# Power and Energy Consumption for Multi-Hop Protocols: A Sensor Network Point of View

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*Abstract*— **Information theoretic approaches often investigate power consumption of mobile nodes in wireless multi-hop networks. In high data rate systems high spectral efficiencies are required to transmit data at a given bandwidth. On the other hand, bandwidth efficiency is not very important in low data rate networks, namely sensor networks. Here, the design criterium number one is energy efficiency, as the nodes are battery operated. Using known results from information theory, we investigate power consumption in multi-hop networks with simple protocols. Moreover we bridge the gap between power consumption and energy consumption and propose a model for the relation between those. Applying real-world radio chips the analysis combines theoretical and practical approaches. We show what transmission distance has to be exceeded to make multi-hop more energy efficient than direct transmission.**

## I. INTRODUCTION

Wireless sensor networks consist of hundreds or thousands of nodes, which are supposed to be very small, low cost, low complexity and are usually battery driven, calling for extremely little energy consumption [1]. Moreover they have to operate in ISM (Industrial-Scientific-Medical)-bands, where transmit power is limited. Operation of those low data rate devices, designed for short distances, was standardized in 2003 [2].

Like all wireless systems sensor networks suffer from multipath fading, usually modeled as time-varying block-fading process. For deep fades or due to obstacles the hidden terminal problems arises. Multi-hop schemes may alleviate this problem by allowing a packet to be relayed over other nodes of the network toward its final destination, thus maintaining reliable communication to all nodes. Moreover, multi-hop protocols increase connectivity and coverage in transmit power limited systems.

Looking from a power perspective multi-hop decreases the required overall transmit power due to the nonlinear-rising nature of path loss. The interference is also decreased. *Conventional relaying* schemes exploit these power gains.

For even more transmit power reduction diversity can be exploited [3], mitigating fading effects by transmitting redundant signals over independent channels [4]. Temporal diversity would require to transmit (redundant) parts of a packet several times, prolonging the time of the node in active mode, preventing it to remain in energy saving sleep mode. Frequency diversity could be accomplished by concurrently transmitting at different frequencies. But this would require two parallel transmitters. Spatial diversity can be achieved using multi antenna systems. As sensor nodes may not be able to handle the computational complexity (algorithms) as well as hardware complexity (multiple antennas) other ways of using spatial diversity have to be found. In a 2-hop system the inherent broadcasting nature of the wireless medium allows the receiver to combine the (weak) signal of the transmitter and the signal of the relay. Protocols exploiting this kind of power and spatial diversity are commonly referred to as *cooperative relaying*, firstly introduced by Sendonaris [5].

Most authors evaluate **power** gains using information theoretic approaches. However, in sensor networks we are interested in the **energy** consumption, which determines the lifetime of battery operated nodes. As it was shown in [6] power and energy scale differently in real-world networks. So the question is: How do power gains translate into energy consumption in multi-hop networks? In this paper we try to bridge this gap. We will first evaluate power gains for simple relaying protocols, suitable to be implemented on sensor nodes. Using real-world power amplifier models we then look at energy consumption, taking into account the energy consumed at the source in transmit mode as well as the energy required at the relay for receiving and retransmitting the packet of the source.

In section II the investigated relaying protocols are explained. Section III derives the required transmit power of all sensor nodes for the given protocols. Unlike other approaches, we herein assume, that all sensor nodes use the same transmit power. Even though this is not an optimal transmit power distribution it saves energy by avoiding additional signaling overhead. Section IV proposes a model for calculating the energy consumption of the complete transmission, given the transmit power of a node. This model is based on a real-world low-rate radio chip. Section V evaluates under what conditions relaying schemes outperform direct transmission concerning energy.

