# Distributed Power and Topology Control for IR-UWB Sensor Networks

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***Abstract*— To extend the lifetime of wireless sensor networks a power-aware design of the communication units is required. This can be accomplished by employing power-controllable impulse radio ultra-wideband (IR-UWB) transceivers. In this paper, two distributed power control algorithms are suggested that are based on a variation of IR-UWB specific parameters. The iterative algorithms converge to the optimal transmit power levels for all nodes of a given network topology. The global transmission power can be further reduced by the construction of a network hierarchy. For this purpose a topology control algorithm is proposed that can be combined with the power control procedures. This combination realises an efficient application specific multiple access scheme for IR-UWB sensor networks.**

## I. Introduction

Wireless sensor networks promise to be an enabling tool for several novel services in various application scenarios. Since the battery driven nodes of those networks usually have to deal with a strictly limited energy budget a power aware design of wireless sensor networks is necessary. Further requirements are robustness against fading in harsh environments as well as cheap and compact hardware of the nodes. These requirements can be met by sensor nodes with IR-UWB transceivers [1]. Furthermore an application specific design of the multiple access (MAC) and networking algorithms should be employed for additional performance improvement. The task of wireless sensor nodes is to collect certain information and to convey it either to a neighbouring node or to a central point, often called base station, access point or fusion centre in distributed detection applications. In [2], [3] and [4] a grouping of nodes into clusters or piconets each controlled by a cluster head or a piconet coordinator to construct a network hierarchy is suggested. Using such a multi-hop hierarchy the mean distance over which a node transmits its observations is decreased resulting in lower transmission power and lifetime extension of the network if the transmission power of the nodes can be adapted accordingly. The algorithms however are designed for a generic transmission technology and therefore some specific properties of IR-UWB are neglected. Particularly, in IR-UWB medium access is realised by non-orthogonal channels if pseudo random time hopping is used, the transmission range of IR-UWB can be flexibly controlled by the number of pulse repetitions [1] and finally IR-UWB provides excellent localisation and ranging capabilities [1], which can improve the process of topology generation.

In this paper, we introduce a novel algorithm for topology generation, which is derived from an existing but more centralised one, suggested in [5] and discuss its properties. The generated network topology reduces the mean distance over that a sensor node has to transmit its observation. To exploit this property the topology control has to be combined with power control. We discuss different IR-UWB specific power control algorithms with different levels of centrality. For applications like distributed detection in a parallel fusion network [6] a centralised computation of the power levels conducted by the fusion centre might be the best solution. For applications without a central unit like data fusion by distributed consensus algorithms [7] however, a distributed computation is advantageous. Distributed computation reduces the network vulnerability, distributes the workload of the computation and reduces the exchange of control information. Therefore, we derive two distributed IR-UWB specific power control algorithms using a framework from [8]. One of these algorithms also conducts a part of the topology generation process and can be combined with the suggested topology control algorithm to build an efficient application-specific multiple access scheme for IR-UWB sensor networks.

The remainder of the paper is organised as follows. Section II introduces the mathematical notation and the analysed system. The topology control algorithms are discussed in Section III and power control for IR-UWB is the subject of Section IV. Finally, in Section V conclusions are drawn.

## II. System model

We consider a network with a set $\mathcal{K}$ of transceiver nodes. The nodes of the non-empty set $\mathcal{M} \subset \mathcal{K}$ are the piconet coordinators. Each remaining client or ordinary node of the set $\mathcal{L} = \mathcal{K} \setminus \mathcal{M}$ is associated to exactly one PNC by the mapping

$$c\colon \mathcal{L} \to \mathcal{M}\colon i \mapsto m_i. \tag{1}$$

The set of nodes that transmit to the same PNC $m$ is denoted by $\mathcal{C}(m)$ and is called a piconet. This model comprises as a

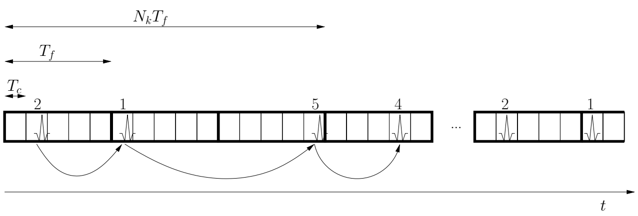


Fig. 1. Illustration of parameters used in the system model. In the example $c^{(k)} = (2, 1, 5, 4)$, $d_1^{(k)} = 1$, $d_2^{(k)} = 0$, and $N_k = 3$.

special case a network with only one PNC to which all other nodes transmit, e.g., a fusion centre for distributed detection applications.

