Wireless Power Transfer for Access Limited Wireless Underground Sensor Networks

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***Abstract*—Wireless underground sensor networks (WUSNs) present a variety of new research challenges. Magnetic induction (MI) based transmission has been proposed to overcome the very harsh propagation conditions in underground communications in recent years. In this approach, induction coils are utilized as antennas in the sensor nodes. This solution achieves larger transmission ranges compared to the traditional electromagnetic (EM) waves based approach. In the past, some efforts have been made to characterize the signal transmission in MI-WUSNs. Those investigations, however, refer mostly to the information transmission. One of the open issues, that may constrain the system design in some of the applications, is the powering of the individual sensor nodes. Due to the low accessibility of the nodes, a new method of wireless power transfer (WPT) for MI-WUSNs is proposed in this work. This method is mainly based on simultaneous signal transmissions from multiple sensor nodes with optimized signal constellations. Furthermore, the optimal scheduling for power transmission and reception is provided, which maximizes the energy efficiency of the network charging procedure. The proposed method is compared with the naive approach and shows a significant improvement of the system performance in terms of energy efficiency.**

I. Introduction

The objective of Wireless Underground Sensor Networks (WUSNs) is to establish an efficient wireless communication in the underground medium. Typical applications for such networks include earthquake prediction, communication in mines/tunnels, etc. [1]. Due to the harsh propagation conditions in the soil medium (including rock, sand, and water sheds), traditional wireless signal propagation techniques using electromagnetic (EM) waves can only be applied for very short transmission ranges due to a high path loss and vulnerability to changes of soil properties, such as moisture [2].

Magnetic induction (MI) based WUSNs were first introduced in [1], and make use of magnetic antennas implemented as coils. This technique has been shown to be less vulnerable to the losses in conductive medium, such that the transmission range and coverage of the sensor network can be significantly improved by using MI based transceivers. So far, most of the previous works aimed at the investigation of the potential and problems of MI-WUSNs from the perspective of the information transmission. For example, some efforts have been made to characterize the channel capacity of a point-to-point signal transmission [3] and the network throughput of tree-based MI-WUSNs [4]. Rescue and disaster aware MI-WUSNs have been proposed in [5].

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An important issue in sensor networks is the battery lifetime [6]. In many applications of WUSNs, the nodes can be charged wirelessly [7], especially if the charging device can be moved closely enough to the sensor node. In such cases, the wireless power transfer (WPT) for traditional WSNs can be directly applied to the WUSNs with a slight change due to the medium characteristics and transceiver design (coils instead of RF antenna). For this, the recently proposed concepts of multiple-input multiple-output (MIMO) based WPT might be useful [8], [9]. The mentioned works assume a single transmitter equipped with several resonant coils. Typically, the optimization of the coil configuration and system parameters refers to impedance matching and search for the optimal carrier frequency, for which the WPT efficiency is maximized [8]. In [9], the actual beamforming is achieved via optimal signal processing of the transmit signals, similarly to the traditional RF beamforming. Unfortunately, this beamforming solution cannot be efficiently used for MI-WUSNs due to very weak couplings between sensor nodes [9].

In modern applications of WSNs, in order to charge all sensor nodes, a mobile charging vehicle with optimized charging parameters is utilized [10]. However, several applications of WUSNs require the deployment of sensor nodes in hardly accessible environments, where a mobile vehicle may not be able to get close enough to each node for charging. This situation occurs e.g. in mines, where the tunnels may not always be suitable for the mobile charger to freely move along, and in oil reservoirs [11]. Then, a stationary power source can be utilized, which may be deployed aboveground and have a wireless or wired connection to one of the sensor nodes. This node is then used to wirelessly charge the whole network. Therefore, one of the sensor nodes (close to the edge of the deployment field) is selected as master node with sufficient power supply. Hence, the focus of this work is on the optimization of the corresponding charging procedure. One possible solution (naive approach) is a transmission solely from the master node, until all batteries are charged. However, more advanced techniques can heavily increase the energy efficiency. In particular, the concept of relayed energy transfer in sensor networks seems promising, especially the recently proposed multihop energy transfer [12]. Here, the energy is guided via intermediate nodes, which are placed between the energy source and the target node. On the other hand, the problem of optimal charging can be viewed as a beamforming problem for a distributed MIMO system, where each node represents a part of a large scale antenna array. Hence, a

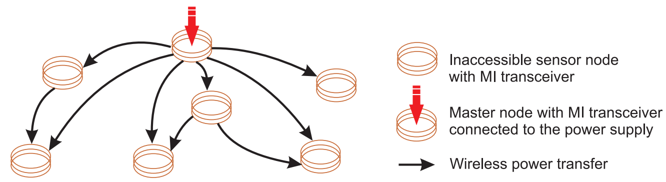

Fig. 1. Example of the network structure with a master node connected to the power supply.

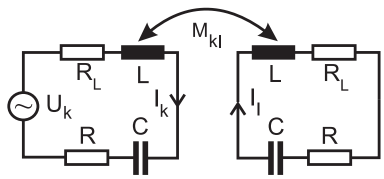

Fig. 2. Magnetic coupling between resonant circuits 'k' and 'l'.

beamforming gain can be expected, if multiple nodes transmit simultaneously and their complex amplitudes are optimized to overlap constructively, especially in case of multiple receivers [9]. Then, multiple sensor nodes may contribute to the efficient charging of each particular sensor node. Of course, one of the necessary conditions for establishing such a distributed MIMO system is the low mobility of sensor nodes, which is valid for WUSNs due to the stationary deployment. For a fair comparison between the different charging procedures, the definition of energy efficiency known from the literature (e.g. [13]) cannot be utilized, since different sensor nodes may require different amounts of energy. Hence, we define the energy efficiency as the ratio of the total amount of required energy for all sensor nodes in the network and the total consumed energy in the master node, which is needed in order to charge all sensor nodes. With this definition, the most energy efficient scheduling of signal transmissions is established.

