Superimposed Radio Signals for Wireless Sensor Networks

Albert Krohn

Telecooperation Office (TecO)
Universität Karlsruhe
krohn@teco.edu

Abstract. Traditional approaches using superimposed signals in wireless sensor networks have high demands on the hardware capabilities of a single network node. This work loosens these constraints and derives a communication system for low-resource wireless sensor networks requiring no *complex signal processing*, no *fast A/D conversion*, no *carrier or phase synchronization*. Therefore, it is applicable for low-resource hardware like low-cost networks, RFID or even polymer electronics. It is based on a new modulation technique (ESK) which only uses the *power* of a signal for encoding and is implemented and evaluated on the pPart particle computer hardware. Various useful applications beyond the state of the art are presented and prove the concept of superimposed signals for wireless sensor networks.

1 Introduction

Wireless sensor networks are one of the hot topics in pervasive computing and computer science research. Wireless sensor networks consist of a number of nodes which carry sensors, computation and a radio link. The work in this thesis is inspired by an example that was raised in the information theory community. It is the so called *sensor reach back problem* [1], [2]. Figure 1 shows the scenario. A wireless sensor network is installed and forms a multi-hop mesh network but cannot communicate back to the base station as the distance is too far and there is no intermediate relay node. The idea now is to synchronize the sensor network and then to cooperatively transmit identical symbols to sum up the total transmit power. With this summed energy, the nodes can reach the base station. This example gives a first idea of the usefulness of superimposed signals. Using superimposed radio signals in wireless sensor network promise to be a helpful mechanism for various applications. Therefore, I state the following

Thesis: "In low-resource wireless sensor networks, superimposed radio signals can solve the problems of synchronization, reliability, data fusion and channel use"

Figure 2 gives an overview of the composition of chapters and content parts of the thesis. After the introduction example and formulation of the thesis claim, the working area is narrowed down to the physical layer of sensor networks. More specific, those sensor network with very low resources in memory, computation,

Tom Pfeifer et al. (Eds.): Advances in Pervasive Computing 2006
Adjunct Proceedings of Pervasive 2006, Dublin, 7-10 May
books@OCG.at Vol. 207, ISBN 3-85403-207-2

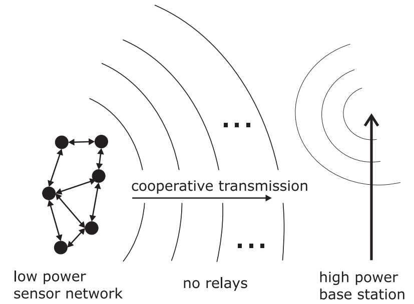

Fig. 1. The sensor reachback problem, solved with superimposed radio signals

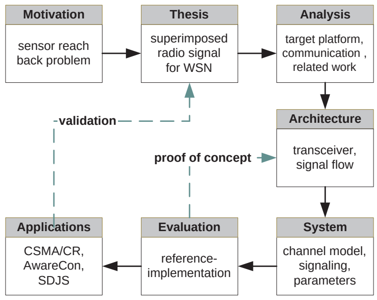

Fig. 2. Layout and composition of the thesis

energy and low overall complexity. The core contribution of the presented work lies in the architecture and signal formation of a communication system consisting of low-resource nodes that take advantage of superimposed signals. Several implementations and simulations prove the concept of superimposed signals for low-resource sensor networks.

2 Analysis and Related Work

Looking on the physical layer at the communication models of WSN in more detail, it is obvious, that superimposed signals only appear when either *two or more stations transmit at the same time* or *signals of one source superimpose due to multi-path propagation* or a combination of both. In this thesis the focus lies on the cases where the superimposed signal originate from different stations. The other case is sufficiently discussed in the wireless signal processing community.

To locate this contribution in the research on superimposed signals, a classification of signals is necessary. *Orthogonal* signaling is a well known technique for sharing the medium. Nearly all systems available today use one of the orthogonal (FDMA, TDMA, CDMA, SDMA) multiple-access methods. Orthogonal superimposed signals can in the reception be separated without further problem. *Non-orthogonal* signal behave differently. When non-orthogonal signals are superimposed, it is normally not possible to re-separate them from each other. From the traditional wireless communication systems, such a case is known as a "collision". But there are still benefits arising from such a situation, which will be discussed in this work.

