Multi-Hop Transmission: Benefits and Deficits

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1 Why (not) multi-hop?

Sensor networks are supposed to operate with very little energy, are build of tens to thousands nodes and may be spread over large distances. In order to interconnect nodes in large areas while spending little energy, a self-evident approach is to use sensors as relays, thus saving transmit power while improving connectivity. In other words, nodes are not necessarily directly connected to a base station, but may use multiple hops to transmit their data. Extensive research has been done in that area for high rate, ad-hoc networks. Nevertheless, the main focus in these works is on network capacity [2] and bandwidth efficiency. As sensor networks are supposed to work at low rate with low duty cycles, these metrics are not nearly as important as energy efficiency. Even if energy is an issue, often only transmit power is considered, neglecting the enormous influence of receive energy and fixed costs. A first approach taking into account those can be found in [1]. Min [6] did a more sophisticated analysis.

So why want we use multi-hop schemes at all? Looking at the exponential path loss model it is immediately obvious, that with more hops n we can save lots of energy:

$$P_{Loss} \sim \left(\frac{d}{n}\right)^{\alpha}, \tag{1}$$

where α denotes the path loss index and P_{Loss} the overall power loss at a distance d. Thus, we can save $10\alpha \lg(n)$dB. In networks, where interference is an issue, the reduced transmit power yields also reduced interference, improving the energy balance even more. But the main advantage of allowing multi-hop is its capability to avoid hidden terminals. Nodes, which can not reach the base station directly are given the possibility to access it via other nodes, making a much larger network feasible.

But this is not the whole truth. Even though the source node may save energy, relaying nodes have to spend transmit energy as well. Moreover, in order to receive the packets properly, the relays have to be in receive mode for some time. Of course, several MAC-schemes were developed to reduce idle listening and overhearing [8], [4]. Nevertheless, even in fully synchronized networks, where all nodes know their neighbors and their duty cycles, the receive energy and transmit energy have to be included in the calculation. Additional communication overhead has to be considered as well. Even worse, nodes close to the base station would have to handle more traffic, leading to an energy-unbalanced system, causing a decreased network lifetime. So the overall energy consumption for a data transmission using multiple hops may be worse than for the single-hop case.

But what are the important parameters, which determine the usefulness of multi-hop? As it is obvious from (1) the distance between source and destination (as well as between the hops) and path loss index are crucial factors. Furthermore, the relation between the cost of receive and transmit power will influence the expediency of multi-hop. Data fusion can have considerable benefits by compressing data from many sources, yielding condensed data. Very much important is the share of the power amplifier to the fixed costs while transmitting. If the power amplifier needs only a small percentage of the energy, then it would be better to spend more power for a single-hop connections, avoiding costs for other nodes. All these parameters have to be considered under different channel conditions; moreover other channel assumptions may have to be made for single- and multi-hop schemes.

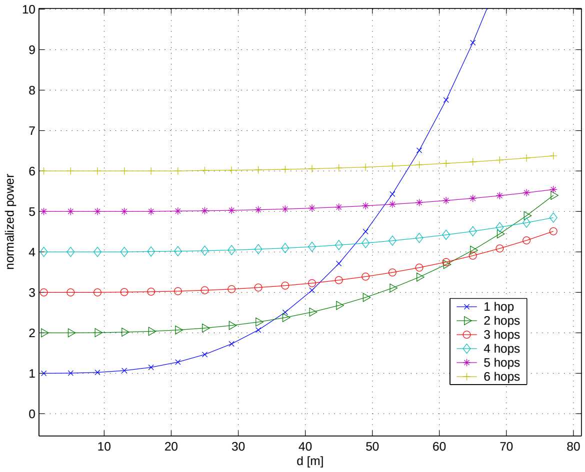

Figure 1: Power consumption for multi-hop, $\alpha = 3$ if $E_{RX} = 0$

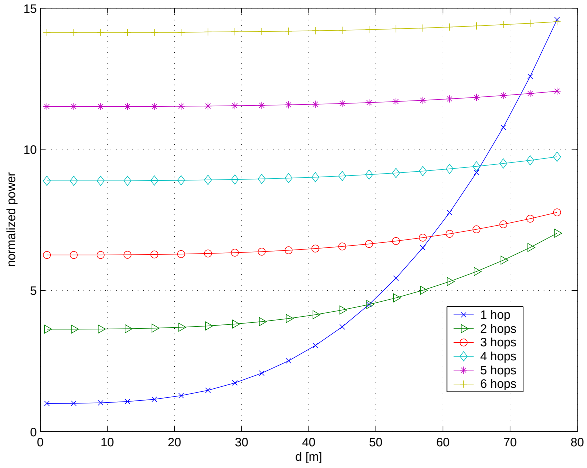

Figure 2: Power consumption for multi-hop, $\alpha = 3$ if $E_{RX} \neq 0$)