This paper is organized as follows. Section II describes the system model, which includes the effects resulting from deployment of the sensor nodes close to the ground surface onto the signal transmission. The novel technique of distributed MIMO based multihop energy transfer for MI-WUSNs is presented in Section III. Section IV provides numerical results and Section V concludes the paper.

II. System Model

As mentioned earlier, we assume that one of the sensor nodes (master node) is connected to the power source in order to provide enough power supply for the other nodes of the network, see Fig. 1. Obviously, there are different ways of how the power signals from the master node can reach the target nodes. Hence, a relayed power transfer with possible retransmissions seems promising.

Each circuit includes a magnetic antenna (an air core coil) with inductivity L, a capacitor with capacitance C, a resistor R (which models the copper resistance of the coil), and a load resistor R_L, see Fig. 2. The capacitor is designed to make the circuits resonant at the carrier frequency $f_0 = \frac{1}{2\pi\sqrt{LC}}$. The optimal value for the load resistor in MI-WUSNs $R_L = R$ is selected according to [4]. As argued in the previous works (e.g. [4]), the passive circuit elements need to be identical for all sensor nodes, in order to reduce the manufacturing costs and simplify the system design. We select the resonance frequency f_0 for the WPT due to the weak coupling between devices in the underground medium.[1] Then, the complex impedance of the capacitor compensates the impedance of the coil completely, such that the inner impedance of each circuit is given by $Z_{\text{in}} = R + R_L$. The induced voltage is related to the coupling between the coils, which is determined by the mutual inductance, denoted as $M_{k,l}$ for coils k and l [4],

$$M_{k,l} = \mu\pi N_w^2 \frac{a^4}{4r_{k,l}^3} \cdot J \cdot G_{k,l}, \tag{1}$$

where $r_{k,l}$ denotes the distance between the coils, a stands for the coil radius, N_w is the number of windings, and μ denotes the permeability of the medium. For the polarization factor J, we assume that all coils' axes show to the ground surface, such that, $J = 1$ holds [3]. $G_{k,l}$ stands for the additional signal attenuation in the conductive medium. In order to simplify the investigations of the MI-WUSNs, all sensor nodes are typically assumed to be deployed deeply in the soil [4]. Then, a large part of the magnetic field propagates directly through the medium and suffers from the effect of eddy currents. However, if the nodes are deployed close to the ground surface, the magnetic field of the coil may penetrate the surface and be less vulnerable to the eddy currents. Obviously the burial depth can be omitted from the theoretical analysis, if it is much less than the distance between adjacent coils. This is a valid assumption as also recognized by [14]. Hence, we consider a deployment exactly at the ground surface. In order to incorporate this effect into the system model, we utilize the results from [14]. Then, $G_{k,l}$ is modeled by

$$G_{k,l} = \frac{2}{\gamma_{k,l}^2}\left(9 - \left(9 + 9\gamma_{k,l} + 4\gamma_{k,l}^2 + \gamma_{k,l}^3\right)\mathrm{e}^{-\gamma_{k,l}}\right) \tag{2}$$

instead of the well-known expression [3]

$$G_{k,l} = \mathrm{e}^{-\gamma_{k,l}}, \tag{3}$$

which is valid for the transmission through the soil in case of a very large burial depth. Here, $\gamma_{k,l} = r_{k,l}\sqrt{\pi f_0 \mu\sigma}$ and σ stands for the conductivity of the soil. It can be shown, that the mutual inductance in [14] based on (2) converges to (1) with $G_{k,l}$ from (3) for an identical conductivity in soil and air. This indicates the correct use of the system model from [14] in this work.

For the following, we define $Z_{k,l} = j2\pi f_0 M_{k,l}, \forall k \neq l$. Due to the symmetry of the magnetic coupling, $Z_{k,l} = Z_{l,k}, \forall k, l$ holds. We consider the complex-valued amplitudes U_k and I_k of the voltages $u_k(t) = U_k \cdot \mathrm{e}^{j2\pi f_0 t}$ and currents $i_k(t) = I_k \cdot \mathrm{e}^{j2\pi f_0 t}, \forall k$, respectively. For each coil k, the current amplitude I_k in the resonant circuit depends on the current amplitudes $I_l, \forall l \neq k$ in all surrounding circuits via the voltage equation

$$I_k \cdot Z_{\text{in}} + \sum_{l \neq k} (I_l \cdot Z_{k,l}) = U_k. \tag{4}$$

In the following, the superscripts $(\cdot)^T$ and $(\cdot)^H$ denote transpose and Hermitian transpose, respectively. In order to calculate the currents in all circuits of the coupled network, a set of voltage equations $\mathbf{Z} \cdot \mathbf{I}_c = \mathbf{U}$ needs to be solved with respect

[1] For the WPT, only a single frequency is utilized [13].

to the current vector $\mathbf{I}_c$. Here, $\mathbf{U}$ is the complex-valued input voltage vector. Both vectors, $\mathbf{I}_c$ and $\mathbf{U}$ are of length N_{nodes}, which corresponds to the number of sensor nodes in the network. The impedance matrix $\mathbf{Z}$ is defined as

$$\mathbf{Z} = \begin{bmatrix} Z_{\text{in}} & Z_{1,2} & \cdots \\ Z_{1,2} & Z_{\text{in}} & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix}. \tag{5}$$

The solution for this set of equations is given by $\mathbf{I}_c = \mathbf{Z}^{-1}\mathbf{U}$. The received power at the load resistor of node l is equal to

$$\begin{aligned} P_{r,l} &= |I_l|^2 R_L = \left|\mathbf{e}_l^T \mathbf{Z}^{-1}\mathbf{U}\right|^2 R_L \\ &= \mathbf{U}^H(\mathbf{Z}^{-1})^H \mathbf{e}_l R_L \mathbf{e}_l^T \mathbf{Z}^{-1}\mathbf{U} = \mathbf{U}^H \mathbf{K}_l \mathbf{U}, \end{aligned} \tag{6}$$

where $\mathbf{e}_l = [0, \ldots, 0, 1, 0, \ldots, 0]^T$ with '1' at the lth position, and with implicit definition of matrix $\mathbf{K}_l$. As shown in [9], the transmit power for each magnetic device k in case of weak couplings between coils can be approximated by

$$P_{t,l} \approx |U_l|^2 \cdot Z_{\text{in}}^{-1} = \mathbf{U}^H \mathbf{e}_l Z_{\text{in}}^{-1} \mathbf{e}_l^T \mathbf{U} = \mathbf{U}^H \mathbf{G}_l \mathbf{U}, \tag{7}$$

with implicit definition of matrix $\mathbf{G}_l$. This approximation is valid for MI-WUSNs [4].

