Joint Convergecast and Power Allocation in Wireless Sensor Networks

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***Abstract*—Convergecast is a critical communication paradigm for data collection in wireless sensor networks, where both energy and bandwidth are scarce resources. Previous convergecast algorithms only focused on minimizing the energy cost without considering the constraint of wireless bandwidth. This article shows that constructing a congestion-free convergecast tree cannot ignore the bandwidth constraint. Considering the adjustable transmission power of sensor nodes, it will affect not only the topology of networks but also the bandwidth of wireless links. In this paper, we formulate the Minimum Total Transmission Power (MTTP) problem, which aims to address the issue of constructing a congestion-free convergecast tree in WSNs with adjustable transmission power of sensor nodes. We transform MTTP to an Integer Linear Programming (ILP) model, by which the optimal solution to MTTP is derived. To strike a balance between scheduling overhead and system performance, we propose a heuristic algorithm called *Nearest-to-Sink*, which searches viable paths in a greedy way and achieves near optimal performance. We build the simulation model and give a comprehensive performance evaluation, which demonstrates the feasibility and the effectiveness of the proposed algorithm.**

Keywords*—Wireless sensor networks; Convergecast; Power allocation; Routing; Energy-efficient scheduling

I. Introduction

In the last decade, wireless sensor networks (WSNs) are widely applied in medical, military and environment monitoring applications, etc. Data collection is the basic operation in WSNs. The sensor node measures and collects required information from physical environments and transmits the data to the base station (i.e. the Sink). The collected data are forwarded to the Sink through sensor nodes over a tree based routing topology. This kind of many-to-one communication paradigm is called *convergecast*, which can be considered as reverse flows generated by data broadcasting [1], where the collected data 'upwards' from branch nodes in the network to a central node. Many previous studies have investigated convergecast in WSNs [2] [3] [4].

Considering the limited power supply and the constrained computational capability, energy-efficient convergecasting is desired in WSNs. In practical applications, especially for those with high sampling rates (such as acoustics, seismology, etc), the aggregated bandwidth requirement can be surprisingly high. When the bandwidth of a link is less than the required transmission data rate, the congestion occurs, which causes only part of the collected data can be transmitted to the Sink. In these applications, the data congestion seriously decreases the performance of convergecasting. Therefore, it is critical to consider the bandwidth constraint when constructing the routing tree for convergecast. On the other hand, advances in the micro-electronics industry and wireless technologies have led to the development of power allocation methods in ad-hoc networks, which can be adopted to adjust the transmission power of sensor nodes to achieve the best signal to noise ratio (SNR) [5]. In view of this, we focus on the issue that the sensor node is able to adjust its transmission power in order to save energy without jeopardizing the performance of data delivery. In other words, we study on the problem of jointing convergecast and power allocation in WSNs with bandwidth constraint to minimize the total energy consumption.

In particular, it is a cross-layer design problem, which requires integrated design in the network layer (convergecasting) and the physical layer (power allocation). To this end, we schedule the data transmission by constructing a congestion-free convergecast tree and propose a power management policy to minimize the total transmission power. Specifically, the allocated power level of each node ensures that the bandwidth of each link in the constructed congestion-free convergecast tree is sufficient to transmit the aggregated data flow. Previous work related to energy-efficient routing did not consider the bandwidth constraint [6] [7], which are not suitable for the applications with high data sampling rates. Some other studies [8] [9] considered the bandwidth issue by reducing the size of data using techniques such as compression and in-network aggregation. However, these solutions are not suitable for applications where raw data instead of summaries are required, such as volcanic monitoring [10], etc. A few studies [11] [12] considered both power optimization and bandwidth constraint. However, they assume a constant transmission power in a

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static network topology. In contrast, this work considers the adjustable power level of nodes, and the data transmission range changes with different power levels, which implies that the topology of the network is dynamic. Relevant works which considered dynamic topology, joint routing and power allocation include [13] and [14]. However, they are designed for end-to-end QoS constraints, which is different from our targets, namely, the many-to-one constraint required for convergecasting. Clearly, it is challenging to allocate power levels and construct congestion-free convergecast tree for energy-efficient convergecasting in such a dynamic network topology environment.

The contributions of this paper are outlined as follows. First, we formulate the problem of jointing convergecast and power allocation in WSNs. Second, we propose an ILP model for deriving the optimal solution to MTTP. In addition, we propose a heuristic algorithm which constructs the tree and generates the schedule for convergecasting in a greedy way. Third, we build the simulation model and give a comprehensive performance evaluation, which demonstrates that the proposed heuristic algorithm can achieve near-optimal performance and it is practical for application with high data sampling rates.

