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Does Proper Coding Make Single Hop Wireless Sensor Networks Reality: The Power Consumption Perspective

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***Abstract*— The common belief is that a multi-hop configuration with rather small per-hop distance is the only viable energy-efficient option for wireless sensor networks. In this paper we discuss a single hop configuration, utilizing the asymmetry between lightweight sensor nodes and a more powerful ”base station” and demonstrate such a single hop configuration can actually have lower overall power consumption than a multi-hop counterpart.**

I. Introduction

Energy constraints are the driving factor in the design of wireless sensor networks (WSN). In order to obtain power-efficient structures, the mainstream of the sensor network research follows the paradigm of strongly limiting the range of radio communication and organizing rather complex multi-hop structures. As a result, routing became a vividly discussed topic in the sensor network research.

On the other hand, simple, single hop structures have also numerous advantages:

- no need for routing considerations, implying simpler protocol stack and no overhead traffic for routing support
- low delay
- simpler time synchronization
- possibility to use centralized media access control (MAC) schemes (like pooling)
- possibility to use centralized application algorithms

Single hop structures are used as dominant option in multiple wireless systems - cellular telephony or wireless LANs being the best example. On the other hand, as for sensor networks it has been shown in quite a few papers, e.g. [11]-[14]that an optimization with respect to power economy leads to multi-hop structures already for very short distances between the data source and data sink. For example, in [12]-[14] already multiple hops are the solution of choice for any source-destination distances exceeding 10 meters.

This “classical” result follows from the assumption that power economy on a single link can be achieved best by using very simple channel coding schemes. Usage of more complex coding schemes has been proved inefficient as either the sender or the receiver (or both!) should have pretty high complexity, and therefore also power usage.

In this paper we advocate on a novel way of designing highly power efficient single hop sensor networks. We exploit the -so far neglected-fact, that in single hop, star formed networks the “kernel” of the star (a.k.a “base station”!) can usually have access to power supply, and possesses rather significant computational power. A perfect example for that comes from the home automation where a central controller (e.g. thermostat) [15] is connected to the mains, and there is no reason why it should not have a rather powerful micro-processor.

To utilize this asymmetry we introduce so called Single Hop Asymmetric Structure (SHAS) supporting single hop coverage via utilization of high transmission power in the downlink and highly efficient coding with low encoding complexity and high decoding complexity in the uplink. Our focus goes to the uplink and we demonstrate that under realistic assumptions as for the parameters of modern low-power radios and available coding techniques efficient communication using low power over significant distances is possible.

II. Existing Work

Cellular networks, WiFi and many other single hop networks have used single hop structures not for energy considerations, but for other reasons: infrastructure constraints, simpler network management and the other benefits of a single hop structure enumerated in the previous section. There also exist designs developed for single hop sensor networks [17] [18]. These work choose a single hop network not because of its energy efficiency, but because it is a less complicated network. [6] has proposed to use a single hop in the downlink such that TDMA can be used. However the uplink still needs multiple hops, making the problem of scheduling extremely hard.

Coding has been considered for WSNs as well [10] [16] [19]. In particular [16] has looked into the impact of the block codes on the energy consumption of a multi-hop WSN and [10] has provided a table of the energy per useful bit for BCH codes, measured on a StrongArm micro-controller. However [16] did not use any real data for the encoder/decoder implementation cost. In addition, one would not expect the block codes can be effective in a slow Rayleigh fading channel, assumed in the paper. [10] did not provide any numerical results supporting the conclusion that coding may be useful, neither did any of the subsequent papers by its authors. In fact, the general census in the WSN design community is that the use of coding introduces too much energy overhead and should be avoided.

In WSNs, where energy is a primary concern, analysis has been done to determine the optimal number of hops needed in terms of energy [11] [12] [13]. This analysis can help us to determine for a given code, what is the optimal hop distance:

$$d_{Hopt} = \sqrt[n]{\frac{C}{G \cdot (n-1)}} \quad (1)$$

where d_{Hopt} is the optimal hop distance, n is the path loss factor, C is the energy overhead per hop and G is the transmit energy per unit distance.

[12]-[14] indicate that without coding the optimal hop distance is usually very short ($<$ 10 meters), so single hop structures are not considered energy efficient when the distance between the data source and sink is beyond 10 meters.

However, when coding is used, the transmit cost (G) will reduce, favoring larger hop distance. At some point, single hop becomes a better solution. But in addition to this analysis, one still needs to compare the case of single hop with coding with the case of multi-hop without coding.