III. WPT for access limited MI-WUSNs

In general, WPT for access limited WUSNs can be done via relaying of the power signals from node to node, until the target node is charged. In this case, only one node is scheduled for transmission per time slot. Interestingly, if multiple nodes are scheduled for transmission in the same time slot, this relayed powering can be viewed as beamforming for a distributed MIMO system with multiple time slots, where each time slot has its own beamforming pattern[2]. For this, we assume that all sensor nodes are perfectly synchronized. Hence, the beamforming patterns can be jointly optimized for all time slots in order to minimize the overall energy losses and to increase the energy efficiency of the charging. Keeping this in mind, we formulate the optimization problem in Section III-A and present a possible solution for this problem in Sections III-B-III-D.

A. Problem formulation

We assign index $l = 1$ to the master node. Hence, the optimization problem can be formulated as follows:

$$\underset{\mathbf{U}(n)\forall 1\le n\le N_{\text{ts}}}{\arg\min} \sum_{n=1}^{N_{\text{ts}}} \mathbf{U}(n)^H \mathbf{G}_1 \mathbf{U}(n), \tag{8}$$

$$\text{s.t.: 1)} \sum_{n=1,\mathbf{e}_l^T\mathbf{U}(n)=0}^{N_{\text{ts}}} \mathbf{U}(n)^H \mathbf{K}_l \mathbf{U}(n) - \sum_{n=1,\mathbf{e}_l^T\mathbf{U}(n)\neq 0}^{N_{\text{ts}}} \mathbf{U}(n)^H \mathbf{G}_l \mathbf{U}(n) \ge b_l, \quad 1 < l \le N_{\text{nodes}},$$

$$\text{2)}\ \mathbf{U}(m)^H \mathbf{G}_l \mathbf{U}(m) \le \sum_{n=1,\mathbf{e}_l^T\mathbf{U}(n)=0}^{m-1} \mathbf{U}(n)^H \mathbf{K}_l \mathbf{U}(n) - \sum_{n=1,\mathbf{e}_l^T\mathbf{U}(n)\neq 0}^{m-1} \mathbf{U}(n)^H \mathbf{G}_l \mathbf{U}(n), \quad 1 \le m \le N_{\text{ts}},\ 1 < l \le N_{\text{nodes}},$$

$$\text{3)}\ \mathbf{U}(m)^H \mathbf{K}_l \mathbf{U}(m) \le b_l - \sum_{n=1,\mathbf{e}_l^T\mathbf{U}(n)=0}^{m-1} \mathbf{U}(n)^H \mathbf{K}_l \mathbf{U}(n) + \sum_{n=1,\mathbf{e}_l^T\mathbf{U}(n)\neq 0}^{m-1} \mathbf{U}(n)^H \mathbf{G}_l \mathbf{U}(n), \quad 1 \le m \le N_{\text{ts}},\ 1 < l \le N_{\text{nodes}},$$

$$\text{4)}\ nnz\left(\mathbf{U}(m)\right) \le N_{\text{simultan}},\ 1 \le m \le N_{\text{ts}},$$

where $\mathbf{U}(n)$ represents the transmission vector in time slot n, N_{ts} stands for the total number of time slots, and b_l is the required battery charge for the node l. The first constraint 1) indicates, that all nodes are supposed to be fully charged within N_{ts} time slots. In this work, N_{ts} is not restricted, since a stationary deployment for the WUSNs can be assumed [4]. The second constraint 2) reflects the need for a sufficient battery level of all nodes before starting the transmission in time slot m. Similarly, the third constraint 3) indicates that the received energy in time slot m cannot exceed the battery capacity. In particular, the right hand side of the inequality represents the remaining charge, which can be received before the battery reaches its maximum capacity. Note, that the nodes are not able to charge their batteries during own transmission, i.e., only if their transmit voltage is zero, a reception is possible. This is due to the difference between the receiving and the transmitting circuits [13], which cannot be connected to the battery at the same time. Therefore, we introduce the conditions $\mathbf{e}_l^T\mathbf{U}(n) = 0$ and $\mathbf{e}_l^T\mathbf{U}(n) \neq 0$ in sums in (8). In addition, we denote the number of non-zero elements of a vector by $nnz(\cdot)$ and the maximum number of nodes that can be selected for transmission in the same time slot by $N_{\text{simultan}} \le N_{\text{nodes}}$. Using this notation, the fourth constraint 4) is introduced in order to restrict the number of simultaneous transmissions and to reduce the complexity of the system.

In general, problem (8) is a non-linear program. As mentioned earlier, one feasible approach (fulfilling all constraints) corresponds to the possibility to transmit solely from the master node (our baseline scheme), until all batteries are charged. In the following, more advanced techniques are proposed.

B. General remarks

In this work, we focus on $N_{\text{simultan}} = 2$, where at most two nodes can be selected for transmission in each time slot. A more general case with $N_{\text{simultan}} \ge 2$ is discussed in the extended version of this paper [15]. If only one node is selected, the corresponding assignment is referred to as 'single node transmission' (SNT). Due to the non-convexity of problem (8), it is not possible to use the well-known tools of convex optimization [16]. Hence, we provide a suboptimal solution by splitting the problem in two parts. The first subproblem is a non-convex QCQP problem (described in Section III-C), which is formulated by relaxing the second and the third constraints of (8) and approximately solved using an iterative algorithm. The solution is the optimal beamforming pattern for each pair of nodes and power allocation for the SNTs. The second subproblem (described in Section III-D) is related to the transmission policy using the results from the first subproblem.

