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Complexity of minimum uplink scheduling in backbone-assisted successive interference cancellation-based wireless networks

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ABSTRACT

Relative to the networks with multiple independent sinks, in backbone-assisted networks, multiple sinks are connected together with high-speed wirelines. So, by exchanging decoded signals of User Equipments (UEs) among sinks through the backbones, more interferences to undecoded signals could be cancelled further. Thus, potential optimization rooms for reducing access delays are provided. In this paper, we study the problem of minimum uplink scheduling for Backbone-Assisted Successive Interference Cancellation-based Wireless Networks (BASICWNs), so as to reduce the mean access delays of UEs. We formulate the problem, and prove that it is NP-Complete by presenting a reduction from the partition problem. We further propose a polynomial-time heuristic algorithm based on the greedy strategy that as many UEs as possible are simultaneously scheduled in one slot. Experimental results show, relative to that with multiple independent sinks, the uplink frame length of BASICWNs is reduced by 48% with the heuristic algorithm proposed, and the performance is virtually very close to the optimum.

1. Introduction

In many practical applications of Industrial Wireless Networks (IWNs) [1,2], User Equipments (UEs) usually sample data in fixed interval, transmit the sampled data to a sink node, and then go sleepy until the next sampling interval. Since they have same sampling intervals and similar packet lengths, the scheduling-based Media Access Control (MAC) scheme is usually chosen for consideration of high efficiency. The realtime performance, which is usually represented by the transmission delays of uplink data packets, is especially important for IWNs. For the scheduling-based MAC, the uplink transmission delay is closely related to the frame length, and the less is the frame length, the better is the realtime performance. Therefore, given the UEs which will transmit in the upcoming frame, to minimize the length of the uplink frame is usually pursued.

A typical application scenario is our previous work on the wireless logging system [1], where several tens of wireless sensors, equivalent to UEs of this paper, sense environment simultaneously, and then transmit the sensed information wirelessly. Several computers, equivalent to the sinks of this paper, receive the sensed information via wireless interfaces. Further data fusions are done on the sinks to provide specific information, such as the well depth, the oil pressure, and etc. to oil-well drilling operator and the fault-safety subsystem. Obviously, the fused result reveals the drilling healthy status at the instant when the corresponding fused data was sampled. Therefore, the response delay of the fault-safety subsystem will be no less than the maximal transmission delay of the sensory data. In other words, a smaller transmission delay will result in a faster response from the fault-safety subsystem, which is especially important for the system reliability.

Since it supports the reception of simultaneous multiple packets from parallel UEs, Successive Interference Cancellation (SIC) technique can be leveraged for improving the realtime performances. For example, if there are n simultaneous UEs for the upcoming frame, n slots have to be included in the frame for regular radio decoders, while less slots are required if SIC is adopted, thus better realtime performance is possible. However, the disadvantage of the high interference of SIC brings restrictions to further performance improvements[3], new improvement methods have thus to be found.

If multiple SIC-based sinks are wireline-interconnected, which forms the so-called Backbone-Assisted Successive Interference Cancellation-based Wireless Networks (BASICWNs), the frame length can be further decreased since the spatial diversity caused by the multiple sinks can be utilized effectively by the SIC decoders. We take Fig. 1 for example to explain the principle of the frame length optimization in BASICWNs. There are two inde-

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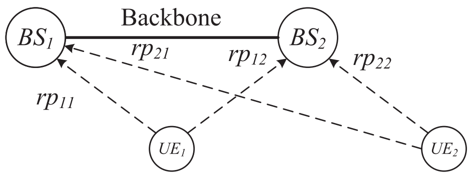

Fig. 1. Optimize uplink scheduling length in BASICWNs.

pendent sinks, BS_1, BS_2, and two UEs, UE_1, UE_2, in an SIC-based wireless network. Assume that the received powers of the signals from UE_1 at BS_1 and BS_2, i.e., rp_{11} and rp_{12}, are both 1 mW, and these from UE_2 i.e., rp_{21} and rp_{22}, are 0.1 mW and 1 mW, respectively. The power of ambient noise n_0 is 0.1 mW and decoding threshold γ is 2. Since Signal-to-Interference plus Noise Ratio (SINR) of UE_1 at BS_1, i.e., $SINR_{(1,1)}$, is $\frac{rp_{11}}{rp_{21}+n_0} = \frac{1mW}{0.1mW+0.1mW} > \gamma$, $SINR_{(2,1)} = \frac{rp_{21}}{rp_{11}+n_0} = \frac{0.1mW}{1mW+0.1mW} < \gamma$, only signals from UE_1 can be decoded at BS_1. Besides, UE_2 still cannot be decoded correctly even after the interference from UE_1 is cancelled, because its SINR at that time is $\frac{rp_{21}}{n_0} = \frac{0.1mW}{0.1mW} < \gamma$. In one word, BS_1 can only decode signals from UE_1. In the same way, it is easy to find that BS_2 cannot decode signals from both UE_1 and UE_2 because $SINR_{(1,2)} < \gamma$ and $SINR_{(2,2)} < \gamma$. Therefore, the minimum uplink scheduling length is 2. However, if BS_1 and BS_2 are wireline-connected, the minimum uplink scheduling length will be 1 as follows. BS_1 decodes signals from UE_1, and then it immediately forwards the decoded signal to BS_2 via the wirelined backbone. Thus, BS_2 can now improve the $SINR(2, 2)$ by subtracting the attenuated signal of UE_1 from its total received signals, i.e., $SINR_{(2,2)} = \frac{rp_{22}}{n_0} = \frac{1mW}{0.1mW} > \gamma$ at that time. Now, signals from UE_2 can be decoded at BS_2 after the above interference cancellation. Obviously, the key to the performance improvement is the message exchange scheme through the backbone, which is achieved by the combination of two features of BASICWNs, i.e., the SIC receiver and the interconnection among sinks via the backbone.

