Abstract

Multiple sinks routing is envisioned as a possible solution to the ‘bottleneck’ research problem in Wireless Sensor Networks (WSN). In addition to focusing on minimizing the energy consumption in a WSN, it is also equally important to design routing protocols that fairly and evenly distribute the network traffic; in order to prolong the network life time and improve its scalability. Gradient Based Routing (GBR) techniques such as the Generic GBR (GBR-G) and the Competing-GBR (GBR-C) have been previously proven to be energy efficient in single sink WSNs. These methods consider that each sensor node constructs a gradient with respect to a unique base station. The drawback of this approach is that, due to the position of sensor nodes next to the sink, their energy is usually overused compared to the one of the other sensor nodes in the network. To overcome this, this paper introduces enhanced GBR-G and GBR-C routing approaches (GB-GBR and CB-GBR) which consider the definition of a new gradient model to maximize network lifetime. In the proposed new approach, the GB-GBR and CB-GBR techniques not only consider the selection of the highest gradient link but also the link that avoids the most overloaded sensor nodes when forwarding packets. Using OMNET++ simulation and the MiXiM framework, it is shown that proposed GB-GBR and CB-GBR approaches achieve better performance in terms of network lifespan when compared to the single sink GBR-G and GBR-C approaches respectively.

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Keywords: Wireless Sensor Networks; Gradient; Routing; Energy; bottleneck; Competing; Generic; balance; network lifetime.

1. Introduction

The general structure of a WSN consists of a large number of sensor nodes whose purpose is to gather information about physical objects of a network area. Traditionally, the gathered information is then routed to a single base station (sink) for processing and analysis purposes. As a general wireless communication principle, sensor nodes have a maximum transmission range. Therefore, to route data to the sink node, a multihop transmission strategy is adopted. In general, the energy consumption of sensor nodes next to the sink is higher compared to the one of other sensor nodes in the network. This is due to the fact that the network traffic is unevenly distributed. Considering their position next to the sink node, most of the network traffic passes through the sink’s neighbour nodes. This effect considerably reduces the network lifetime as the energy of the sensor nodes next to the sink rapidly depletes resulting in no possibility to reach the sink. This effect is referred to as the ‘bottleneck’ problem and is accentuated as the network’s scalability increases in terms of number of nodes. The ‘bottleneck’ problem is accentuated in large-scale networks because of the many-to-one network traffic pattern which increases the energy unbalance in WSNs with a single sink node.

The use of a multiple sinks network topology can provide multiple alternative routes from a source node to one of the interconnected sink nodes. This can shorten transmission distances and therefore reduce the network energy cost. Since sensor nodes play the dual role of both event detectors and data routers, the larger the number of hops involved in the routing of data packets to the sink, the greater are the overheads experienced, leading to higher energy cost. Energy efficient broadcast algorithms such as the GBR Network Coding (GBR-NC) in have been proposed to solve
the additional overheads energy consumption problem. Multiple-sinks topology with proper routing protocol can also improve the routing reliability as it provides alternative routes to the sink\textsuperscript{3,5}.

The Gradient Based Routing protocol as described in \textsuperscript{6} has been developed and simulated with a single sink. The outcomes of the simulation have revealed that it is an energy-efficient query-based routing protocol. Its performance has been enhanced through the development of the Competing-GBR algorithm that makes use of the broadcast nature of wireless networks instead of the basic point-to-point message delivery technique. The idea is to increase the probability of successful transmission by using multiple candidate forwarders instead of one on every link. This paper proposes the multiple-sink network architecture. It defines a new gradient approach and evaluates its performance vis-a-vis the conventional GBR and GBR-C approaches. Throughout the paper, we adopt the following nomenclature:

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>WSN</td>
<td>Wireless Sensor Network</td>
</tr>
<tr>
<td>GBR</td>
<td>Gradient Based Routing</td>
</tr>
<tr>
<td>GB-GBR</td>
<td>Generic energy Balancing Gradient Based Routing</td>
</tr>
<tr>
<td>CB-GBR</td>
<td>Competing energy Balancing Gradient Based Routing</td>
</tr>
<tr>
<td>GBR-C</td>
<td>Competing-Gradient Based Routing</td>
</tr>
</tbody>
</table>

2. GBR with energy balancing implementation

In general, one can think of two possible approaches for implementing energy balancing strategies when considering GBR protocols: (a) Using only the information from 1-hop neighbours at a time and (b) An energy balancing approach that makes use of the cumulative energy of a full path. In both approaches, the energy link cost can be used for establishing a gradient of each sensor node.

