Single-hop vs. Multi-hop – Energy efficiency analysis in wireless sensor networks

Uroš M. Pešović, Jože J. Mohorko, Karl Benkič, Žarko F. Čučej

***Abstract* — Wireless sensor networks are networks of devices with restrained resources, used for environmental, military, automation and home applications. Radio transceiver is one of the biggest power consumer in sensor node, so it's usage need to be very efficient in order to maximize node's operational life. Node can route it's messages towards destination either by using small or large hops. Theoretical knowledge favours using of smaller hops, known as multi-hop, which is considered as more efficient then single-hop. This paper shows that single-hop transmission is more efficient, when power consumption of real wireless sensor node's transceivers are taken into account.**

***Keywords* — single-hop, multi-hop, wireless sensor networks, energy efficiency.**

I. Introduction

Wireless sensor networks (WSN) consist of a number of spatially distributed sensor nodes, which cooperatively monitor physical or environmental conditions. These nodes usually have restrained resources, such as limited battery power, processing power and memory storage. One of the main issues in WSN is increasing energy efficiency in order to achieve months of node autonomy with signle a set of batteries. Such long node's lifetime is possible by using long periods of inactivity and use of low-power components.

Network coverage area is often much larger then radio range of single node(s), so in order to reach some destination node can use other nodes as relays. This type of communication is known as multi-hop routing in wireless mesh networks.

Overall WSN node power consumption depends on processor's, transceiver's power consumption and on the operation regime of these components (switching between idle and operating mode). Most of the node energy is consumed by radio transmission. Power savings in radio transmission are usually achieved by use of energy efficient medium access and routing protocols. The most modern radio transceivers could adjust their transmitting power, so some destination could be reach with either large number of smaller hops (multi-hop) or small number of larger hops (single-hop). Energy efficiency of these two approaches depends on:

- path loss between transmitter and receiver
- power consumption of the radio transceiver in various operating modes

It is theoretical known from state of the art [1,2] that multi-hop routing is more efficient then single-hop routing. This is in an opposite to observations in some real world WSN, which shows that single-hop routing, can be much more energy efficient then multi-hop routing [3,4]. Besides energy efficiency, single-hop routing can also have advantages for other network parameters, such as end-to-end delay, lower packet loss, etc. In this paper, we present some research results about conditions, when is better to use one communication strategy, then other.

II. Theoretical analysis

Radio channel between transmitter and receiver can be established only when strength of the received radio signal is grater then receiver's sensitivity threshold. The reduction in signal power density, on the path between transmitter and receiver, is called path loss. Realistic path loss modeling can be a very complex task because transmitted radio waves could be reflected, absorbed or scattered by the obstacles. Receivers in a real environment receive not one but many delayed components of the original signal. Such phenomenon is called multipath fading.

The simplest path-loss model, called free-space, assumes that there are no obstructions between transmitter and receiver. Free-space path loss is proportional to the square of the distance between the transmitter and receiver. Other models take into account effects of multipath fading and one of the most commonly used is log-distance path loss model [5].

$$PL \approx \left(\frac{1}{d}\right)^{\alpha} \quad (2.1)$$

This model employes path loss exponent α which is emirically measured under different propagation scenarios. Typical values of path loss exponent in such scenarios are presented in Table 1.

Using this model we can express receiving power P_r at distance d from the transmitter:

$$P_r = P_0 \cdot \left(\frac{d_0}{d}\right)^{\alpha} \quad (2.2)$$

Uroš Pešović - Technical Faculty, Svetog Save 65, 32000 Čačak, Srbia (telephone: 381-32-302721, e-mail: pesovic@tfc.kg.ac.rs, rasin@tfc.kg.ac.rs)

Jože Mohorko, Karl Benkič, Žarko Čučej - Faculty of electrical engineering and computer science, Smetanova 17, 2000 Maribor, Slovenia (e-mail: mohorko@uni-mb.si, k.benkic@uni-mb.si, zarko.cucej@uni-mb.si)

TABLE 1: TYPICAL VALUES OF PATH LOSS EXPONENT

Environment	***α***
Free-space	2
Urban area LOS	2,7 ÷ 3,5
Urban area no LOS	3 ÷ 5
Indoor LOS	1,6 ÷ 1,8
Factories no LOS	2 ÷ 3
Buildings no LOS	4 ÷ 6

where P_0 represents known received power at distance d_0 from a transmitter and α is the path loss exponent.

Pure theoretical model of wireless transmission, assumes that all consumed energy is radiated into the air by a transmitter, and a receiver doesn't spend any energy during a reception. Topologies of various types of single-hop and multi-hop communication are presented in Figure 1.

