information content of packets to convey an accurate representation of the pump to the sink node.

This section has presented the results obtained for the pumping station under normal operating conditions. It has been seen that the traditional simulation 'a' has a very short lifetime, due to the sending of redundant data, and lack of information management. The addition of vibration harvesting in 'b' does not provide a reliable or dependable network, and so has a limited practical benefit. When IDEALS/RMR is present in simulation 'c', a significant increase in the network lifetime is obtained. With the addition of vibration harvesting, 'd', an accurate representation of the network is communicated to the sink node for the entirety of the simulation. Therefore, under normal working conditions, IDEALS/RMR provides a considerable extension to the network lifetime and, when coupled with energy harvesting, can permit perpetual operation.

B. Operation under Fault Conditions

The fault data represent the case where multiple pump and sensor faults occur during the duration of the simulation. The basic data was generated in the same way as for the normal operating conditions. However, faults (detailed in Table 2) were added to this to determine how the network reacts to an influx of packets, and to identify if the RMR reporting mechanism portrayed an accurate representation of the events to the sink node. The data created for node-08 for the duration of the simulation can be seen in fig. 8. Sensor failure (occurring between hours 58 and 71), and overheating (occurring at every node between hours 100 and 110) can be clearly seen. Additionally, these data have a large period (around 36 hours) during which only a very small amount of energy is harvested due to the timing of the pump cycles. This enables the investigation of the operation of the network while it operates for intermittent periods with very little energy harvesting.

1) Node Energy Levels: Fig. 9 shows the energy levels of node-08 for the duration of the fault simulation. When compared with the energy levels shown in fig. 5, it can be seen that the energy depletion of simulations 'a' and 'b' are virtually identical. However, the simulations featuring IDEALS/RMR demonstrate that the nodes adapt energy usage depending on occurring events, and so a greater energy depletion occurs around areas of faults to ensure that the sink node is notified. In particular, the overheating pumps (detected by every node in the network) have caused a 50% drop in energy level in simulation 'd'. This is because every node in the network is flooding a packet reporting this fault. If IDEALS/RMR was coupled with a form of data fusion/aggregation, this energy expenditure could be limited.

2) Network Connectivity: Fig. 10 shows the network connectivity statistics obtained under each simulation. It can be seen that the network connectivity for simulations 'a', 'b' and 'c' are virtually identical to the normal operating data shown in fig. 6. The network connectivity of simulation 'd' is also very similar to the normal operating data shown in fig. 6 up until the pumps overheat in hour 100. Because all of the nodes are reporting this occurrence, they observe a drop in their energy reserves. This drop means that their power priority (PP) drops. As their PP drops, the node no longer participates in routing messages where the PP < MP. Therefore, the network connectivity for the lower PPs drops. However, towards the end of the simulation, the connectivity is beginning to rise, where it should eventually return to its earlier state.

3) Packet Success: Fig. 11 shows the packet success statistics for node-08. It can be seen that simulation 'a' misses both faults that occur at node-08, as packets are only successfully received by the sink node for the first 5 hours 25 minutes. In simulation 'b', the sensor failure in hour 58 is detected, while both the rectification of this (in hour 71), and the pump overheating (in hour 100) is unreported. Due to the sporadic nature of vibration harvesting, the ability to report particular events is random. In simulations 'c' and 'd', IDEALS/RMR has managed the network to allow both faults to be reported, while vibration harvesting in 'd' has permitted reporting with greater resolution.

This section has presented the results obtained for the pumping station under fault conditions. The obtained results have highlighted the ability of IDEALS/RMR to control the degradation of the network, and also to report specific faults. Additionally, as with the 'normal operation' data (shown in section Va), IDEALS/RMR has provided a significant increase in the network lifetime, and when coupled with energy harvesting, can permit perpetual operation. Successful operation relies on the careful selection of IDEALS/RMR parameters such as reporting rules and MP/PP thresholds.