The contributions from this paper are: 1) it demonstrated using realistic radio parameters that single hop can be a very attractive alternative for the WSNs at practical ranges (30 to 100 meters) **even from the energy perspective**, despite the many doubts in the WSN design community. 2) It studied the tradeoff between the encoder implementation cost and transmit power level when coding is used, an area few have explored. 3) It also proposed several ways to combat the slow fading, where coding is deemed ineffective. Even though the ideas of using single hop or coding are not new, applying them to sensor networks to develop a practical low-energy scheme and evaluating them from the energy perspective have been done by very few people, according to our best knowledge.

The rest of this paper is organized as follows. First we will describe the generic sensor node radio architecture, giving the major blocks and discussing their energy consumption. Next we will discuss selected coding approaches, especially the asymmetric codes having low encoding complexity and high decoding complexity. After this, we will present our SHAS architecture and compare it to the traditional multi-hop structures where no forward error control (FEC) is used. Lastly, we discuss how to use path diversity in such networks to mitigate the effects of slow channel fading which can not be handled by the FEC itself.

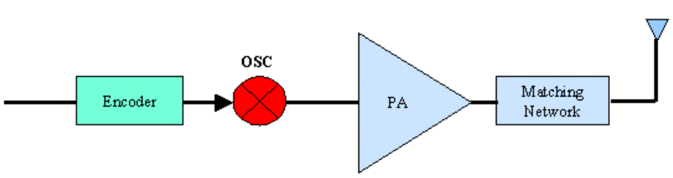

Fig. 1. Transmit chain

III. Description of the Generic Sensor Node Radio Architecture

Fig.1 shows the components consuming most of the power in the transmit chain of a typical sensor node.

A PA amplifies the input signal to the desired radiated power level. Its power consumption is therefore closely related to the radiated power level. The efficiency of a PA reduces significantly as the radiated power level gets lower. However, the rated PA efficiency (its efficiency at the peak power level) changes only slightly. For the sake of simplicity, the rated PA efficiency is assumed to be the same for different peak power levels. With advanced coding, the required radiated power level reduces. A PA optimized for this new peak power level should be used to avoid the efficiency loss.

For a particular PHY using on-off keying (OOK), [1] gives the average power consumption of the PA as function of the $\frac{E_b}{N_0}$ required for a target bit error rate (BER):

$$\begin{aligned} P_{T\_PA} &= \frac{1+\chi}{2\cdot\eta} \cdot \frac{(4\pi f_c)^2 \cdot L'}{G_t \cdot G_r \cdot c^2 \cdot {d_0}^{n-2}} \cdot d^n \\ &\cdot \sqrt{\frac{E_b}{N_0} \cdot \frac{R}{BBW}} \cdot k \cdot T \cdot BW \cdot NF \end{aligned} \quad (2)$$

where P_{rad} is the radiated power level, η is the power efficiency of the PA and χ is the ratio of the power consumption of the PA between the off and on state (of OOK), n is the path loss exponent, d_0 is the close-in reference distance, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, L' is the system loss factor, c is the speed of the light, and f_c is the carrier frequency in Hertz, k is Boltzmann's constant, T is the absolute temperature in kelvin, BW is the bandwidth of the noise, NF is the system noise figure, BBW is the data filter bandwidth and R is the information data rate.

An oscillator generates the transmitted carrier frequency as well as the local oscillator signal. Its power consumption is independent of the distance or the coding used. Besides the oscillator, there are other components (e.g. buffer) in the transmit chain whose power consumption is independent of the radiated power level. From now on, P_{T_osc} is used to denote the total power consumption of the oscillator and these components. P_{T_osc} is part of the energy overhead (C). The higher the P_{T_osc}, the larger the optimal hop distance.

An encoder encodes information so as to deliver it reliably while using a lower radiated power level. The complexity of an encoder, represented by the gate count of its circuitry, determines its power consumption. For the same clock frequency and supply voltage, the higher the gate count of an encoder, the more power will it consume. The power consumption of an encoder has two components: dynamic power and leakage power. The dynamic power is consumed when a gate switches, charging a previously discharged load. It can be roughly estimated by $C \cdot V^2 \cdot f_{clk} \cdot P_{0\to1}$, where C is the capacitance of the load, whose value is proportional to the gate count, V is the supply voltage, f_{clk} is the clock frequency, which can be made equal to or even smaller than the incoming data rate R, and $P_{0\to1}$ is the probability of switching from low to