As transmission scheme of the transceiver nodes we assume IR-UWB as described by Scholtz et al. [9]. In this scheme in each frame of length $T_f$ one ultra short pulse with shape $w(t)$ is transmitted resulting in an ultra-wide occupancy of the frequency spectrum. Data bits are assumed to be coded by binary pulse position modulation (PPM) with modulation index $\delta$. Multiple access to the channel is realised by pseudo random time hopping codes $c_j$ which reduce the probability of repeated collisions of pulses from two transmitters at a receiver position. Inside a frame the pulse is delayed by an integer multiple of the chip length $T_c$ given by the hopping code. The maximum integer is denoted by $N_h$. The resulting transmitted signal $s_i(t)$ of user $i$ then reads as

$$s_i(t) = A_i \sum_{j=-\infty}^{\infty} w(t - jT_f - c_j^{(i)} T_c - \delta d_{\lfloor j/N_i \rfloor}^{(i)}). \quad (2)$$

Here $d^{(i)}$ are the data bits of user $i$, which are transmitted by a number of $N_i$ subsequent equally modulated impulses of amplitude $A_i$. A more detailed description of the considered transmission scheme including a transmitter and receiver modelling is given, e.g., in [5].

The signal to interference and noise ratio (SINR) in the multi-user system builds the basis for the development of our medium access policies. For one link between the $i$th node and its PNC $m_i$ it can be written as

$$\mathrm{SINR}_i = \frac{g_{im_i} \frac{N_i}{N_h^{(i)}}}{\sigma^2 \sum_{j \neq i} g_{jm_i} \frac{1}{N_h^{(j)}} + \frac{\eta_{m_i}}{T_f}}, \quad (3)$$

where $\sigma^2$ is a parameter depending on the correlation properties of the employed impulse form and $\eta_{m_i}/T_f$ is an additional noise term. In (3) we use that the mean transmitted power is given by $P_i = E/N_h^{(i)} T_c$, where $E$ denotes the energy of one impulse. The main parameters to control the SINR in an IR-UWB system are therefore $N_h^{(i)}$ and $N_i$. To meet a required data rate with a bit length $T_b^{(i)}$ the following equation has to be fulfilled

$$N_h^{(i)} N_i = \frac{T_b^{(i)}}{T_c}. \quad (4)$$

Additionally, we might have technological constraints on a minimum and maximum value of $N_h^{(i)}$ resulting from the design of the hopping code. The number of transmitted pulses per bit $N_i$ is greater than or equal to one.

With these constraints we can state sets of valid parameter allocations. If there is only the requirement of a fixed rate we get the following set of valid parameters

$$\mathcal{N}_i^{(1)} = \{(N_h^{(i)}, N_i) \mid N_h^{(i)} N_i \leq \frac{T_b^{(i)}}{T_c}, \quad N_h^{(\min)} \leq N_h^{(i)} \leq N_h^{(\max)}\}. \quad (5)$$

Or there might be the requirement of a maximal acceptable bit error rate (BER) which can be expressed as a minimal necessary value of the spreading factor $N_i$ resulting in the set

$$\mathcal{N}_i^{(2)} = \{(N_h^{(i)}, N_i) \mid N_i \geq N_i^{(\min)}, \quad N_h^{(\min)} \leq N_h^{(i)} \leq N_h^{(\max)}\}. \quad (6)$$

And finally there is the combination

$$\mathcal{N}_i^{(3)} = \mathcal{N}_i^{(1)} \cap \mathcal{N}_i^{(1)} \quad (7)$$

of both sets.

The task of adaptive medium access control algorithms is to choose the optimal element from the corresponding set or an intersection of the sets for a given environment.

## III. Topology Control in Sensor Networks

The topology of a network has great impact on the system performance. Controlling the topology can therefore be used to optimise the network. We define the network topology as the partition of the network into several smaller sub-networks. In each subnetwork the sensor nodes transmit their information to the PNC that might or might not process or fuse the received signals and conveys them to a central point via a channel orthogonal to the one used by the ordinary nodes. In the following we concentrate on the process of node-clustering to piconets and neglect the much lower number of channels between the PNCs and the central point. Then the process of topology generation consists of two steps: determining the set of PNCs $\mathcal{M} \subset \mathcal{K}$ among all nodes and assigning the ordinary nodes to the PNCs according to (1). Since finding an optimal network topology for a given objective is computationally infeasible for large networks, efficient heuristics have to be found.

