Efficient Scheduling for Delay Constrained CDMA Wireless Sensor Networks

Min Chen Changyoon Oh Aylin Yener
Wireless Communications and Networking Laboratory
Electrical Engineering Department
The Pennsylvania State University
University Park, PA 16802
mchen@psu.edu *cxo155@psu.edu* *yener@ee.psu.edu*

***Abstract*— We consider efficient scheduling for a delay constrained CDMA Wireless Sensor Network (WSN). Given a two-tiered WSN model, we first find the optimum schedule for the intra-cluster communications, that minimizes the total transmit power of the sensor nodes, while maintaining the short term average throughput at each sensor. We show that the specifics of the scheduling problem enables it polynomially solvable. Next, We consider the inter-cluster communications where cluster heads are capable of employing two antennas and use Alamouti scheme to achieve the transmit diversity (TD). We observe that our proposed scheduling protocol applied to the inter-cluster communications provides a near-optimum solution, with a modest sacrifice in performance and significant savings in computational complexity as compared to the optimum scheduler. Simulation results are presented to demonstrate the performance of the proposed scheduling protocols, and the considerable power savings they provide with respect to the TDMA-type scheduling.**

I. INTRODUCTION

Efficient transmission strategies are of great interest in Wireless Sensor Networks (WSNs) due to the limited battery resources of the sensor nodes [1]. Scheduling plays an important role in efficient data collection and network lifetime maximization by coordinating the sensor data transmissions in WSNs [2], [3]. As Code Division Multiple Access (CDMA) technology has recently been applied to WSNs to support applications with high bandwidth and strict latency requirements [4], [5], careful coordination of transmissions are needed for CDMA WSNs as well with emphasis on battery efficiency and delay requirement. Given the fact that in many WSNs, fairness among sensor nodes is a critical design issue [6], existing scheduling protocols for CDMA systems [7], [8] cannot be directly applied to CDMA WSNs since fairness in terms of the throughput of each node is not considered. This motivates us to find the efficient schedule that will provide not only the efficient reliable communication but also a short term average throughput guarantee at each sensor for CDMA WSNs.

In this paper, we investigate the efficient scheduling and the resulting power allocation problem for a delay constrained CDMA WSN, which is modeled as a two-tiered network shown in Fig. 1. The tiered network structure is preferred especially in large-scale WSNs due to the advantages such as simpler logic functions on sensor nodes, easier management of the network, and longer system lifetime [9], [10]. The data collection includes two phases, *intra-cluster* collection at each cluster head (CH) from sensors belonging to that cluster, and *inter-cluster* collection at the sink from all CHs. Specifically, we consider a multi-rate CDMA WSN facilitated by the aid of multiple codes. Multiple codes belonging to each node become *virtual* nodes, and will create interference for each other if they transmit at the same time. Our aim is to schedule the virtual nodes into a given number of time slots with equal duration, such that the total transmit power is minimized, while the Signal-to-Interference-plus-Noise-Ratio (SINR) target is satisfied at all CHs and the sink.

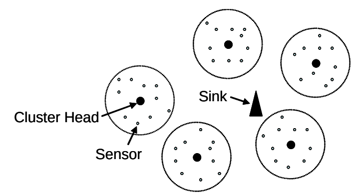

Fig. 1. A two-tiered wireless sensor network model.

The scheduling problem looks similar to the bin packing problem which is NP-complete [11], fortunately, the specifics of the intra-cluster communications enables it polynomially solvable by a shortest path algorithm. Next, we investigate the scheduling problem for inter-cluster communications when each CH employs the Alamouti scheme to achieve the transmit diversity (TD). We show that the proposed scheduling strategy with polynomial complexity provides a near-optimal solution in such case. Our numerical results demonstrate that considerable power savings can be obtained by the proposed schemes with respect to the Time Division Multiple Access (TDMA)-type scheduling scheme, which schedules nodes in a round robin fashion, i.e., one node transmitting in one slot.