VI. CONCLUSIONS

In this paper, we have introduced the IDEALS/RMR system, which operates locally upon a combination of information control (assessed through a custom set of rules describing the sensed environment) and energy management (balancing residual energy and energy harvesting with packet importance) that we believe has not been considered before. Results obtained from simulating a hypothetical scenario where a WSN is used for temperature monitoring in a pumping station have shown that a considerable extension in the network lifetime can be obtained through the use of IDEALS/RMR. Additionally, the IDEALS/RMR reporting mechanism accurately portrays faults occurring in the environment (for example a pump overheating) to the sink node. Furthermore, when coupled with harvesting energy from the environment (such as mechanical vibrations), it has been shown that it is possible to obtain perpetual operation. We are currently in the process of updating the simulator to incorporate better communication (including energy efficient routing), sensing and energy models to further improve the accuracy of our simulations.

APPENDIX - WSNSIM

WSNsim creates a virtual environment over which sensor nodes and events (properties that can be monitored by a sensor node) are scattered. When the simulation is executed, nodes in the network detect events in their local area and, if required, propagate packets throughout the network using multi-hop routing. The routing algorithm currently implemented in WSNsim is packet flooding [20], due to its inherent simplicity. In packet flooding, each node repeats received packets by broadcasting them to all of its neighbouring nodes. In this way, packets are 'flooded' throughout the network. We believe that advantages proposed by IDEALS/RMR can be applied to a wide range of different routing algorithms, and this is a direction of future investigation. Energy harvesting can be modelled in WSNsim using a mathematical representation, tabulated data, or a combination of both. The WSN can be configured to have either a fixed sink node (all nodes attempt to send data to a single processing node), or a distributed network (nodes send data to other nodes in the network). WSNsim can simulate a wide variety of different configurations and applications, and provides a platform upon which objective observations can be made.

WSNsim uses a radio model similar to that described in [21], where the radio transceiver dissipates energy to power the transceiver circuitry (E_{elec}, with units of energy per bit), and transmit data a certain distance (calculated using E_{amp}, the energy required to transmit a single bit a distance r_0). The energy consumed by the radio transceiver to transmit a packet of length L a distance r_{tx} is given by equation 1, where α determines the channel loss. In the simulations given in this paper, a channel loss of 2 was used (representing free space propagation [22]). Reception probability is implemented simplistically in the current version of the simulator, with all nodes that are deemed to be neighbouring receiving packets with certain probability. Nodes are deemed to be neighbouring if they are within a certain distance of the transmitting node. This model is simplified from practicality, but it is believed that the abstract model allows objective observation to be made about algorithms. Extending this model to incorporate a more representative propagation model and consideration of noise and bit errors is currently being undertaken for the next version of the simulator.

The energy consumed by the radio transceiver to receive a packet of length L is given by equation 2. The energy obtained through vibration harvesting is calculated at discrete points using equation 3, where $E_h[n]$ is the discrete function describing the energy increase given at the end of discrete time period n, $P_h(t)$ is the continuous function characterising the power harvested from the vibration source at time t, and T is the harvesting separation period (related to the frequency at which the simulator provides the node with harvested energy increments). E_{elec}, E_{amp} and $E_{harvest}$ are all expressed as a fraction of the maximum battery capacity. The values used for the simulations in this paper are shown in table 3.

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Fig. 1. The proposed IDEALS/RMR system diagram

Fig. 2. Priority balancing in IDEALS

Fig. 3. A snapshot of the network under simulation. In this snapshot, the black dots represent sensor nodes, the lines between them represent possible communication links, the large grey circles represent the radio ranges of the sensor nodes, and the smaller white circles represent areas of mechanical vibration (suitable for energy harvesting)

Table 1 - RMR Rules Used in the Simulations

Fig. 4. Temperature data used for node-08 in the simulation. Grey areas represent the times at which the pump was vibrating

Fig. 5. Energy level of node-08 (attached to pump-08) for four simulations: a) traditional, b) vibration harvesting, c) IDEALS/RMR, and d) IDEALS/RMR with vibration harvesting

Fig. 6. Network connectivity for four simulations: a) traditional, b) vibration harvesting, c) IDEALS/RMR, and d) IDEALS/RMR with vibration harvesting

Fig. 7. Packet success statistics for node-08 (on pump-08) for four simulations: a) traditional, b) vibration harvesting, c) IDEALS/RMR, and d) IDEALS/RMR with vibration harvesting. Grey dots represent packets sent by node-08, and successfully received by the sink node.