The remainder of the paper is organized as follows. Section II reviews the related work. Section III describes the system model and formulates the MTTP. In Section IV, we derive an ILP model and propose a heuristic algorithm. Section V gives performance evaluation. Finally, we conclude this work and discuss future research directions in Section VI.

II. Related Work

Convergecast is the aggregation of data collected at each node in the network towards a central node. Existing solutions for convergecast normally consist of two phases: a tree construction phase and a scheduling phase. A heuristic algorithm called CTCCAA is proposed by Annamalai et al. [2]. It constructs a tree and assigns different time slots to each node to achieve collision-free convergecasting. The algorithm supports code allocation (Direct Sequence Spread Spectrum (DSSS)/ Frequency Hopping Spread Spectrum (FHSS)) to minimize the total duration required for convergecasting. Malhotra et al. [3] considered the problem of scheduling in WSNs for aggregation convergecast. However, energy-efficient communication were not considered in these studies.

Considering the limited power supply, energy-efficient communication is essential in WSNs. Upadhyayula et al. [6] proposed a heuristic solution to minimize the energy and data latency in convergecast. It addressed the problem of energy-efficient convergecast communication by proposing a CDMA/TDMA based algorithm that constructs a tree and schedules its nodes for collision-free transmission. Then, it allocates DSSS or FHSS codes. However, it did not consider the bandwidth constraint in scheduling.

The bandwidth constraint has been demonstrated critical in convergecast, especially for applications with high data sampling rates. Concentrating on throughput performance, Fu et al. [15] proposed a new type of many-to-one cooperative schemes with MIMO for both static and mobile networks. The hierarchical cooperation scheme under static networks can achieve a high aggregate throughput. Lai et al. [11] separated the problem of optimizing data-collecting throughput to avoid interference and collisions into two stages: 1) constructing a routing structure on a given deployment; 2) scheduling the activation time of each link. They improve the throughput by arranging communications to minimize the length of the schedule. Cheng et al. [12] discussed the sufficient condition on link bandwidth that makes a routing solution feasible, and then they proposed mathematical optimization models to tackle both energy and bandwidth constraints. The routing structures considered in these works are static. In this work, the transmission range of a node varies with the different selected power levels, which makes the network topology change dynamically.

Considering dynamic topology in WSNs caused by adjustable transmission power of nodes, a number of researches have put effort on the problem of joint routing and power allocation. Cheng et al. [16] addressed the problem of maximizing throughput in WSNs through cross-layer optimization. First, they use transmission power control to decide the link topology, and then they use joint routing and link rate control to decide the maximum achievable throughput on the topology. However, they only considered the transmission radius coverage without addressing the bandwidth variation due to various transmission power levels. The physical model is applicable only when the bandwidth (i.e. the capacity of a link) parameter is static. Different from the above efforts,, we investigate the problem that both the transmission range and the bandwidth change with different transmission power levels.

To sum up, distinguishing from previous studies, the formulated problem in this work considers the energy efficiency from the power perspective and bandwidth assurance from the QoS perspective simultaneously, and the proposed solution is committed to scheduling the power allocation and constructing a congestion-free convergecast tree to achieve energy-efficient convergecasting.

III. Problem Description

In this section, we first present the system model and introduce the unique characteristics of convergecast in such a system. Then, we formulate MTTP. Last, we give an example to highlight the critical issues in MTTP.

A. System Model

1) Transmission power: Similar with [17] [18], in this model, we consider multiple discrete transmission power levels, in which the power of a sensor node at each level is fixed. For example, $CC2240$ [19] supports five transmission power levels. Let K denote the number of power levels. TX_k represents the transmission power of power level k, where $1 <= k <= K$. The transmission radius with the power level k is denoted by R_k. The system consists of N wireless sensor nodes. Each node equips with a transceiver which can transmit data up to the maximum range of R_K. Neighboring sensors refer to those which are within the transmission range of each other.

The receiver node could correctly decode the data only when the signal to noise ratio (SNR) at the receiver is above a certain threshold SNR_{min}. The transmission power (in dBm) is obtained by $TX_k = R_k^{\alpha} \times SNR_{min} \times P_{\eta}$ [20], where P_{η}

denotes the noise power and α denotes the power attenuation factor which is usually between 2 to 4.