## II. INVESTIGATED PROTOCOLS

We will limit our investigations to the very basic relaying schemes, namely conventional and cooperative relaying. The latter was covered in detail in [4]. Adaptive schemes require channel state information (CSI). As data packets are very short we believe that it is not useful to exchange signaling

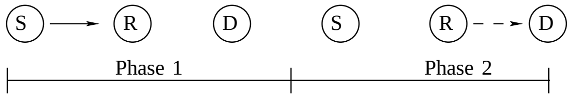

Fig. 1. Phases of conventional relaying (depending on the protocol the second phase may be skipped)

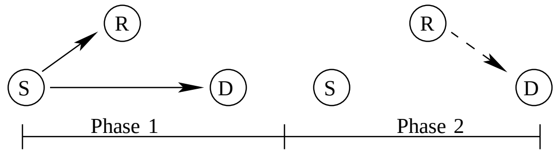

Fig. 2. Phases of cooperative relaying

information to gather CSI prior to data transmission. Instead data retransmissions will take place in case of transmission failure. The same argumentation holds for protocols with feedback. So we do not consider them in this context. Conventional and cooperative relaying schemes are compared to direct transmission, also called single-hop.

In the following we assume that data has to be transmitted from a node (source) to a central base station (destination). One relay (R), situated in between source (S) and final destination (D), assists the transmission.

*Conventional Relaying*

As illustrated in Fig. 1 in conventional relaying the source transmits in a first phase the data to the relay. After the relay received the data, it retransmits it further to the destination in a second phase. The destination only evaluates the data transmitted by the relay. This schemes only benefits from reduced path loss. However, the relaying node has to provide additional energy for receiving, processing and retransmitting the packet.

*Cooperative Relaying*

As in conventional relaying the source transmits in a first phase its packet to the relay. Due to the broadcasting nature of the wireless medium, the destination can also receive a (weak) signal, compare Fig. 2. Like in conventional relaying the relay retransmits the packet to the destination in a second phase. Using *maximum ratio combining* the destination combines the signal from source and relay and starts decoding the symbols. This scheme not only gains power savings from path loss reduction, but also from diversity reception since the two channels, source-destination and relay-destination, are independent. The disadvantage is again the additional energy consumption needed for the relay.

Also important is the kind of processing at the relay. We can distinguish between two basic schemes: amplify&forward (AF) and decode&forward (DF).

*Amplify&Forward*

This scheme is simple and does not require any computational resources at the relay. As known from analog transmission, the relay acts as a plain repeater. The signal received from the source is impaired by noise from the relay, amplified and retransmitted. The destination again adds noise to the received signal.

*Decode&Forward*

There are different possible schemes. We will concentrate on the simplest scheme, which is known as *Simple Adaptive Decode and Forward* and was introduced in [7]. In this paper it was also shown that only minor losses of performance compared to more complex protocols are expected while keeping the protocol very simple.

The relay demodulates and decodes the signal. If the error correcting code (ECC) can correct all occurred errors, it does so and retransmits the newly encoded packet. If there are too many errors it refrains from retransmission. The destination has then to rely on the signal of the source only.

In order to provide a fair comparison between relaying and direct transmission, the so called orthogonality constraint has to be met. If both schemes want to use the same resources (time, bandwidth), relaying schemes have to transmit faster as nodes can not send and receive at the same time. In a 2-hop scheme that implies, that nodes have to transmit double as fast, i.e. with double spectral efficiency compared to direct transmission.

