RF/FSO Wireless Sensor Networks: 
A performance study

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Abstract—Power consumption is an important design consideration for wireless sensor networks (WSNs). Hybrid radio frequency/free space optical (RF/FSO) WSNs have the potential to reduce this power consumption substantially. This paper studies the performance of the RF/FSO WSN by comparing its network lifetime against the lifetime of a traditional RF-only WSN. Two types of networks are considered: reconfiguring and non-reconfiguring networks. The results show that for the range of network parameters considered, the RF/FSO WSN lasts at least twice as long as its RF-only counterpart. This paper also discusses parameter selection for the best RF/FSO network coverage.

Keywords—free space optics, network architectures, sensor networks, wireless communications

I. INTRODUCTION

Wireless sensor networks (WSNs) have received much attention, both in academia and industry [1-4]. Power consumption is an extremely important factor in the design of WSNs, as lower power consumption translates to longer node and network lifetime. Due to size restrictions, sensor nodes have a limited and irreplaceable source of power [4]. The total energy available to a typical smart dust sensor node, for example, is only 1J [4]. Sensing, communication and data processing contribute to the power consumption of a sensor node, with most power being consumed for communications [2]. Therefore, the lifetime of the network might be extended by employing more energy-efficient communications.

Currently, most WSNs employ radio frequency (RF) channels for communications [5]. An optical-based WSN is analyzed in [6]. There is some work on radio frequency/free space optical (RF/FSO) networks, but these are mainly focused on wireless broadband networks [7-10]. In [11], the authors proposed a hybrid RF/FSO WSN. The proposed RF/FSO WSN is shown in Fig. 1.

II. THE RF/FSO WSN

In Fig. 1, the base station is elevated over the RF/FSO WSN deployment area. There are two types of channels in the RF/FSO WSN: RF broadcast-based peer-to-peer channels (e.g. between node 2 and nodes 4-6 in Figure 1), and narrow line of sight (LOS) FSO channels connecting nodes to the base station. Nodes that have LOS with the base station and which are sufficiently close to the base station communicate using FSO links (nodes 1-3 in Fig. 1). The FSO link is achieved by using a passive modulating optical retroreflector mounted on each node [12]. The base station steers a narrow optical beam to interrogate all the nodes in the field, as described in [13]. (For further information, please refer to [11].) Nodes that are too far from the base station, or which do not have LOS to the base station, communicate with the base station using RF peer-to-peer multihop links (nodes 4, 5 and 6 in Fig. 1). This requires a portion of nodes to act as cluster heads (node 2). In the RF/FSO WSN, none of the nodes communicate directly to the base station using RF links.

Two types of networks are considered: reconfiguring and non-reconfiguring networks. In a non-reconfiguring network, nodes in the cluster become isolated from the network when the cluster head dies. In Fig. 1, nodes 2, 4, 5 and 6 would become inoperative when node 2 dies. In a reconfiguring network, nodes 4, 5 and 6 would find new cluster heads through which to route their data should node 2 die.

To compare the performance of the RF/FSO WSN, an RF-only WSN is used for comparison. There are three types of channels in the RF-only WSN: RF peer-to-peer channels, and RF node to base station channels with and without LOS. In the RF-only WSN, nodes communicate directly to the base station.
using RF links if they are sufficiently close. Nodes which are too far away communicate using peer-to-peer multihop RF links, similar to those in the RF/FSO WSN.

III. RF AND FSO CHANNEL MODELS

The energy per bit required to transmit data is proportional to $d^n$ where $d$ is the transmission distance and $n$ is the path loss exponent [5]. For low-lying antenna and near ground channels which characterize WSNs, $n$ is close to 4. The value of $n=4$ is adopted for the RF peer-to-peer channels in both the RF/FSO and RF-only WSNs. For LOS channels, $n$ is close to 2 [4, 5]. This is the value assumed for the node to base station channels with LOS in the RF-only WSN. The value of $n$ typically has a range of $2 \leq n \leq 4$ [4, 5]. So, for the non-LOS RF channels between nodes and the base station in the RF-only WSN, a mid-value of 3 is assumed for $n$.

The binary phase shift keying (BPSK) modulation scheme is used for all the RF links. For the node to base station channels without LOS and peer-to-peer channels, Rayleigh fading is assumed. Ricean fading is assumed for the node to base station channels with LOS. The sensor nodes employ direct conversion receivers [14-16]. Though less sensitive than superheterodyne receivers, direct conversion receivers are preferred for WSNs due to their lower power consumption [14].

It is assumed that code division multiple access (CDMA) is used for RF resource management in the sensor networks, as discussed in [17]. Each node is assigned a unique code, thus enabling multiple nodes to transmit simultaneously. The number of unique codes available will depend on the spreading sequence used. If there are more nodes than there are unique codes, some nodes will have to reuse the same codes, and this might cause data collisions if the nodes are too close to each other. Code assignment is expected to be done by the base station, which would have knowledge of the locations of the individual nodes. Code reuse is possible for sufficiently separated nodes. The base station is expected to calculate the best code assignment possible at the beginning of the network’s lifetime, based on individual node locations. This will ensure that multiple access interference (MAI) is kept to a minimum. For the simulations, it is assumed that each node is able to transmit successfully without MAI.