Table 2 - Details of the faults that occur in the fault data

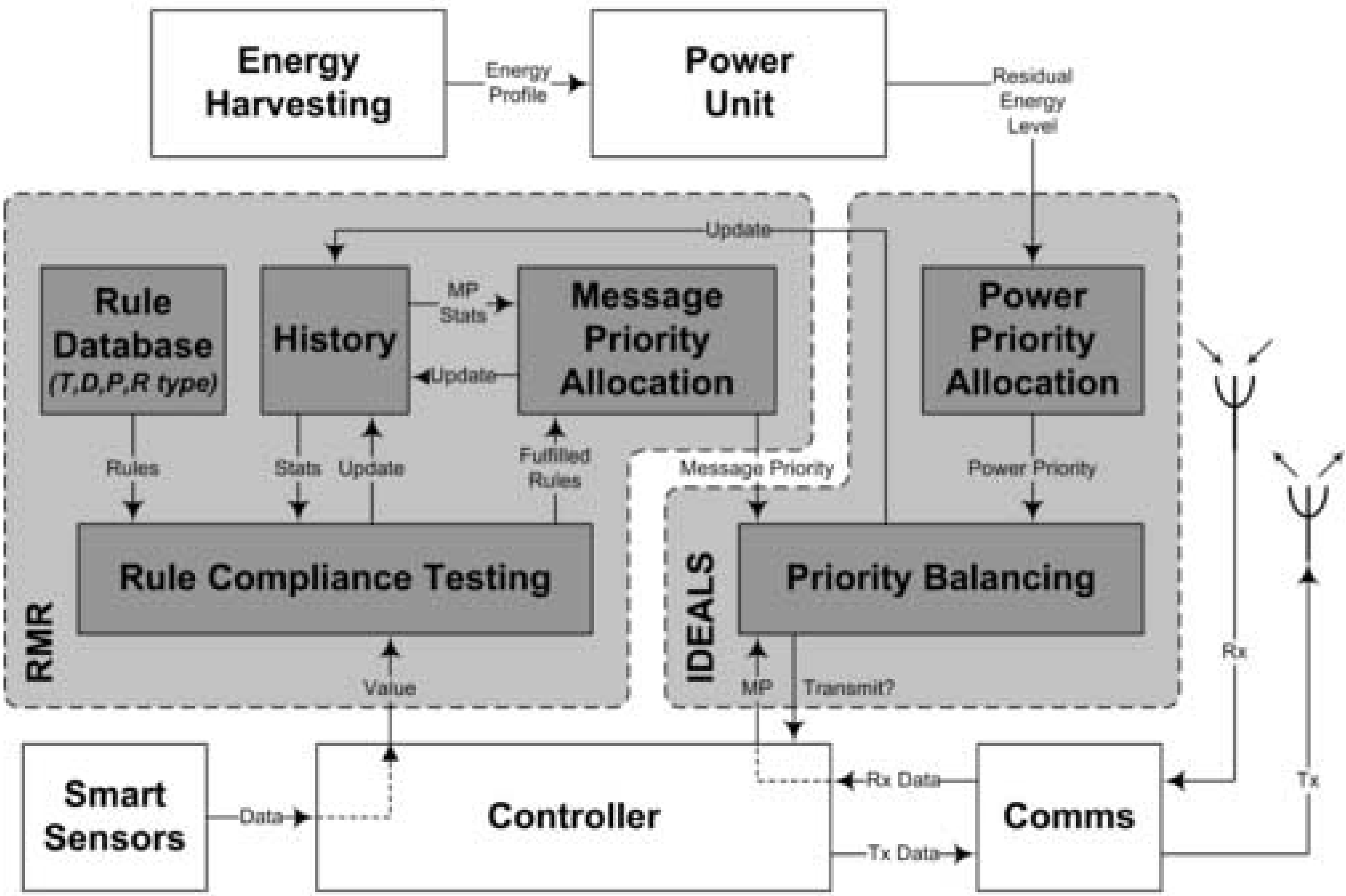
Fig. 8. Temperature data used for pump 08 in the fault data simulation. Grey areas represent the times at which the pump was vibrating)

