Beamforming Design for Full-Duplex Wireless Powered Communication Networks

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Abstract—Radio frequency (RF) energy harvesting is key in attaining perpetual lifetime for time-critical wireless powered communication networks due to full control on energy transfer, far field region, small and low-cost circuitry. In this study, we formulate a novel minimum length scheduling problem to determine the optimal beam-forming weights, power control and time allocation to minimize the schedule length. We consider the traffic demand, maximum transmit power, scheduling and energy causality constraints for a full-duplex wireless powered communication network. The formulated optimization problem is a mixed integer non-linear optimization problem therefore, difficult to solve for global optimum. As a future work, we present an efficient solution strategy based on the decomposition of the problem into power control problem and scheduling problem.

Index Terms—Energy harvesting, wireless powered communication networks, beam-forming, full-duplex networks, scheduling.

I. INTRODUCTION

After a tremendous success of wireless sensor networks (WSNs), the time-critical WSNs are very popular in cyber physical systems, automotive industry, emergency alert systems and health services due to their low cost, easy installation, and flexibility. Several studies have been conducted on minimizing the schedule length given the traffic demand and limited battery lifetime of the users [2]–[4]. The life time of such battery limited networks can be prolonged by radio frequency (RF) based energy harvesting, which offers full control on the energy transfer along with small form factor and high range. Wireless powered communication networks (WPCNs) are the most suitable RF energy harvesting network in which users are powered up by dedicated energy transmission in the downlink [5]. In half-duplex WPCNs, the energy harvesting time is constant and equal for all the users. Therefore, transmission order of the users is not important. On the other hand, full-duplex (FD) WPCNs are used to efficiently utilize the spectrum and improve the energy transfer rate by a simultaneous energy transmission and information reception at the HAP. Self-interference (SI) mitigation is the main challenge in such networks but thanks to the recent advances in SI mitigation techniques and their practical implementations, the FD technology is a key transceiving technique for 5G and beyond networks [6]. In FD, the users can harvest energy during the transmission of other users which necessitates the scheduling algorithms for such networks which is missing in the literature except [2]–[4]. The poor energy transfer efficiency is also a major challenge for RF energy harvesting. This motivates the usage of advanced beam-forming techniques in which the energy transfer weights to each user are carefully adjusted to achieve high energy transfer efficiency without increasing the transmit power and bandwidth. For energy beam-forming authors in [7] maximized the worst case harvested energy for the users. [8], [9] proposed joint beam-forming and time allocation designs to maximize the system throughput for a single hop and relay based systems, respectively. However, sum throughput maximization objective does not guarantee the timely delivery of the data of all users, which is a basic requirement of the time-critical networks.

The goal of this study is to determine the optimal beam-forming weights, time allocation, power control, and scheduling with the objective of minimizing the schedule length subject to the traffic requirement, the maximum transmit power constraint, and the energy causality constraint of the users, for a time-critical WPCN.

II. SYSTEM MODEL AND ASSUMPTIONS

The WPCN architecture consists of a HAP and N users denoted by $R_1, \cdots, R_N$; i.e., sensors. The HAP is equipped with $M$ FD antennas and all the users are equipped with single FD antenna. We consider Time Division Multiple Access (TDMA) as medium access control protocol for the uplink data transmission from the users to the HAP. The HAP is equipped with a stable energy source and continuously transfers wireless energy with a constant power $P_h$. Each user can use the energy it harvests from the beginning of the frame till the end of its transmission. Each user $i$ harvests energy from the HAP and stores it in a rechargeable battery with an initial energy $B_i$ at the beginning of the scheduling frame. The initial energy includes the harvested and unused energy in the previous frames. The channel gains for the downlink and uplink channels are assumed to be different. The downlink channel gain from the HAP to user $i$ is denoted by $h_i$. The uplink channel gain from user $i$ to the HAP is denoted by $g_i$. Both channels are assumed to be block-fading. We assume that the HAP has perfect channel state information; i.e., the channel gains are perfectly known at the HAP [2]–[5]. The energy harvesting rate of user $i$, denoted by $C_i$, depends on the downlink channel gain $h_i$, beam-forming weight $\omega_{m,i}$, transmit power of HAP $P_h$ and antenna efficiency $\eta_i$ as $C_i = \eta_i \omega_{m,i} P_h$. We assume user $i$ has a traffic demand $D_i$ bits to be transmitted over the scheduling frame. We...
use continuous rate transmission model, in which Shannon’s channel capacity formulation for an AWGN wireless channel is used in the calculation of the maximum achievable rate as a function of Signal-to-Interference-plus-Noise Ratio (SINR) as \( x_i = W \log_2 (1 + k_i P_i) \), where \( x_i \) is the transmission rate of user \( i \), \( P_i \) is the transmission power of user \( i \), \( W \) is the channel bandwidth, and \( k_i \) is defined as \( ||g_i||^2/(N_0 W + \beta P_h) \), in which the term \( \beta P_h \) is the power of self-interference at the HAP and \( N_0 \) is the noise power.

III. MINIMUM LENGTH SCHEDULING PROBLEM

In this section, we introduce the minimum length scheduling problem referred as \( \text{MLSP} \).