Lot of attention has been put on the topic of superimposed signals, or — more general — on the subject of *cooperative transmission*. All related work in this research area assumes complex and high-power processing and ignores the constraints for implementation on low-cost hardware. The literature can be separated into two fields: Firstly, *coherent cooperative transmission* where stations superimpose their signals to achieve coherent phase in the destination receiver ([3], [4]) and secondly, *non-coherent cooperative transmission* where the station superimpose their signals without aligning their phases according to the receiver. For the latter case, the most related work can be found in [5] and [6]. In those publications, the authors understand cooperative transmission in the sense that several sensor nodes transmit symbols simultaneously to achieve a power gain. The authors propose a system using wide-band signals and derive an optimal receiver. This is generally very close to the ideas follow in this contribution but still imposes high processing power on the nodes. All referenced mechanisms are based on a complex base band processing which cannot be assumed for the class of hardware targeted at in this work:

2.1 Target Platform

All methods and mechanisms developed in this thesis apply to low-resources wireless sensor networks with very limited memory and processing power. The radio front-ends are very low-tech such that in extreme cases only a simple quartz-oscillator is turned on an off or detuned for OOK or 2-FSK modulation. Examples are the ultra-small rfPIC radio family of microchip[1], other full analog front ends or even RFID or polymer electronic circuitry. For the reason of low-lower hardware, it cannot be assumed that a complex I-Q- signal processing in the transceiver is possible. Further, high sampling rates in the base band or high resolution of A/D converters are normally not available. In the best case, the base-band processing should work without any digital signal processing. The techniques known today do not apply to low-tech sensor nodes, but the proposed solutions in this thesis will fulfill these outstanding tight constraints on the system:

- no complex base band signal processing
- no high sampling rates
- simple modulation techniques like (OOK, ASK 2-FSK)
- no carrier or phase synchronization in the receiver

3 Communication System and Signals

Figure 3 shows the communication architecture. When communicating the symbol $\underline{S}_i$, the nodes (denoted with index $l \in [1; N]$) emit the identical signals $\underline{t}_l(t) = \underline{S}_i w(t - \tau_l) e^{j\omega_l + \varphi_l}$. After the channel influence and AWGN, the sum of signals is demodulated, filtered and sent into a detector. Generally, the local carrier frequencies $\omega_l = \omega_c + \Delta\omega_l$ (ω_c is the carrier of the receiver), phases φ_l and time shifts τ_l are not perfectly aligned. For the case of non-orthogonal, incoherent superimposed signal (which is the focus of this work), it is even *impossible* to e.g. align the receiver with more than one transmitter at the same time and therefore frequency- and phase synchronization will not take place. Looking at the single contribution term of one transmitter; after non-coherent (non-synchronized) down mix and low passing, the received signal of the l-th

[1] http://www.microchip.com

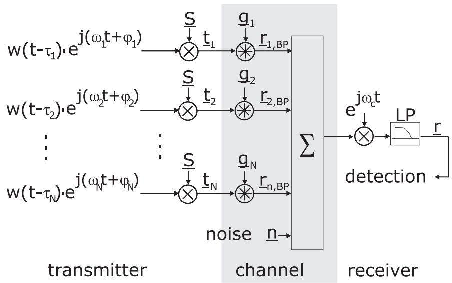

Fig. 3. Superimposed signals

transmitter without noise and channel influence is (in the base band area of the receiver):

$$\underline{r}_l(t) = w(t - \tau_l)|\underline{S}_i| \cdot e^{-j(\Delta\omega_l t + \varphi_l - \angle S_i)} \tag{1}$$

Equation (1) shows a typical behavior of a non-coherent receiver. The received signal $\underline{r}_l(t)$ carries an oscillation with the frequency $\Delta\omega_l$. In contrast to [6], this oscillation is not considered to be negligible. The oscillations of the multiple received signals leads to periodic interference patterns. To avoid destructive interference, signatures can be applied on the emitted signals of the transmitters.

Two common fading models, namely *flat fading* and *rayleigh fading* plus additional white gaussian noise (AWGN) are discussed as the channel model. During the derivation, it can be shown that for both channel models, the signal model for the received signal is identical. The pdf for the received signal $\underline{r}(t) = \sum_{l=1}^{N} \underline{r}_l(t)$ (as marginal distribution over the amplitude) is a rayleigh distribution:

$$f_{S_i}(|\underline{r}(t)| = u) = \frac{u}{(N\alpha^2\sigma_{S_i}^2 + \sigma_N^2)}\; e^{-\frac{u^2}{2(N\alpha^2\sigma_{S_i}^2 + \sigma_N^2)}} \tag{2}$$

where α is the channel damping, ${\sigma_{S_i}}^2 := \frac{1}{2}|S_i|^2$ and σ_N^2 the variance of the noise. Based on (2), an optimal signal constellation for a ML-Detector is proposed [7] that fulfills

$$P = \sum_{i=0}^{M-1} P(S_i)P(H_i|S_i) \rightarrow \max \tag{3}$$

where H_i is the assumption (hypothesis), that the symbol S_i has been received. Due to (2), the only relevant parameter for S_i are the powers $\sigma_{S_i}^2$. With (2) in (3) it can be shown [7], that *the optimal signal constellation (with respect to minimum total error) is achieved, when the powers of the received symbols fulfill the iterative condition:*

$$\sigma_i^2 = k \cdot \sigma_{i-1}^2 \quad \text{with } 1 < i < M\ ; \quad k > 1,\ k \in \mathrm{R} \tag{4}$$

The right side of figure 4 illustrates a signal constellation according to (4).