[2] We follow the convention of the literature on WPT using electromagnetic waves [13] and adopt the term beamforming for the optimization of the transmit signal vector in spatial domain.

C. Beamforming

Due to the constraint relaxation in the first subproblem, the optimization problem becomes independent from the particular time slot assignments. It can be shown, that the beamforming solution (orientation of the vector $\mathbf{U}(n)$) for a given pair remains unchanged throughout the charging procedure, such that only the transmit energy may vary from time slot to time slot whilst the beamforming pattern remains the same[3].

In total, there are $N_{\text{pairs}} = N_{\text{nodes}}(N_{\text{nodes}} - 1)/2$ pairs and N_{nodes} SNTs. We introduce the complex voltage $U_{s,x}$ of node s transmitting in pair x. For $x = 0$, $U_{s,0}$ corresponds to the SNT of node s. In addition, vector $\mathbf{V} = [\mathbf{V}_1^T, \mathbf{V}_2^T]^T$ is defined, where vector $\mathbf{V}_1 = [U_{1,0}, U_{2,0}, \ldots, U_{N_{\text{nodes}},0}]^T$ contains the voltages for SNTs and $\mathbf{V}_2 = \left[[U_{1,1}, U_{2,1}], \ldots, [U_{N_{\text{nodes}-1},N_{\text{pairs}}}, U_{N_{\text{nodes}},N_{\text{pairs}}}]\right]^T$ contains the beamforming vectors for the node pairs.

Assuming that the node pair x with nodes $\{s_1(x), s_2(x)\}$ starts transmitting in time slot q, the total transmitted energy from node $s_1(x)$ using only pair x is given by[4]

$$\begin{aligned}
&\sum_{\substack{n=1, nnz(\mathbf{U}(n))=2,\\ \mathbf{e}_{s_1(x)}^T\mathbf{U}(n)\neq 0, \mathbf{e}_{s_2(x)}^T\mathbf{U}(n)\neq 0}}^{N_{\text{ts}}} \mathbf{U}^H(n)\mathbf{G}_{s_1(x)}\mathbf{U}(n) \\
&= \mathbf{U}^H(q)\mathbf{G}_{s_1(x)}\mathbf{U}(q) \sum_{\substack{n=1, nnz(\mathbf{U}(n))=2,\\ \mathbf{e}_{s_1(x)}^T\mathbf{U}(n)\neq 0, \mathbf{e}_{s_2(x)}^T\mathbf{U}(n)\neq 0}}^{N_{\text{ts}}} \left| \frac{\mathbf{e}_{s_1(x)}^T\mathbf{U}(n)}{\mathbf{e}_{s_1(x)}^T\mathbf{U}(q)} \right|^2 \\
&= \mathbf{U}^H(q)\mathbf{G}_{s_1(x)}\mathbf{U}(q)\alpha_x = \mathbf{V}^H\mathbf{W}_x^T\mathbf{G}_{s_1(x)}\mathbf{W}_x\mathbf{V}, \quad (9)
\end{aligned}$$

where $\mathbf{W}_x = \mathbf{E}_{s_1(x),N_{\text{nodes}}+2x-1} + \mathbf{E}_{s_2(x),N_{\text{nodes}}+2x}$ and $\mathbf{E}_{g_1,g_2}$ stands for a matrix of size $N_{\text{nodes}} \times N_{\text{nodes}}^2$ with all zero elements except for '1' at the position (g_1, g_2), and α_x has been defined implicitly. Here, $\mathbf{U}(q)\sqrt{\alpha_x}$ is included in vector $\mathbf{V}$, such that $\mathbf{W}_x\mathbf{V} = \mathbf{U}(q)\sqrt{\alpha_x}$. For SNTs from node s, $\mathbf{E}_{s,s}$ is utilized instead of $\mathbf{W}_s$. Hence, the variables can be exchanged ($\mathbf{U}(n) \to \mathbf{V}$) by summing up the transmit and receive signals over all x, such that (8) is reformulated:

$$\arg\min_{\mathbf{V}} \mathbf{V}^H\mathbf{D}\mathbf{V}, \text{ s.t.: } \mathbf{V}^H\mathbf{F}_l\mathbf{V} \geq b_l,\ 1 < l \leq N_{\text{nodes}}, \quad (10)$$

where we define the matrices $\mathbf{D}$ and $\mathbf{F}_l$ as

$$\mathbf{D} = \sum_{\substack{x=1,\\ 1\in\{s_1(x),s_2(x)\}}}^{N_{\text{pairs}}} \mathbf{W}_x^T\mathbf{G}_1\mathbf{W}_x + \mathbf{E}_{1,1}^T\mathbf{G}_1\mathbf{E}_{1,1}, \quad (11)$$

$$\begin{aligned}
\mathbf{F}_l = &\sum_{\substack{x=1,\\ l\notin\{s_1(x),s_2(x)\}}}^{N_{\text{pairs}}} \mathbf{W}_x^T\mathbf{K}_l\mathbf{W}_x + \sum_{s=1, s\neq l}^{N_{\text{nodes}}} \mathbf{E}_{s,s}^T\mathbf{K}_l\mathbf{E}_{s,s} \\
&- \sum_{\substack{x=1,\\ l\in\{s_1(x),s_2(x)\}}}^{N_{\text{pairs}}} \mathbf{W}_x^T\mathbf{G}_l\mathbf{W}_x - \mathbf{E}_{l,l}^T\mathbf{G}_l\mathbf{E}_{l,l}. \quad (12)
\end{aligned}$$

[3]The prove of the respective theorem is presented in the extended version of this paper [15].

[4]Although the transmission starts at time slot q, not all subsequent time slots may be used for transmission by pair x, which is reflected in the condition $\mathbf{e}_{s_1(x)}^T\mathbf{U}(n) \neq 0$, $\mathbf{e}_{s_2(x)}^T\mathbf{U}(n) \neq 0$ for the summation in (9). Also, we exploit, that the beamforming pattern remains unchanged and only the relative amplification given by $\left| \frac{\mathbf{e}_{s_1(x)}^T\mathbf{U}(n)}{\mathbf{e}_{s_1(x)}^T\mathbf{U}(q)} \right|^2$ varies among all time slots n.