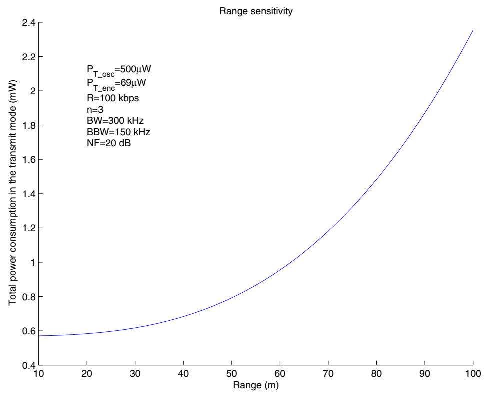

Fig. 2. Total transmit power as function of range

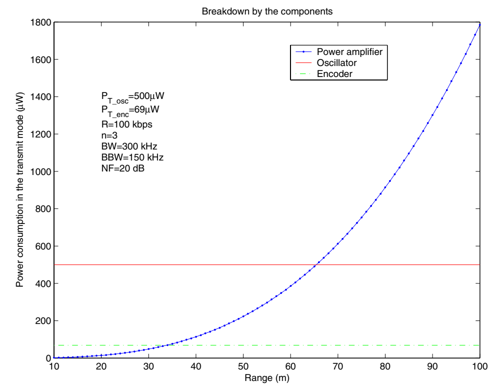

Fig. 3. Breakdown by the components

high. More accurate estimate can be obtained through Register Transfer Language (RTL) simulation if a circuitry is available. Among many things, the probability of actual gate switching is more accurately assessed in a RTL simulation than in a hand calculation.

The leakage power is consumed even when a gate does not switch. This is because there is always a leakage current flowing through the gate. At low data rates, the leakage power consumption dominates the total power consumption of an encoder. Therefore it is crucial to keep the leakage power consumption in check. The use of low-leakage (high V_T) device can help reduce the leakage power consumption. Another way to reduce the leakage power consumption is to turn off the circuitry completely between incoming data bits and only store some important state information. Leakage power consumption mainly depends on the manufacturing technology used (e.g. 0.13 um). The way to estimate the leakage power consumption is to go to the technology file of the fabrication process used to find the leakage power consumption for a gate, from which and the gate count the total leakage power consumption can be obtained. Once again, RTL simulation can provide a much more accurate estimate of the leakage power consumption than this hand calculation.

Fig. 2 shows how the total transmit power consumption changes with the distance between a sender and its receiver. Here a reconfigurable convolutional encoder (made by STMicroelectronics Inc.) with constraint length $K = 7$ and rate 1/2 [8] is used. Soft-decision Viterbi decoding is used at the receiver side, so the code is 4.6 dB from the Shannon bound [8]. The encoder has 456 gates. RTL simulation (done by Srikanth Muroor of STMicroelectronics Inc.) indicates that the dynamic power consumption of this encoder is only $2\mu W$ at the clock frequency of $100kHz$, while its leakage power consumption is $67\mu W$. Thus the power consumption of this encoder is $69\mu W$. A non-reconfigurable version of this encoder can be implemented using only 100 gates, bringing down the power consumption to only $15\mu W$. What is more, leakage control techniques mentioned above can be used to further reduce the leakage power consumption. The RF frontend developed by the pico radio group, described in details in [1] is used to produce Fig. 2 and other figures in this paper. The noise bandwidth is 300 kHz, the data filter bandwidth is 150 kHz and the system noise figure is 20 dB. These parameters correspond to a receiver sensitivity of -93 dBm at 100 kbps when no FEC is used. The receiver sensitivity increases when FEC is used, since the required $\frac{E_b}{N_0}$ for a target BER reduces. For example, the receiver sensitivity becomes -98.5 dBm at 100 kbps for the convolutional code just mentioned. Fig. 3 shows the breakdown of power consumption among the PA, oscillator and encoder. The oscillator [2] itself consumes 300 μW, while the other components (e.g. buffer) in the transmit chain consume a total of 200 μW. They are lumped into P_{T_osc} (i.e. 500 μW).

Other radios (e.g. MICA and Zigbee) usually have much higher P_{T_osc} than the radio used here, so the single hop structure is even more attractive to the networks using these radios.

IV. Selected Coding Approaches

The information theory specifies the fundamental limit on what coding can do: to achieve reliable communication, with as small an error probability as desired, the minimum $\frac{E_b}{N_0}$ required is $ln2$. This is known as the Shannon limit, which is the benchmark for accessing code performance. Advanced coding nowadays can get very close to this bound. For example, Turbo codes can get within 1dB of the Shannon bound, while Low-Density Parity-Check (LDPC) codes can get within 0.1dB of the bound.