## III. MATHEMATICAL DESCRIPTION OF PROTOCOLS

In the following we derive the required transmit power necessary to obtain a given maximum outage probability $p_{out}$. For Rayleigh block fading channels the probability density function of $p_{out}$ is continuous whereas for AWGN it is either 1 (no error free transmission possible) or 0 (error free transmission possible). In order to avoid energy intensive exchange of signaling information, the transmit power of nodes will be fixed prior to installation and is therefore the same for all nodes. Thus, the signal-to-noise ratio SNR at the receiver may vary, depending on the transmit distance and the fading coefficient of a particular channel. We assume, that the noise power spectral density is the same at the relay and the destination. Supposed, the distance between node $i$ and $j$ is denoted by $d_{ij}$, the SNR at the receiver $j$ is given by $\text{SNR}_j = P_{RX\_j}/P_N$ and the path loss coefficient is denoted by $\alpha$. Then the transmit power of node $i$ can be obtained by $P_{TX\_i} = P_{RX\_j}\, d_{ij}^{\alpha} = \text{SNR}_j P_{N\_j}\, d_{ij}^{\alpha}$. At this point we neglect antenna gains and additional loss, we will incorporate them later in our energy considerations. In the following we use notation $P_{TX}$ for the transmit power of the source normalized to the noise power at the receiver, i.e. it is a parameter without unit. Moreover, we use $\text{SNR}_{ij}$ as description for the SNR at the receiver $j$, when $i$ was the source. Thus, we can write: $P_{TX} = SNR_{ij}\, d_{ij}^{\alpha}$. Moreover, in the following $i$ is replaced either by $s$-source or $r$-relay, $j$ by either $r$ or $d$-destination.

The position of the relay is described by the factor $f_e$ and the total distance between source and destination $d_{sd}$. So the distance between source and relay is $d_{sr} = f_d d_{sd}$ and between relay and destination $d_{rd} = (1 - f_e)d_{sd}$.
For analysis of direct transmission and of cooperative schemes in Rayleigh channels we follow the approaches shown by Laneman [4]. All the other cases can be derived from it.

### A. *Direct Transmission between Source and Destination*

Capacity $C$ of the direct transmission in AWGN channels is well known from Shannon [8]. Error-free transmission is only possible, if the used spectral efficiency $R_{dir}$ does not exceed the maximum spectral efficiency $R_{AD} = C/B$[1] ($B$ denotes the used bandwidth, $\text{ld}(x)$ denotes $\log_2(x)$):

$$R_{AD} = \text{ld}(1 + \text{SNR}_{sd}) = \text{ld}\left(1 + P_{TX}/d_{sd}^{\alpha}\right). \tag{1}$$

Thus, a minimum transmit power $P_{TX}$ is required:

$$P_{TX} = \left(2^{R_{dir}} - 1\right) d_{sd}^{\alpha}. \tag{2}$$

For Rayleigh block-fading channels between node $i$ and $j$ with fading coefficient $a_{ij}$, the maximum possible spectral efficiency $R_{RD}$ is:

$$R_{RD} = \text{ld}\left(1 + |a_{sd}|^2 \text{SNR}_{sd}\right). \tag{3}$$

Since the magnitude of the fading coefficient $|a|$ follows a Rayleigh-distribution, $|a|^2$ follows an exponential distribution. Using notation $p[z]$ for probability density function of $z$ and the relation $1 - e^{-x} \approx x$ for small $x$, the outage probability $p_{out}$ can then be obtained for large SNR (i.e. small $p_{out}$):

$$p_{out} = p\left[\text{ld}\left(1 + |a|^2 \frac{P_{TX}}{d_{sd}^{\alpha}}\right) < R_{dir}\right] \tag{4}$$

$$p_{out} = p\left[|a|^2 < \left(2^{R_{dir}} - 1\right) \frac{d_{sd}^{\alpha}}{P_{TX}}\right] \tag{5}$$

$$= 1 - e^{-\frac{2^{R_{dir}-1}}{P_{TX}} d_{sd}^{\alpha}} \text{ for small exponents} \tag{6}$$

$$\Rightarrow P_{TX} \approx \frac{2^{R_{dir}} - 1}{p_{out}} d_{sd}^{\alpha}. \tag{7}$$

### B. *Cooperative Relaying with Amplify&Forward*

According to [4] the maximum average spectral efficiency possible in Rayleigh channels is:

$$R_{RPA} = \text{ld}\left(1 + |a|^2 \text{SNR}_{sd} + f\left(|a|^2 \text{SNR}_{sr}, |a|^2 \text{SNR}_{rd}\right)\right) \tag{8}$$

with $f(x, y) = xy/(x+y+1)$. Thus, the outage probability is:

$$p_{out} =$$
$$p\left[\text{ld}\left(1 + |a|^2 \frac{P_{TX}}{d_{sd}^{\alpha}} + f\left(|a|^2 \frac{P_{TX}}{d_{sr}^{\alpha}}, |a|^2 \frac{P_{TX}}{d_{rd}^{\alpha}}\right)\right) < R_{rel}\right]$$