2.1. Single-hop energy balancing approach:

Once the minimum required transmission power on a link has been established, a simple way to estimate the required energy consumption would be to assume a 100 percent probability of successful transmission. By using the known transmission rate BR, with a transmission power $P_{TX}$ and an estimated transmission time $\Delta T$, the energy consumption on a link $ij$ can be estimated as follows:

$$\Delta E_{ij} \approx P_{TX} \times \Delta T$$

(1)

Nevertheless, a much more accurate way of modelling the estimated time duration for the propagation of a packet on a link taking into account the stochastic nature of the wireless channel would be:

$$\Delta T = \frac{S}{BR \times P}$$

(2)

Consider that $P$ is the probability of successful transmission on the link $ij$ and $S$ is the packet data size.

In order to balance energy consumption throughout the network, the single-hop approach defines a next hop selection method that gives nodes that has more energy remaining greater chance to forward their neighbour’s data packets. For a realistic implementation of the approach, sensor node $i$ transmits its data packet together with its gradient as part of the overhead. When its neighbour sensor node $j$ receives the packet, it determines whether or not to forward the received packet, based on its residual energy as well as the energy gradient of $i$.

2.2. Full route energy balancing approach:

This approach works similarly to the previous one. The main difference between the two is that the routing decision is taken once and considers an estimated cumulative energy cost of different possible paths from the source node to the sink. This cumulative energy cost is usually equal to the sum of link costs along the path. There have been considerable research studies that have adopted this approach such as the PWave protocol as described in \textsuperscript{9}. Most protocols in this category that can be found in literature including the PWave protocol make use of an optimisation approach as they all start by properly defining a global objective function which is minimised. The two methods proposed in this paper also define a well-supported linearised objective function. The approach does not analytically solve the optimisation problem but it rather experimentally tests its performances by means of simulation using OMNET++ and making use of the MiXiM framework.

3. The proposed GB-GBR and CB-GBR developed protocols

3.1. The Generic Energy-Balancing GBR protocol (GB-GBR)

The generic energy-Balancing Gradient-Based Routing protocol (GB-GBR) is a variant of the generic GBR as described in \textsuperscript{6}. The GBR protocol is itself a variant of the Directed Diffusion (DD) protocol. It is a query-based routing protocol where information from a sensor node (source) or a group of sensor nodes is normally routed to the Base Station (BS) in response to a query from the sink node. The query is propagated in the form of an interest message from the sink node and it normally describes a task.
The main concept of GBR resides in making sure that the sensed data is sent from the source node back to the sink node following the shortest possible route. There are many existing routing protocols which strive to achieve the shortest possible path. Among the ones proposed for WSNs, the GBR protocol is preferable in the case of high scalability since it is designed in such a way that sensor nodes are not required to maintain the information about the network topology. The packet is forwarded on the link with the largest gradient, which means that the packet is always transmitted along the shortest path.

Each sensor node establishes different heights by using the information about the minimum number of hops of its neighbours list with respect to the multiple sinks of the WSN. It then defines different gradients with respect to each of the multiple sinks of the network. From the different heights for each sink, the estimated remaining average energy of sensor nodes on each path, $\text{Avg}RE_k$, the number of hops of the path $Nhops_k$, and the estimated energy consumption on the $ij$ hop $\Delta E_n$, an optimisation problem that guides the choice of a particular route $k$ over another, may be defined as follows:

$$\text{Max}\{\text{Avg}RE_k - (Nhops_k \times \Delta E_n)\}$$

$$\text{Subject to} \quad Nhops_k, \text{Avg}RE_k, \Delta E_n \geq 0 \text{ and } 0 \leq \Delta E_n \leq E_{\text{max}}$$

Consider that $Nhops_k$ and $\text{Avg}RE_k$ are the optimization parameters and $E_{\text{max}}$ is the maximum available energy at network deployment time.

\textbf{Algorithm 1: GB-GBR}

- Network random deployment
- Initialise parameters:
  - $n_{\text{mhops}} = 0$, $n_{hops}[k] = 0$
  - data cache: for ($k$=ID of all sensor nodes deployed)
    - if ($k$=ID) then $n_{hops}[ID][k] = 0$
    - else $n_{hops}[ID][k] = -1$
- Continuous process:
  - while (network alive)
    - INTRMsg flooding:
      - Schedule next INTRMsg injection: start 60 seconds timer
      - If (INTRMsg received successfully at node $n_{ID}$) then
        - If (value attribute changed) then
          - update interest cache
          - $n_{\text{mhops}}++$
          - update data cache (Routing table):
            - Add srcID to neighbour list
            - Height(srcID) = min ($n_{hops}[n_{ID}]$ row in data cache) flood INTRMsg
        - Else drop INTRMsg packet
      - Else INTRMsg packet lost
  - Sensed data routing to one of four sink nodes:
    - If (Sensed data = Value attribute in interest cache at node srcID) then
      - Remaining Energy = 0
      - for ($i = 1$ to 4: paths to all possible four sink nodes)
        - for ($k$=ID in neighbour list of srcID node)
          - next hop[k] = position of (min (Height[srcID] row))
          - path[i][k] = push in next hop[k] (add at the back of the list)
          - Remaining Energy = Remaining Energy + Energy[k]
        - end for
        - $k++$
      - to $n_{hops}[i]$ = k and Estimated link cost $\Delta E$
      - EnergyGrad[i] = ($\text{Remaining Energy}_{i} - \text{to}n_{hops}[i] \times \Delta E$)
    - end for
    - Maximum Energy gradient = Max (Energy Grad[i])
    - Forward sensed data according to path of Maximum Energy gradient
  - Else
    - Reschedule sensing of data: start 10 seconds timer