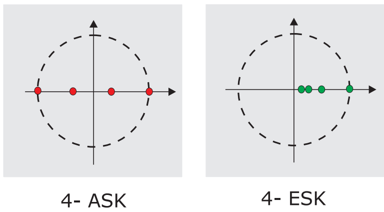

Fig. 4. Example signal constellation in the I-, Q-plane for traditional (left) and cooperative (right) transmission

		Estimated number of nodes				
		0	1	2	3	4
Number of nodes	0	100%				
	1		100%			
	2			100%		
	3			7,3%	83,3%	9,4%
	4			6,3%	12,7%	81%

Fig. 5. Confusion matrix of the reference experiment

4 Implementation and Application

In the reference implementation [8] on pPart particle computer [2], the additive behaviour of the power of superimposed signals was proved in experiments. From the received energy, the number of simultaneous emitting nodes can be estimated. Figure 5 shows the satisfying experimental results. Several further uses of superimposed codes have been implemented and proved the concept, architecture and the claims in the thesis. Those are:

synchronization The synchronization in the AwareCon [9] protocol on pPart particle computers uses superimposes signals for a distributed synchronization technique without the need of a central master node. It achieves a synchronization of $4 \mu s$ between any pair of nodes in the network.

data fusion A method for data fusion and parameter estimation based on superimposed signals was developed in [10]. It is especially suitable to generate a common consensus on a physical event that was measured with a distributed WSN. With this technique, a data fusion of distributed measurements can directly be performed on the physical layer. In [10] the system is derived with an ML estimator and used for the fast estimation of the number of active nodes in a wireless sensor network. Traditional approaches are outperformed by 6000%.

channel access The bit wise non-destructive arbitration method known from the industrial field bus CAN is based on the use of dominant and recessive bits. With superimposed signals, this concept of a tri-state bus in the wired world can be applied to wireless systems. AwareCon includes the world's first implementation of this technique on a wireless protocol.

connectivity In [11], the *sensor reach back problem* is again picked up and analyzed in depth. It is shown, that superimposed signals can significantly improve the overall connectivity in a sparse setting of a WSN.

[2] http://www.particle-computer.de

5 Conclusion

The traditional approaches using superimposed signals all have high demanding on the underlying hardware. They require high quality A/D conversion and complex signal processing. According to the analysis of section 2, such a solution does not apply to low-resources wireless sensor networks. But with the modulation technique of section 3, superimposed signals are also implementable on low-resources wireless sensor network even without digital signal processing. Additionally, section 4 explores the use of superimposed signals in applications beyond the state of the art.

References

1. João Barros and Sergio D. Servetto. Network information flow with correlated sources. In *IEEE Transactions on Information Theory*, volume 52, pages 155–170, january 2006.
2. L. R. Varshney and S.D. Servetto. A distributed transmitter for the sensor reachback problem based on radar signals. *NSF-RPI Workshop on Pervasive Computing and Networking*, april 2004.
3. Y.-S. Tu and G. Pottie. Coherent cooperative transmission from multiple adjacent antennas to a distant stationary antenna through awgn channels. In *Proceeding of the IEEE VTC Spring 02*, Birmingham, Alabama, USA, May 2002.
4. D.Brown III, G.Prince, and J McNeill. Method for carrier frequency and phase synchronization of two autonomous cooperative transmitters. In *5th IEEE Signal Processing Advances in Wireless Communications (SPAWC) 2005*, 2005.
5. A. Scaglione and Y.-W. Hong. Opportunistic large arrays: Cooperative transmission in wireless multihop ad hoc networks to reach far distances. *IEEE Transaction on Signal Processing*, 51(8), August 2003.
6. B. Sirkeci-Mergen and A. Scaglione. Signal acquisition for cooperative transmissions in multi-hop ad-hoc networks. In *Proceeding of the International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, Montreal, Canada, May 2004.
7. Albert Krohn. Optimal non-coherent m-ary energy shift keying for cooperative transmission in sensor networks. In *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, Toulouse, France, May 14-19 2006.
8. Markus Hermann. Evaluierung der Empfangsleistungen von überlagerten Funksignalen. Master's thesis, TecO, University of Karlsruhe, 2005.
9. C. Decker, A. Krohn, M. Beigl, and T. Zimmer. The Particle Computer System. In *IPSN Track on Sensor Platform, Tools and Design Methods for Networked Embedded Systems (SPOTS). Proceedings of the ACM/IEEE Fourth International Conference on Information Processing in Sensor Networks*, Los Angeles, USA, 2005. to appear.
10. Albert Krohn, Michael Beigl, and Sabin Wendhack. SDJS: Efficient statistics for wireless networks. In *Proceedings of the 12th IEEE International Conference on Network Protocols*, Berlin, Germany, 2004.
11. Albert Krohn, Michael Beigl, Christian Decker, Till Riedel, Tobias Zimmer, and David Garces. Increasing connectivity in wireless sensor network using cooperative transmission. In *submitted to 3rd International Conference on Networked Sensing Systems (INSS)*, Chicago, USA, May 31- June 2 2006.