II. TWO-TIERED CDMA WSN MODEL AND ASSUMPTIONS

We consider a WSN consisting of a data sink and K_c clusters. Each cluster includes K sensor nodes equipped with single antenna due to the size and cost limitations, and a CH which is the device of larger size and more power that can be equipped with two antennas and apply Alamouti space-time coding [12] to achieve TD. We assume passive clusters waiting for data queries from the sink, which is a common approach [13]. When the clusters are triggered by a query, the data collection starts, and all nodes are synchronized by the trigger signal from the sink. It involves two consecutive phases Ph_1 and Ph_2, consisting of a frame of n and m time slots, respectively. All intra-cluster communications simultaneously happen in Ph_1, when each CH collects data from sensors belonging to the same cluster. By the end of Ph_1, CHs complete the local sensor data aggregation and processing. Next, the inter-cluster communications proceed in Ph_2, when CHs transmit the processed data to the sink. We assume all slots have equal duration.

We consider a multi-rate CDMA WSN where each node (sensor node as well as CH) may change its transmission rate by the number of codes it uses in each slot, but maintains the required average rate in a frame. Multiple codes are considered as *virtual* nodes, and interfere with each other if they transmit in the same slot. The spreading codes are assumed to be randomly generated signature sequences.

We assume all channels are quasi-static with flat fading, i.e., the fading coefficients remain constant during a frame. Given the fact that in many applications, each cluster would be deployed at a strategic location, we can safely assume that the clusters are sufficiently far away from each other. Thus, rather than considering a schedule over multiple clusters, we assume that the inter-cluster interference is included in the noise term and concentrate on each cluster. We also assume that the power levels of sensor nodes are much lower as compared to CHs, a reasonable assumption in light of the fact that CHs are considered to be able to communicate over longer distances to the sink, and this enables us to consider each tier separately. Having this two-tiered WSN model, we next address the efficient scheduling problem for both intra- and inter-cluster communications.

III. Scheduling for Intra-cluster communications

In this section, we investigate the scheduling protocol for the communications in one cluster, which would be implemented in each cluster in Ph_1.

A. Problem Formulation

We consider a cluster where K sensor nodes communicate with a CH. Let g_i denote the channel fading coefficient of the ith sensor node to the CH, for $i = 1, ..., K$, and σ^2 denote the variance of the Additive White Gaussian Noise (AWGN) term at the CH. The CH employs matched filters to decode the sensors' data from the received signals. The SINR of the kth virtual sensor of node i in time slot l is defined as

$$SINR_{i_k l} = \frac{N p_{i_k l}|g_i|^2}{(\sum_{j=1}^{K}\sum_{j_k=1}^{K_{jl}} p_{j_k l}|g_j|^2 - p_{i_k l}|g_i|^2) + I} \quad (1)$$

where $p_{j_k l}$ denotes the transmit power of the kth virtual sensor of the jth node in the lth slot, K_{jl} denotes the number of virtual sensors of node j in slot l, for $j = 1, ..., K$ and $l = 1, ..., n$, N denotes the processing gain, and $I = N\sigma^2$. The average throughput of node i, R_i, during the frame of n slots is

$$R_i = \sum_{l=1}^{n} \frac{K_{il} \times R_{\text{base}}}{n} \quad (2)$$

where $R_{\text{base}} = W/N$ is the rate of a virtual node in one slot, and W is the spreading bandwidth.

We aim to minimize the total power expenditure of all sensors belonging to this cluster in n slots, while satisfying the received SINR target, $SINR_{\text{target}}$, for each virtual node in each slot and the short term throughput requirement, $R_{i_{\text{target}}}$ for node i, $i = 1, ..., K$. The optimization problem can be expressed as

$$\min_{\{K_{il}, p_{i_k l}\}} \quad \sum_{l=1}^{n}\sum_{i=1}^{K}\sum_{i_k=1}^{K_{il}} p_{i_k l} \quad (3)$$

$$\text{s. t.} \quad SINR_{i_k l} \geq SINR_{\text{target}}, \quad \forall i_k, l \text{ such that } p_{i_k l} > 0 \quad (4)$$