\textbf{Fig. 1. Multiple Base Stations network topology}
3.3. The Competing Energy-Balancing GBR protocol (CB-GBR)

The basic concept of the GBR-C algorithm is to improve the lifespan of the network by reducing retransmission attempts. It proposes that instead of a single next hop sensor node, multiple next hops compete for forwarding the information. That way, it reduces the probability of transmission failure as the data packet is each time provided with alternative paths in case of a transmission failure on a link.

The CB-GBR is also a variant of the Competing GBR (GBR-C). It is also very similar to the GBR-GBR protocol. However, the main difference between the two protocols lies in the fact that the CB-GBR considers the competing data packet forwarding technique of the GBR-C with the exception that it considers multiple sinks unlike the GBR-C which only considers a single sink. The other main difference resides in the fact that in addition to the interest and the data messages, the CB-GBR uses other control messages such as:

- **The “ACK” and “DACK” acknowledgments**: These two acknowledgment messages of 32 bits each allow the receiver of the data message on a transmission link to notify successful reception of the data message to the sender. A receiver sensor node sends an “ACK” message in case of a unique data message destination address and a “DACK” message in case the data message has got two different destination addresses.

- **“TOGO” message**: If the sender node receives either a first “DACK” message, it sends a “TOGO” message of 32 bits to the neighbour which sent the acknowledgment message as an instruction to forward the message to the second destination address. Otherwise, it deletes the message.

Each of the above control messages comprises of a message ID and a time stamp that allow a proper synchronization for their exchange between sensor nodes. The extra energy cost associated with these control messages is modelled as follows:

- For the ACK or the TOGO control messages:

\[ E_{ACK,TOGO} = \frac{32(P_{TX} + P_{RX})}{BR} \]  

- For \( m > 1 \) competing neighbour nodes with the probability of successful transmission on a single link being of \( P \), the total probability of successful transmission becomes \( mP \) and the energy cost of the DACK message is modelled as:

\[ E_{DACK} = \frac{32mP(P_{TX} + P_{RX})}{BR} \]  

Consider that \( P_{TX} \) and \( P_{RX} \) are the transmit and receive powers respectively and \( BR \), the transmission bitrate.