Since BASICWNs have great potentiality for decreasing the frame length, a problem has arisen naturally as follows. To achieve the minimum uplink frame length, how to design the optimal scheduling strategy in the scenario of BASICWNs? The problem is intuitively NP-Complete, but is that true?

We solve the problem in three steps. First, by controlling the grouping strategy of UEs, the minimum uplink scheduling problem is formulated as a combinatorial optimization problem. Second, by presenting a reduction from the classic partition problem, we prove that the problem is NP-Complete. To the best of our knowledge, this is the first work on the scheduling complexity of BASICWNs. Third, we propose a polynomial-time heuristic algorithm based on a greedy strategy that as many UEs as possible are scheduled in one slot. The three steps are also the three novelties of this paper.

The remainder of this paper is organized as follows. Section 2 reviews related works. The network models and problem formulation are elaborated in Section 3. Complexity proof is presented in Section 4, and a low-complexity heuristic algorithm is presented and analyzed in Section 5. Performance evaluation of the heuristic algorithm is carried out in Section 6, and the last section is conclusions.

2. Related works

SIC has been intensively investigated for future 5G networks. It can achieve near Shannon capacity under the assumption of perfect interference cancellation. To fully leverage the capability of SIC, some cross-layer optimization frameworks aiming for maximizing delay and throughput performances are setup [4,5]. Signal-to-interference ratio balancing and a general weighted utility sum are formulated in [6,7] by a joint power allocation and link scheduling scheme.

Besides above works which are suitable for multi-hop wireless networks, transmission scheduling for SIC-based cellular networks has also attracted research interests in recent years, due to its strong background on 5G communications. Significant research works lay emphasis on downlink scheduling using SIC, including these in [8–13]. Distinct from them, the following papers focus on the uplink transmissions. Xu et al. propose a distributed uplink power allocation algorithm, which is used for random access for massive connections [14]. In [15], the complexities of uplink scheduling aiming for maximizing throughput and proportional fairness are studied, where the two problems are formulated with the received powers rather than the transmit powers. In [16], a game theory based distributed uplink power control algorithm is proposed for two interfering cells. Qian et al. take the component of dynamic base station association into considerations in uplink scheduling [17].

Our works are closely related with two papers. In [18], the authors propose the principle of BASICWNs, i.e., relative to only one SIC-based sink, how the backbone-connected multiple SIC-based sinks are leveraged to enhance network performances. While [19] proves that, in a wireless network with multiple SIC-based sinks which are not interconnected, the minimum frame length problem without power control is NP-hard. Note that “not interconnected” is the key feature of [19], while “backbone connected” is the key feature of this paper. In other words, the network which this paper discussed is same with that in [18], and the optimized target of this paper is same with that in [19].

3. Network models and problem formulation

3.1. Network models

The considered network consists of n UEs and m sinks, which are denoted as $u_1, u_2, \ldots, u_n$, and $R_1, R_2, \ldots, R_m$ respectively. Each sink is equipped with an SIC receiver, so they can do SIC decoding. For BASICWNs, these sinks are wireline-connected, while for the Non-Backbone Wireless Networks (NBWNs), these sinks are not wireline-connected, or alternatively, independent.

A signal can be decoded successfully if and only if its SINR is not less than a given threshold γ, where $\gamma > 1$ in general[1] For an SIC decoder, the maximal number of decodable parallel UEs is not restricted in this paper, and any signal can be decoded correctly if its SINR is no less than γ, which is different from the k-SIC model used in [20]. The SIC model used in this paper is suitable for the SIC decoder with iterative decoding architecture [21] (Table 1).

We employ the parameter G_{ik} to capture the loss in signal strength as it propagates through wireless channel from u_i to R_k, i.e., its received power at R_k is $G_{ik}P$, if u_i transmit with power P. It is assumed that $G_{ik} = d(u_i, R_k)^{-\alpha}$ where $d(u_i, R_k)$ is the distance between u_i and R_k, and α is the power decay factor, which is greater than 2 in general. We assume that channel gains keep constant during a scheduling frame. Obviously, for n UEs and m sinks, a channel gain matrix G is thus defined as

$$G = \begin{pmatrix} G_{11} & G_{12} & \ldots & G_{1m} \\ \ldots & \ldots & \ldots & \ldots \\ G_{n1} & G_{n2} & \ldots & G_{nm} \end{pmatrix},$$

which represents channel gains between UEs and sinks completely.

[1] Generally, any signal could be decoded correctly only if its power is greater than the power of interference. Although it is not the case for signals of Code Division Multiple Access (CDMA) and Direct Sequence Spread Spectrum (DSSS), the signal power after spectrum de-spreading is still larger than the power of interference.