$$R_i = R_{i_{\text{target}}}, \quad \forall i \quad (5)$$

$$p_{i_k l} \geq 0, \quad \forall i_k, l \quad (6)$$

We note that the optimum received power for each virtual sensor is achieved when the SINR constraint in (4) is satisfied with equality [14]. Thus, the optimum received power for each virtual sensor in slot l is

$$q_l^* = \frac{I\gamma}{(1+\gamma) - |s_l|\gamma} \quad (7)$$

where $\gamma = SINR_{\text{target}}/N$, s_l denotes the set of virtual sensors scheduled in slot l, and $|s_l| = \sum_{i=1}^{K} K_{il}$. Note that the maximum number of virtual sensors in a slot is limited by $\lfloor (1+\gamma)/\gamma \rfloor$ due to the fact that $q_l^* \geq 0$.

Given the relation between the optimum transmit and received power, $p_{i_k l}^*|g_i|^2 = q_l^*$, the problem in (3)–(6) can be rewritten as

$$\min_{\{K_{il}\}} \quad \sum_{l=1}^{n} q_l^* \sum_{i=1}^{K} \frac{K_{il}}{|g_i|^2} \quad (8)$$

$$\text{s. t.} \quad \sum_{l=1}^{n} K_{il} = \frac{nR_{i_{\text{target}}}}{R_{\text{base}}} \quad \forall i \quad (9)$$

The problem in (8)–(9) is to find K_{il}, the number of virtual sensors of node i in time slot l, for $i = 1, ..., K$ and $l = 1, ..., n$, to minimize the total transmit power in n slots, while node i has $T_i = \frac{nR_{i_{\text{target}}}}{R_{\text{base}}}$ virtual sensors in n slots.

B. Optimum Schedule

In this section, we provide the solution to the optimization problem in (8)–(9). First, we have two observations which give the structure of the optimum scheduling policy.

***Observation** 1:* The optimum policy always schedules a virtual sensor with a lower channel gain to a slot with a lighter load, i.e., a slot with fewer virtual sensors.

To see the validity of observation 1, we suppose that two virtual sensors j and i are scheduled to slot 1 and 2, respectively, with $|g_i|^2 > |g_j|^2$, and $|s_1| > |s_2|$. If we exchange i and j between the two slots, all the virtual sensors except i and j remain the same transmit power level, since q_1^* and q_2^* remain the same. However, the sum of the transmit power of i and j is decreased, i.e., $\frac{q_1^*}{|g_i|^2} + \frac{q_2^*}{|g_j|^2} < \frac{q_1^*}{|g_j|^2} + \frac{q_2^*}{|g_i|^2}$. Hence, the total transmit power is decreased.

Observation 1 provides a valuable clue as to the structure of the optimum schedule. Note that, the collection of virtual sensor sets resulting from *any* scheduling policy can be reordered as $\{s_1, s_2, ..., s_n\}$, such that $|s_1| \leq |s_2| \leq ... \leq |s_n|$, $|s_l| \neq 0$ for $l \in \{1, ..., n\}$, and $\sum_{l=1}^{n} |s_l| = T$. This reordering of virtual sensor sets does not change the total transmit power. Therefore, we only need to find the optimum solution with the reordered virtual sensor sets. Next, we have the following observation.

Observation 2: For any given group of reordered virtual sensor sets, the optimum scheduling order of T virtual sensors is in the order of increasing channel gain, i.e.,

$$\underbrace{|g_K|^2, ..., |g_K|^2}_{T_K}, \underbrace{|g_{K-1}|^2, ..., |g_{K-1}|^2}_{T_{K-1}}, ..., \underbrace{|g_1|^2, ..., |g_1|^2}_{T_1} \quad (10)$$

where $|g_K|^2 \leq |g_{K-1}|^2 \leq ... \leq |g_1|^2$.

Note that the scheduling order in (10) satisfies Observation 1. Hence, the optimization problem in (8)–(9) is to find the best group of reordered virtual sensor sets such that the sum of the total transmit power is minimized, given the optimum scheduling order as in (10). By appropriate transformation, this problem can be formulated as a graph partitioning problem with polynomial complexity, as described next.