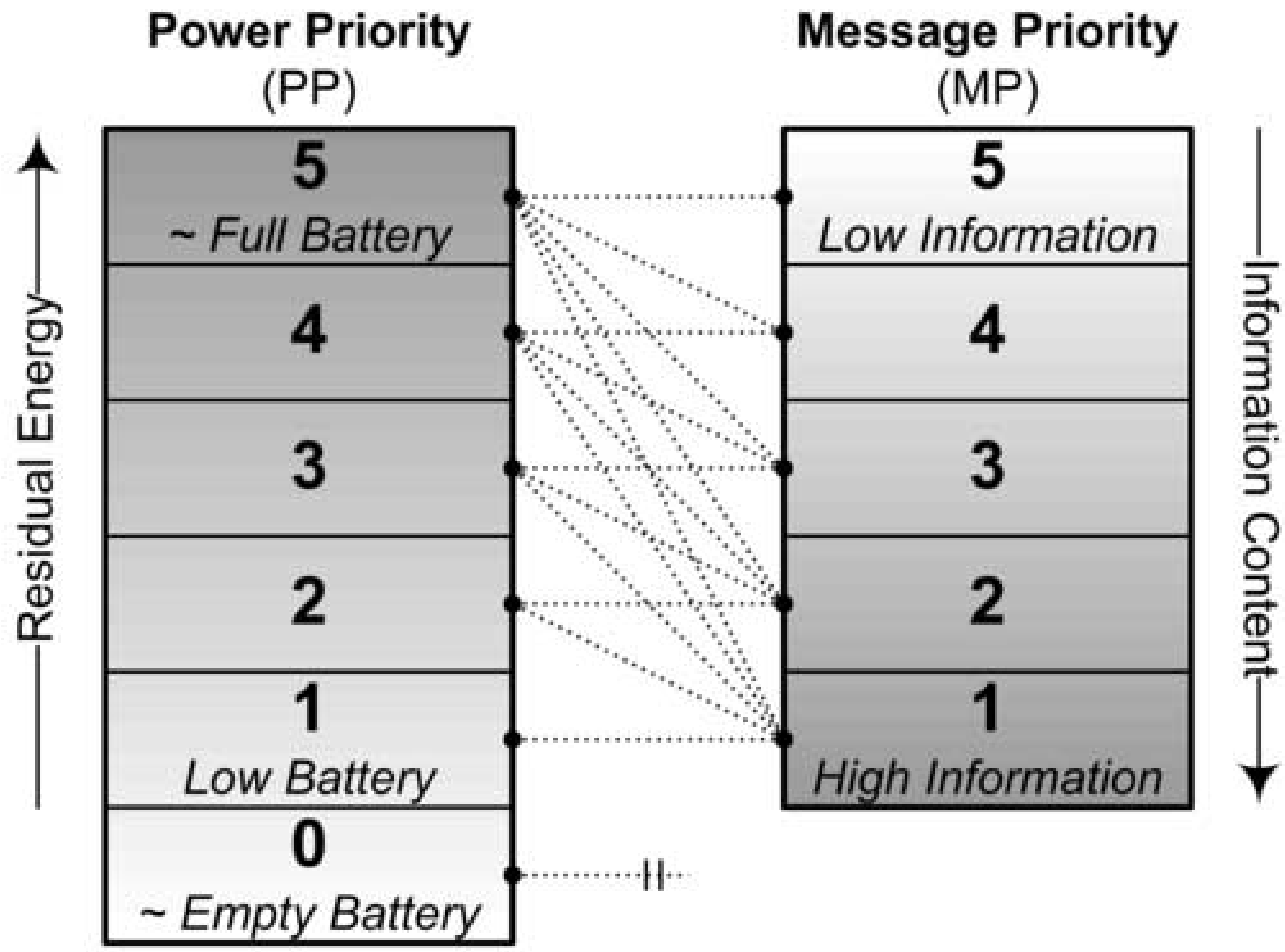
Fig. 9. Energy level for node-08 (attached to pump-08) for four simulations