2) Bandwidth model: The bandwidth between a sender and a receiver depends on the modulation of the sender. Adaptive modulation can increase bandwidth by taking advantage of signal quality at the receiver. On the one hand, advanced modulation (e.g. 64QAM) could be used at the sender to achieve higher bandwidth when the signal quality is good at the receiver. On the other hand, ordinary modulation (e.g. BPSK) at the sender could be used in case of poor signal quality with lower supported bandwidth. For example, in IEEE 802.11a, the effective bandwidth could be 6, 9, 12, 18, 24, 36, 48, and 54Mbps corresponding to different signal quality levels. More sophisticated modulation schemes require higher SNRs to maintain the same bit error rate (BER) for decoding at the receiver. In general, the bandwidth between the sender and the receiver is closely related to the link distance and the sender transmission power. The function $SB(d, R_k)$ is adopted to represent the supported bandwidth of a link, where d indicates the distance between two nodes and R_k indicates the sender transmission radius in power level k.

3) Network architecture: We assume a fixed and known location of each node in this model, which is practical in many applications requiring the pre-deployment of sensor nodes [21]. The rate of the data being sensed by a node is called the sampling rate [22]. Each sensor node has a unique sampling rate, which is known and fixed [23]. Apparently, the bandwidth of a link should be at least as large as the sender's sampling rate to avoid congestion.

Let $G = \{V, SR, D\}$ be the network deployment, where $V = \{v_1, v_2, ...v_N\}$ and $D = \{d_{1,2}, ..., d_{i,j}, ..., d_{N-1,N}\}$, which are the sets of nodes and the distances between each pair of nodes, respectively. $d_{i,j}$ represents the distance between node i and node j. Let sr_i represent the sampling rate of node i. The set is SR represented by $SR = \{sr_1, ..., sr_i, ..., sr_N\}$.

B. Minimum Total Transmission Power (MTTP) problem

Considering N sensors are deployed in a multihop WSN. G is the topology of the network. For convenience, we consider the node v_N as the Sink. A node in the WSN is not only a sensor node, but also a relay node. One node transmits its sampling data to its next hop and in the meantime, relays the received data to its next hop. It implies that the sampling rate of a node is the minimum required transmission rate when it is not relaying any data. We use $throughput_i$ to denote the required transmission data rate of node i. In other words, $throughput_i$ is the the sampling rate plus the relay rate of node i. If node j is the next hop of node i and node i is working in power level k, to ensure that the sampling data of all nodes could arrive at the Sink without congestion, the transmission bandwidth has to satisfy:

$$SB(d_{i,j}, R_k) >= throughput_i, \forall 1 <= i <= N-1. \quad (1)$$

To enable the required bandwidth, each node is expected to work in a sufficient power level. Since energy-efficient transmission is critical in WSNs, the power allocation and convergecast tree construction should be designed aligning with such a purpose. As mentioned in [20], the transmission power is the most critical factor which influences the overall power consumption. Therefore, in this paper, we consider the problem of minimizing the total transmission power.

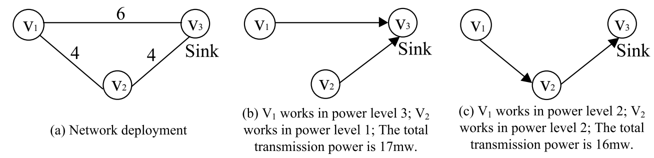

Fig. 1. An example of convergecast in WSNs.

We formulate the Minimum Total Transmission Power (**MTTP**) problem as follows: *Given a graph $G = \{V, SR, D\}$, the sensor node with K power levels, the transmission power of each level TX_k, and the supported bandwidth function $SB(d, R_k)$, the objective is to construct a convergecast tree and allocate a power level to each node such that (1) The bandwidth of each link is no less than the minimum required link throughput. (2) The total transmission power of the nodes is minimized.* In other words, MTTP is to achieve $\min \sum_{i=1}^{N-1} p_i$, subject to Equation 1, where p_i denotes the allocated power of node i.

C. An example

We give an example to better illustrate MTTP. As shown in the Figure 1(a), v_3 is the Sink. The distance between each pair of nodes is marked on the edge (with the unit of miles). The sampling rates of v_1 and v_2 are $sr_1 = 30kbps$ and $sr_2 = 10kbps$, respectively. Assume that each sensor node has three transmission power levels, namely, $TX_1 = 5mw$, $TX_2 = 8mw$, $TX_3 = 12mw$. The supported bandwidth SB is shown in Table I. For example, when the transmission power level is 3, the distance between the sender and the receiver must be within 6 miles to achieve the bandwidth of 40 kbps.