Even though the decoders for these advanced codes are normally very complicated, their encoders are much simpler. Generally speaking, an asymmetric code is a code whose encoder is much simpler than the corresponding decoder. Many codes are asymmetric codes. Convolutional codes for instance are asymmetric codes. The same are true for Turbo codes and LDPC codes. For example, the gate count of a LDPC decoder is typically five times of that of the corresponding encoder.

If only the power in the transmit chain is concerned, the choice of coding depends on the tradeoff between the power consumption of the PA and encoder. As a code is getting

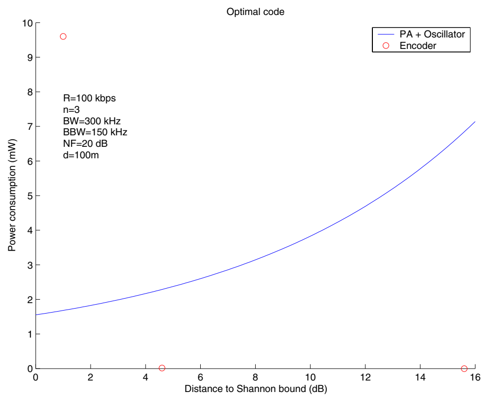

Fig. 4. Coding power as function of the distance to the Shannon bound

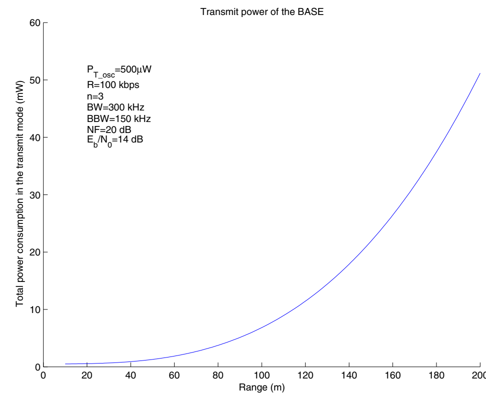

Fig. 5. Power consumption in the BASE

closer to the Shannon bound, lower radiated power level is needed to achieve the same BER at the receiver. Therefore the power consumption of the PA can be reduced (assuming of course a different PA is used, which is optimized for the new peak power level). On the other hand, the corresponding encoder becomes more complicated, requiring higher number of gates. As a result, the power consumption of the encoder goes up. Hence, we can expect the existence of an optimal point somewhere between the usage of the best possible FEC and no usage of FEC at all.

While it is easy to compute the necessary power consumption of a PA using (2), it is quite difficult to obtain the precise numbers for encoder power consumption since very little data has been published on the gate counts of various encoders. Fig. 4 shows the power consumptions of three encoders whose data are available. These encoders include a LDPC encoder by Flarion Technologies, the convolutional encoder mentioned earlier and a cyclic redundancy check (CRC) encoder. The LDPC encoder has 128 parallel paths and requires 64k gates. Fig. 4 also shows how the power consumption of the PA changes as a function of the distance to the Shannon bound. Here the radiated power level is set to assure a BER of 10^{-3}. When the distance to the Shannon bound becomes larger, higher radiated power level is required to maintain this BER. Consequently, the power consumption of the PA increases as the distance to the Shannon bound increases. It can be seen from Fig. 4 that the convolutional code outperforms the uncoded case. Hence the optimal point must be within 4.6 dB of the Shannon bound. But exactly where the optimal point lies strongly depends on the implementation. As new architectures emerge, enabling the use of less gates to implement the same encoder, and as leakage reduction techniques are used, the optimal point will be very likely to move towards the Shannon bound.

V. Definition of the Single Hop Asymmetric Structure

A SHAS consists of a BASE and a set of sensors/actuators called hereafter satellites. The BASE has a good power supply and is thus NOT energy limited. The satellites are - as usually assumed within sensor networks - strongly energy limited. We assume that satellites communicate in one hop with the BASE. Let us discuss separately the uplink and the downlink (as seen from the BASE).

In the downlink no FEC is used and only CRC is used to trigger retransmissions. This is done on purpose, so that only a simple decoder is needed in a satellite. To cover a long distance, the BASE must use a high radiated power level. The power consumption of the BASE in the transmit mode is plotted in Fig. 5 as function of the distance it covers. Due to the low data rate, the power consumption of the BASE is still much lower than that of a wireless LAN base station.