For the FSO link, each sensor node is equipped with a modulating retroreflector (MRR) [12]. Light from the base station illuminates the MRR and the light is returned to the base station due to the action of the retroreflector. Data is transmitted by modulating the returned signal and this can be achieved by changing the shape of the retroreflector, using a corner cube retroreflector [18]. (The RF and FSO channel models are discussed in more detail in [11]).

IV. NETWORK LIFETIME

Nodes have a limited power supply as they are designed to be small [4]. They therefore expire quickly and are not always replaceable. Network lifetime is dependent on the lifetime of the nodes, and is an important criterion in the design of wireless sensor networks. Several definitions are available for network lifetime [19, 20]. Most of them define network death as the time when a percentage of nodes fail or when the total coverage area drops below a certain percentage. The definitions of node failure and network lifetime adopted for the work in this paper are given in the Table I. The network lifetime ratio, $L_r$, is introduced to compare the lifetimes of the RF/FSO and the RF-only WSN.

| Node Failure: Definition | | |
|--------------------------|-----------------------------|
| Failure of the node to transmit and/or receive data due to the lack of power (dead node) or the lack of a suitable cluster head to connect to the base station (isolated node). | |

Network Lifetime: Definition

Time from when the network begins sensing and transmitting data, until time when network coverage falls to 0% of the total deployment area.

The network lifetime ratio is defined as:

$$L_r = \frac{RF/FSO\ WSN\ lifetime}{RF-only\ WSN\ lifetime}.$$ (1)

V. SIMULATION PARAMETERS

Simulations for the work described in this paper were completed using MATLAB. The amount of energy used by each node for radio transmission is capped to encourage multihop routing. Multihop routing consumes less energy as the radio transmission energy required is range-dependent [11]. For RF transmission, continuously-variable transmit power control is assumed. The RF transmission energy per bit is capped at 1nJ/bit, the typical value for the Bluetooth standard [21]. For both the RF and FSO links, the maximum probability of error tolerated is $10^{-3}$ (discussed in [11]). These limits mean that there is a maximum radio range over which the sensor node can transmit to satisfy quality of service requirements. These are summarized in the Table II. (The maximum radio ranges in Table II are derived in [11]).

The energy per bit for FSO communications is set to 19pJ/bit, 20nJ/bit and 50nJ/bit respectively [11]. The energy per bit for FSO communications is set to 19pJ/bit [21]. The energy per bit required for radio transmission is range-dependent, and is summarized in Table III [11]. For the network lifetime simulations, each node is given an energy budget of $10^{-3}$J. The base station height, $h$, is set to 140m. (These simulation parameters are discussed in more detail in [11]).

For the simulations, the time-driven data reporting method is adopted [22]. Half the nodes are randomly selected to transmit 100 bits to the base station (simulating low bit-rate sensor node traffic) during each time slot.
TABLE II. MAXIMUM RADIO RANGES

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>$d_{PP}$</td>
<td>maximum peer-to-peer radio range</td>
<td>5.6m</td>
</tr>
<tr>
<td>$d_L$</td>
<td>maximum node to base station radio range (with line of sight)</td>
<td>145.7m</td>
</tr>
<tr>
<td>$d_{NL}$</td>
<td>maximum node to base station radio range (without line of sight)</td>
<td>9.9m</td>
</tr>
</tbody>
</table>

TABLE III. TRANSMITTED RF ENERGY

<table>
<thead>
<tr>
<th>RF link</th>
<th>Energy per bit (nJ/bit)</th>
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<tbody>
<tr>
<td>node-to-node</td>
<td>$\varepsilon_{PP} \cdot d^4$</td>
</tr>
<tr>
<td>node-base station (LOS)</td>
<td>$\varepsilon_L \cdot d^2$</td>
</tr>
<tr>
<td>node-base station (NLOS)</td>
<td>$\varepsilon_{NL} \cdot d^3$</td>
</tr>
</tbody>
</table>

$\varepsilon_{PP} = 1.04 \text{ pJ/bit/m}^4$, $\varepsilon_L = 0.047 \text{ pJ/bit/m}^2$, $\varepsilon_{NL} = 1.04 \text{ pJ/bit/m}^3$, $d$ is the communications distance

VI. NETWORK PARAMETERS

The base station hotspot is a circular area with radius $r_c$ shown in Fig. 2. In the base station hotspot, all nodes are less than $d_{opt}$ from the base station. The parameter $d_{opt}$ is the maximum optical distance over which nodes in the RF/FSO WSN can transmit to satisfy quality of service requirements. Nodes in the hotspot communicate directly to the base station if they are not optically obstructed from it.