TABLE I. THE SUPPORTED BANDWIDTH UNDER DIFFERENT POWER LEVELS AND NODE DISTANCES.

Parameters			Supported
Power level	Radius (miles)	Distance (miles)	Bandwidth (kbps)
1	4	4 < d	0
		2 < d ≤ 4	20
		0 < d ≤ 2	40
2	6	6 < d	0
		4 < d ≤ 6	20
		0 < d ≤ 4	40
3	8	8 < d	0
		6 < d ≤ 8	20
		0 < d ≤ 6	40

Intuitively, there are two viable schedules for power allocation and convergecast tree construction to guarantee congestion-free convergecast. Figures 1(b) and (c) show these two solutions in detail. The arrow indicates the transmission direction in convergecast tree. For example, in Figure 1(c), node 1 sends its sampling data to node 2, and node 2 sends the data (including its own sampling data and the received data) to node 3 (i.e. the Sink). In this case, node 1 transmits data with power level 2 (i.e. 8 mw), and the distance between node 1 and node 2 is 4 miles. According to Table I, the supported bandwidth between node 1 and node 2 is $SB(d_{1,2}, R_2) = 40kbps$, which is larger than the throughput of node 1 (i.e. $30kbps$). In contrast, if power level 1 is selected, we have $SB(d_{1,2}, R_1) = 20kbps$, which cannot satisfy the throughput requirement. Therefore, the power level 2 is chosen by node 1 to satisfy the throughout requirement with minimum power consumption. Similarly, the allocated power level of node 2 is level 2. The total transmission power in Figures 1(b) and (c) are $17mw$ and $16mw$, respectively. Therefore, the solution shown in Figure 1(c) is the optimal in this example.

IV. Proposed Solutions

In this section, we first derive an ILP model to find the optimal solution. Then, we propose a heuristic algorithm to strike a balance between the scheduling overhead and the system performance.

A. Optimal ILP Model

1) Input transformation: First, we integrate two of MTTP's inputs, namely, the set D and the function SB into a set denoted by $Band$, where $Band = \{..., band_{i,j,k}, ...\}, 1 \leq i, j \leq N, 1 \leq k \leq K$. $band_{i,j,k}$ represents the bandwidth of node j receiving from node i when node i is working in power level k. With such a setup, we have $band_{i,j,k} = SB(d_{i,j}, R_k)$.

2) Binary variable:

- $X_{i,j,k}$ is a binary variable such that $X_{i,j,k} = 1$ if and only if the next hop of node i is node j and node i works in power level k. For example, in Figure 1(b), $X_{1,3,3} = 1$.

$$X_{i,j,k} \in \{0,1\}, \quad \forall i,j,k(1 \leq k \leq K, 1 \leq i \leq N, 1 \leq j \leq N). \tag{2}$$

- $Y_{i,j}$ is a binary variable such that $Y_{i,j} = 1$ if and only if the data are sent from node i to the Sink via node j. For example, in Figure 1(b), $Y_{1,3} = 1$, and $Y_{1,2} = 0$.

$$Y_{i,j} \in \{0,1\}, \forall i,j(1 \leq i \leq N, 1 \leq j \leq N). \tag{3}$$

- $Z_{i,s,j}$ is a binary variable such that $Z_{i,s,j} = 1$ if and only if the next hop of node i is node s and the data are sent from node s to the Sink via node j. For example, in Figure 1(c), $Z_{1,2,3} = 1$.

$$Z_{i,s,j} \in \{0,1\}, \forall i,s,j(1 \leq i,s,j \leq N). \tag{4}$$

3) Constraints:

- The next hop of one node could not be itself and the node is included in the path of itself to the Sink:

$$Y_{i,j} = 1, X_{i,j,k} = 0, \quad \forall i,j,k(1 \leq i \leq N, 1 \leq j \leq N, 1 \leq k \leq K, i = j). \tag{5}$$

