Opportunistic Energy Trading between Co-located Energy-Harvesting Wireless Sensor Networks

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ABSTRACT

Wireless sensor networks are increasingly using energy harvesting to extend their lifetime and avoid battery replacement. However, ambient energy sources typically exhibit temporal-spatial variation, and complex power management algorithms have been proposed to model and adapt to variation and achieve energy-neutral operation. However, existing algorithms are limited in the scale of spatial variation that they can accommodate, as they are restricted by the physical boundaries of the network. This paper proposes *Opportunistic Energy Trading* (OET) to overcome this limitation, and allow networks to trade energy to neighbouring networks which may either be heavily energy-constrained or else suffering from a temporary drought of harvested-energy. To show the potential of OET, we present a case study consisting of an energy-constrained battery-powered WSN which neighbours an energy-harvesting WSN. The case study considers a simplified version of OET, whereby the harvesting WSN transfers (i.e. trades for free) its excess energy to the constrained WSN in order to extend its lifetime. The case study is evaluated through simulation, and shows that the lifetime of the energy-constrained network increases by 40% while the effects on the harvesting network can be considered insignificant.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design

Keywords

Wireless sensor networks, energy harvesting, power management, resource scheduling

1. INTRODUCTION

Wireless sensor networks (WSNs) are gaining considerable traction in applications pervasive to our daily lives, promising wearable health monitors, intelligent buildings, and environmental monitoring systems [1]. To overcome problems associated with limited lifetime and inconvenient or often impossible battery replacement, considerable research into energy harvesting WSNs (EH-WSNs) has been reported [2]. However, ambient sources suitable for energy harvesting (for example light, vibration, wind and temperature gradients) are uncontrolled sources which typically exhibit temporal-spatial variation [3]. For example, the power obtainable from a solar cell will usually depend on both the time of the day (whether being illuminated by the sun or artificial light) and specific location. Adaptive algorithms have been proposed to manage energy resources and adapt each node's activity appropriately, in order to deliver 'energy-neutral operation', and hence operate indefinitely. Such algorithms typically adjust parameters such as the duty-cycle or sampling rate [4, 5].

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Energy-neutral algorithms primarily exploit the temporal variation in harvestable energy; that is they dynamically manage their operation in order to throttle activity during times of limited energy and increase activity when energy is readily available. An alternative category of algorithms operates over a longer time period, delivering a constant activity or performance in response to a prediction of future energy availability.

Other energy-neutral algorithms have been proposed which exploit the spatial variation in harvestable energy, for example by routing packets through locations in the network which are harvesting more energy (or have more abundant energy reserves), even if these are sub-optimal in terms of traditional metrics such as hop count or latency [6]. However, the spatial variation that can be tolerated is limited by the bounds of the network; that is if the entire network has ceased to harvest energy (for example if an obstacle such as a building temporarily stands between the network and its energy source), no solution can be found. A secondary class of algorithms attempts to address problems such as these by using mobile rechargers, whereby sensor nodes are mobile and hence able to travel to recharge batteries or harvest ambient energy [7]. However, the applications in which such systems can be applied are somewhat restricted by a multitude of significant factors including terrain, cost, reliability and disrupted coverage.

In this paper, we present a method for tolerating spatial variation across a much larger scale than has previously been possible. This is enabled through allowing energy-neutral algorithms to leverage an area wider than its own network

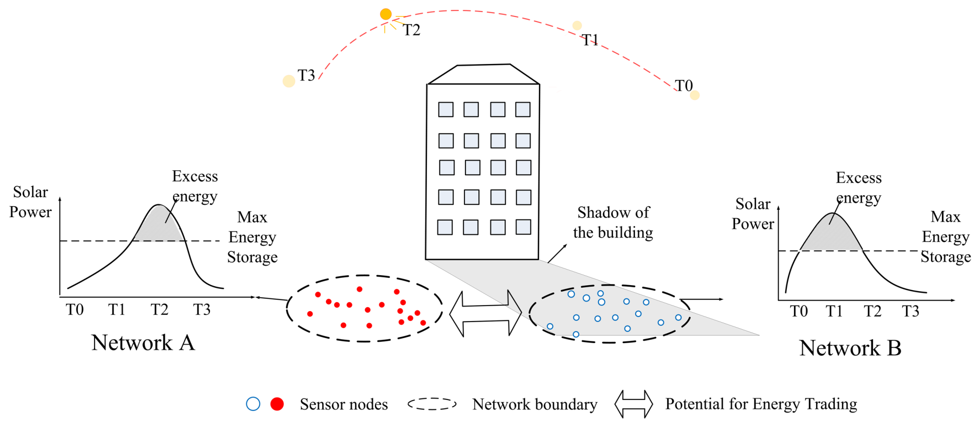

Figure 1: The motivation for Opportunistic Energy Trading (OET): existing power management algorithms are limited to managing resources within their network boundary, whereas OET enables the effective transfer of energy across multiple networks