The reordered virtual sensor sets in (10) constitute a string $G = (V, E)$ with vertices $V = \{v_1, v_2, ..., v_T\}$ and edges $E = \{(v_1, v_2), ..., (v_{T-1}, v_T)\}$, by sequentially mapping each virtual sensor to the vertex along the string from the left to the right. Given the string G, the virtual sensor sets $\{s_1, s_2, ..., s_n\}$ represent the partition of the set of vertices V into n subsets, with each subset s_l consisting of a set of connected vertices. The cost of a virtual sensor set s_l is $q_l^* \sum_{i \in s_l} \frac{1}{|g_i|^2}$. Therefore, the optimization problem in (8)–(9) is equivalent to finding a feasible n-partition such that the total cost is minimized, i.e.,

$$\min_{\{s_1, ..., s_n\}} \quad \sum_{l=1}^{n} q_l^* \sum_{i \in s_l} \frac{1}{|g_i|^2} \quad (11)$$

$$\text{s. t.} \quad |s_1| \leq |s_2| \leq ... \leq |s_n| \quad (12)$$

We note that, although optimum partitioning an arbitrary graph with an arbitrary cost function is NP-hard, optimum partitioning a string with a separable cost function can be achieved in polynomial time, i.e., the problem in (11)–(12) is reduced to a shortest path problem with complexity $O(nT^2)$ [15]. The solution is described in the following.

We construct a network from the string G which represents the ordered virtual sensors. The nodes that lie between the origin-destination pair are given by the set

$$\{(i, j) : 1 \leq i \leq n-1; i \leq j \leq T-n-1\} \quad (13)$$

An edge is placed from node $(i1, j1)$ to node $(i2, j2)$ if $i2 = i1 + 1$ and $j2 > j1$. Otherwise, there is no edge between $(i1, j1)$ and $(i2, j2)$. There is a one-to-one mapping between the cost function of a feasible partition in a string, and that of a path in the network constructed from the string. For node (i, j), i and j denote the index of the time slot and the index of the virtual sensor, respectively. The cost of a path between nodes $(l-1, t)$ and $(l, t+x)$ is the transmit power cost of the virtual sensor set s_l, i.e., $q_l^* \sum_{i \in s_l} \frac{1}{|g_i|^2}$,

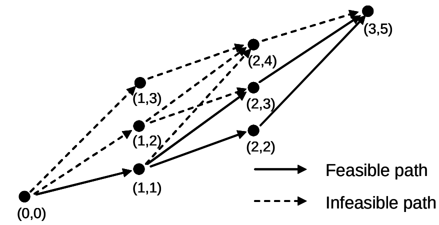

Fig. 2. A network constructed by a 3-partitioning of a 5-vertex string.

where $x = |s_l|$. Note that the optimum policy should satisfy $|s_1| \leq |s_2| \leq ... \leq |s_n|$, and $|s_l| \leq \lfloor (1+\gamma)/\gamma \rfloor$ for any l. If a path violates any of these two constraints, the cost of the path is set infinite, i.e., the path is infeasible. In Fig. 2, we present a network constructed from a 5-vertex string with 3 partition sets, i.e., $T = 5$ and $n = 3$. Next, a shortest path from the origin to the destination with minimum cost is obtained by a shortest path algorithm such as Dijkstra's algorithm with complexity $O(nT^2)$. The resulting optimum partition $\{s_1, s_2, ..., s_n\}$ provides the optimum schedule with K_{il}, for $i = 1, ..., K$and $l = 1, ..., n$.

IV. Scheduling for Inter-cluster communications

In this section, we investigate the efficient scheduler for the inter-cluster communications in phase Ph_2. As assumed in Section II, when the CHs are nodes of larger size that have more complicated hardware and more processing capacity, it is feasible to have each CH be equipped with two transmit antennas and employ Alamouti scheme [12] to exploit the TD.