Be aware that unlike [4] we do not use a factor 1/2 in (8) to model the two phase nature in order to meet the orthogonality constraint. Instead we introduce an individual spectral efficiency $R_{rel} = 2R_{dir}$. Using Claim 1 in [4] the minimum required transmit power given a certain $p_{out}$ can be calculated for large SNR:

$$P_{TX} = \left(2^{R_{rel}} - 1\right) \sqrt{\frac{d_{sd}^{\alpha}\left(d_{sr}^{\alpha} + d_{rd}^{\alpha}\right)}{2p_{out}}}. \tag{9}$$

For AWGN channels the spectral efficiency simply depends on the SNR of the two paths:

$$R_{APA} = \text{ld}\left(1 + \text{SNR}_{sd} + f\left(\text{SNR}_{sr}, \text{SNR}_{rd}\right)\right) \tag{10}$$

for large $P_{TX}$, i.e. large SNR, the required transmit power is:

$$P_{TX} = \left(2^{R_{rel}} - 1\right) \frac{d_{sd}^{\alpha}\left(d_{sr}^{\alpha} + d_{rd}^{\alpha}\right)}{d_{sd}^{\alpha} + d_{sr}^{\alpha} + d_{rd}^{\alpha}}. \tag{11}$$

### C. *Cooperative Relaying with Decode&Forward*

There are two possibilities that the transmission is not successful in a Rayleigh channel:

1) The relay can not decode the packet with probability $1 - p_r$. If then the instantaneous spectral efficiency $R_{RPD1}$ between source and destination is less than the used spectral efficiency, the transmission fails.

$$1 - p_r = p\left[\text{ld}\left(1 + |a|^2 \text{SNR}_{sr}\right) < R_{rel}\right] \tag{12}$$

$$R_{RPD1} = \text{ld}\left(1 + |a|^2 \text{SNR}_{sd}\right). \tag{13}$$

2) The relay can decode the packet and the spectral efficiency gained from source-destination and relay-destination $R_{RPD2}$ is not sufficient to decode the packet:

$$R_{RPD2} = \text{ld}\left(1 + |a|^2 \text{SNR}_{rd} + |a|^2 \text{SNR}_{sd}\right). \tag{14}$$

Hence, we get:

$$R_{RPD} = \min\{R_{RPD1}, R_{RPD2}\} \tag{15}$$

$$P_{TX} = \begin{cases} \frac{2^{R_{rel}-1}}{p_{out}} d_{sd}^{\alpha} & \text{Case 1} \\ \left(2^{R_{rel}} - 1\right) \sqrt{\frac{d_{sd}^{\alpha} d_{rd}^{\alpha}}{2p_{out}}} & \text{Case 2} \end{cases} \tag{16}$$

Obviously, in order to exploit the diversity gain, the transmit power has to be adjusted such that the relay can decode the packet.

For AWGN channels the calculation of transmit power depends on the position of the relay. If it was in the middle between source and destination, then the link between source and relay would be the critical one since the second phase would additionally profit from the information gathered from source to destinaton. For arbitrary relay position, the spectral efficiency is defined by the weakest phase:

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[1] In the following the first index indicate the channel, A-AWGN, R-Rayleigh block fading, the second the protocol, D-direct transmission, P/V-cooperative/conventional relaying, A/D-amplify&forward, decode&forward

$$R_{APD} = \min\left\{\text{ld}\left(1+\text{SNR}_{sr}\right), \text{ld}\left(1+\text{SNR}_{rd}+\text{SNR}_{sd}\right)\right\}$$
$$P_{TX} = \begin{cases} \left(2^{R_{rel}}-1\right) d_{sr}^{\alpha}, & \text{if } \frac{1}{f_e^{\alpha}} < 1 + \frac{1}{(1-f_e)^{\alpha}} \\ \left(2^{R_{rel}}-1\right) \frac{d_{sd}^{\alpha}\, d_{rd}^{\alpha}}{d_{sd}^{\alpha}+d_{rd}^{\alpha}}, & \text{otw.} \end{cases} \tag{17}$$