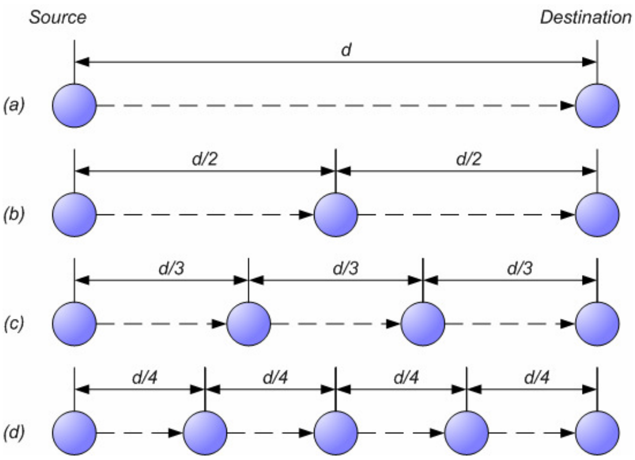

Figure 1. Transmission distances for: (a) signle-hop, (b) double-hop, (c) triple-hop, (d) quad-hop.

If we assume that transmitter, in single-hop scenario, emits at such as power P_1 which is just enough to be received by destination node, we can address this power as receiver's sensitivity threshold P_M

$$P_M = P_1 \cdot \left(\frac{d_0}{d}\right)^{\alpha} \quad (2.3)$$

In case of the double-hop, triple-hop, quad-hop… and *n*-hop necessary transmitting powers P_2, P_3,P_4,.., P_n will be:

$$P_M = P_2 \cdot \left(\frac{d_0}{d/2}\right)^{\alpha} \quad (2.4)$$

$$P_M = P_3 \cdot \left(\frac{d_0}{d/3}\right)^{\alpha} \quad (2.5)$$

$$P_M = P_4 \cdot \left(\frac{d_0}{d/4}\right)^{\alpha} \quad (2.6)$$

$$P_M = P_n \cdot \left(\frac{d_0}{d/n}\right)^{\alpha} \quad (2.7)$$

If we equalize equations 2.3 ÷ 2.7 we will get:

$$P_1 = P_2 \cdot 2^{\alpha} = P_3 \cdot 3^{\alpha} = P_4 \cdot 4^{\alpha} = .. = P_n \cdot n^{\alpha} \quad (2.8)$$

Over all transmitter's power consumption used for single-hop (P_{1H}), double-hop (P_{2H}), triple-hop (P_{3H}) and *n*-hop (P_{nH}) will be:

$$P_{1H} = P_1 \quad (2.9)$$

$$P_{2H} = P_2 + P_2 = 2 \cdot \frac{P_1}{2^{\alpha}} \quad (2.10)$$

$$P_{3H} = P_3 + P_3 + P_3 = 3 \cdot \frac{P_1}{3^{\alpha}} \quad (2.11)$$

$$P_{4H} = P_4 + P_4 + P_4 + P_4 = 4 \cdot \frac{P_1}{4^{\alpha}} \quad (2.12)$$

$$P_{nH} = n \cdot \frac{P_1}{n^{\alpha}} \quad (2.13)$$

We can clearly see that for any value of the path loss exponent greater than one, multi-hop transmission will be more energy efficient than single-hop transmission. If we assume that receiver is not ideal and for its work requires power P_R, equations will get following form:

$$P_{1H} = P_1 + P_R \quad (2.14)$$

$$P_{2H} = 2 \cdot \left(\frac{P_1}{2^{\alpha}} + P_R\right) \quad (2.15)$$

$$P_{3H} = 3 \cdot \left(\frac{P_1}{3^{\alpha}} + P_R\right) \quad (2.16)$$

$$P_{4H} = 4 \cdot \left(\frac{P_1}{4^{\alpha}} + P_R\right) \quad (2.17)$$

$$P_{nH} = n \cdot \left(\frac{P_1}{n^{\alpha}} + P_R\right) \quad (2.18)$$

From this equations follows that multi-hop communication will be more efficient than single-hop only if received power consumption is:

$$P_R < \frac{n^{\alpha-1} - 1}{(n-1) \cdot n^{\alpha-1}} P_1 \quad (2.19)$$

Reception power required for energy efficient multi-hop transmissions for various values of α and n is presented in Table 2

TABLE 2: NECESSARY VALUES OF RECEIVED POWER

α	***Double-hop***	***Triple-hop***	***Quad-hop***
2	$P_R < \frac{1}{2} P_1$	$P_R < \frac{1}{3} P_1$	$P_R < \frac{1}{4} P_1$
3	$P_R < \frac{3}{4} P_1$	$P_R < \frac{4}{9} P_1$	$P_R < \frac{5}{16} P_1$
4	$P_R < \frac{7}{8} P_1$	$P_R < \frac{13}{27} P_1$	$P_R < \frac{21}{64} P_1$
5	$P_R < \frac{15}{16} P_1$	$P_R < \frac{40}{81} P_1$	$P_R < \frac{85}{256} P_1$

We can conclude that primary condition for energy efficient multi-hop transmission is that receiver's power consumption must be small enough in comparison to transmitter's power consumption, required to achieve single-hop.

III. Overview of WSN transceivers

WSN nodes usually use transceivers, which operate in 2.4 GHz band, compliant to IEEE 802.15.4 standard. This band has sixteen channels, each of them with data rate of 250 kbps. It employs Direct Sequence Spread Spectrum (DSSS) modulation in combination with Offset - Quadrate Phase Shift Keying (O-QPSK) modulation. Radio transceiver has standard output power at 0 dBm and receiver's sensitivity threshold is at least of - 85 dBm. Power consumption of cc2420 [6], IEEE 802.15.4 compliant radio transceiver, in various operating modes, is presented in Table 3.