- All sampling data will converge to the Sink. In another word, the Sink is the end of all data paths:

$$Y_{i,N} = 1, Y_{N,i} = 0, \forall i(1 \leq i \leq N-1). \tag{6}$$

- If there exists at least one node (denoted as s) which is the next hop of node i and the data are sent from node s to the Sink via node j, we can determine that node j is also in the path of node i to the Sink. The relationship can be formulated as follows:

$$\exists s, \sum_{k=1}^{K} X_{i,s,k} = 1 \cap Y_{s,j} = 1 \Leftrightarrow Y_{i,j} = 1. \tag{7}$$

To transform the sufficient and necessary condition (i.e. Equation 7) to linear inequalities, we use the intermediate variable $Z_{i,s,j}$. Equation 7 can be divided into two parts:

$$\sum_{k=1}^{K} X_{i,s,k} = 1 \cap Y_{s,j} = 1 \Leftrightarrow Z_{i,s,j} = 1. \tag{8}$$

$$\exists s, \ Z_{i,s,j} = 1 \Leftrightarrow Y_{i,j} = 1. \tag{9}$$

We formulate two linear inequalities (Equation 10 and Equation 11) to represent Equation 8 and Equation 9 respectively:

$$(\sum_{k=1}^{K} X_{i,s,k} + Y_{s,j} - 1)/3 \leq Z_{i,s,j} \leq (\sum_{k=1}^{K} X_{i,s,k} + Y_{s,j})/2, \quad \forall i,j,s(1 \leq i,j,s \leq N, i \neq s, j \neq s). \tag{10}$$

$$\sum_{s=1,s\neq i}^{N} Z_{i,s,j}/(N-1) \leq Y_{i,j} \leq \sum_{s=1,s\neq i}^{N} Z_{i,s,j}, \quad \forall i,j(1 \leq i,j \leq N, i \neq j). \tag{11}$$

- Obviously, a loop must be avoided in a path. We formulate the constraint as:

$$Y_{i,j} + Y_{j,i} \leq 1, \forall i,j(1 \leq i,j \leq N, i \neq j). \tag{12}$$

- Each sensor node has only one next hop and works in one power level given a certain schedule. The Sink does not have the next hop. This is formulated as:

$$\sum_{j=1}^{N}\sum_{k=1}^{K} X_{i,j,k} = 1, \sum_{j=1}^{N}\sum_{k=1}^{K} X_{N,j,k} = 0, \forall i(1 \leq i \leq N-1). \tag{13}$$

- All sampling data should arrive at the Sink, which implies that the bandwidth of a link should be larger than the data rate transmitted via the link. This constraint is formulated by:

$$\sum_{s=1}^{N}(Y_{s,i} \times sr_s) \leq \sum_{j=1}^{N}\sum_{k=1}^{K}(X_{i,j,k} \times band_{i,j,k}), \quad \forall i(1 \leq i \leq N-1). \tag{14}$$

4) Objective function: The objective is to minimize the total transmission power. Let p_i represent the transmission power of node i. p_i is computed by:

$$p_i = \sum_{k=1}^{K}(TX_k \times \sum_{j=1}^{N} X_{i,j,k}). \tag{15}$$

Accordingly, the optimal solution to MTTP can be derived by solving the following constrained optimization problem:

$$\min \sum_{i=1}^{N-1} p_i, \tag{16}$$

subject to [2 3 4 5 6 7 12 13 14 15].

Although the above ILP model gives the optimal solution to MTTP, it is time consuming. In order to strike a balance between the scheduling overhead and the system performance, we propose a heuristic algorithm as follows.

B. Heuristic: Nearest-to-Sink Algorithm

In this section, we propose a heuristic algorithm named *Nearest-to-Sink* to construct a congestion-free convergecast tree and achieve near optimal energy cost. The algorithm begins with the node which is the farthest to the Sink and starts iteratively finding the next hop from other nodes in a greedy strategy. The process of iteration in *Nearest-to-Sink* is similar with the Kruskal algorithm of Minimum Spanning Tree. Both Kruskal and *Nearest-to-Sink* add an edge with minimum weight to the forest if it connects two different trees. However, the edge adding proceeding of *Nearest-to-Sink* follows a rule that the node which is farther to the Sink finds its next hop before the ones which is closer to the Sink. The main idea of the greedy strategy in *Nearest-to-Sink* is that a node tries to find a feasible next hop as close to the Sink as possible with a low transmission power. A feasible next hop means that the bandwidth between the sender and the receiver is no less than the link throughput. The algorithm follows the following greedy strategies.