### D. *Conventional Relaying with Amplify&Forward*

No cooperation takes place in this case, so the information from source to destination is not evaluated. Hence (8) can be intuitively alternated by deleting the term belongig to the link source-destination to obtain the spectral effciency (in fact, the same result is obtained by in-dept derivation, not shown here):

$$R_{RVA} = \text{ld}\left(1 + f\left(|a|^2\text{SNR}_{sr}, |a|^2\text{SNR}_{rd}\right)\right). \tag{18}$$

Using Lemma 1 in [4] we can calculate the transmit power:

$$P_{TX} = \frac{2^{R_{rel}}-1}{p_{out}}\left(d_{sr}^{\alpha} + d_{rd}^{\alpha}\right). \tag{19}$$

For AWGN channels the spectral efficiency, similar to (18) is:

$$R_{AVA} = \text{ld}\left(1 + f(\text{SNR}_{sr}, \text{SNR}_{rd})\right) \tag{20}$$
$$\text{and thus } P_{TX} \approx \left(2^{R_{rel}}-1\right)\,\left(d_{sr}^{\alpha} + d_{rd}^{\alpha}\right) \tag{21}$$

### E. *Conventional Relaying with Decode&Forward*

The quality of transmission is determined by the weaker of the two links. Thus, for Rayleigh channels we get:

$$R_{RVD} = \min\left\{\text{ld}\left(1+|a|^2\text{SNR}_{sr}\right), \text{ld}\left(1+|a|^2\text{SNR}_{rd}\right)\right\}$$
$$P_{TX} = \begin{cases} \frac{2^{R_{rel}}-1}{p_{out}}\, d_{sr}^{\alpha} & \text{if } f_e \geq 0.5 \\ \frac{2^{R_{rel}}-1}{p_{out}}\, d_{rd}^{\alpha} & \text{else.} \end{cases} \tag{22}$$

For AWGN channels, the quality of transmission again depends on the weaker of the two links:

$$R_{AVD} = \min\left\{\text{ld}\left(1+\text{SNR}_{sr}\right), \text{ld}\left(1+\text{SNR}_{rd}\right)\right\} \tag{23}$$

Depending on the position of the relay, the required transmit power is:

$$\Rightarrow P_{TX} = \begin{cases} \left(2^{R_{rel}}-1\right) d_{sr}^{\alpha}, & \text{if } f_e \geq 0.5 \\ \left(2^{R_{rel}}-1\right) d_{rd}^{\alpha}, & \text{if } f_e < 0.5. \end{cases} \tag{24}$$

## IV. ENERGY MODEL

After deducing the required transmit power for a given protocol, we need to know, how a certain power level translates into the energy consumed in transmit mode. This step basically bridges the gap between theory and practice. For it we use the CC1000 chip from Chipcon, a commonly used radio for low data rate applications [9]. The data sheet specifies a current consumption of 8.6 mA@$P_{TX} = -20$ dBm and of 25.4 mA@$P_{TX}$ =5 dBm. We now develop a normalized characteristic between transmit power and current consumption. For the reference transmit power used for normalization, we apply a real world link budget, calculate the required transmit power for this scenario and determine the current consumption of the radio. We then approximate the current consumption of arbitrary transmit powers using the values specified in the data sheet. For the link budget we use the following reference values: $d_{sd} = 1$ m, $\alpha = 2$, AWGN channel, omnidirectional antennas, additional path loss due to walls etc. 50 dB, binary modulation, noise figure 6 dB, operation at 900 MHz. This results in a power-current consumption characteristic as shown in Fig. 3. Current consumption in receive mode for CC1000 is 9.6 mA, i.e. 1.1 times higher than minimum current consumption. We model the current consumption in receive mode slightly higher with $f_p = 1.5$, taking into account the values of other low rate radios. It is important to note at this point, that even though transmit power increases by around 50 dB, current consumption scales only with a factor of 6. Moreover the increase in current consumption heavily depends on the operating point in the curve.

