# Power considerations for very low duty cycle wireless sensor networks powered by energy harvesting

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***Abstract*—We examine the power usage for various network configurations specifically for low duty cycle wireless sensor networks powered solely by energy harvesting. We focus mainly on minimizing power usage given the communication requirements, and base our study on Microchip's commercially available MRF24J40MA and MRF24J40MB radio modules.**

***Keywords-wireless sensor networks; ultra low duty cycle; power usage minimization***

## I. INTRODUCTION

Typically, a multi-hop approach is preferred for power saving and minimizing interference when implementing a wireless sensor network (WSN) over a reasonably large deployment area [1]. This is because of the inverse square law that governs radio frequency (RF) propagation loss. However, the propagation loss aspect should not be the sole determining factor and this intuitive approach needs to be re-evaluated by considering other factors in the design [2].

Putting aside the fact that single hop networks can be easier to design, single hop networks can also consume less power, as compared to some multi-hop networks, even when the transmission power is increased many fold. This counter intuitive statement stems from the fact that to achieve synchronization among nodes (for multi-hop to be efficient) is non-trivial. Clock timing uncertainties can result in radio receivers in multi-hop networks needing to be on for long periods and consequently consume considerable energy, so much so that for a given network topology, increasing the transmission power to communicate over fewer hops (or even directly over one hop) can consume less power than keeping the transmission power low and communicating over more hops [3]. Multi-hop relaying also requires stricter timing than single hop, requiring clocks that generally use greater power.

## II. MULTI-HOP ASYNCHRONOUS AND SYNCHRONOUS TIMING

Throughout this discussion, we will assume that we are interested in infrequent transmissions, e.g. once a day, of packets that contain accumulated sensed data, which is not uncommon for long term environmental or structural monitoring [4]. We will base our examples on Microchip's MRF24J40MA (MA) and MRF24J40MB (MB) radio modules. The MA module uses 75.9mW when transmitting, 62.7mW when receiving, and can transmit up to 100m, whilst the MB module uses 429mW when transmitting, 82.5mW when receiving, and can transmit up to 1000m. We observe, through experimentation, that these modules take about 5ms from sleeping state to send one 10-byte packet. This approximate time varies according to packet size, whether carrier sense multiple access with collision avoidance (CSMA-CA) is used, and time needed to stabilize the module after it is activated.

Assume we have a sensor node (A) that is 200m away from a sink node (C), which has no power constraints. To achieve this distance, we will use the MA module and place another node (B) between nodes A and C, as shown in Fig. 1 For node C to receive a packet from node A, node B must relay the packet node A wishes to send to node C. If node A operates at a very low duty cycle and sends one packet a day to node C, node B could always stay awake listening for node A to send its packet in order to guarantee that it is awake to receive the packet, and thus consume 62.7mW. This is an example of asynchronous communication and, in some cases, consumes too much energy; we therefore disregard this as a viable option.

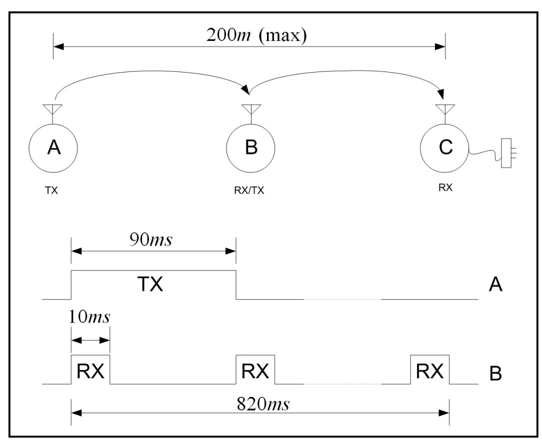


Fig. 1 Multi-hop network with RX switching timing.

We now consider a synchronous approach where nodes A and B are equipped with crystal oscillators that keep track of time, node A sends its packet at the same time every day and node B only has to listen for a short period during node A's scheduled transmission time. For simplicity, we assume that initial synchronization has been achieved.

Despite extensive research to alleviate the clock drift problem in WSNs [5], it is not possible for node B to start listening exactly when node A transmits. A common crystal uncertainty is in the order of 10ppm. Even if we assume the crystals to have an uncertainty of 5ppm, node B must listen with a window period of 869ms every day to be certain of hearing node A's packet transmission. Node A consumes 4.4pW whilst node B consumes 630nW; clearly node B is consuming much more energy than node A.

### *A. Multi-hop synchronized timing with energy leveling*

We can improve on the previous situation using a receiver (RX) switching method which can be shown that to minimize the maximum energy consumed by nodes A and B, both nodes must consume equal amounts of energy. However, due to the fact that we are unable to split up packets into infinitely small items, it is realistically impossible to exactly distribute the energy usage evenly between nodes A and B. We first illustrate this with a simple example. Assume node A transmits its packet 18 times in quick succession (i.e. 90ms transmission period) whilst node B listens for ten 10ms periods spread uniformly over 820ms, as shown in Fig. 1 It can be seen that node B will receive at least one copy of node A's packet and the energy consumed by both nodes is approximately 81nW, which is roughly an order of magnitude improvement over the multi-hop synchronous method described before.