- Step 1 (Algorithm IV.1): A node i tries to find a feasible next hop which is closer to the Sink than itself with the lowest transmission power. If there exist more than one feasible next hops, the one which is the nearest to the Sink will be chosen. If there is no feasible next hop in the transmission range of i, the algorithm tries to increase the transmission power of i to increase the bandwidth of links as well as find more neighbors.

Algorithm IV.1 Nearest-to-Sink Algorithm

Require: A graph $G = \{V, SR, D\}$, K, TX_k, $Band$, SB
Ensure: The power level and next hop of each sensor node in G
Initiate $V_{Calculated}$ and $V_{NotCalculated}$ to be $\emptyset$ and V, respectively. $pl_{min} \leftarrow 1$. For each node i in V, set the $throughput_i$, pl_i to be sr_i and pl_{min}, respectively.
while $V_{NotCaculated}$ is not $\emptyset$ **do**
  Find a node i that $d_{i,sink}$ is the largest in $V_{NotCalculated}$.
  repeat
    Find a feasible next hop j for the node i, where the node j is the nearest node to the Sink in the transmission range R_{pl_i} of node i and $d_{j,sink} < d_{i,sink}$. If not exist a node j, $pl_i \leftarrow pl_i + 1$.
  until ($pl_i > K$) or (Exist a node j)
  if Exist a node j **then**
    Update $throughput_i$ and $throughput_j$, record pl_i and next hop j of i, put node i in $V_{Calculated}$.
  else
    Record the tree rooted at i in $Tree_i$.
    Invoke Algorithm IV.2 to prune the tree rooted at i.
  end if
end while

- Step 2 (Algorithm IV.2): If the transmission power of i has been adjusted to the maximum and there is still no feasible next hop, the node i tries to reduce its throughput by pruning a subtree. A subtree rooted at node s will be pruned and the iteration of *Nearest-to-Sink* will restart from s (i.e. the root node of the pruned subtree). The node i will not be considered as a feasible next hop of s again. As for which subtree will be pruned, the idea is that the node s is the nearest node to the Sink and i is the next hop of s.

Algorithm IV.2 Pruning(node i)

Find a node s that $d_{s,sink}$ is the smallest from among the nodes selecting i as their next hop.
if Exits a node s **then**
  Update $throughput_i$.
  repeat
    Find a feasible next hop j for the node s, where the node j is the nearest node to the Sink in the transmission range R_{pl_s} of node s and $d_{j,sink} < d_{s,sink}$. If not exist a node j, $pl_s \leftarrow pl_s + 1$.
  until ($pl_s > K$) or (Exist a node j)
  if Exist a node j **then**
    while Node j is in the node set $V_{Calculated}$. **do**
      Find the next hop e of node j, update $throughput_e$. Restore the node j to the initiate state, put the node j in $V_{NotCalculated}$. $j \leftarrow e$.
    end while
    Update $throughput_j$, record the pl_s and next hop j of s.
  else
    If s is a leaf node, invoke Algorithm IV.3 to deal with the black hole node s, otherwise, invoke Algorithm IV.2 to prune the tree rooted at s.
  end if
else
  Invoke Algorithm IV.3 to deal with the black hole node i.
end if

- Step 3 (Algorithm IV.3): If a feasible next hop cannot be found by the above two steps, the node i will be denoted as a virtual 'black hole node' (In the field of geographic routing [24], a node is called 'black hole node' if it has no neighbor closer to the destination). The virtual black hole node i will try to find a next hop following the process of above two steps, excepting that the node i will find a next hop from the node which is farther to the Sink than itself in step one. If there is still no feasible node found, the algorithm terminates and returns no feasible solution.

V. Performance Evaluation

A. Setup

Simulations are carried out over graphs randomly generated by OPNET with node densities varying from $0.05 node/mile^2$ to $0.6 node/mile^2$ and node scope from 5 to 500. The simulation platform used to solve ILP is 'Gurobi Optimizer' (Cutting planes algorithm). The transmission power TX_k is set to R_k^α and the signal power attenuation constant α is set to 3 [20]. Table II shows the bandwidth configuration ($SB(d, R_k)$), which is a common setting in related works [20]. There are four power levels. There is a fixed supported bandwidth given a certain power level and a distance. For example, in power level 4, when the distance between the two nodes is 2 to 3 miles, the supported bandwidth is 10 Mbps. The bandwidth is 0 when the node distance is beyond the transmission radius. We set that the same sampling rate for each node and examine sampling rate from $5kbps$ to $5000kbps$ in our experiments.