boundary (i.e. an area covered by multiple networks). In our previous work, a MAC algorithm is proposed which permits direct opportunistic interconnect between co-located WSNs [8]. In this paper, we build upon this work by showing how OI-MAC can be used to trade resources and hence propose a novel power management strategy called *Opportunistic Energy Trading* (OET). Compared to existing power management strategies, OET permits cross-boundary trading of energy resources, for example allowing a network to 'sell' excess harvested energy to neighbouring networks. In this way, a WSN can manage its energy not only using resources within its own network, but also among a group of networks that have a wider geographical coverage and resource capacity.

To illustrate the potential of cross-boundary energy transfer, a fundamental component of OET, we present a realistic case study and evaluate its operation through simulation. Results show that the excess energy in one network can support packet routing for its neighbouring energy-constrained network, hence extending its lifetime. As a result, the average power consumption of the constrained network (the energy 'buyer') is reduced by 20% and the expected lifetime is extended by 40%. Minimal impact is observed on the harvesting network (the energy 'seller'), with no noticeable effect on lifetime and a packet latency increase of less than 3%.

2. OPPORTUNISTIC ENERGY TRADING (OET) THROUGH DIRECT INTERCONNECTION

In this section, the concept and operation of OET is explained, a power management strategy utilising cooperation between co-located WSNs.

2.1 Why OET?

Traditional power management is an intra-network resource management process, which tries to achieve the desired energy target (whether energy-neutrality or a target lifetime) by adjusting the behaviour of sensor nodes. Considering that a single WSN has limited coverage and energy storage capacity, intra-network power management faces a bottleneck when dealing with spatially varying energy reallocation and utilizing excess energy. Consider the scenario illustrated by Fig. 1. In this simplified scenario, networks A and B are solar-harvesting EH-WSNs, which harvest energy when directly illuminated by the sun, but harvest no energy when in the shadow. Due to the sun's movement, the energy harvested by the two networks is different at different time. As a single WSN is located within a relatively constrained area, intra-network power management may be inefficient in smoothing this spatial-variance. In addition, a WSN may harvest so much energy while under the sun's illumination that its energy reserve becomes full and the excess harvested energy is wasted. Traditional power management algorithms often utilise this excess energy by increasing sample/packet generation rates above that actually desired by the application. OET, proposed in this paper, allows energy to be managed beyond a single network's boundary and allows it to be used by multiple networks and applications.

OET allows each WSN to transfer, or trade, energy resources with neighbouring networks. Because this process cannot be conceived at design time, it must be identified and established *opportunistically* after deployment. Compared to traditional intra-network energy management, OET provides greater flexibility. For example, in order to survive when the energy budget is tight, a network can either reduce the intra-network power consumption or, if available, 'buy' energy from neighbouring networks. Likewise, when a network has excess energy, it can either improve the performance of its own application, or 'sell' this excess energy to other networks. Using OET, Network A in Fig. 1 can buy energy at time T1, while selling the same amount of energy back during time T2. Therefore, compared to intra-network power management strategies, the cross-boundary approach adopted by OET improves both the energy management capability and scope.

While it is convenient to consider OET as physically transferring (buying and selling) energy across a network boundary, energy is actually logically transferred through the trading of energy-hungry services (for example data processing or packet routing). The trading process uses negotiation to ensure fairness, i.e. networks evaluate the cost and price of tasks and decide whether or not to accept the trade.

2.2 Interconnection Requirements

At present, every WSN is designed and configured for a specific application and deployment. As a result, it can be considered that a virtual 'wall' exists around its perimeter to avoid interference. As such, interaction with neighbouring networks is deliberately rendered impossible [9]. Therefore, the most widely adopted way to build cooperation between separate WSNs is to connect them via the Internet, using dedicated gateways. While this structure can support resource discovery and limited task sharing, it requires each WSN to maintain a connection to the Internet (which may not be possible in some scenarios). Furthermore, only limited task sharing is supported, for example data processing and storage. This provides little benefit to energy management as, for the majority of WSN scenarios, communication tasks are the most energy consuming.