In [5] a heuristic for this purpose is suggested. A formal description of the algorithm is given in Algorithm 1. A detailed explanation of the algorithm can be found in [5]. This algorithm jointly conducts both steps of the topology generation. In particular, the number of piconet coordinator nodes is implicitly determined. If this number is known or can be determined by other approaches, e.g., by assuming a mean number of nodes per piconet $C$ and then computing $\mid \mathcal{M} \mid = \mid \mathcal{L} \mid / C$, we propose another more efficient algorithm. The algorithm employs the idea of the last steps of the previous algorithm and determines iteratively the centres of gravity of

**Algorithm 1** Algorithm for topology generation from [5]

Initialise:
$d_{ij} \leftarrow \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}\ \forall\ i, j \in \mathcal{K}$
$(\mathcal{M} = \mathcal{H}) \leftarrow \emptyset$, $(\mathcal{S} = \mathcal{L}) \leftarrow \mathcal{K},\ d_{\max}$
$\overline{d_k} \leftarrow \frac{1}{K'} \sum_{i=1}^{K'} d_{ki}\ \forall\ \{k \in \mathcal{K} | d_{ki} < d_{\max}\}$
**while** $\mathcal{S} \neq \emptyset$ **do**
  $k^* \leftarrow \{k \in \mathcal{S} | \overline{d_k^*} < \overline{d_k}\}$;
  $\mathcal{M} \leftarrow \mathcal{M} \cup k^*$;
  $\mathcal{L} \leftarrow \mathcal{L} \setminus k^*$;
  $\mathcal{H} \leftarrow \{k_i \in \mathcal{S} | d_{k^* i} < d_{\max}\}$;
  $\mathcal{S} \leftarrow \mathcal{S} \setminus \mathcal{H}$;
**end while**
$\mathcal{C}(m) \leftarrow \{n \in \mathcal{L} | d_{nm} < d_{nl}\ l \in \mathcal{M}\}\ \forall\ m \in \mathcal{M}$;
$\mathrm{CG}(\mathcal{C}(m)) \leftarrow \begin{pmatrix} \sum_{i=1}^{|\mathcal{C}(m)|} \frac{\sqrt{(x_i - x_m)^2}}{|\mathcal{C}(m)|} \\ \sum_{i=1}^{|\mathcal{C}(m)|} \frac{\sqrt{(y_i - y_m)^2}}{|\mathcal{C}(m)|} \end{pmatrix}\ \forall\ m \in \mathcal{M}$;
$i^* \leftarrow \{i \in \mathcal{C}(m) | d_{i^* CG} < d_{iCG}\}\ \forall\ m \in \mathcal{M}$;
$m \leftarrow i^*\ \forall\ m \in \mathcal{M}$;

**Algorithm 2** Iterative centre of gravity based algorithm for topology generation

Initialise:
$m \leftarrow$ Number of PNCs
$N \leftarrow$ Number of iterations
$d_{ij} \leftarrow \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}\ \forall\ i, j \in \mathcal{K}$
choose randomly $\mathcal{M} \subset \mathcal{K}$ with $|\ \mathcal{M}\ | = m$
**for** $k$=1:N **do**
  $\mathcal{C}(r) \leftarrow \{s \in \mathcal{L} | d_{sr} < d_{st}\ t \in \mathcal{M}\}\ \forall\ r \in \mathcal{M}$;
  $\mathrm{CG}(\mathcal{C}(r)) \leftarrow \begin{pmatrix} \sum_{i=1}^{|\mathcal{C}(r)|} \frac{\sqrt{(x_i - x_r)^2}}{|\mathcal{C}(r)|} \\ \sum_{i=1}^{|\mathcal{C}(r)|} \frac{\sqrt{(y_i - y_r)^2}}{|\mathcal{C}(r)|} \end{pmatrix}\ \forall\ r \in \mathcal{M}$;
  $i^* \leftarrow \{i \in \mathcal{C}(r) | d_{i^* CG} < d_{iCG}\}\ \forall\ r \in \mathcal{M}$;
  $r \leftarrow i^*\ \forall\ r \in \mathcal{M}$;
**end for**

the piconets and assigns in each iteration the temporal role of a piconet coordinator to the nodes nearest to these centres. The remaining nodes pick the PNC that is nearest to them. Then the next iteration starts with the determination of the new centres of gravity. As an initialisation the $|\ \mathcal{M}\ |$ PNCs can be randomly determined. A formal description of the algorithm is given in Algorithm 2. In Figure 2 it can be observed that the mean distance of the nodes in the network to the corresponding PNC decreases with the number of iterations of the algorithm. This can be exploited if the transmission power of the nodes can be adapted correspondingly. A quasi-static topology is attained after a very short number of iterations.