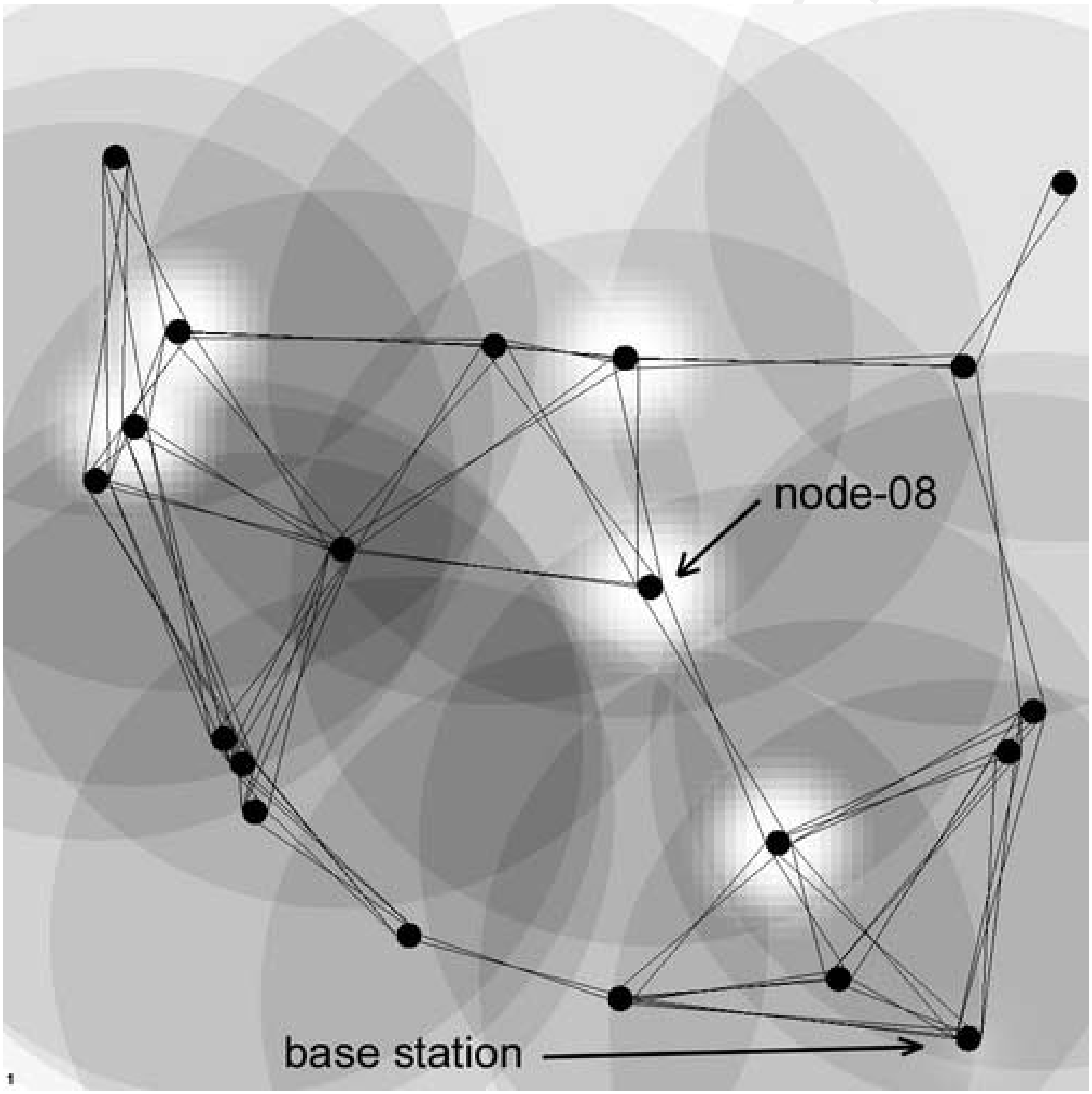
Fig. 10. Network connectivity for four simulations: a) traditional, b) vibration harvesting, c) IDEALS/RMR, and d) IDEALS/RMR with vibration harvesting

Fig. 11. Packet success statistics for node-08 (attached to pump-08) for four simulations: a) traditional, b) vibration harvesting, c) IDEALS/RMR, and d) IDEALS/RMR with vibration harvesting. Grey dots represent packets sent by node-08, and successfully received by the sink node

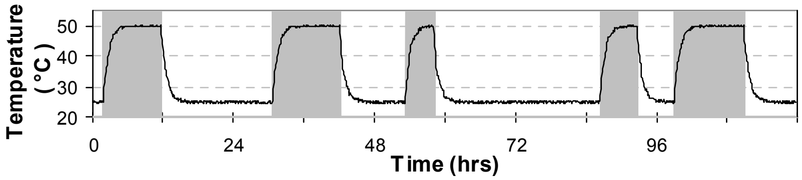
Table 3 - Energy parameter values used in the simulation