As previously assumed, the nodes are not able to charge their batteries during own transmission. This has been taken into account in (12) by restricting the indices of the sums with $l \notin \{s_1(x), s_2(x)\}$ and $l \in \{s_1(x), s_2(x)\}$ for the node pairs. For the SNTs, we use $s \neq l$ and $s = l$.[5]

Obviously, (10) is non-convex due to the non-convex constraints. In particular, the matrices $\mathbf{F}_l$ can be indefinite. Some methods have been proposed to cope with non-convex QCQPs, among which the semi-definite relaxation (SDR) approach is most popular [16]. Unfortunately, SDR fails to reach a feasible solution in most of the cases with indefinite matrices [17]. Therefore, in previous works, successive convex approximation (SCA) algorithms have been proposed [18], [17]. Typically, these iterative algorithms are utilized in order to convert non-convex constraints into convex constraints by approximating the non-convex part and using the solution from the previous iteration. We apply the recently proposed Feasible Point Pursuit (FPP)-SCA algorithm described in [17] for solving (10). In each iteration of the algorithm, a convex second-order cone program (SOCP) results, which is solved via SDR. In case of convergence, the solution may not always be feasible (unsuccessful FPP), however, the probability of failure is very low with this algorithm (less than 7.2% in [17] and 0% for the simulated scenarios in this work).

The result of the optimization is vector $\mathbf{V}$, which contains the beamforming voltages of all pairs and SNTs. These voltages not only provide the optimal beamforming pattern for each pair or single node x, but also contain a scaling factor $\sqrt{\alpha_x}$ according to (9), which indicates the overall energy to be transmitted by this pair in order to obtain the solution of the first subproblem.

D. Scheduling

The second subproblem is related to the question, which nodes and node pairs should transmit in particular time slots, such that the second and third constraints from (8) are not violated. Hence, we provide a transmission policy, which guarantees that only the nodes with enough energy transmit using their optimum beamforming vectors, and that the energy is not transmitted to the nodes with already charged batteries.

We propose the following strategy for the scheduling and scaling of the transmit vectors. In each time slot, a scaled version of the optimal beamforming vector is transmitted. The optimal beamforming vector for each SNT and each node pair is obtained from the solution of the first subproblem, whereas the optimal scaling factor is determined, such that the problem constraints are not violated. This scaling factor is related to the maximum portion of the total energy the respective node or node pair has to transmit according to the solution of the first subproblem. In each time slot, the node/node pair with the largest portion is selected for transmission. For this, the scaling factors $h_{l,1}(m)$ and $h_{x,2}(m)$ are introduced for SNTs and node pairs, respectively. This strategy has been chosen, since it guarantees that all problem constraints are satisfied. A distinct advantage is that the largest portion of the total transmit energy of the particular node/node pair is transmitted in each time slot. Intuitively, this leads to a faster charging, since the

[5]In the latter case, no summation is performed, since only one element of the sum satisfies $s = l$.

energy is transmitted in large portions instead of small ones. At first, we consider only the SNTs. Assume that node l transmits in time slot m. Since no overlap with the signals from other nodes can be expected, the phase of the complex voltage $\mathbf{e}_l^T\mathbf{V}_1$ is irrelevant. However, the amount of energy to be transmitted by node l is restricted by the following events, that can occur during transmission:

1) the battery of node l is depleted $\Rightarrow$ not enough energy for further transmissions (constraint 2) from (8) is active);
2) the total amount of energy transmitted by l over all time slots reaches $\left|\mathbf{e}_l^T\mathbf{V}_1\right|^2 Z_{\text{in}}^{-1}$ (optimality criterion according to the first subproblem, as mentioned in Section III-C);
3) the battery of node $p \neq l$ gets fully charged $\Rightarrow$ no more energy can be received by node p (constraint 3) from (8) is active).

Each of these events means violation of the constraints and must be avoided. Hence, the maximum energy to be transmitted in time slot m is upper bounded by the minimum energy, for which one of the three events becomes active. The corresponding factor $h_{l,1}(m)$ can be determined via

$$h_{l,1}(m) = \min\{A_l(m), B_l(m), C_l(m)\}, \tag{13}$$

where $A_l(m)$ stands for the normalized available energy at node l (event 1 occurs), $B_l(m)$ represents the normalized maximum energy to be transmitted by node l according to the first subproblem (event 2 occurs), and $C_l(m)$ denotes the normalized minimum transmit energy needed until the battery of any other node gets fully charged (event 3 occurs). These values are given by

$$\begin{aligned} A_l(m) \;=\; & \sum_{\substack{n=1,\\ \mathbf{e}_l^T\mathbf{U}(n)=0}}^{m-1} \frac{\mathbf{U}^H(n)\mathbf{K}_l\mathbf{U}(n)}{\left|\mathbf{e}_l^T\mathbf{V}_1\right|^2 Z_{\text{in}}^{-1}} \\ & - \sum_{\substack{n=1,\\ \mathbf{e}_l^T\mathbf{U}(n)\neq 0}}^{m-1} \frac{\mathbf{U}^H(n)\mathbf{G}_l\mathbf{U}(n)}{\left|\mathbf{e}_l^T\mathbf{V}_1\right|^2 Z_{\text{in}}^{-1}}, \end{aligned} \tag{14}$$

$$B_l(m) \;=\; 1 - \sum_{\substack{n=1,\\ \mathbf{e}_l^T\mathbf{U}(n)\neq 0,\\ nnz(\mathbf{U}(n))=1}}^{m-1} \frac{\mathbf{U}^H(n)\mathbf{G}_l\mathbf{U}(n)}{\left|\mathbf{e}_l^T\mathbf{V}_1\right|^2 Z_{\text{in}}^{-1}}, \tag{15}$$

$$\begin{aligned} C_l(m) \;=\; & \min_{p\neq l}\Bigg\{\Bigg(b_p - \sum_{\substack{n=1,\\ \mathbf{e}_p^T\mathbf{U}(n)=0}}^{m-1} \mathbf{U}^H(n)\mathbf{K}_p\mathbf{U}(n) \\ & + \sum_{\substack{n=1,\\ \mathbf{e}_p^T\mathbf{U}(n)\neq 0}}^{m-1} \mathbf{U}^H(n)\mathbf{G}_p\mathbf{U}(n)\Bigg) \frac{\mathbf{e}_l^T\mathbf{G}_l\mathbf{e}_l}{\mathbf{e}_l^T\mathbf{K}_p\mathbf{e}_l\left|\mathbf{e}_l^T\mathbf{V}_1\right|^2 Z_{\text{in}}^{-1}}\Bigg\}. \end{aligned} \tag{16}$$