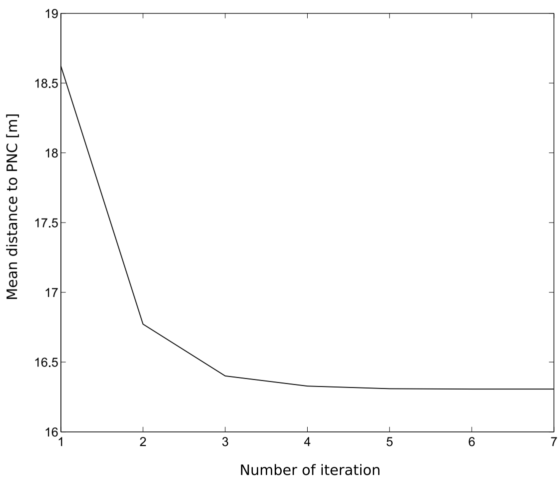


Fig. 2. Simulated mean distance between a node and its PNC averaged over 5000 realisations of a random scenario with 30 nodes.

## IV. Power Control in IR-UWB Networks

To take advantage of the suggested topology generation the transmission power of the nodes has to be controllable. The goal of the considered power assignment strategies is to find transmission power levels for all transceivers such that the individual quality of service requirements, expressed by minimal necessary SINRs $\gamma_i$, are met for all nodes.

### A. Centralised Power Control

A vector $\boldsymbol{P}$ with the optimal transmission power levels of the nodes as elements can be computed by (compare [5])

$$\boldsymbol{P} = [\boldsymbol{I} - \boldsymbol{\Gamma} \boldsymbol{N}^{-1} \boldsymbol{B}]^{-1} \boldsymbol{\tau}. \tag{8}$$

The diagonal matrices $\boldsymbol{\Gamma}$ and $\boldsymbol{N}$ contain the target SINR $\gamma_i$ and the number of pulse repetitions for one data bit $N_i$ of the $i$th node as the $i$th entry. The entries $b_{ij}$ of matrix $\boldsymbol{B}$ contain the path gain $g_{im_i}$ between node $i$ and its PNC $m_i$ and read as

$$b_{ij} = \begin{cases} \sigma^2 g_{jm_i} / g_{im_i}, & i \neq j \\ 0, & i = j \end{cases}.$$

The elements of the positive vector $\boldsymbol{\tau}$ are

$$\tau_i = \frac{\eta_{m_i} \gamma_i}{T_f N_i g_{im_i}}.$$

A positive solution $\boldsymbol{P} > \boldsymbol{0}$ exists if and only if the spectral radius of the matrix $\boldsymbol{\Gamma} \boldsymbol{N}^{-1} \boldsymbol{B}$ is less than one which follows from a generalisation of the Perron Frobenius theory. The computation of $\boldsymbol{P}$ involves an inversion of a $|\ \mathcal{L}\ | \times |\ \mathcal{L}\ |$ matrix which has a complexity of approximately O($|\ \mathcal{L}\ |^3$) and hence is computationally infeasible for large networks. For the computation all necessary information from the entire network has to be available at the location where the computation is carried out. On the other hand this algorithm is flexible since it is independent of the network topology meaning that arbitrary peer to peer topologies are possible, which might be required for some applications. To decrease the computational effort in [5] a more application specific algorithm that takes the network topology into account is suggested. The approach is based on a reformulation of the equations describing the SINR requirements of the nodes in one piconet. For piconet coordinator $m$ the system can be written as

$$\frac{N_i}{\gamma_i} g_{im} P_i - \sigma^2 \sum_{j \in \mathcal{C}(m) \setminus \{i\}} g_{jm} P_j = \tau_m, \ i \in \mathcal{C}(m), \tag{9}$$

where

$$\tau_m = \frac{1}{T_f} \eta_m + \sigma^2 \sum_{j \notin \mathcal{C}(m)} g_{jm} P_j \tag{10}$$

agglomerates the interference at $m$ caused by nodes of other piconets and the additional noise term. The solution to this system is given by