### *B. Single hop transmission*

Next, we show how further energy savings can be achieved. The MB module can easily transmit 200m in one hop and uses 24.9nW to send one packet a day which is around three times less energy than the best achievable with multi-hopping and the RX switching method. In a network with a large number of nodes, a multi-hop approach can reduce interference and achieve higher throughput. However, under low duty cycle conditions, a single-hop approach can achieve better performance with appropriate scheduling and consume less energy.

### *C. Sink-synchronized multi-hop*

A sink-synchronized multi-hop architecture is one where the sink (node C) transmits a stream of small synchronization packets to all nodes (using the MB module.) Node A and B use this timing information to synchronize a hopping schedule using MA modules. Fig. 2 illustrates this method along with the appropriate timing structure to send a packet a day. If we assume the synchronization stream can synchronize the clocks of nodes A and B to within a few milliseconds, then this method uses even less energy than the single hop method. Node A consumes 11.7nW whilst node B consumes 16.8nW.

## III. OVERHEADS

The energy used by overheads from sources such as timing circuitry, microprocessor circuitry, and leakages can be significant. Even with modern electronics, when dealing with long periods of time between communication activities, the overheads can use more energy than the energy used to transmit the data.

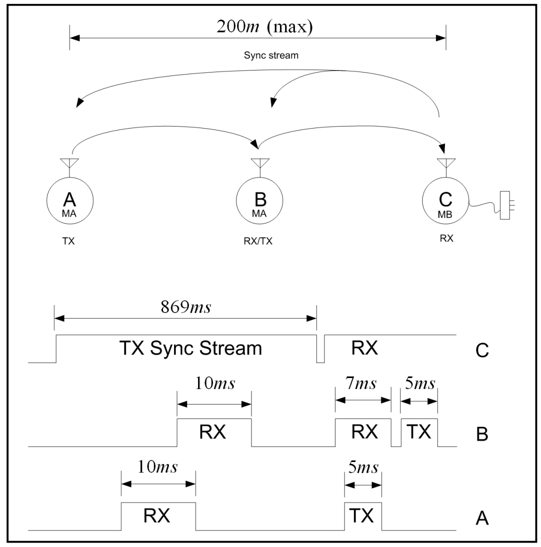


Fig. 2 Sink-synchronized multi-hop transmission.

Generally as a rule of thumb, the stricter the timing requirements are, the greater the overheads are. When developing a prototype WSN node board that uses a crystal oscillator, and a real-time calendar and clock (RTCC), we measured the power overheads to be around 7μW. Changing the oscillator to an RC oscillator, the power overheads became 4μW. Whilst removing both the oscillator and the RTCC, and allowing the WSN node to activate itself only when sufficient energy has been harvested and stored in a reservoir reduced the power overheads to 2μW. This fits the rule of thumb that stricter timing uses more overheads.

The single hop method does not require as strict timing as the sink synchronized multi-hop method. This allows the single hop method to exploit lower overheads from using less strict timing methods. The sink synchronized multi-hop method, on the other hand, occasionally still needs very strict timing.

We created a sink-synchronized multi-hop network with our prototype WSN boards using MA modules. Each board typically incurs 2μW of overhead while harvesting energy until it has acquired enough to operate and listen for synchronization packets from the sink in order to acquire timing information. Once the packet has been received, each node uses 4μW of overhead until data have been relayed back to the sink. The time between checking for synchronization packets depends on the amount of energy the nodes acquired; this means that the nodes lose their ability to keep track of time when using 2μW. As we programmed the maximum time between sensor node data retrieval to be 19 minutes, these boards can use 7μW when data are retrieved once every 19 minutes. If one of these boards is refitted with a MB module, programmed as a single hop network node using the RC oscillator with the RTCC, and set to transmit data every 19 minutes, it would then use 6μW, which is less than our multi-hop node.

## IV. MODELING

We now model the energy usage per packet transmission using a generalized *m* node linear topology with the following equations, while ignoring the overheads as discussed above.