To overcome the limitations of a gateway-based interconnection scheme, OET is enabled through a philosophy whereby communication is permitted between co-located networks. However, it is important that individual stakeholders maintain control and ownership of their own networks, and hence real boundaries are still enforced between networks. Hence, if an individual network decides that it does not wish to participate in any OET, the impact of the underlying cooperation on energy consumption and packet latency should be minimal.

3. ACHIEVING OPPORTUNISTIC DIRECT INTERCONNECT USING OI-MAC

In our previous work we proposed OI-MAC [8], which supports opportunistic discovery and direct interconnection between co-located WSNs. Readers are directed to this paper for full details of OI-MAC's operation. However, for conciseness, in this section only discovery and cross-boundary transmission schemes are explained.

OI-MAC is a receiver-initiated MAC protocol that is extended from RI-MAC [10]. Unlike RI-MAC, OI-MAC supports multiple channels: one channel is reserved as a common channel (for discovery and negotiation) while the other channels are treated as data channels. Neighbouring networks adopt different data channels in order to avoid interference and therefore maintain the network independence.

3.1 Opportunistic Discovery Scheme

To discover neighbouring networks, OI-MAC uses a combination of both active and passive discovery modes (shown in Fig.2).

During passive discovery, each sensor node periodically (the time period is defined by the discovery period) switches to the common channel and, after performing a clear channel assessment, broadcasts a discovery beacon. The discovery beacon includes only the network ID, which is unique for each WSN. After the broadcast is complete, the node waits

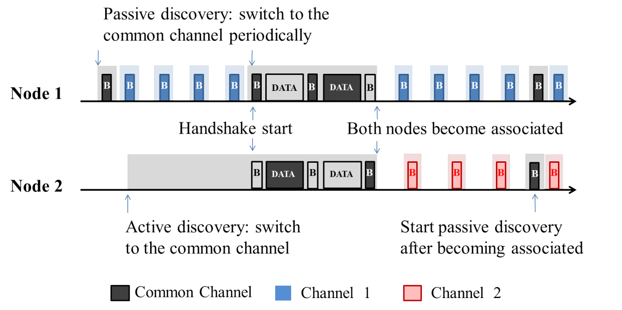

Figure 2: Discovery and data transmission processes in OI-MAC

for an additional period of time (the *dwell time*) to listen for responses from neighbouring networks. If a response is received, the node enters into a handshake process to exchange network profile information and to decide whether or not to build a direct interconnection. If the negotiation is a success, both transmitters will gain details (e.g. channel frequency and wakeup period) of each other and hence become 'associated'. During active discovery, sensor nodes switch to the common channel and listen for the entire duration of a discovery period. During this period, if a discovery beacon is received containing a network ID that is different to its own, the receiver will respond immediately and enter into the handshake process.

3.2 Cross-boundary Data Transmission

Using OI-MAC, cross-boundary data transmission is supported through the associated nodes, which act as network bridges. Once a node has discovered a neighbouring network, it informs the other nodes in its network by broadcasting or 'piggybacking' information onto beacons. If a packet is generated which is destined for a neighbouring network, it is first collected at the associated nodes and then transmitted across the boundary by switching to the neighbouring network's data channel. After transmission is finished, the boundary node switches back to its original data channel.

4. OET: A CASE STUDY

To illustrate how energy can be transferred across a network boundary, we present a realistic case study. While the provision of true 'trading'- whereby resources (e.g. energy, QoS, memory, data, internet connectivity, processing etc) are traded for either other resources or else monetary reward- is central to our vision for OET, in this case study it is excluded for reasons of clarity and simplicity. Instead, it is assumed that all networks are 'ideal' neighbours- that is they will freely donate energy to their neighbours that would otherwise go to waste. This allows the evaluation of the underlying principles, without the results being confused by higher level trading mechanisms. The case study is evaluated through simulation, and results presented for both energy efficiency/consumption and packet delay.

4.1 Scenario

The scenario used in this case study is illustrated by Fig 3. Network A and B are two networks deployed adjacently.