$$P_i = \frac{1}{g_{im}(\frac{N_i}{\sigma^2\gamma_i}+1)(1-\sum_{j\in\mathcal{C}(m)}\frac{1}{\frac{N_j}{\sigma^2\gamma_j}+1})} \tau_m = \gamma_i(m)\tau_m, \tag{11}$$

with $i \in \mathcal{C}(m)$. By inserting these solutions into equation (10) and setting

$$c_{nm} = \sigma^2 \sum_{j \in \mathcal{C}(n)} g_{jm} \gamma_j(n),$$

the compact representation

$$(\boldsymbol{I} - \boldsymbol{C})\boldsymbol{\tau} = \boldsymbol{\eta}, \quad \boldsymbol{\eta} > 0, \tag{12}$$

is achieved, where the $M \times M$ matrix $\boldsymbol{C}$ is defined by

$$\boldsymbol{C} = (c_{nm}\overline{\delta}_{nm})_{n,m=1,\dots,M}. \tag{13}$$

Solving this system of linear equations the missing $\tau_m$ in (11) is obtained for all piconets. This algorithm has a complexity of approximately O($|\ \mathcal{M}\ |^3$) which can be by orders of magnitude less than O($|\ \mathcal{L}\ |^3$). The algorithm might be computed by the PNCs that have to exchange the necessary information. Further details are given in [5]. For the special case when there is only one PNC, which is the case for the parallel fusion network for distributed detection in wireless sensor networks the solution simplifies to

$$P_i = \frac{\frac{\eta}{T_f\sigma^2}}{g_i\left(\frac{N_i}{\sigma^2\gamma_i}+1\right)\left(1-\sum_k \frac{1}{\frac{N_k}{\sigma^2\gamma_k}+1}\right)}, \tag{14}$$

where no system of equations has to be solved.

In IR-UWB control of the mean transmit power can be implemented by controlling the time hopping parameter $N_h$. The corresponding individual parameter $N_h^{(i)}$ of node $i$ is adopted from the results in (8), (11) and (14) by setting

$$N_h^{(i)} = \left\lfloor \frac{E}{P_i T_c} \right\rfloor. \tag{15}$$

The other IR-UWB control parameter $N_i$ is chosen such that $(N_h, N_i)$ is the element that maximises the intended performance metric and is an element of the corresponding set $\mathcal{N}_i^{(k)},\ k = 1, 2, 3$. In case of a minimal required rate ,e.g., the maximal SINR is simply attained by $N_i = T_b^{(i)}/T_c N_h^{(i)}$.

### B. Distributed Power Control

The previous algorithms require an exchange of all necessary information to compute the power assignment which can results in a high transmission overhead. In the following two distributed iterative algorithms are presented that reduce this overhead since only local information is required. The algorithms are derived using a general framework by Yates [8]. The paper states that an interference function $I(\boldsymbol{P})$ is standard if and only if it fulfills the following three properties

- $I(\boldsymbol{P}) > 0$ (positivity)
- $\boldsymbol{P} > \boldsymbol{P}' \Rightarrow I(\boldsymbol{P}) \geq I(\boldsymbol{P}')\ \forall\ \boldsymbol{P} > \boldsymbol{P}'$ (monotonicity)
- $\alpha > 1 \Rightarrow \alpha I(\boldsymbol{P}) > I(\alpha\boldsymbol{P})\ \forall \alpha > 1$ (scalability)

If these conditions hold there exits an iterative power assignment algorithm of the form

$$\boldsymbol{P}(t+1) = I(\boldsymbol{P}(t)),$$

which converges against a fixed point if such a fixed point exists. This fixed point is equal to the solution of (8).

The first interference function for the IR-UWB system is

$$I_i(\boldsymbol{P}(t)) = \frac{\gamma_i\sigma^2 \sum_{j\neq i} g_{jm_i} P_j + \frac{\eta_{m_i}}{T_f}}{g_{im_i}}$$

which can easily be proofed to be standard.