Energy Harvesting
Energy Profile
Power Unit
Residual Energy Level
Update
Rule Database (T,D,P,R type)
History
MP Stats
Message Priority Allocation
Update
Power Priority Allocation
Rules
Stats
Update
Fulfilled Rules
Message Priority
Power Priority
Rule Compliance Testing
Priority Balancing
RMR
IDEALS
Value
MP
Transmit?
Rx
Smart Sensors
Data
Controller
Rx Data
Tx Data
Comms
Tx

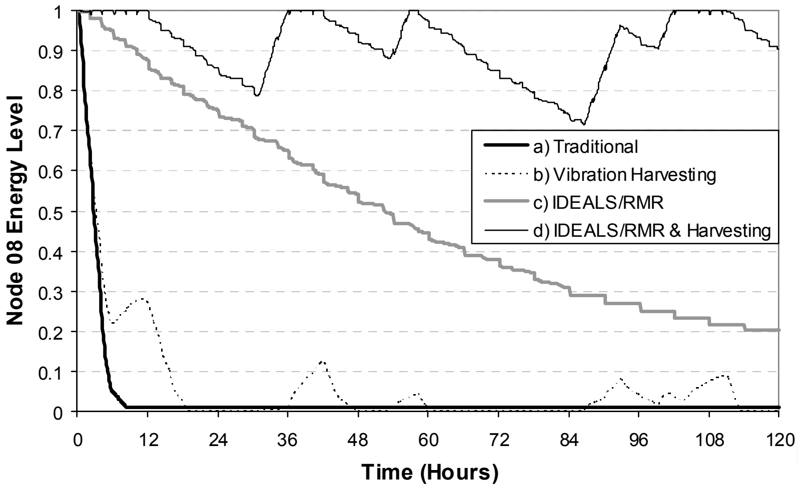

Power Priority
(PP)
Message Priority
(MP)
5
~ Full Battery
4
3
2
1
Low Battery
0
~ Empty Battery
5
Low Information
4
3
2
1
High Information
Residual Energy
Information Content


node-08
base station
1

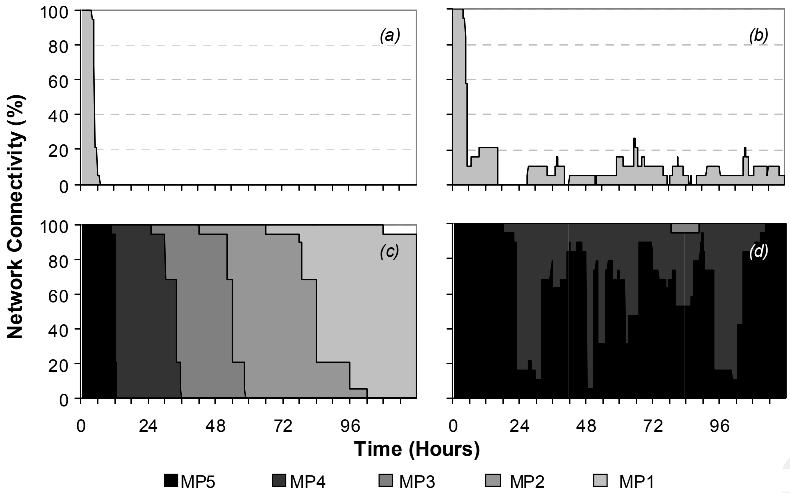
ID	Rule Type	Value	Priority	Primary Use
T(37.5)	Threshold	37.5°C	4	Detect pump on/off operation
T(20)		20°C	2	Detect pump too cool
T(10)		10°C	1	Detect pump very cool
T(55)		55°C	2	Detect pump too hot
T(70)		70°C	1	Detect pump very hot
D(2)	Differential	2°C	2	Detect pump on/off operation
D(10)		10°C	1	Detect sensor failures
R(2)	Routine	2hrs	5	Provide routine reports
R(4)		4hrs	3	
R(6)		6hrs	1	