A. Transmission Scheme of CHs with TD

We first present the transmission scheme of the CHs employing the Alamouti scheme. Contrary to [16] which studies the space-time spreading scheme for systems with orthogonal spreading codes, we assume here a CDMA WSN with non-orthogonal spreading codes. We consider the WSN with K_c CHs, and m time slots in Ph_2. The ith CH cooperatively communicates zero-mean independent signals s_{i1} and s_{i2} from two antennas with the sink in two time slots. The transmission scheme of CH i is shown in Fig. 3. We assume that both antennas of CH i have the same transmit power level, i.e., $p_{i1} = p_{i2} = p_i$, so that the total power is $2p_i$. The channel fading coefficients of the antenna 1 and 2 of CH i are denoted by g_{i1} and g_{i2}, respectively, and c_i denotes the randomly generated spreading code of CH i, for $i = 1, ..., K_c$. We next investigate the efficient scheduling protocol for inter-cluster communications.

B. Scheduling for CHs Transmissions

In this section, we provide the solution to the problem that schedules the transmissions of K_c CHs with TD into m time slots. We define the simultaneous transmissions of the signals s_{i1} and s_{i2} from CH i's antenna 1 and 2 as a *super transmission* TX_i, and the simultaneous transmissions of the conjugate

		slot m_1	slot m_2
CH i	Antenna 1 (g_{i1})	$s_{i1}c_i$	$-s_{i2}^* c_i$
	Antenna 2 (g_{i2})	$s_{i2}c_i$	$s_{i1}^* c_i$

Fig. 3. Transmission scheme of CH i with Alamouti scheme.

	other slot	slot m_1	slot m_2	other slot
CH i		T_i	T_i^*	
CH j: case 1		T_j	T_j^*	
CH j: case 2		T_j		T_j^*
CH j: case 3	T_j		T_j^*	
CH j: case 4	T_j			T_j^*

Fig. 4. Possible scheduling schemes of CH j with Alamouti scheme.

signals, i.e., s_{i1}^* and $-s_{i2}^*$ as a *super transmission* TX_i^*, $i \in \{1, ..., K_c\}$. Since each CH has two super transmissions, each taking one slot, there are $2K_c$ super transmissions to be scheduled into m slots. We have two observations showing that with some scheduling constraints, the optimum scheduling protocol proposed in Section III is readily applicable to the scheduling problem for the inter-cluster transmissions.

***Observation** 3:* The super transmission of CH i, TX_i, should not be scheduled into the same time slot with the super transmission TX_j^* of CH j, for $i, j \in \{1, ..., K_c\}$.

It is easily seen that if TX_i, the transmissions of s_{i1} and s_{i2}, are scheduled in the same time slot with TX_j^*, the transmissions of s_{j1}^* and $-s_{j2}^*$, for $i, j \in \{1, ..., K_c\}$, the decoder structure of the Alamouti scheme cannot decouple either s_{i1} and s_{i2}, or s_{j1} and s_{j2}, and therefore cannot successfully recover the data at the sink. Thus, any schedule violates Observation 3 should be avoided.

For any scheduler consistent with Observation 3, let CH i be the target CH, then the other CH j ($j \neq i$) has four possible schedule schemes as shown in Fig. 4: $[(T_j T_i), (T_j^* T_i^*)]$, $[(T_j T_i), (T_j^* | T_i^*)]$, $[(T_j | T_i), (T_j^* T_i^*)]$, and $[(T_j | T_i), (T_j^* | T_i^*)]$, where (XY) means that super transmissions X and Y are scheduled in the same time slot, and $(X|Y)$ means that X and Y are scheduled in different time slots. It is easily shown that the SINR of CH i can be written as

$$\begin{aligned} &SINR_{s_{i1}} = SINR_{s_{i2}} \\ &= \frac{N|g_i|^2 p_i}{\left\{ A_i \sum_{j \in \mathcal{F}_i} |g_j|^2 p_j + B_i \sum_{j \in \mathcal{L}_i} |g_j|^2 p_j \right\} + I} \end{aligned} \tag{14}$$