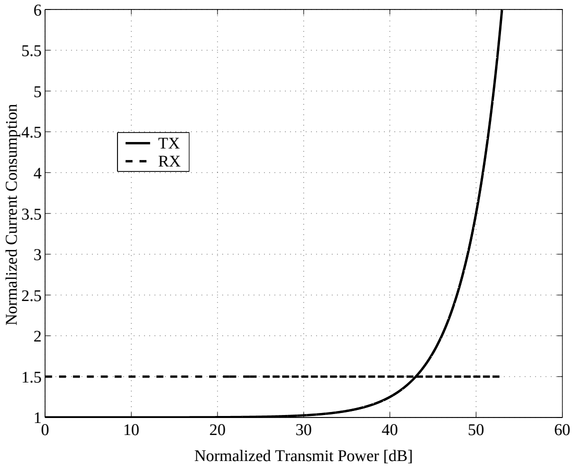

Fig. 3. Relation between transmit power and current consumption

Let us assume, that the destination is a base station connected to a power-line. Furthermore, we do not use acknowledgments, so the only energy consumed by battery-operated nodes is the sources contribution for sending the packet, and the relays contribution for receiving $E_{RX}$ and retransmitting $E_{TX}$ the packet. Since all nodes use the same transmit power, they consume the same energy in transmit mode, which can be derived from $P_{TX}$ (computed in section III) using the characteristics given in Fig. 3. Be aware that transmit current is a function $g$ of $P_{TX}$ For calculating the energy consumption voltage and duration $t$ of the transmission come into play. Voltage is just a scaling factor, so we normalize it to one here. But as the spectral efficiency changes, $t$ changes as well and we have to consider it in the energy calculation.

Thus, the overall energy consumption $E_a$ for one transmission using relaying from source to destination, neglecting energy for processing and overhead, and assuming low outage

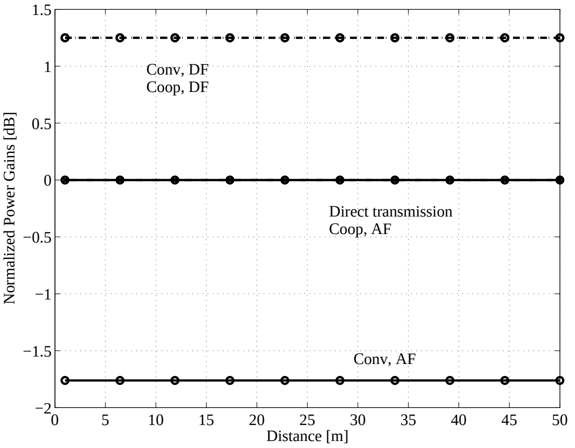

Fig. 4. Normalized required transmit power in AWGN channels, $\alpha = 2$

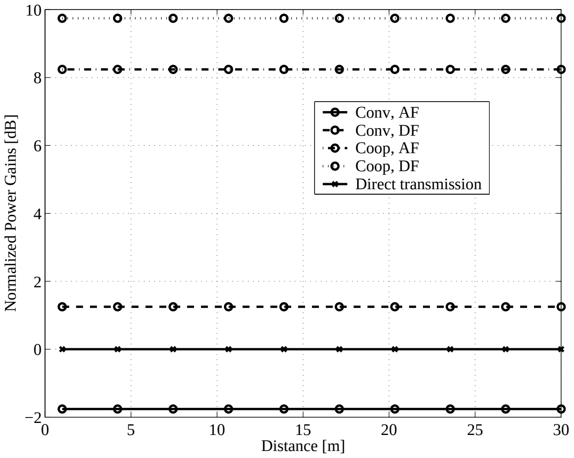

Fig. 5. Normalized required transmit power in Rayleigh Channels, $p_{out} = 0.01$, $\alpha = 2$

probabilities, is:

$$E_a = 2\, E_{TX} + E_{RX} = \left(2\, g(P_{TX}) + P_{RX}\right) / R_{rel}. \quad (25)$$