Network A is composed of 25 solar-harvesting sensor nodes

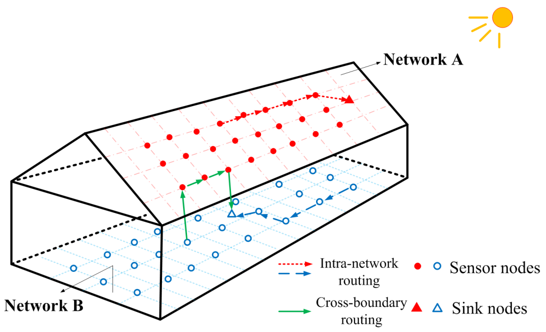

Figure 3: Case Study: OET between indoor and outdoor WSNs

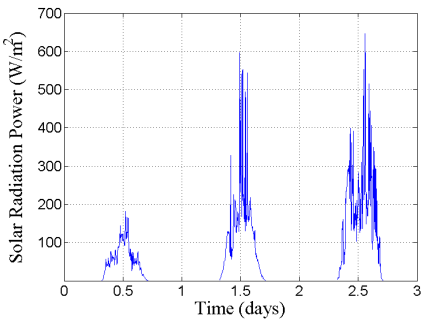

Figure 4: Solar radiation power [11] available to the energy harvesting sensor nodes.

which have been deployed on the roof of the building with an application to monitor the spatial distribution of temperature. The sensor nodes are modelled to be Memsic eKo mote, containing a $3.3cm \times 6.35cm$ photovoltaic to recharge the 600 mAh battery. The available solar energy is modelled using the radiation power provided by Humboldt State University ($40.99^\circ N$, $124.08^\circ W$, Elevation $36m$) between Jan. 7th to Jan. 9th (shown in Fig. 4), and each photovoltaic is assumed to be 10% efficient. Each node in Network A samples data every 60s, and communicates these to the sink node. Network B is composed of 25 battery-powered sensor nodes which have been deployed inside the building to monitor moisture levels. The sensor nodes are modelled to be MICAz motes, containing 600 mAh AAA non-rechargeable battery. Each node in Network B samples data every 180s, and communicate these to the sink node.

While the nodes in both networks are arranged in a grid, the position of the sink node is randomly selected. Both networks adopt OI-MAC as their MAC layer protocol. The routing protocol used is a collection tree routing protocol. The radio coverage of each sensor is set as 10m [1] and the height of the roof is 5m. Therefore, every node in Network B can reach at least one node in Network A within a single hop.

4.2 The Energy Transfer Process

The design aim of this simplistic energy transfer process is to use excess energy harvested by Network A to extend the lifetime of Network B. Network A should inform Network B when it has excess energy to donate, and as a result Network B will transfer energy consuming tasks (here, we consider this to be the process of packet routing) to Network A. This cooperation should be terminated when Network A no longer has excess energy to donate.

After discovery and association, each sensor node in Network A sends its battery information (the percentage of remaining energy) to the sink node along with data packets. In this way, the sink of Network A can maintain a map of battery conditions across the whole network. In order to identify whether or not there is excess energy, a threshold is set. Once the sink realises that all batteries are above the threshold, it initiates a broadcast to inform the associated nodes to start the energy transfer process. Hence, the sink node decides upon when cooperation should occur, while associated nodes are simply the messengers: once they receive the ‘enable transfer’ command, they forward this message to the associated nodes in Network B.

On receipt of an ‘enable transfer’ message, the associated nodes in Network B initialise a global broadcast. After the broadcast is complete, each node in Network B evaluates the hop distances of two different routes to the sink i.e. the intra-network route and cross-boundary route. Therefore, if the node is only one-hop from the sink, it will continue to select the intra-network route by sending packets directly to the sink (this is because the cost of relaying through the neighbouring network would be is higher). However, nodes those are greater than one-hop from the sink will send packets directly across the boundary and into Network A. The sensor nodes in Network A subsequently route the packets to the associated node closest to the sink in Network B (the selection of these nodes are finished during the discovery and handshake process), which will then send it back across the boundary to its destination.

Once the sink in Network A observes that one of the node’s residual energy level has dropped below the threshold, it will inform all the associated nodes to shut down cooperation through the same signalling procedure. This is because harvester output is no longer able to generate excess energy, and hence the energy transfer process should be suspended in order to maintain the network’s own energy budget.

5. SIMULATION AND RESULTS

The scenario shown in Fig. 3 was evaluated using the OMNeT++. The effects of OET are evaluated both on packet delay and energy consumption. The results presented in this section are analysed across 50 simulation runs. The channel model used is IEEE 802.15.4 path loss model with log-normal shadowing [12], while the OI-MAC configuration and radio parameters [2] used are summarized in Table 1. In the simulation, we assume that the battery-level threshold for enabling and suspending cooperation is 99.9%.