where $|g_i|^2 = |g_{i1}|^2 + |g_{i2}|^2$, $|g_j|^2 = |g_{j1}|^2 + |g_{j2}|^2$, $A_i = |g_{i1}|^2 / |g_i|^2$, $B_i = |g_{i2}|^2 / |g_i|^2$, and $A_i + B_i = 1$. $\mathcal{F}_i$ denotes the set of CHs whose TX_j are scheduled in the same time slot as TX_i of CH i, and $\mathcal{L}_i$ denotes the set of CHs whose TX_j^* are scheduled in the same time slot as TX_i^* of CH i.

We note that in the SINR expression given in (14), we lose the form given in Section III, and the scheduler with polynomial complexity is no longer guaranteed. However, when $\mathcal{F}_i = \mathcal{L}_i$, the SINR in (14) is reduced to

$$SINR_{s_{i1}} = SINR_{s_{i2}} = \frac{N|g_i|^2 p_i}{\sum_{j \in \mathcal{F}_i} |g_j|^2 p_j + I} \tag{15}$$

Note that (15) is in the same form as (1). Thus, we have the following observation.

***Observation** 4:* The problem of scheduling $2K_c$ super transmissions into m time slots for inter-cluster communications is equivalent to scheduling K_c sensor nodes into $m/2$ time slots[1] for intra-cluster communications, given that each CH is considered as a single-antenna node with the equivalent channel gain $|g_i|^2 = |g_{i1}|^2 + |g_{i2}|^2$, and the two time slots it takes are bounded together into one.

With Observation 4, we note that the scheduling protocol proposed in Section III achieves a near-optimum schedule to the inter-cluster transmissions, by excluding the scheduling schemes of case 2 and 3 in Fig. 4. It significantly reduces the computational cost of finding the optimum schedule with the modest performance penalty, shown in Section V by numerical results. Note that same results can be directly applied to the multi-rate CDMA CHs as well.

V. NUMERICAL RESULTS

We consider a two-tiered CDMA WSN consisting of 5 clusters distributed without overlapping in a circle area with radium $1000m$, and a sink located in the center. Each cluster includes 20 sensor nodes distributed in a circle area with radium $100m$, and a CH in the center. The spreading bandwidth is $W = 1.228MHz$, and the processing gain is $N = 128$, equivalently, $R_{\text{base}} = 9.6Kbps$. The duration of Ph_1 and Ph_2 is 5 and 10 time slots, respectively. The fading coefficient of sensor i, g_i, is modeled as independent complex Gaussian with variance $\sigma_{g_i}^2 = C/d_i^\alpha$, where d_i denotes the distance between sensor i and its CH. We assume that the two antennas of CH i have the same distance to the sink, denoted by d_{CH_i}, and therefore the fading coefficients of the two antennas are independent complex Gaussian with the same variance, i.e., $\sigma_{g_{i1}}^2 = \sigma_{g_{i2}}^2 = C/d_{CH_i}^\alpha$. The path-loss exponent is denoted by α, and C is a constant. The values $\alpha = 3$, $C = 7 \times 10^{-4}$, and $SINR_{\text{target}} = 7dB$ are used throughout our simulations. The AWGN variance is assumed to be 10^{-13}.

Simulation results are presented to demonstrate the performance of the proposed scheduling protocols, compared with the TDMA-type schedule, in which node i transmits with rate $nR_{i_{\text{target}}}$, and all nodes transmit in a round robin fashion, i.e., only one node transmits in one time slot. Specifically, we plot the total transmit power versus the average throughput requirement at each node.

We first compare the performance of different schedules for inter-cluster communications. Fig. 5 shows the total transmit power for a common average throughput requirement at each sensor node as $R_{i_{\text{target}}} = \{1.92Kbps, 3.84Kbps, 5.76Kbps, 9.6Kbps\}$, for $i = 1, ..., 20$. We observe that a substantial amount of power is saved by employing the optimum schedule, with respect to the TDMA-type schedule. As the average throughput requirement increases, i.e., the sensors loads get heavier, the gap between the performance of the optimum schedule and that of the TDMA-type schedule increases. This result clearly indicates the benefit of the optimum schedule for a loaded CDMA WSN.