Here, $A_l(m)$ results from the difference between the total received energy at node l and its transmitted energy before the time slot m. The result is normalized by the total energy $\left|\mathbf{e}_l^T\mathbf{V}_1\right|^2 Z_{\text{in}}^{-1}$ to be transmitted by this node. $B_l(m)$ is calculated by subtracting the already transmitted energy of node l from the total energy to be transmitted by this node and normalizing by $\left|\mathbf{e}_l^T\mathbf{V}_1\right|^2 Z_{\text{in}}^{-1}$. Furthermore, in order to calculate $C_l(m)$, the remaining energy to be received by node p is also normalized by $\left|\mathbf{e}_l^T\mathbf{V}_1\right|^2 Z_{\text{in}}^{-1}$ and scaled by the factor $\frac{\mathbf{e}_l^T\mathbf{G}_l\mathbf{e}_l}{\mathbf{e}_l^T\mathbf{K}_p\mathbf{e}_l}$, which represents the inverse charging efficiency for the node p using node l. The resulting scaling factor $h_{l,1}(m)$ is used to determine the optimal transmit voltage $\mathbf{e}_l^T\mathbf{V}_1\sqrt{h_{l,1}(m)}$ in time slot m, if node l is selected for transmission as SNT.

Similarly, for the node pairs, consider the entries of vector $\mathbf{V}$ that correspond to the pair x with nodes $\{s_1(x), s_2(x)\}$. The respective voltage vector is given by $\mathbf{U}_x = \mathbf{U}(q)\sqrt{\alpha_x} = \mathbf{W}_x\mathbf{V}$, as mentioned earlier. Furthermore, in each time slot m occupied by pair x, a scaled version $\mathbf{U}(m) = \mathbf{U}_x\sqrt{h_{x,2}(m)}$ of this beamforming solution is transmitted. $h_{x,2}(m)$ is selected similarly to (13) via $h_{x,2}(m) = \min\{A_x(m), B_x(m), C_x(m)\}$, where $A_x(m)$, $B_x(m)$, and $C_x(m)$ are defined for pair x as

$$\begin{aligned} A_x(m) \;=\; & \min_{i\in\{1,2\}}\Bigg\{\sum_{\substack{n=1,\\ \mathbf{e}_{s_i(x)}^T\mathbf{U}(n)=0}}^{m-1} \frac{\mathbf{U}^H(n)\mathbf{K}_{s_i(x)}\mathbf{U}(n)}{\left|\mathbf{e}_{s_i(x)}^T\mathbf{U}_x\right|^2 Z_{\text{in}}^{-1}} \\ & - \sum_{\substack{n=1,\\ \mathbf{e}_{s_i(x)}^T\mathbf{U}(n)\neq 0}}^{m-1} \frac{\mathbf{U}^H(n)\mathbf{G}_{s_i(x)}\mathbf{U}(n)}{\left|\mathbf{e}_{s_i(x)}^T\mathbf{U}_x\right|^2 Z_{\text{in}}^{-1}}\Bigg\}, \end{aligned} \tag{17}$$

$$B_x(m) \;=\; 1 - \sum_{\substack{n=1, nnz(\mathbf{U}(n))=2\\ \mathbf{e}_{s_1(x)}^T\mathbf{U}(n)\neq 0,\\ \mathbf{e}_{s_2(x)}^T\mathbf{U}(n)\neq 0}}^{m-1} \frac{\mathbf{U}^H(n)\mathbf{G}_{s_1(x)}\mathbf{U}(n)}{\left|\mathbf{e}_{s_1(x)}^T\mathbf{U}_x\right|^2 Z_{\text{in}}^{-1}}, \tag{18}$$

$$\begin{aligned} C_x(m) \;=\; & \min_{p\notin\{s_1(x),s_2(x)\}}\Bigg\{\Bigg(b_p - \sum_{\substack{n=1,\\ \mathbf{e}_p^T\mathbf{U}(n)=0}}^{m-1} \mathbf{U}^H(n)\mathbf{K}_p\mathbf{U}(n) \\ & + \sum_{\substack{n=1,\\ \mathbf{e}_p^T\mathbf{U}(n)\neq 0}}^{m-1} \mathbf{U}^H(n)\mathbf{G}_p\mathbf{U}(n)\Bigg) \frac{1}{\mathbf{U}_x^H\mathbf{K}_p\mathbf{U}_x}\Bigg\}. \end{aligned} \tag{19}$$