2 Possible Approaches

2.1 Theoretical Approach

Let us start with a very simple model for the overall energy consumption when transmitting a single packet as already proposed in [1]. For conventional relaying, illustrated in Fig. 3a), the packet is received by a relay, which will simply retransmit it. For a first estimation, hops with equal distance are assumed. If the final receiver is a power-independent base station (BS), we find

$$\begin{aligned} E(n,d,\alpha) &= n\,E_{TX} + (n-1)\,E_{RX} \qquad (2) \\ &= n(E_0\left(\frac{d}{nd_0}\right)^{\alpha} + E_{fix}) + (n-1)E_{RX}. \end{aligned}$$

Herein, the overall energy E is a function of the number of hops n, the path loss index α, ranging from 1.5 to 6 according to [3], the distance d and also depends on the energy consumption in receive mode and a fixed share in transmit mode, E_{RX} and E_{fix}, respectively. E_0 is the radiated energy at 1m distance to the transmitter.

Looking at an indoor scenario, a rough estimate about the efficiency of multi-hop protocols can be obtained. We apply a link budget with parameters provided in the table in 4. Furthermore, the power consumption characteristics of Chipcon CC1000 are oriented on. This model assumes fixed energy costs for low transmit power ($\leq$-20 dBm) and a linear increase in power consumption for high radiated powers at a linear scale (i.e. in W). In Fig. 1 and 2 we look at the power consumption, normalized to the consumption for single-hop at 1m, as function of distance for several hops, which are assumed to be equally spaced. The former sets E_{RX} in (2) to 0, i.e. it assumes that no energy is needed for receiving. This gives us a lower bound for the distance, where multi-hop is superior to single-hop. For Fig. 2 a receive power of 42mA according to Chipcons specifications is presumed. Clearly, multi-hop is only useful for distances larger than 35m and 50m, respectively. For indoor scenarios those large gaps are rather rare.

More sophisticated approaches can be adapted from well-established high data rate ad-hoc networks. The idea is to consider more elaborated schemes like cooperative relaying [5]. As shown in Fig. 3b) the data is sent to a relay. At the same time the base station can also receive that signal. Depending on the quality of the signal at the relay, data might be forwarded to the BS, which will combine both signals. This method exploits the advantages of reduced path losses and spatial diversity. Several modifications are known, which differ in the decision *when* to forward and *how* to forward (amplify&forward or decode&forward). Drawbacks are possible error propagations, required channel state information (which might be costly to gather)

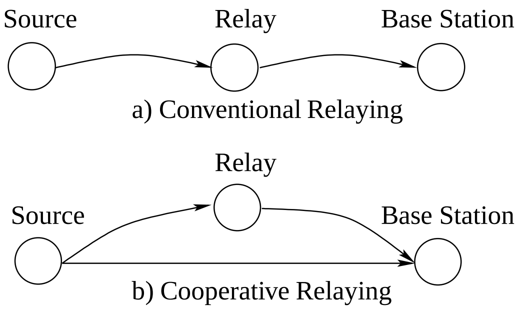

Figure 3: Conventional vs. Cooperative Relaying

and how to divide the power between source and relay node. Instead of using performance measures like outage probability, capacity, spectral efficiency etc. our new measure will be the energy consumption of all relaying nodes and the probability of a successful decoding of the data at the base station. The calculation of possible transmit energy savings has to be counterbalanced against the costs of the relay for receiving, computation and forwarding.

2.2 Practical Approach

Real networks are much more complex. The above described theoretical approach can provide a bound, what can be achieved with multi-hop. It assumes perfect knowledge about routing path, the channel, disregards overhearing and idle listening etc. For practical analysis these and many more parameters have to be regarded. These include retransmission schemes, the transmission of acknowledgments, employment of error correcting codes, physical transmission parameters. Due to those it can be expected that the brute reality may look much worse than the results from theory may suggest. To a certain extend the analysis model proposed in [7] can be used to estimate multi-hop expenses in real networks. Furthermore, simulations with real network protocols would gain a deeper insight.

3 Quo vadis?

Obviously, first rough calculations do not clearly vote for multi-hop schemes. Nevertheless, it remains unclear how the various parameters influence the overall energy consumption of the nodes and the cost for a single transmission. However, in order to provide good coverage for large scaled networks multi-hop may be just inevitable. Thus, we have to be interested in: How much does it cost? So putting up this question we now have a new focus of our research.

4 Appendix

Transmission Rate	250 kbps
Frequency	2.4 GHz
Path Loss Index	3
Add. Losses	35 dB
Gain TX Antenna	1.76
Gain RX Antenna	1.76
Noise Figure	10

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