We also investigate the performance of the schedule for inter-cluster communications. We first compare the optimum

[1]It is assumed that m is an even integer, i.e., the delay requirements can accommodate up to one wasted slot if necessary.

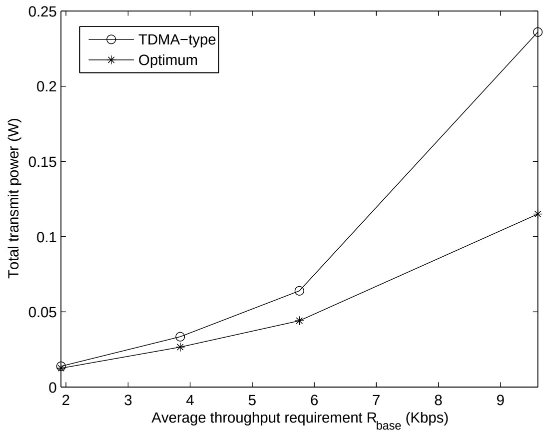

Fig. 5. Total power consumption of intra-cluster communications.

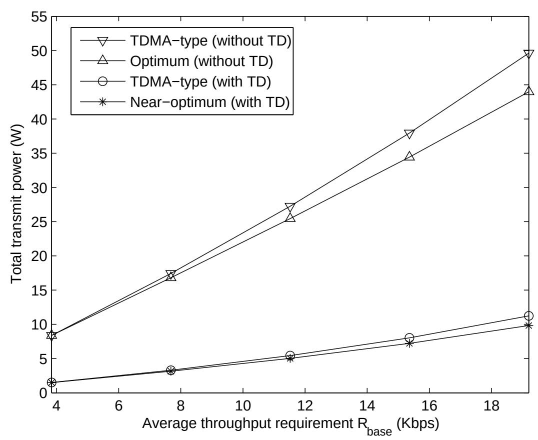

Fig. 6. Total power consumption of inter-cluster communications.

and the near-optimum schedule for a WSN consisting of $\{4, 5, 6\}$ CHs, each taking 2 slots to transmit and having the average throughput requirement $R_{i_{\text{target}}} = 9.6Kbps$. The frame consists of 6 slots. Table I shows that the near-optimum schedule incurs less than 10% performance penalty while significantly reduces the computational complexity of the optimum schedule, which is achieved by exhaustive search. Next, we consider the larger system with 5 CHs and 10 slots. The common average throughput requirements are $R_{i_{\text{target}}} = \{3.84Kbps, 7.68Kbps, 11.52Kbps, 15.36Kbps, 19.2Kbps\}$, for $i = 1, ..., 5$. For the case without TD, we assume that each CH is equipped with single antenna and no TD is exploited. Comparing the performance with and without TD shown in Fig. 6, we observe that a large amount of power is saved by TD. At the same time, more power is saved by the near-optimum schedule with respect to the TDMA-type schedule.

VI. Conclusions

In this work, we have considered efficient scheduling strategies for delay constrained multi-rate CDMA WSNs. Short term average throughput requirements are imposed to maintain an average throughput in addition to the QoS requirements (SINR target) for each node. It is assumed that multiple data rates are provided by means of multiple spreading codes, each of which is treated as a virtual node and interferes with each other when transmitting simultaneously. We have provided the efficient scheduling algorithm with polynomial complexity, which is the optimum and near-optimum solution to the intra-cluster and inter-cluster communications, respectively. The numerical results demonstrate that significant power savings is achieved by the proposed scheduling protocols.

TABLE I
Comparison of the optimum and near-optimum schedule on total transmit power.

Number of CHs	Optimum (W)	Near-optimum (W)	Penalty
4	0.5516	0.5738	4.03%
5	0.6915	0.7386	6.82%
6	0.8307	0.8993	8.26%

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