For direct transmission $E_a = g(P_{TX})/R_{dir}$. If we meet the orthogonality constraint, then $R_{rel} = 2R_{dir}$. As can be seen from the equation this may imply less energy consumption for relaying schemes as the duration of transmission is shortened. We neglect increased power consumption for increased hardware complexity for higher spectral efficiencies.

## V. RESULTS

### A. Impact of Relaying on Transmit Power

To understand the differences of the investigated protocols, let us first take a look at the required transmit power. In low-rate systems we are interested in energy efficiency rather than high spectral efficiency, so we look at a system with a low spectral efficiency $R_{dir} = 1$ bit/s/Hz. In order to have a fair comparison concerning the spectral efficiency, we use $R_{rel} = 2\, R_{dir}$ bit/s/Hz. Moreover we assume an optimal position of the relay, i.e. $f_e = 0.5$.

Fig. 4 and 5 show the power gains of the protocols relative to the required transmit power of direct transmission at a given distance using a path loss index of $\alpha = 2$. Remember that transmit power is the same for all nodes, even though this is often not the optimal power distribution strategy. Also, the power gains relative to direct transmission are independent of the transmission distance. Relaying schemes generally profit from less path loss, but suffer increased power needed for a higher $R_{rel}$.

In AWGN channels cooperative schemes cannot profit from diversity gains, but only from power gains (additional power from source-destination transmission). For the given system set-up cooperative AF has the same performance as direct transmission (for higher path loss indices the relaying scheme would profit). AF schemes suffer from the additional noise induced by the relay and increased power due to a higher spectral efficiency. Therefore both DF schemes outperform the AF protocols. All relaying schemes benefit from decreased path losses. For higher path loss indices all relaying schemes would outperform direct transmission.

Considerable gains can be achieved by relaying schemes in Rayleigh channels. Clearly, in Rayleigh channels cooperative schemes profit from the spatial diversity gains. As one can expect, the cooperative DF scheme is better than the cooperative AF scheme. The results differ from the ones obtained in [4] because of equal-power-for-all-nodes policy. Thus, the power has to be designed for the link between source and relay, even though less power would be necessary for the second hop. For conventional relaying schemes DF also outperforms AF. Again, at higher path loss indices, relaying scheme would need less transmit power than direct transmission.

### B. Impact of Relaying on Energy Consumption

Finally, we are interested at what minimum distance multi-hop schemes are more energy-efficient than single-hop. How do the path loss coefficient and the spectral efficiency influence this distance?
The advantage of direct transmission is, that it has no additional costs for receiving and retransmitting at a relay node. The advantages of multi-hop are decreased path loss, array/spatial diversity gains, and due to the required double spectral efficiency only half of the transmission time. Let us first look at a simple scenario.

Fig. 6 and 7 show the energy consumption of all protocols as function of the distance in AWGN and Rayleigh channels, respectively. Looking at the results in AWGN-channel it is clearly visible, that at short ranges direct transmission is more energy efficient than multi-hop. This is due to the high energy costs of the relay for receiving and retransmitting the packet. At low transmit powers, doubling $P_{TX}$ yields only little more current consumption, as shown in Fig. 3. Thus it is better to transmit directly at slightly higher transmit