\( \text{MLSP} \): 
\[
\begin{align*}
\text{minimize} & \quad \sum_{i=0}^{N} \tau_i \\
\text{subject to} & \quad W \tau_i \log_2 (1 + k_i P_i) \geq D_i, \quad i \in \{1, ..., N\} \\
& \quad B_i + \eta P_h \sum_{m=1}^{M} h_{im} \omega_m \sum_{j \neq i} \alpha_j \tau_j + \eta P_h \sum_{m=1}^{M} h_{im} \omega_m \tau_i \\
& \quad - \tau_i P_i \geq 0, \quad i \in \{1, ..., N\}, i \neq j \\
& \quad a_{ij} + a_{ji} = 1, \quad i < j, i, j \in \{1, ..., N\}, i \neq j \\
& \quad \sum_{m=1}^{M} \omega_m \leq 1 \\
& \quad P_i \leq P_{\text{max}}, \quad i \in \{1, ..., N\} \\
\text{variables} & \quad \omega_m \geq 0, \quad \tau_i \geq 0, \quad \omega_m \geq 0, \quad a_{ij} \in \{0, 1\}, \quad i, j \in \{1, ..., N\}, m \in \{1, ..., M\}.
\end{align*}
\]

The objective of the \( \text{MLSP} \) is to minimize the schedule length as given in Eq. (1a). The variables of the optimization problem are \( \omega_m \), the beam-forming weights, \( \tau_i \), the transmission time of user \( i \), \( i \in \{1, ..., N\} \), \( P_i \), the transmit power of user \( i \), \( i \in \{1, ..., N\} \) and \( a_{ij} \) is a binary variable for scheduling, which takes value 1 if user \( j \) is scheduled before user \( i \) and 0 otherwise. In addition, \( \tau_0 \) is the waiting time, in which all the users harvest energy and no user transmits information. Eq. (1b) represents the traffic demand of each user. Eq. (1c) represents the energy causality constraint, i.e., the consumed energy must be less than the available energy. Eq. (1d) represents the scheduling constraint, i.e., if user \( i \) transmits before user \( j \), then, user \( j \) cannot transmit before user \( i \). The beam-forming weights constraint and maximum transmit power constraints are presented in Eqs. (1e) and (1f), respectively. \( P_{\text{max}} \) is the maximum transmit power allowed for any user.

IV. SOLUTION STRATEGY

The formulated optimization problem is a mixed integer non-linear optimization problem which is in general difficult to solve for the global optimum. We aim to analyze the problem for a simpler on-off transmission scheme and a general continuous power model. In on-off transmission scheme, we assume that the users can only transmit information at \( P_{\text{max}} \) power, i.e., \( P_i \) in \( \text{MLSP} \) is replaced with \( P_{\text{max}} \). However, if a user cannot afford \( P_{\text{max}} \), it will remain silent until it harvests enough energy. In the continuous power model, the users may transmit information by using any power below the \( P_{\text{max}} \) value.

As a solution strategy, we aim to first decompose the both problems into power control problems (PCP) and scheduling problems. In the power control problems, we assume a predetermined transmission order of the users, for which we will determine the optimal beam-forming weights, transmission time and the waiting time based on the optimality analysis of the optimization problem. Once the PCPs are solved for optimal solution, Brute-force is one possible approach to solve the scheduling problems optimally, in which the schedule length for all the possible transmission orders is determined and then, the one with minimum schedule length is selected. The computational complexity of this approach is a major bottleneck. To overcome this computational complexity, we will propose polynomial time heuristic algorithms based on the optimality analysis of the problems which will perform close to the optimal solution. The general PCP problem for pre-determined transmission order is denoted by \( \text{PCP} \) and is given as below:

\( \text{PCP} \): 
\[
\begin{align*}
\text{minimize} & \quad \sum_{i=0}^{N} \tau_i \\
\text{subject to} & \quad W \tau_i \log_2 (1 + k_i P_i) \geq D_i, \quad i \in \{1, ..., N\} \\
& \quad B_i + \eta P_h \sum_{m=1}^{M} h_{im} \omega_m \sum_{j \neq i} \alpha_j \tau_j + \eta P_h \sum_{m=1}^{M} h_{im} \omega_m \tau_i \\
& \quad - \tau_i P_i \geq 0, \quad i \in \{1, ..., N\}, i \neq j \\
& \quad a_{ij} + a_{ji} = 1, \quad i < j, i, j \in \{1, ..., N\}, i \neq j \\
& \quad \sum_{m=1}^{M} \omega_m \leq 1 \\
& \quad P_i \leq P_{\text{max}}, \quad i \in \{1, ..., N\} \\
\text{variables} & \quad \omega_m \geq 0, \quad \tau_i \geq 0, \quad \omega_m \geq 0, \quad a_{ij} \in \{0, 1\}, \quad i, j \in \{1, ..., N\}, m \in \{1, ..., M\}.
\end{align*}
\]

The aim of \( \text{PCP} \) is to minimize the schedule length for a given transmission order of the users for a continuous power model.

REFERENCES