For performance comparison, we implement CTCCAA [2], which is a famous convergecasting technique in WSNs. As all the sensor nodes work in the same power level by CTCCAA, to give best performance, we adopt the tree constructed by CTCCAA with the minimum total transmission power which

Algorithm IV.3 Hole(node s)

Set pl_{temp} to be pl_{min}.
repeat
  Find a feasible next hop j for the node s, where the node j is the nearest node to the Sink in the transmission range $R_{pl_{temp}}$ of node s and $d_{j,sink} > d_{s,sink}$. If not exist a node j, $pl_{temp} \leftarrow pl_{temp} + 1$.
until ($pl_{temp} > K$) or (Exist a node j)
if Exist a node j **then**
  while Node j is in the node set $V_{Calculated}$. **do**
    Find the next hop e of node j, update $throughput_e$. Restore the node j to the initiate state, put the node j in $V_{NotCalculated}$. $j \leftarrow e$.
  end while
  Update the throughput of node j, record the power level pl_{temp} and next hop j of s.
else
  Find the next hop j of node s in $Tree_i$.
  if Exist a node j **then**
    Update $throughput_j$, invoke Algorithm IV.3 to deal with the black hole node j.
  else
    $pl_{min} \leftarrow pl_{min} + 1$.
    if $pl_{min} > K$ **then**
      There is no solution for the problem, **Exit**.
    else
      Initiate the power level of each node in G to be pl_{min}, reset the throughput of all the nodes to be its sample rate, restore all the nodes in the node set $V_{Calculated}$ to the initiate state. Reset $V_{Calculated}$ and $V_{NotCalculated}$ to be $\emptyset$ and V, respectively.
    end if
  end if
end if

TABLE II. THE SUPPORTED BANDWIDTH UNDER DIFFERENT SCENARIOS

Parameters			Supported	Parameters			Supported
Power level	Radius (miles)	Distance (miles)	Bandwidth (Mbps)	Power level	Radius (miles)	Distance (miles)	Bandwidth (Mbps)
1	2	$2 < d$	0	3	4	$4 < d$	0
		$1.2 < d \le 2$	2			$3 < d \le 4$	2
		$0.7 < d \le 1.2$	5			$2 < d \le 3$	5
		$0.5 < d \le 0.7$	10			$1 < d \le 2$	10
		$0.4 < d \le 0.5$	20			$0.8 < d \le 1$	20
		$0.2 < d \le 0.4$	30			$0.5 < d \le 0.8$	30
		$0.1 < d \le 0.2$	40			$0.3 < d \le 0.5$	40
		$0 < d \le 0.1$	75			$0 < d \le 0.3$	75
2	3	$3 < d$	0	4	5	$5 < d$	0
		$2 < d \le 3$	2			$4 < d \le 5$	2
		$1.3 < d \le 2$	5			$3 < d \le 4$	5
		$0.8 < d \le 1.3$	10			$2 < d \le 3$	10
		$0.5 < d \le 0.8$	20			$1.5 < d \le 2$	20
		$0.4 < d \le 0.5$	30			$1 < d \le 1.5$	30
		$0.2 < d \le 0.4$	40			$0.5 < d \le 1$	40
		$0 < d \le 0.2$	75			$0 < d \le 0.5$	75

can enable congestion-free convergecasting. We evaluate the performance with two metrics, namely, the total transmission power and the maximum supported sampling rate. We compare the total transmission power among *Optimal ILP*, *Nearest-to-Sink* and CTCCAA with different node densities. The result of *Optimal ILP* is the minimum. Comparing *Nearest-to-Sink* with *Optimal ILP* and CTCCAA, we will verify the performance of *Nearest-to-Sink* in terms of achieving balance between scheduling overhead and energy-efficiency. For the