By replacing the power $\boldsymbol{P}_i(t)$ in the formula by the corresponding IR-UWB control parameter we get the following iterative algorithm to determine the control parameter $N_h^{(i)}(t+1)$

$$N_h^{(i)}(t+1) = \left\lfloor \frac{g_{im_i}}{\gamma_i\sigma^2\sum_{j\neq i} g_{jm_i}\frac{1}{N_h^{(j)}(t)} + \frac{\eta_{m_i}}{T_f}} \right\rfloor \tag{16}$$

The necessary convergence for discrete iterative power control algorithms is analysed, e.g., in [10]. Figure 3 illustrates the mean velocity of convergence to the solution of (8) obtained by simulations. For the simulation 30 nodes were randomly placed in an area of 100 m × 100 m. The pathloss between the nodes and the PNC, which were elected by Algorithm 2 from the previous section was determined by $d^{-2}$, where $d$ is the distance between node and PNC. Another standard interference function is

$$I_i^{(2)}(\boldsymbol{P}) = \min_{m_i} \frac{\gamma_i\sigma^2 \sum_{j\neq i} g_{jm_i} P_j + \frac{\eta_{m_i}}{T_f}}{g_{im_i}} \tag{17}$$

leading to the iterative algorithm

$$N_h^{(i)}(t+1) = \max_{m_i} \left\lfloor \frac{g_{im_i}}{\gamma_i\sigma^2\sum_{j\neq i} g_{jm_i}\frac{1}{N_h^{(j)}(t)} + \frac{\eta_{m_i}}{T_f}} \right\rfloor. \tag{18}$$

In both cases the corresponding $N_i$ is chosen as in the centralised case.

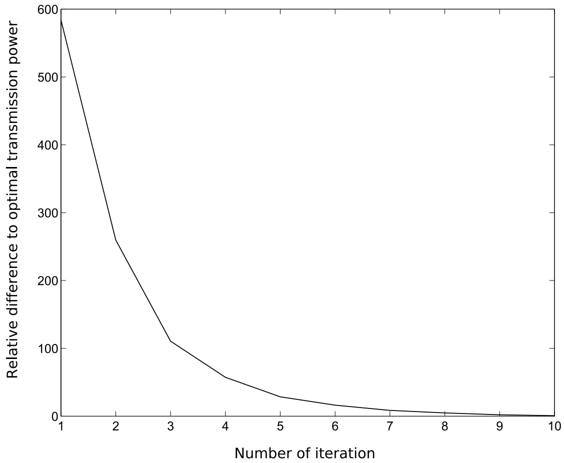


Fig. 3. Mean relative difference of the transmission power (in %) between the iterative algorithm (16) and the optimal transmission power level (8).

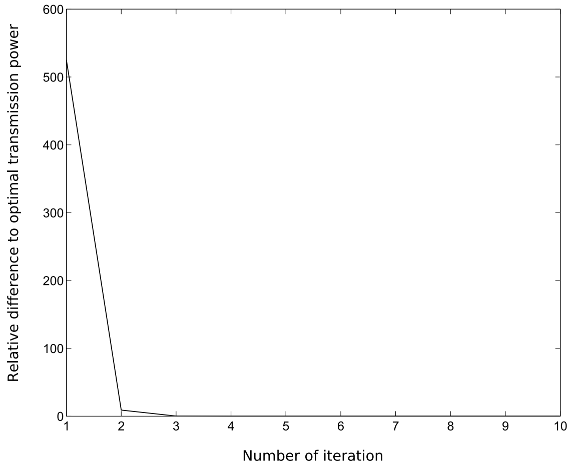


Fig. 4. Mean relative difference of the transmission power (in %) between the iterative algorithm (18) and the optimal transmission power level (8).

The velocity of convergence of the second algorithm is shown in Figure 4. The second algorithm implicitly also conducts the second step of topology generation described by (1) since in each iteration each node is assigned to the PNC where the minimal interference is achieved to meet the QoS requirement. Therefore it can be combined with the suggested algorithm for topology control. After an appropriate set $\mathcal{M}$ of PNCs is found the remaining nodes are not associated to the spatially nearest PNC but to the one with the lowest resulting interference according to (17). Note that the power assignment algorithm fits only for a given fixed set of PNCs into the framework of [8]. By changing a PNC it may happen that the transmission power of a node that was nearby the former PNC can be increased in an iteration of the topology control algorithm although the global amount of transmission power is lowered.

## V. Conclusions

We proposed algorithms for the distributed computation of the optimal node power levels and the generation of a network topology for IR-UWB sensor networks. The algorithms are compared to other approaches with different levels of centrality. Which algorithms and which combinations of topology and power control are advantageous for the design of a wireless sensor network depends heavily on the type of application of the sensor network. Future work will be spend on the extension of the topology control to arbitrary network topologies like tree or multi-hop peer to peer structures, which requires a general framework to evaluate the performance of different network structures.

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