[1]In practice, the radio coverage of a sensor node depends on the hardware and environment, which is beyond the scope of this research.

[2]Data used are those of the Texas Instruments CC2420 transceiver

Table 1: Simulation Parameters

Retry limit	3	Backoff window	0-127
CCA	128 μs	Size of Beacon	16 byte
Dwell time	Variable	Node wakeup period	2 s
Frequency	2.4 GHz	Idle listen current	18 mA
Data rate	250 kbps	Sleep current	0.02 mA
Tx current	17.4 mA	Rx current	18.8 mA
Voltage	3 V	Rx-Tx current	17 mA
Slot time	320 μs	SIFS	192 μs

5.1 Residual Battery Energy

Fig. 5 shows how the residual energy level changes in the nodes of Network A during the simulation period. The results follow a cyclical pattern, and hence for brevity only the results of the first day are explained in detail.

During the first period of daylight ($0.31 < T < 0.69$), the solar energy harvested is so high that the battery is recharged to 100% in a very short period of time. Without cross-boundary energy transfer (red lines), most of the harvested energy is wasted during this period as the node is unable to store it. After adopting energy transfer (blue lines), a cooperative relationship is established and Network A expends its excess energy to perform routing tasks for Network B. It can be observed from Fig. 5 that both red and blues lines overlap and remain at around 100%, indicating that the excess energy is sufficient to support both tasks. However, immediately after the sun has set ($0.69 < T < 0.7$) and Network A no longer harvests excess energy, the scenario with OET clearly sees an increased rate of battery drain as it continues to route packets for Network B (see the inset in Fig. 5). However, when $T = 0.7$, the minimum residual battery energy of Network A drops below the threshold (i.e. 99.9%) and cooperation ceases. After committed tasks are completed, the rate of battery drain reduces to that expected after $T > 0.71$. It can be seen that the difference in Network A's residual energy with- and without-OET scenarios is barely observable, and hence it is concluded that only the excess energy has been transferred.

For Network B (shown in Fig. 6), it is clear that OET has helped to reduce power consumption and hence extend the network lifetime [3]. During the day, each node in Network B needs to expend energy to transmit packets across one-hop to an associated node in Network A. This is especially beneficial for nodes close to the sink as they no longer need to forward packets for more distant nodes. This explains why the minimum residual battery energy sees the greatest improvement through OET. After the three days of simulated operation, OET has increased the minimum residual battery energy by 6%. By continuing the trends into the future, an increase in network lifetime of 40% could be seen through OET (i.e. the first node dies after another 17 days instead of 11.3 days). Through OET, although Network B does not have the hardware to harvest solar power, it is still able to benefit from it during the day to extend its lifetime. Naturally, in practice this benefit would be accompanied by a cost to Network B, whether this is monetary or through the provision of data.

[3]The time to the first node in the network dying

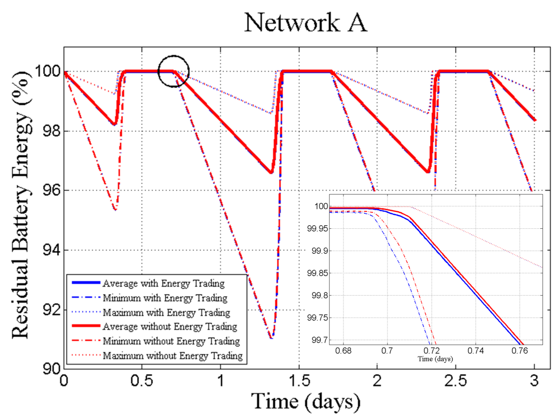

Figure 5: Residual battery energy in Network A (harvesting solar energy)

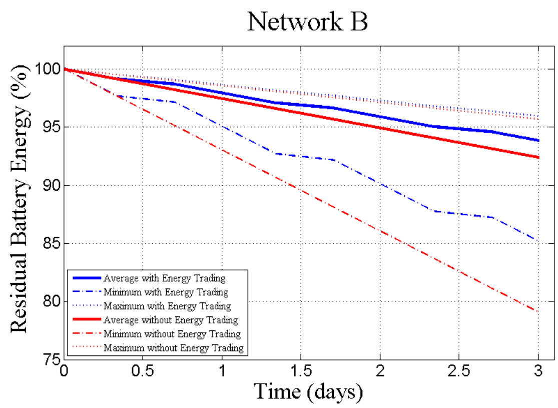

Figure 6: Residual battery energy in Network B (non-rechargeable batteries)

5.2 Packet Delay

The effects on original packet delay (i.e. considering only packets generated in that network) are shown in Fig. 7. The median value is used because the data is not following a normal distribution and the error bar represents the data ranging between 5% and 95%.