The operation processes of the CB-GBR algorithm is clearly depicted in the following pseudo-code:

```
Algorithm 2: CB-GBR

All of the steps prior to data transmission are the same as the ones described in GB-GBR above.

- Sensed data routing to one of four sink nodes:
  - Handling data message packets:
    - If (one DestAddress) then
      - Send back to source ACK message
      - forward data packet according to the same gradient definition in GB-GBR
    - Else if (Two DestAddresses) then
      - Send back to source DACK message Wait for time T
    - Handling Acknowledgments messages on the source side: If (ACK or second DACK received) then Delete sent data packet
    - Else Send TOGO message
  - Handling TOGO msg:
    - If (TOGO msg received) then If
      - (T greater than 0) then
        - forward data packet according to the same gradient definition in GB-GBR
      - Else delete data packet
    - Else data packet lost

4. Performance Evaluation and results

The performance evaluations were conducted using the OMNET++ discrete event simulator and making use of the MiXiM framework. The obtained results are presented and compared to the generic GBR protocol in terms of network lifetime as well as the average remaining energy and the energy consumption. The behaviour of the network lifespan is also evaluated and analysed as the network scalability is increased in order to study its effect on the performance. The idea of using four interconnected sinks is also to allow much more distributed energy consumption throughout the network as a mechanism to facilitate energy balance.

4.1. Simulation settings

Taking into account the mentioned assumptions that are considered in this study and trying to have a more realistic simulation scenario, the settings configured in OMNET++ for evaluation are presented in Table 1 below.
### Table 1. OMNET++ simulation parameters

<table>
<thead>
<tr>
<th>Parameter types</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of nodes and Number of sinks</td>
<td>50,400,800,1600 sensor nodes and 4 sinks as placed in Fig. 1</td>
</tr>
<tr>
<td>Sensor nodes deployment type</td>
<td>Random</td>
</tr>
<tr>
<td>Sensor node structure modules</td>
<td>Nic (PHY+MAC)$\leftrightarrow$netwl$\leftrightarrow$appl+battery, batStas and arp (Address Resolution protocol)</td>
</tr>
<tr>
<td>Frequency</td>
<td>2.4 GHz</td>
</tr>
<tr>
<td>Data rate</td>
<td>250 kbps</td>
</tr>
<tr>
<td>Data packet size</td>
<td>100 Bytes</td>
</tr>
<tr>
<td>MAC protocol and NIC types</td>
<td>CSMA and IEEE.802.15.4 (Zigbee network card)</td>
</tr>
<tr>
<td>Max. Transmission power</td>
<td>1.1 mWatt</td>
</tr>
<tr>
<td>Trans. interval of periodic traffic (INTRmsgs)</td>
<td>60 seconds</td>
</tr>
<tr>
<td>Trans. interval of event-driven traffic (Sensed-data)</td>
<td>25 seconds</td>
</tr>
<tr>
<td>Battery (Nominal voltage, Capacity)</td>
<td>(3 V, 1000 mAh)</td>
</tr>
<tr>
<td>Simulation durations</td>
<td>100 min = 6000 seconds and 10 min = 600 seconds</td>
</tr>
</tbody>
</table>

### 4.2. Obtained results

The following comparative results between GBR and GBR-C and the proposed GB-GBR and CB-GBR, are extracted:

- The network lifetime with respect to the network scalability in terms of number of sensor nodes as illustrated in figure 2. These results demonstrate the effect of increasing network scalability in general referring to the “network lifetime” which is defined as follows:
  
  **Network lifetime**: In the context of the simulations, network lifetime is defined as the amount of time elapsed from the deployment of the network to the instant when one of sensor nodes becomes dead. To simulate this, a stopping event is set (defined) at the beginning of the simulation in OMNET++ to be the first sensor node’s output voltage $V_{out}$ to fall below a given threshold.

- The average energy consumption behaviour for each sensor node in the network as time elapses as illustrated in figure 3;

- The average remainder energy of the network in percentages as time elapses as illustrated in figure 4;

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**Fig. 2.** Network lifetime and scalability: Balanced and generic

**Fig. 3.** Average Energy consumption with network scalability for 10 min

**Fig. 4.** Average remainder energy for 50 nodes for 10 min
4.3. Discussion of results

Considering an overall view of the set of results on the network lifetime, it can be clearly seen that the objective of balancing energy consumption in the network by means of multiple sinks as opposed to a single one; has considerably improved the network lifetime. As can be observed in the bar graph in figure 2, the GB-GBR algorithm considerably outperforms the generic GBR approach. It can also be clearly seen that the network scalability stills impact negatively on the network lifetime. However, the use of multiple sinks significantly improves the energy consumption efficiency and balance performance of the generic GBR and the GBR-C techniques even in large scale WSNs.

It can also be noticed from figure 3 and 4 that the generic GBR consumes more energy when compared to the GB-GBR, the GB-GBR and the CB-GBR algorithms. The GB-GBR and GBR-C performance in terms of energy consumption are not very different despite the fact that their design targets are different since the GBR-C design target mainly focuses on minimizing energy consumption of the network while the main target of the GB-GBR is balancing energy consumption throughout the network. It is also clear that the combination of both forwarding competition and multiple sinks results in considerably outperforming the generic GBR, GBR-C and even the GBR-GBR approach. An interesting element to be observed from results obtained in figure 3 is the impact of energy balancing techniques on the average energy consumption as network scalability increases. Because of the evenly distributed network traffic, due to the use of multiple sinks, the average energy consumption of the network actually reduces and becomes more or less steady as network scalability increases from 800 nodes to 1600 nodes as illustrated in figure 3.

5. Conclusion

In this paper, two energy balancing modifications of existing GBR and GBR-C routing techniques are proposed. The two algorithms use multiple sinks as a solution to the well-known 'bottleneck' problem in WSNs. Using OMNET++ with the MiXiM framework, it was demonstrated that the obtained results clearly show that the proposed algorithms considerably improve both the energy efficiency and balancing of the network even in large scale WSN deployments. This work adds an advantage to the GBR techniques in terms of simultaneously achieving energy consumption efficiency and balance in the network. Its outcomes can be quite useful for research and development in the WSN routing protocol design field. Further work can consider an analysis of the impact of the four sink nodes’ position on both the energy efficiency and balance of the WSN. This study can for example consider the localisation of sink nodes which uses the correlation between distance and RSSI as described in [10]. A fuzzy approach similar to the one in [12] can also be used to assess the accuracy of data measurements in order to discard the transmission of certain data. This can considerably reduce the amount of energy consumption spent unnecessarily in the network.

References