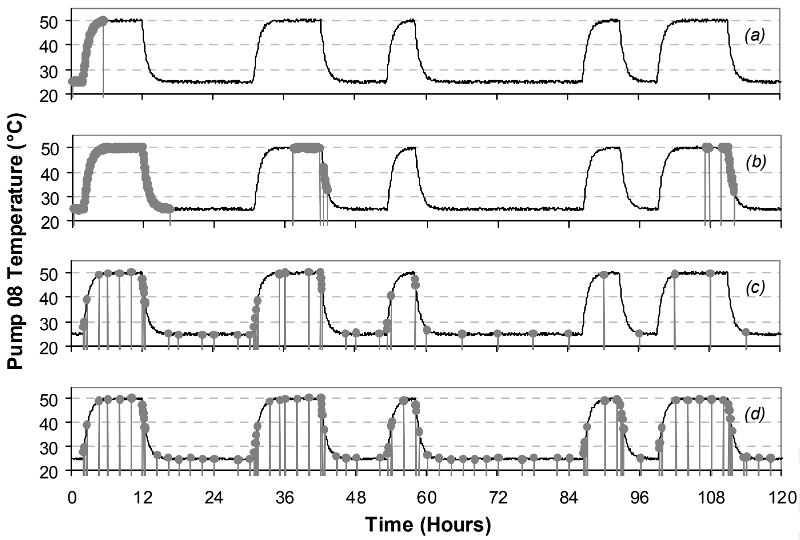
Temperature (°C)
50
40
30
20
0
24
48
72
96
Time (hrs)



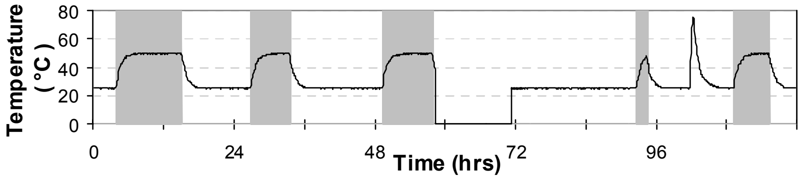
Node 08 Energy Level
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
12
24
36
48
60
72
84
96
108
120
Time (Hours)
a) Traditional
b) Vibration Harvesting
c) IDEALS/RMR
d) IDEALS/RMR & Harvesting



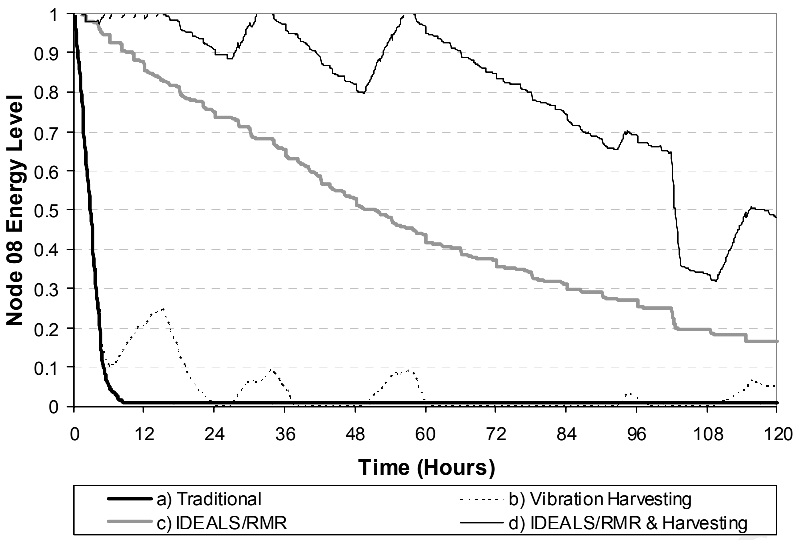
Network Connectivity (%)
100
80
60
40
20
0
(a)
(b)
(c)
(d)
0
24
48
72
96
Time (Hours)
MP5
MP4
MP3
MP2
MP1