$$X_{\text{RX SWITCH}} = \left[ \frac{(n+1)P_{\text{TX}}T_{\text{PKT}}}{Du_1}, P_{\text{RX}}Du_1T + \frac{(n+1)P_{\text{TX}}T_{\text{PKT}}}{Du_2}, .. \right. \quad (1)$$

$$\left. .., P_{\text{RX}}Du_{m-1}T + \frac{(n+1)P_{\text{TX}}T_{\text{PKT}}}{Du_m} \right]$$

$$X_{\text{MULTI-HOP}} = \left[ nP_{\text{TX}}T_{\text{PKT}}, P_{\text{RX}}T + nP_{\text{TX}}T_{\text{PKT}}, .. \right. \quad (2)$$

$$\left. .., P_{\text{RX}}T + nP_{\text{TX}}T_{\text{PKT}} \right]$$

$$X_{\text{SINGLE}} = \left[ nP_{\text{TX}}T_{\text{PKT}} \right] \quad (3)$$

$$X_{\text{SINK-SYNC}} = \left[ (2P_{\text{RX}} + nP_{\text{TX}})T_{\text{PKT}}, (2T_{\text{PKT}} + T)P_{\text{RX}} + nP_{\text{TX}}T_{\text{PKT}}, .. \right. \quad (4)$$

$$\left. .., (2PT_{\text{PKT}} + T)P_{\text{RX}} + nP_{\text{TX}}T_{\text{PKT}} \right]$$

$$T = nT_{\text{PKT}} + \varepsilon\tau + \alpha \quad (5)$$

where $X_{\text{RXSWITCH}}$, $X_{\text{MULTI-HOP}}$, $X_{\text{SINGLE}}$, and $X_{\text{SINK-SYNC}}$ denote the energy usage for all the nodes, excluding the sink node, for the RX switching method, asynchronous multi-hop, single hop, and the sink-synchronized multi-hop method respectively. $m$ is the number of nodes, $n$ is the number of unique packets transmitted by any node every time data is retrieved from the network, $T_{\text{PKT}}$ is the packet transmission time, $P_{\text{TX}}$ is the power needed to transmit, $P_{\text{RX}}$ is the power needed to receive, $T$ is the communication window, $\varepsilon$ is the accuracy of the synchronous timing per unit time, $\tau$ is the time since last synchronization, $\alpha$ is the initial synchronization error, and $Du$ is the realizable duty cycles for the RX switching method that minimizes the maximum element of $X_{\text{RXSWITCH}}$. Fig. 3 shows a plot comparing the maximum power usage of a node for these four situations using the models given above where $n$ equals one.

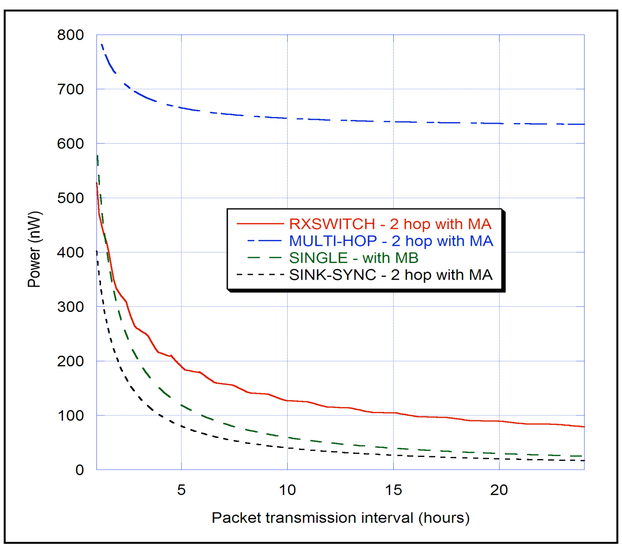


Fig. 3 Power usage versus packet interval for various configurations.

Therefore, ignoring the power consumption overheads of the four different methods, a sink-synchronized multi-hop network is better in the sense of using less energy than any of the other methods we have investigated. However, a single hop network performs surprisingly well given its simplicity and with the ability to use less strict timing requirements results in lower overheads than multi-hop networks. Furthermore, in the multi-hop network scenarios, delivery of node A's data to the sink will be unsuccessful when node B fails, whereas an equivalent single hop network does not experience this problem, thus making single hop networks more robust.

## V. Conclusions

When deciding on what type of network structure and protocol to use for a WSN network where sensor data is required only infrequently, energy consumption overheads are a major consideration, especially for WSNs powered solely by energy harvesting and do not have power available all the time. Choosing a protocol influences what hardware can be used, and this in turn dictates what overheads are incurred by the entire system. This makes choosing a protocol more than just picking the protocol that minimizes the energy while ignoring overheads incurred by the system components.

From what we have observed, the difference in power consumption between a sink-synchronized multi-hop network and a single hop network is insignificant compared to the overheads. This means a single hop network should use roughly the same amount of energy as a multi-hop network when ignoring operating overheads incurred by the hardware. It is the overheads incurred by the various components that make the difference. This aspect has been neglected by most, if not all, proposals for battery-powered WSN protocols and even recent studies of WSNs powered by energy harvesting [6]. This is a critical factor that must be accounted for when WSNs rely on energy harvesting for power.

By considering different aspects of the various network configurations carefully without prejudice, a better decision can be made when deciding which configuration to use. While we have only experimented with single-hop and two-hop configurations using commercial-off-the-shelf modules, extending the model to more nodes and different radios is straightforward using the analytical models presented above.

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