The hotspot factor, $\delta$, is given as:

$$\delta = \frac{R}{r_c},$$  \hspace{1cm} (2)

where $R$ is the radius of the circular deployment area in which the nodes are deployed. The hotspot radius, $r_c$, is:

$$r_c = \sqrt{d_{opt}^2 - h^2}.$$  \hspace{1cm} (3)

The node density, $\mu$, is given as [2]:

$$\mu = \frac{N \cdot d_{pp}^2}{R^2},$$  \hspace{1cm} (4)

where $N$ is the number of nodes. Uniform node distribution is assumed, so the number of nodes is roughly equal in equal areas. The sensing range of the nodes has been set to $d_{pp}$ for the simulations. The range ratio, $\beta$, is given as:

$$\beta = \frac{d_{opt}}{d_L}.$$  \hspace{1cm} (5)

For the simulations, the value of $d_{pp}$, $d_{NL}$ and $d_L$, fixed and given in Table II. The maximum optical range, $d_{opt}$, depends on $\beta$ in (5). The deployment area radius, $R$, and the number of nodes deployed, $N$, are determined from (2) and (4) respectively.

The blocking factor, $b_f$, is used to simulate this, and is defined as the percentage of sensor nodes without LOS to the base station.

VII. SIMULATION RESULTS AND DISCUSSION

A wide range of network parameters were considered, but the simulation results of a representative sample are presented in Figs. 3-10. Figs. 3, 5, 7 and 9 show that the RF/FSO WSN lasts at least twice as long as the RF-only WSN. This is because the network’s lifetime depends on the last surviving node in the network. Compared to other nodes, this last node would expend the least amount of energy. As such, it would be connected directly to the base station and not serve as a cluster head for any other nodes. In the RF-only WSN, the last node expends $20\text{nJ/bit}$, $20\text{nJ/bit}$, and a maximum of $51\text{nJ/bit}$ for sensing, data processing and communications respectively. In the RF/FSO WSN, the energy expended by the last node for sensing and data processing are the same, but the communications energy expended is $19\text{pJ/bit}$. Therefore, on average, the ratio between the energies expended by the final nodes in the RF-only WSN to the final node in the RF/FSO WSN is $9140.019 = 2.27$. This explains the $2 \leq L_r \leq 2.5$ lifetime ratio range in Figures 3, 5, 7 and 9.

Figure 3. WSN lifetime ratio vs. hotspot factor, $\delta$ for $b_f=20\%$, $\beta=1$
Figs. 4, 6, 8 and 10 show the average coverage area of the RF/FSO WSN for the network parameters considered. Fig. 4 shows that the average coverage area falls after $\delta=1$. This is because for $\delta>1$, the deployment area lies outside the base station’s hotspot, as shown in Fig. 2. As $\delta$ increases, a larger portion of the nodes use radio multihops to reach the base station. This increases the energy required for communications, causing nodes to expire more quickly. This results in a decrease in the average coverage area of the RF/FSO WSN.

Fig. 6 shows that the average coverage area of the RF/FSO WSN reduces with the blocking factor. This is because more nodes radio multihop to reach the base station. This increases the energy required per node, causing more nodes to die quickly which thus reduces the average coverage area. Fig. 8 shows that a higher node density increases the average network coverage. However, beyond a certain value, increasing the node density fails to further increase the average coverage area. This value is $\mu=4$ in Fig. 8. Fig. 10 shows that the coverage area is almost constant as $\beta$ increases. This is because as the deployment area increases with $\beta$, the number of nodes increases proportionately (as the node density, $\mu$, is fixed at 3). So, similar network connectivity and coverage are maintained as $\beta$ increases.

The simulation results also suggest that network reconfiguration is less beneficial when the blocking factor is low. This can be seen in Figs. 6 and 10. When the blocking factor is low, fewer nodes require network reconfiguration to remain operational. In the base station hotspot, a low blocking factor means most nodes in the RF/FSO WSN are connected
This paper has studied the performance of the RF/FSO wireless sensor network. The best RF/FSO network coverage is achieved when the blocking factor is low and the node density is high. A larger range ratio translates to longer FSO communications range and a larger base station hotspot. The deployment area should be kept within the base station’s hotspot. Results also suggest that network reconfiguration is most beneficial when the blocking factor is high. This work shows that the RF/FSO WSN offers the advantages of a narrow line-of-sight channel, together with the robustness of RF coverage. Simulations show that the RF/FSO WSN lasts at least twice as long as its RF-only counterpart for a range of circumstances, thus offering a better alternative for future work.

VIII. CONCLUSION

This paper has analyzed the performance of the RF/FSO wireless sensor network. The best RF/FSO network coverage is achieved when the blocking factor is low and the node density is high. A larger range ratio translates to longer FSO communications range and a larger base station hotspot. The deployment area should be kept within the base station’s hotspot. Results also suggest that network reconfiguration is most beneficial when the blocking factor is high. This work shows that the RF/FSO WSN offers the advantages of a narrow line-of-sight channel, together with the robustness of RF coverage. Simulations show that the RF/FSO WSN lasts at least twice as long as its RF-only counterpart for a range of circumstances, thus offering a better alternative for future work.

REFERENCES