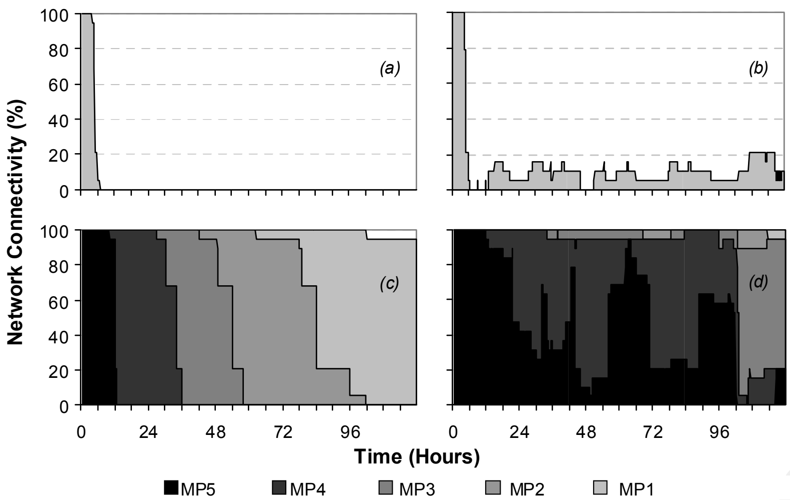

Pump 08 Temperature (°C)
50
40
30
20
(a)
(b)
(c)
(d)
0
12
24
36
48
60
72
84
96
108
120
Time (Hours)

Node/Pump	Fault	Seen As	Time Span (hrs)
Node-03	Sensor Failure	Reads 0°C	21-49
Node-06	Sensor Drift	Reading Decreases	25-49
Node-08	Sensor Failure	Reads 0°C	58-71
Pump-10	Bearing Failure	Temperature Rise of 8°C	32-55
Node-13	Sensor Drift	Reading Increases	72-90
All Pumps	Fire	Temperature Rise of 50°C	100-110

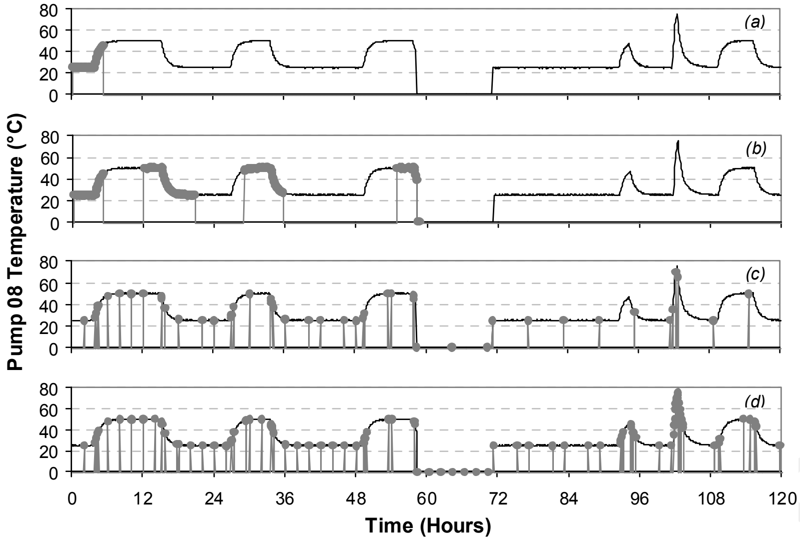


Temperature (°C)
80
60
40
20
0
0
24
48
72
96
Time (hrs)


Node 08 Energy Level
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
12
24
36
48
60
72
84
96
108
120
Time (Hours)
a) Traditional
b) Vibration Harvesting
c) IDEALS/RMR
d) IDEALS/RMR & Harvesting



Network Connectivity (%)
100
80
60
40
20
0
(a)
(b)
(c)
(d)
0
24
48
72
96
Time (Hours)
MP5
MP4
MP3
MP2
MP1


Pump 08 Temperature (°C)
Time (Hours)
(a)
(b)
(c)
(d)
0 20 40 60 80
0 12 24 36 48 60 72 84 96 108 120

Parameter	Value
E_{elec}	3×10^{-07}
E_{amp}	3×10^{-05}
max ($E_{harvest}$)	1.5×10^{-05}

$$E_{transmit} = E_{elec} L + E_{amp} L \left(\frac{r_{tx}}{r_0} \right)^{\alpha} \quad (1)$$

$$E_{receive} = E_{elec} L \quad (2)$$

$$E_h[n] = \int_{T \cdot (n-1)}^{T \cdot n} P_h(t)\, dt \quad (3)$$