Table 3: Power consumption of cc2420 transceiver

Operating mode	*P [mW]*	*η (%)*
Reception	65	----
Transmission (0 dBm)	57.4	1.74
Transmission (-5 dBm)	46.2	0.68
Transmission (-10 dBm)	36.3	0.27
Transmission (-15 dBm)	32.7	0.09
Transmission (-25 dBm)	28	0.01

We can see that power consumption while transceiver receiving is higher than transmission at full power. Furthermore, energy efficiency of transmitting stage is very low (less than 2 % at full power). Energy efficiency decrease, as we lower transmission power, because many parts of a transceiver have constant energy consumption, no matter of transmission power.

Typical radio range of these transceivers is usually about 100m outdoor and 30 m indoor. Range can be increased using analog front ends which increase transceivers' transmitting power as well decrease transceiver's sensitivity threshold. Such layout is used for cc2520 radio transceiver, which is equipped with cc2591 analog front end [7]. Such transceiver has transmitting power of 17 dBm with receiver's sensitivity threshold of 98 dBm. Its power consumption in various operating modes is presented in Table 4.

Table 4: Power consumption of cc2520 transceiver with cc2591 analog front-end

Operating mode	*P [mW]*	*η (%)*
Reception	73.5	----
Transmission (17 dBm)	408	12.28
Transmission (16 dBm)	363	10.97
Transmission (14 dBm)	306	8.21
Transmission (11 dBm)	234	5.38
Transmission (-1 dBm)	171	0.46
Transmission (-8 dBm)	165	0.09

We can see that power consumption while transceiver receiving is much smaller than transmission at full power. Energy efficiency of transmitting stage is still low, about 12 % at full power, and decreases as we lower transmission power.

IV. Simulation results

First step of simulation was polynomial approximation of transceiver power consumption, which is performed with third degree polynomial. It's used to extract transceivers power consumption for required level of transmission power. In real world transceivers output power can be changed in discrete steps, but to simplify calculation we make assumption that it can be changed continuously.

Simulation experiments we performed using relative distances. For single-hop, transmitter with is maximum transmission power can reach receiver at distance *d*, for given path loss exponent. This distance is then split into smaller hops, and required transmission power is calculated. According to required transmission power, we extracted transceivers power consumption using approximated function mentioned in section above. Finally overall power consumption required to perform transmission was calculated for single-hop, double-hop, triple-hop and quad-hop.

Results for previously described WSN transceivers, cc2420 and cc2520 are presented in Figures 2 and 3, respectively.

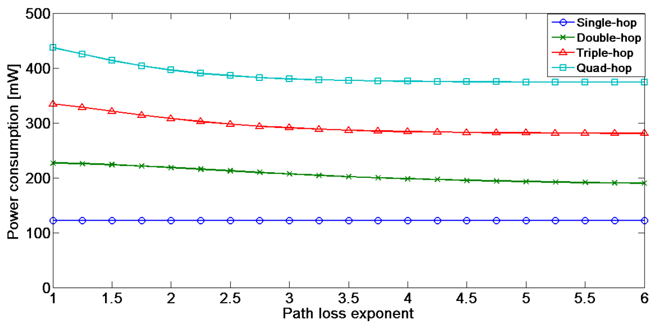

Figure 2. Power consumption of cc2420 transceiver

It's clearly that single-hop transmission is the most energy efficient for cc2420 transceiver, no matter of path loss exponent. This can be explained because reception power for cc2420 transceiver is much higher than maximum transmitting power. Also, single-hop has smaller power consumption because radio transmitter is more efficient at higher transmitting powers then lower. In same manner we can comment results for cc2520 transceiver equipped with cc2591 analog front-end.

V. Conclusion

Results from simulations show that single-hop roputing is much more energy efficient than multi-hop routing, using real world WSN transceivers. Besides energy efficiency, single-hop routing can also have advantages for other network parameters.

Future work will be concentrated into development of mathematical model, which will more precisely model power consumption of real WSN transceivers, so that model can be employed in some of the routing strategies.

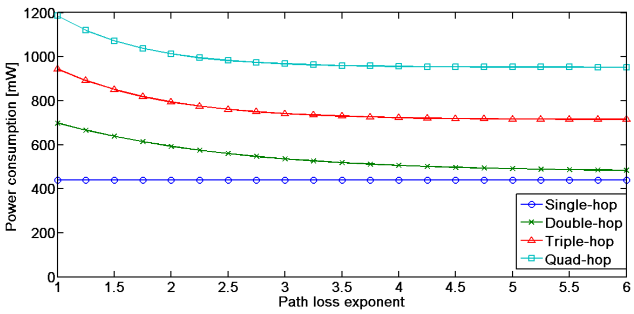

Figure 3. Power consumption of cc2520 transceiver

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