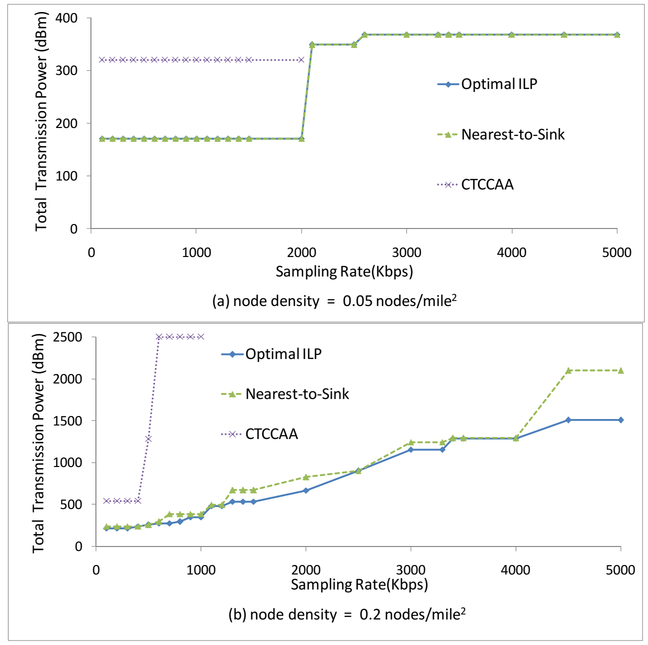

Fig. 2. Total transmission power vs. Sampling rate

metric of maximum supported sampling rate, we evaluate the performance with different number of nodes for the purpose of demonstrating the scalability of *Nearest-to-Sink*.

B. Experimental Results

1) Total transmission power: This set of experiments examines the performance of algorithms in terms of energy-efficiency. Figure 2 shows the result of total transmission power versus different sampling rates. For example, in Figure 2(b), when the sampling rate of each node is $2000kbps$, *Nearest-to-Sink* locates the solution of 825 total transmission power. The performance of *Nearest-to-Sink* is always very close to the optimal result. Especially, when the node density is not high as shown in Figure 2(a), *Nearest-to-Sink* performs completely the same with the optimal result under different sampling rates (i.e. the two lines representing *Nearest-to-Sink* and *optimal ILP* are overlapped). Even in high node density networks, *Nearest-to-Sink* still performs near optimal as shown in Figure 2(b). Meanwhile, we observe that *Nearest-to-Sink* always outperforms *CTCCAA* significantly. Note that the line representing CTCCAA stops when the sampling rate exceeds certain threshold. For example, in Figure 2(a), the CTCCAA line stops after $2000kbps$. This is because CTCCAA can not find a congestion-free solution in such settings.

2) Maximum supported sampling rate: This set of experiments examines the performance of algorithms in terms of maximum supported sampling rates under different number of nodes. For example, as shown in Figure 3, when the network has 50 nodes, *Nearest-to-Sink* can derive congestion-free solution when the sampling rate of each node is upto $760kbps$, whereas *CTCCAA* is only support the maximum sampling rate of $280kbps$. The superiority achieved by *Nearest-to-Sink* is mainly due to the designed pruning strategy, which efficiently avoid the congestion. As shown, *Nearest-to-Sink* constantly

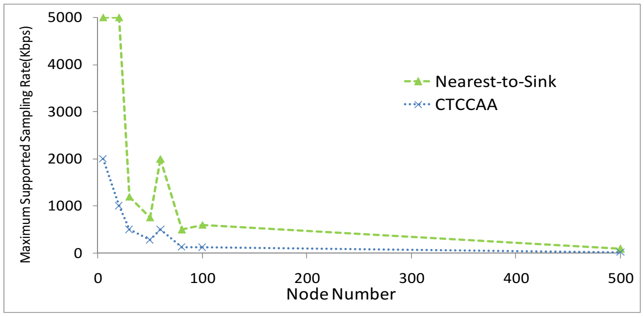

Fig. 3. Maximum Supported Sampling Rate under Different Number of Nodes

outperforms *CTCCAA* in all ranges, which demonstrates the scalability of the algorithm.

VI. Conclusion and Future Work

In this paper, we have explored the problem of jointing power allocation and convergecast in WSNs. We formulate MTTP by considering the dynamic network topology and the bandwidth constraint. The objective of MTTP is to minimize the total transmission power and achieve a congestion-free convergecast. First, we propose an ILP model to formulate the problem and derive the optimal solution to MTTP. Then, we propose a heuristic algorithm called *Nearest-to-Sink*, which constructs the routing tree in a greedy way for the sake of saving the transmission power and enabling congestion-free convergecasting. We build the simulation model using OPNET and implement CTCCAA for performance comparison. The comprehensive simulation results demonstrate that *Nearest-to-Sink* can achieve near optimal performance and outperform CTCCAA significantly.

In WSNs, it is necessary to consider energy balance to prolong entire network lifetime. In our future work, we will incorporate the issue of energy balance into consideration and further enhance the system performance.

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