Fig.7.(a) shows the effect of OET on packet delay in Network A. The effect is reasonably insignificant (< 2%), and is a result of OI-MAC allowing sequence data transmission within a single cycle. Fig.7.(b) shows the effect of OET on packet delay in Network B. It can be seen that after energy is transferred, the average packet delay increases by 15%, while the maximum delay increases by around 20%. There are two reasons for this increase. First, packets from all sensor nodes which are further than one-hop from the sink will be transmitted via Network A, thus increasing the hop distance and hence average delay (Fig.7.(c)). Second, because there is more traffic in Network A than Network B (as the sample rates are three times higher), packets which are injected into Network A suffer from a higher probability of collision. Clearly the acceptability of this increased packet delay is dependent upon the application requirements. However we propose that in the majority of applications, this relatively minor increase in packet delay is likely to be outweighed by

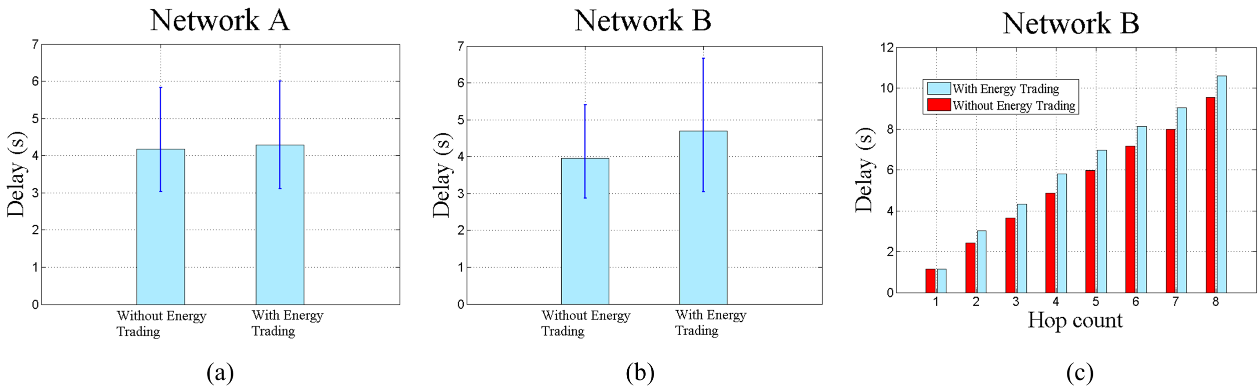

Figure 7: Packet delay before and after enabling OET, (a) in Network A (solar energy harvesting), (b) in Network B (non-rechargeable batteries), and (c) in Network B but broken down by number of hops from the sink.

the 40% increase in network lifetime that is enabled.

6. CONCLUSIONS

In this paper, we have proposed Opportunistic Energy Trading (OET), which enables co-located EH-WSNs to cooperatively trade resources. Differing from existing intra-network power management strategies, OET uses the concept of resource trading to optimise the usage of excess energy and expand the spatial area available for energy management. As OET is based on cross-boundary energy transfer, which is implemented through the transfer of tasks, OI-MAC is used to provide direct interconnection between adjacent networks. A case study is simulated to demonstrate and evaluate the possibility of cross-boundary energy transfer. The simulation results show:

- Excess harvested energy can be used to perform energy consuming tasks such as packet routing for neighbouring energy-constrained networks. In the case study, this extended the network lifetime of the constrained network by 40%, while having virtually no effect on the residual battery energy in the harvesting network.
- Cross-boundary energy transfer is actually a process of transferring energy consuming tasks into the network which has rich energy resources. As a result, the performance of these transferred tasks may be affected. In the case study, the packet delay increased by approximately one hop. However, little effect on packet delay was observed in the harvesting network.

The case assumes that the two neighbouring networks overlap; hence, every node is only a single hop away from the neighbouring network. Our future work will consider networks which share only a limited boundary rather than being completely overlapped. In this situation, the network which has excess energy may help to perform data collection and processing tasks in order to reduce the traffic burden on neighbouring networks. We will also research algorithms and processes to allow networks to effectively advertise and trade the resources that they have available to them. This will include not only energy, but also other resources such as data processing and storage.

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