In the uplink, advanced coding is used to extend the range of a satellite so that it can reach the BASE with a single hop (at a reasonable energy cost). The code used has to be asymmetric, that is the power consumption of the encoder must be much lower than that of the decoder. The optimal code (if found) discussed in the previous section is suggested to be used here.

In SHAS, the satellites have very low power consumption. The power consumption of the BASE is high, but it is not energy limited.

Discussions: 1) One can take this game further by reducing the receiver sensitivity of the satellite and increasing that of the BASE, as a result of which significant power reduction of the satellite in both transmit and receive mode can be achieved [1]: the BASE can use a even higher power level, such that the receiver in a satellite is almost passive (low receiver sensitivity), greatly reducing its receive power. On the other hand, the receiver sensitivity of the BASE may also be increased in order to extend the range of a satellite. Ways to increase the receiver sensitivity of the BASE include: increase the RF amplifier gain, reduce the thermal noise through the use of cooling techniques, and use better receiver architecture.

2) The SHAS also opens the door for centralized MAC designs which are not feasible in multi-hop structures. These designs use scheduling, which eliminates the collisions and interferences within the network. Additionally, a satellite needs to be powered on only during the scheduled slots. In conclusion, the SHAS fits nicely in a system level solution that keeps

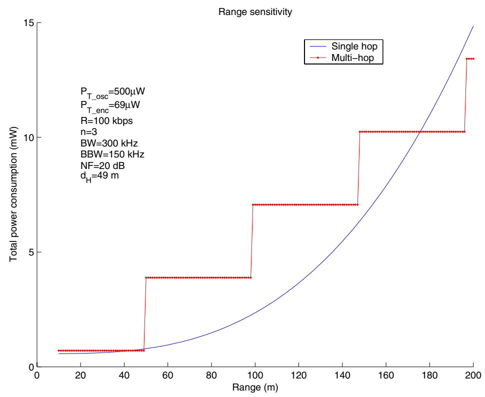

Fig. 6. Comparison to the multi-hop approach

the power consumption of a satellite low.

VI. Comparison to the Multi-hop Structures

In the following, the average power consumption of a satellite in the SHAS is compared with that of a multi-hop structure. In the uplink, if there are N hops between the BASE and a satellite, N transmissions and $N-1$ receptions will be needed. In both approaches, the power consumption of the BASE is excluded since it has an unlimited power supply. In the downlink, the power consumption of the SHAS is definitely lower since no forwarding is needed. Hence we will focus on the comparison of the uplink from now on. The assumptions include: the required BER is the same in both, no collisions, only data packets are sent, no time spent in overhearing/monitoring, as well as the BASE and the satellites have same receiver sensitivity.

A convolutional code (soft decision, K=7, 1/2 rate) is used in this numerical result. It can be seen from Fig. 6 that the SHAS outperforms the multi-hop case at distances up to 175 meters. For many applications, this range is good enough. The reason that the SHAS has lower total power consumption at short ranges is that the use of advanced coding has reduced the power consumption's sensitivity to the range (but still exponential). Another reason is the overhead in the multi-hop structure (i.e. $N-1$ receptions) is not small compared to the transmit power needed for short ranges. But as the range goes beyond 175 meters, the exponential growth of power consumption in the SHAS surpasses the linear growth in the multi-hop case. Hence, the SHAS should not be used if the distance is too long. As noise level increases, this threshold will reduce. On the other hand, the use of a better code makes this threshold higher.

Discussions: In Fig. 6, the power estimate for the SHAS is accurate, but that of the multi-hop is conservative: First, multi-hop structures have collisions. Secondly, they have additional overhead: e.g. RTS/CTS and/or the handshakes in the power management component to synchronize a sender and its receiver. Furthermore, their channel monitoring time is longer since a satellite does not know when to expect a packet. Thirdly, the required BER is much lower (due to more hops) for the same end-to-end packet loss rate. On the other hand, the power consumption of the SHAS can be made even lower by adjusting the receiver sensitivity as discussed in the previous section. A more comprehensive analysis using the modeling framework established in [1] will be done in the future to incorporate all these factors.