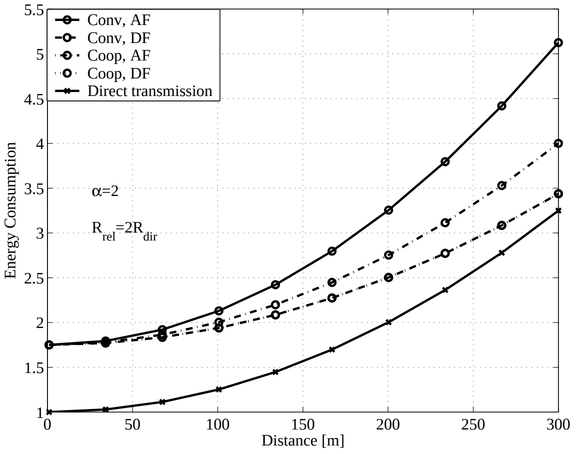

Fig. 6. Overall energy consumption of nodes for one transmission in AWGN channels

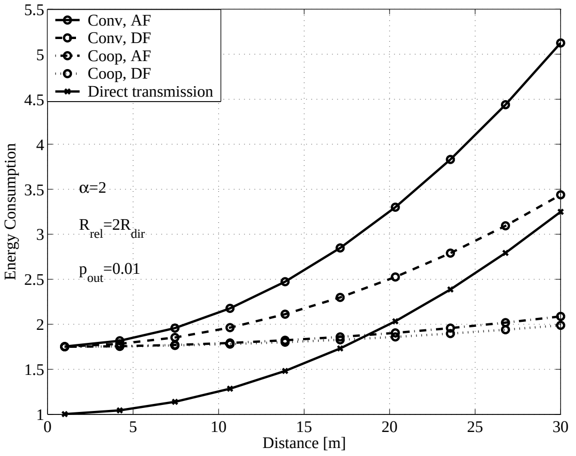

Fig. 7. Overall energy consumption of nodes for one transmission in Rayleigh channels

power than using relays. As expected, conventional AF has the highest energy consumption, followed by cooperative AF and the DF-schemes.

In the Rayleigh channel direct transmission becomes already worse than relaying at around 20 m. This is because we need much more transmit power, working at a higher operating point in curve 3. In Rayleigh channels only minor differences between AF and DF of cooperative schemes are visible. But clearly, the cooperative schemes benefit from higher diversity orders compared to conventional relaying.

To get a deeper insight, we now look at different path loss indices and spectral efficiencies and look for the minimum distance $d_{mh}$ for which multi-hop outperforms single-hop transmission. Herein we assume the ideal case of the relay being situated in between source and destination ($f_e = 0.5$). Moreover the comparison is between direct transmission and cooperative relaying with DF. As sensor networks operate at low data rates, we only consider low spectral efficiencies.

| $\alpha$ | $R_{dir}$ | $d_{mh\_AWGN}$ [m] | $d_{mh\_Rayl}$ [m] |
|---|---|---|---|
| 2 | 1 | 347 | 20 |
| 3 | 1 | 37 | 7 |
| 4 | 1 | 14 | 5 |
| 2 | 2 | - | 12 |
| 3 | 2 | 30 | 5 |
| 4 | 2 | 11 | 4 |

TABLE I
MULTI-HOP VS. SINGLE-HOP

Table I shows the results. In AWGN channels only high path loss indices make multi-hop a suitable choice. Moreover, at high spectral efficiencies, multi-hop will never be more efficient, since the cost for the increased transmit power for the double spectral efficiency is too high. But in Rayleigh channels, multi-hop is advantageous already at distances much less than 10 m! If more than 2 hops would be applied, direct transmission would be more attractive for slightly larger distances, since additional receive energy would be required at the nodes (the second receive cycle is not managed by a power-line driven base station anymore).

## VI. CONCLUSIONS

Using information theoretic approaches we derived in this paper the required transmit power for each node in low data rate multi-hop networks using simple protocols. Herein we assumed, that each nodes uses the same transmit power, avoiding signaling overhead prior to transmission at the cost of slightly higher transmit powers. We then developed a model for translating transmit power consumption into energy consumption of a node for a complete transmission. It was shown, that even though most relaying schemes need less transmit power than direct transmission, direct transmission is more energy efficient at low distances. But in Rayleigh channels, the diversity gains of cooperative relaying schemes clearly yield a more energy efficient behavior than direct transmission.

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