For $A_x(m)$, the available energy at nodes $s_1(x)$ and $s_2(x)$ is normalized by the respective total transmit energies. In order to determine which node will be depleted first, the resulting energy ratios are compared and the minimum value is taken. Obviously, the relative depletion rate is equal for both nodes of the same pair, since the beamforming vector $\mathbf{U}_x$ remains unchanged in all time slots, in which pair x is scheduled for transmission. Hence, $B_x(m)$ can be calculated using node $s_1(x)$ or $s_2(x)$ by subtracting the energy, which has already been transmitted by node $s_1(x)$ or $s_2(x)$, respectively, via pair x from the total energy to be transmitted by the respective node in pair x. The result is normalized by the respective total transmit energy $\left|\mathbf{e}_{s_1(x)}^T\mathbf{U}_x\right|^2 Z_{\text{in}}^{-1}$ or $\left|\mathbf{e}_{s_2(x)}^T\mathbf{U}_x\right|^2 Z_{\text{in}}^{-1}$. For $C_x(m)$, we obtain a result similar to (14). The inverse charging efficiency for node p using node $s_i(x)$, $i \in \{1, 2\}$, via node pair x is given by $\frac{\mathbf{U}_x^H\mathbf{G}_{s_i(x)}\mathbf{U}_x}{\mathbf{U}_x^H\mathbf{K}_p\mathbf{U}_x}$. We exploit the definition of matrix $\mathbf{G}_l$ from (7), which yields $\mathbf{U}_x^H\mathbf{G}_{s_i(x)}\mathbf{U}_x = \left|\mathbf{e}_{s_i(x)}^T\mathbf{U}_x\right|^2 Z_{\text{in}}^{-1}$. Hence, after the normalization of the inverse charging efficiency by $\left|\mathbf{e}_{s_i(x)}^T\mathbf{U}_x\right|^2 Z_{\text{in}}^{-1}$, a scaling factor $\frac{1}{\mathbf{U}_x^H\mathbf{K}_p\mathbf{U}_x}$ remains.

As mentioned earlier, the node/node pair with the largest scaling factor $h_{l,1}$ (or $h_{x,2}$) is selected for transmission. In order to illustrate this strategy, we give an example for charging a

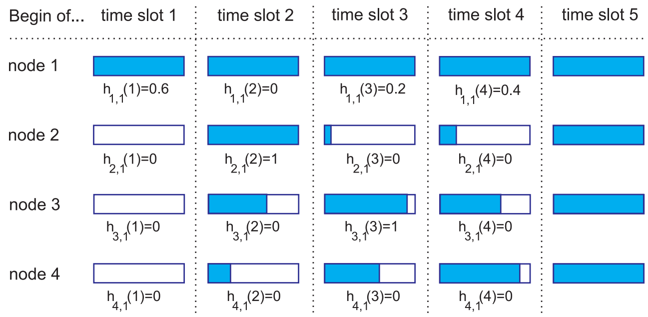

Fig. 3. Proposed scheduling for charging of three sensor nodes. Master node corresponds to node 1. Energy levels of nodes' batteries are shown.

network with four nodes (including master node) and using only SNTs ($N_{\text{simultan}} = 1$ is selected for better comprehension), see Fig. 3. In the beginning of time slot 1, only the master node (node 1) has enough energy to transmit. $A_2(1) = 0$, $A_3(1) = 0$, and $A_4(1) = 0$ holds, such that $h_{2,1}(1) = 0$, $h_{3,1}(1) = 0$, and $h_{4,1}(1) = 0$ result, respectively. The transmit energy is chosen via the scaling factor $h_{1,1}(1) = 0.6$, such that one of the nodes gets fully charged. In the beginning of the second time slot, all nodes have enough energy to start a transmission. However, if node 1, 3, or 4 would transmit, node 2 may not be able to receive this energy, since its battery is already full. Hence, $C_1(2) = 0$, $C_3(2) = 0$, and $C_4(2) = 0$ holds. This yields $h_{1,1}(2) = 0$, $h_{3,1}(2) = 0$, and $h_{4,1}(2) = 0$, respectively. Then, node 2 is selected and transmits with $h_{2,1}(2) = 1$. This means, that the total energy to be transmitted by this node is sent at once in time slot 2. In the third time slot, $h_{1,1}(3) = 0.2$, which is lower than $h_{3,1}(3) = 1$, such that node 3 is selected. Here, the total energy to be transmitted by node 3 is completely consumed during time slot 3. Finally, in the fourth time slot, $B_2(4) = 0$, $B_3(4) = 0$, and $B_4(4) = 0$ holds, since nodes 2, 3, and 4 have reached their total transmit energy obtained from the first subproblem. Hence, the master node transmits with $h_{1,1}(4) = 0.4$ and all nodes get fully charged, such that the whole charging procedure only takes four time slots[6]. After that, the master node has consumed the total transmit energy suggested by the solution of the first subproblem, as can be seen from the sum $h_{1,1}(1) + h_{1,1}(4) = 1$.

With the proposed scheduling, all constraints of (8) are satisfied and a close-to-optimum performance of the proposed solution can be expected[7].

IV. Numerical Results

In this section, we discuss numerical results on the performance of the proposed relayed powering of the sensor nodes in access limited WUSNs. In our simulations, a set of N_{nodes} sensor nodes is randomly (uniform distribution) deployed in a square field of size $F \times F$ for each simulated scenario. In this set, a master node is selected, which is the closest node to the lower left field corner. We utilize coils with wire radius 0.5 mm, coil radius 0.25 m, and $N_w = 500$ coil windings. The conductivity of soil is $\sigma = 0.01$ S/m [5]. Since the permeability of soil is close to that of air, we use $\mu = \mu_0$ with the magnetic

[6]In Fig. 3, time slot 5 is introduced solely to show the result of charging.

[7]Actually, the performance bound given by the solution of the first subproblem can be reached using this strategy.

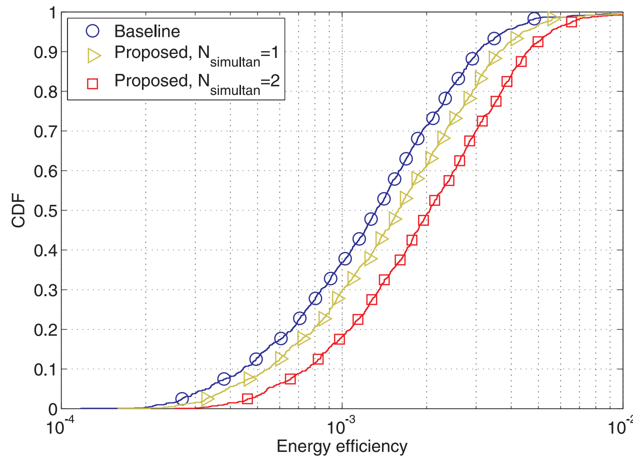

Fig. 4. Cumulative distribution of the energy efficiencies of 1000 random WUSNs with 5 nodes in 20 m × 20 m field.