We have demonstrated the comparison of energy consumption between the SHAS and multi-hop structures. This is not quite precise, because for multi-hop structures, so many factors come into the consideration. Besides there are additional advantages and disadvantages: for example, multi-hop structures have their own advantages. First, spatial diversity can be exploited. Different routes might be used between a satellite and the BASE. Secondly, aggregation can be done to reduce the total traffic to the BASE: a relaying node can be smart enough to filter out the redundant information in the packets it receives. Scalability is also a very important issue, given a sensor network can have many nodes. Multi-hop structures are certainly scalable. But in the SHAS, the BASE can poll different types of sensors at different frequencies. As a result, a large number of satellites can also be supported by a single BASE. Based on these observations, the decision whether to go multi-hop or single hop is still open.

VII. Dealing with Slow Fading Channel

It is well known that coding is very effective in Additive White Gaussian Noise (AWGN) and fast fading channel, but is not effective in slow fading channel. [3] points out that the measured values for the Doppler spread are normally less than 10 Hz in indoor environment, resulting in a channel coherence time of 100 ms. Since the packets in WSNs are short, the channel a node sees is a slow fading channel. The time diversity provided by coding can not help dealing with the deep fade, since the fade duration is longer than the packet duration.

There are two ways to address the slow fading channel. The first approach is to have a second BASE to obtain receiver diversity. This BASE is needed in many applications anyway to provide necessary redundancy. When a satellite is sending a packet to both BASEs, if the channel between the 1st BASE and itself is undergoing the deep fade, it is very unlikely the channel between the 2nd BASE and itself is also bad. Similar ideas were used in [9] and [7] for wireless local area networks (WLAN). Since in slow fading channel, the channel coherence time is much longer than the packet duration, the average BER is not a good measure of Quality of Service. The instantaneous BER when the channel is in deep fade can significantly deteriorate the average BER, even if the probability that the channel is bad is small. So we propose using the outage probability instead. When the channel is bad, there is nothing coding can do, so the packet will be lost. The outage probability is therefore defined as the probability that this happens. But when there are two BASEs, the outage probability is much smaller than that of the case when there is only one BASE. For example, if the outage probability is 1% when there is only one BASE, the SHAS can provide a range of 175m 99% of the time; with two BASEs, the SHAS can provide a range of 175m 99.99% of the time, assuming the two paths are independent.

Retransmissions are obviously needed when both BASEs do not receive the packet correctly. Even though this does not happen very often, the delay when it does happen can be large especially when there are a large number of satellites. The pooling scheme (MAC) needs to be designed accordingly. We will not explain the polling scheme in great details in this paper. Briefly speaking, retransmissions need not start after the BASE finish polling all the other satellites, which may take a long time when the number of satellites is large. For example, the BASE can have several groups of slots. Within each group, the slots at the beginning are for initial data transfer and the slots at the end (separated by channel coherence time) are for potential retransmissions. Consequently, retransmissions can happen shortly after the channel coherence time, resulting in lower delay.

Another approach is to convert a slow fading channel into a fast fading channel, in which coding is very effective. When the same data is sent from two transmit antennas, even through the channel between each and the receiver is a slow fading one, the sum of the two signals at the receiver is changing quickly with time, due to the random phase shift and amplitude difference between the two signals. As a result, a fast fading channel is created. This idea was used in [4] to make opportunistic communications effective even in slow fading channel. In sensor networks, a node does not need to have more than one antenna. Through local coordination, antennas from different sensors can be used to provide the transmit diversity as if the antennas were located in the same sensor [5]. Similarly, these antennas can help convert a slow fading channel into a fast fading one. The local coordination does not need to be done very often, so most of the time, the communication is still between the BASE and the satellites. In addition, no routing is needed here. When the data between the neighboring sensors are highly correlated, the local coordination can be minimized.

VIII. Conclusions

Multi-hop communication has been widely accepted as the structure of choice for sensor networks containing low-power devices. On the other hand the single-hop structures have numerous advantages, like: simpler MAC, easier network management, low delay and simple time synchronization.

In this paper we suggested and discussed a new paradigm of Single Hop Asymmetric Structure, exploiting computational power while not being energy limited because of direct power supply. We demonstrate that in such cases the usage of powerful asymmetric codes, with low sender side complexity in the uplink, combined with higher transmission power in the downlink, assure feasibility of single hop links having significant length. In fact, we have demonstrated, using numbers typical for contemporary solutions, that single hop links in range of 175 meters are feasible, as compared to 10 meters recommended as optimal solution in CLASSICAL structures, built TOTALLY out of ENERGY limited nodes.

As technology progresses, power consumption of an encoder can be made very low, even though its code performance is very close to the Shannon limit. The noise in the RF frontend can also be reduced. When these come true, the additional benefits of a single hop structure will make it the preferred choice for many wireless sensor networks.

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