constant $\mu_0 = 4\pi \cdot 10^{-7}$ H/m. The resonance frequency is set to $f_0 = 1$ MHz. Moreover, for the charging mode, we assume that all batteries have the same capacity of 0.1 J [11]. In this work, we focus on minimum spanning tree-based WUSNs [4]. Furthermore, in the information transmission mode (while not being charged), we assume that each node not only transmits its own packets, but also relays the previously received data packets. Hence, the more data streams each node has to serve, the more packets need to be transmitted from this node [19]. Correspondingly, the depletion of the nodes' batteries is not uniform in the network [20]. We assume, that the network starts the charging procedure, if one of the nodes' batteries is completely empty. Obviously, the empty battery belongs to the node $l_{\max}$, which serves the largest number of data streams $\max_n\{N_{\text{streams},n}\}$, where $N_{\text{streams},n}$ denotes the number of data streams served by node n. The amount of energy consumed by node l until the battery of node $l_{\max}$ gets completely depleted corresponds to the required battery charge b_l given by $b_l = \dfrac{N_{\text{streams},l}}{\max_n\{N_{\text{streams},n}\}} \cdot 0.1$ J. Note, that the energy efficiency is defined as a ratio of $\sum_l b_l$ over total transmitted energy from the master node, as mentioned earlier.

In the following, we provide a cumulative distribution of energy efficiency for 1000 realizations for each of the considered scenarios and compare the baseline scheme (only master node transmits) with the proposed solution for $N_{\text{simultan}} = \{1, 2\}$. Here, the solution for $N_{\text{simultan}} = 1$ can be easily obtained either by setting all entries of the respective matrices $\mathbf{W}_x$ to zero for all pairs and solving the problem as described in Section III, or by formulating a simplified optimization problem with reduced complexity (typically a linear program), which can be solved via the Simplex algorithm.

For a small network with only 5 nodes and $F = 20$ m, the results are depicted in Fig. 4. We observe an average energy efficiency gain of 20% and 60% compared to the baseline scheme using $N_{\text{simultan}} = \{1, 2\}$, respectively. The respective peak efficiency gains are 54% and 150%. Using $N_{\text{simultan}} = 2$, an average energy efficiency of 0.25% can be achieved, which is a considerable transfer efficiency, since the transmission distance between any sensor node and the master node can be up to 25 m. The peak energy efficiency is 3.4%.

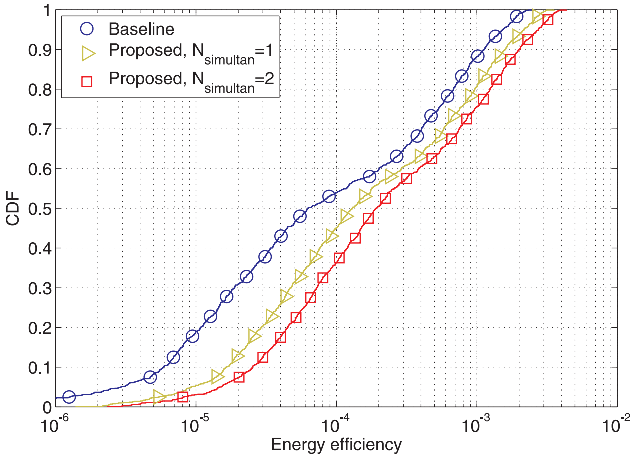

Fig. 5. Cumulative distribution of the energy efficiencies of 1000 random tunnel-based WUSNs with 5 nodes in 20 m $\times$ 20 m field.

In addition, we investigate a scenario which is even more realistic for the WUSNs in mines and tunnels. For this, we assume that the directions of the network links correspond to the directions of the tunnels. Therefore, if a particular link is not part of the spanning tree (which is the assumed topology in this work), the corresponding devices might be separated by soil. In such cases, the assumption that the coils are deployed at the ground surface is not valid. Hence, we use $G_{k,l}$ from (3) instead of (2). The resulting energy efficiency is depicted in Fig. 5. Due to much weaker coupling, it is hardly possible for the master node to charge the leaf nodes via direct coupling. In principle, the performance of the baseline scheme relies mostly on the passive relaying of magnetic field, which is, however, very weak [3]. This explains the remarkable average efficiency gain of 134% and 245% for the proposed solution using $N_{\text{simultan}} = \{1, 2\}$, respectively. With $N_{\text{simultan}} = 2$, we obtain more than 109% gain in 50% of considered realizations, and a peak efficiency gain of 5733% compared to the baseline scheme. Unfortunately, the average energy efficiency ($\approx 6.6 \cdot 10^{-4}$) further decreases compared to Fig. 4 (approximately by factor 3.9), which is because less nodes can be charged simultaneously, such that more hops are needed in order to charge the leaf nodes. Hence, the losses per hop accumulate and decrease the overall charging efficiency.

V. Conclusion

In this work, a novel solution for the wireless power transfer in access limited WUSNs is presented. In our approach, we assume that several sensor nodes can synchronize their transmissions for the charging procedure in order to maximize the energy transfer efficiency in each time slot. Hence, a multinode scheduling needs to be established, such that the optimal beamforming pattern is obtained in all consecutive time slots. This optimization problem is non-linear and non-convex in general. In the proposed approach, the optimization problem is split in two subproblems, and each subproblem can be solved independently. The first subproblem turns out to be a non-convex QCQP problem, which is solved using a recently proposed FPP-SCA algorithm. The proposed suboptimal solution for the second subproblem represents a power transfer policy, where the best beamforming vector is selected and optimally scaled in each time slot. Significant energy efficiency gains compared to the baseline scheme are observed even for small networks with few sensor nodes. Furthermore, MI-WUSNs in tunnels have been investigated, where the signal transmission between two devices is exposed a much larger path loss, if these devices are separated by soil instead of a tunnel. In this constellation, even larger efficiency gains can be achieved by the proposed solution. However, the expected energy efficiency for MI-WUSNs in tunnels is heavily reduced due to a lower number of nodes that can be charged simultaneously.

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